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NAVAL TACTICAL DECISION AIDS

Daniel H. Wagner

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NAVAL TACTICAL DECISION AIDS

Lecture Notes

by

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Monterey, California

FOREWORD

Interest in Tactical Decision Aids is a healthy trend in the operations analysis profession, carrying us back toward our roots, which were the application of scientific methods to improve the effectiveness of forces in combat. I mean here to emphasize the grounding of OA in field operations as it was documented by Philip Morse and George Kimball in *Methods of Operations Research* shortly after World War II, in contra-distinction from what in many minds later became its principal application, the selection and procurement of better weapon systems, exemplified by another fundamental work, Charles Hitch and R. N. McKean's *The Economics of Defense in the Nuclear Age*. The former is characterized by tactics for specific weapons in specific theaters against a comparatively well defined threat. The latter deals with new sensors and weapons designed on paper to operate against an ill-defined threat in a problematic environment. The former has withstood the test of time; the latter has led to disappointment and skepticism. The former has been marked by close collaboration between the analyst-developer and the tactician-user, which was a basic premise of Morse and Kimball. The latter was and occasionally still is marked by decisions through analysis without the collaboration of the uniformed user of the new weapon system. The former dealt with tactical decisions in which every second counted, the latter with results so remote that its decisions were made months--or years--later. With the former the consequences of a decision were immediate, obvious, and sometimes decisive; with the latter decisions were made, unmade, and remade until it was hard to trace the link between analysis and statecraft in the weapon's final characteristics.

We may hope that this book will hasten the development of and peacetime practice with TDAs by illustrating in sufficient detail how they work. It will be clear that both the development and employment of TDAs are an art form, and their wise application is the result of line officers' thorough understanding of both TDAs and naval operations.

The developer-user partnership is so basic that it requires illustration. Without defining the following two systems in or out of the TDA domain (the boundary is exceedingly fuzzy), let us look at aids to maneuver and navigation, because all line officers are intimately familiar with both. They are not only well understood, but more robust and thoroughly developed from constant *peacetime* use than any combat TDAs described herein.

Throughout my seagoing career a maneuvering board was the simple, basic, but ingenious aid to maneuver. Its value was taken for granted, so well appreciated that it was taught in school and every new line officer reporting to his ship or aircraft squadron was assumed to know its mechanics and be able to work out solutions in seconds that would take minutes (or forever) if he had to do the trigonometry. But a new officer was truly skilled only after several months of practice at sea.

Take, for instance, the simplest of problems, maneuvering from one station to another with respect to the guide. The relative motion of the ship is the input and its true course and speed to station the output. But a maneuvering board solution is based on instantaneous course and speed changes. One won't end up on station without taking the motion of the guide into account during the final turn onto station. The need to supplement the mathematical (scientific) skill with the maneuvering board with the seaman's (artistic) skill of judging motion in a turn is one of the first humbling experiences of a JOOD on the bridge. Without seamanship his ship will at best be embarrassingly off station, at worst be in a collision. I am not the only officer to witness the latter. In the instance I observed, the maneuvering destroyer was darkened on an ink-black night off Korea and both she and the guide were changing course simultaneously. Radar and the maneuvering board were insufficient guides.

The second example is position keeping out of sight of land. Having done more than the average line officer's share of celestial navigation, I was delighted to learn late in professional life that (a) I could throw away those awkward chronometers and use any watch with a quartz crystal to keep accurate time, and (b) I could solve the mathematics of the celestial triangle by pressing a few keys on a hand held calculator. If I was going to repeat the operation very often I could also preprogram the computations involved.

But I still had to shoot the stars (lots of them in my case) and carry the pubs (I used the Air Almanac and H. O. 249 on the basis that I couldn't shoot the altitude of a star closer than a 60th of a degree, so why compute to a 600th of a degree?). Now we have navigation systems that employ their own accurately placed stars called satellites, that imbed the clock, publications, and computation in the system software, and that produce virtually instantaneously at the touch of a button a fix the accuracy of which was unimaginable by Columbus, Matthew F. Maury or me.

Observe, however, that the perfect fix tells you only where you are, not where you want to go. With some more computation the nav aid can be made to tell you (within less stringent limits) where you are going and how fast, but not where you want to be. We even have some new aids, some of which will be described herein, that will tell you (with still less accuracy) how to go somewhere to reduce hazards like the weather and the enemy, but no navigation aid purports to dictate your destination or purpose. Naive resistance to decision aids based on some presumed arrogation of the human decision process rests on ignorance of the aims, means, and ends of the aids and of the role of the decision maker. Because of great experience with them the resistance to the use of navigation aids is past, and all concerns are over backup systems in case our satellites are destroyed or the nav aid is otherwise compromised.

I believe that TDAs for combat operations, many of which are described in this work by Daniel H. Wagner, would be farther advanced if their wartime utility was as obvious and appreciated as nav aids are now. Our operational skills are finely honed for things we do every day at sea: launch and land aircraft, underway replenishment alongside, vertical replenishment and transfer, navigation, piloting and maneuver. Wagner's work shows much of what has been done and by implication what might have been done to hasten the development of aids for naval combat--the detection, identification by correlation, tracking, targeting, and delivery of ordnance on the enemy and the avoidance of the same by the enemy. It will take a change of emphasis, but not a great one, to bring along these wartime aids with the energy that has gone into aids to safe operations in peacetime.

Communicating the workings of a TDA takes a rare balance of verbal, mathematical, and computer skills. If I had thought about it, I'd probably have said this book could not be written. But if somebody had asked who could write it I'd have said fewer than 10 Americans, living or dead; that I only knew four or five of them all of whom worked or had worked for Daniel H. Wagner, Associates; and the best man to write about TDAs was Wagner himself. And so he has. This will be the seminal work in the field as basic as Morse and Kimball, Hitch and McKean, or B. O. Koopman's *Search and Screening*. It was assembled in the short space of a year, and so it will not satisfy anyone in every respect, including me, and least of all Dan himself. But the book shows what can be done--must be done--if TDAs are going to move ahead with the vigor that is possible.

There are many references to Wagner Associates in this work. That is partly because an author writes best about what he knows best, but also because Wagner Associates have been so much in the maelstrom of TDA development. It is not, I'm sure, self-aggrandizement: I can think of two or three successes of great merit which go unmentioned because they did not strictly speaking advance the science of TDAs--the Suez Canal ordnance clearance project being one.

The historical track record herein is invaluable perspective, including the professional relationship between the civilian and uniformed analysts and their operator users. Its great virtue is, however, that it describes TDAs with the *right* amount of detail, so that the student (not the casual reader) can grasp how they are put together and what each aid does and does not do. The student by the end knows what aids are for and how future aids will probably work and the proper relationship between aid and user, much like the relationship between the maneuvering board's geometric contribution and the seaman's educated eye.

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PREFACE

These lecture notes are intended as an instruction text for a course in development and evaluation of tactical decision aids (TDAs) at the Naval Postgraduate School. I began their preparation during a student-faculty seminar course on the subject at the School in the Fall quarter 1988.

While there has been considerable naval activity in development and use of TDAs on desk-top computers in the past decade, there does not appear to be a general text on the subject. There also does not appear to have been developed a general theory of TDAs, and that is not intended here. What is done here is a review of the models in and the functionality and inputs and outputs of several TDAs in some important areas of naval applications. These areas are search TDAs, target motion analysis TDAs, integrated TDAs for battle group command, and environment-dominated TDAs. It must be expected that many, perhaps most, of the TDAs reviewed here will be superceded in a few years or so, but I believe that lessons learned from such reviews will be instructively helpful to future developmental approaches.

User-friendliness is fundamentally important to TDA success, and Appendix A by LCDR John Yurchak of the School's Computer Science faculty addresses that subject. Although Appendix A is presented in terms of computer rather than tactical considerations, it is written from the background of LCDR Yurchak's Fleet experience, primarily as a tactical air controller in E-2 carrier-based airborne early warning aircraft. Training and user's guides for TDAs and some mathematical topics that are relevant to TDAs are discussed in other appendices.

Each chapter after the introduction contains a history of the subject of that chapter. I believe that historical perspectives and lessons learned from history can be useful when one is contemplating new TDA development. The historical discussions are also the means by which I attempt to credit numerous contributions to TDA development over the years.

I hope I will be forgiven for rather frequent historical mention of the operations research consulting firm, Daniel H. Wagner, Associates (abbreviated as DHWA hereafter), with which I was previously associated for almost 25 years. The same remark applies to alumni of DHWA. The fact is that DHWA has been very active in naval TDA development primarily through its Fleet field representatives in past years, especially in computer-assisted search, and I must acknowledge the contributions of these former colleagues along with those of many others. I have earnestly endeavored to cover the more important contributions to naval TDA development by all individuals of whom I am aware. I have tried to prevent my pride in DHWA accomplishments from interfering with my objectivity, but it is possible that that attempt has not entirely succeeded. On the other hand, in reviewing models of former colleagues, in some ways I believe I have been harder on them than other reviewers would have been. It is easier to find reservations on even good OR models than it is to create such models.

My DHWA experience is the main part of the TDA knowledge base from which I write. That base has been considerably enhanced by my experience at the Naval Postgraduate School. Its earlier roots were, long before desk-top computers, in my experience as a Fleet field representative of the OPNAV Operations Evaluation Group (after which I tried to pattern DHWA field representation) and in consulting on naval problems in partnership with John Kettelle.

Since the primary intended readership of this work is the students of the Naval Postgraduate School, I have tried to identify alumni of the School as such among the contributors to TDA development. It will come as no surprise that these identifications are very numerous, and I am certain that there are *many* alumni and other naval and civilian contributors whom I have not identified.

This alumni identification and my hope that reader interest will extend beyond the School give rise to another plea for forgiveness: I hope that the management of the School will pardon my use of "NPGS" as an abbreviation of the School, rather than the locally used "NPS." My reason is that outside of the Monterey Peninsula, this institution is known and highly esteemed throughout the naval community as "the PG School," hence "NPGS" has more immediate reader recognition. (Locally "PG" means Pacific Grove.)

Throughout, all officers referred to are USN unless otherwise identified.

I must make *numerous* grateful acknowledgements for support and assistance in the preparation of this text.

First of all I feel highly privileged to be spending 15 months on the distinguished operations research faculty of the Naval Postgraduate School. I especially appreciate the opportunity to spend a majority of this tour on the above-mentioned TDA seminar course and this text. For arranging this opportunity, I particularly thank Professor Peter Purdue, Chairman, Department of Operations Research; Professor R. Neagle Forrest, Chairman, ASW Academic Group; and CAPT Gordon Nakagawa, Tactical Analysis Chair. For CAPT Nakagawa's support, I further thank CAPT Thomas Latendresse, OP-73, and his deputy, CAPT Thomas Ferguson.

Needless to say, views expressed herein are my own and do not purport to reflect policy of the Naval Postgraduate School, the Chief of Naval Operations, or the Department of the Navy.

The initial impetus for this text came from discussion with Dr. Stanley Benkoski, Vice President of DHWA and a prominent leader in TDA development. His seminar lecture at NPGS September 1988 on evaluation of search TDAs is my primary source on TDA evaluation. He has been a frequent source of useful information and critiques.

I greatly appreciate the stimulus I have received from the interest and advice of various NPGS faculty colleagues and students through their participation in my TDA seminar and in other ways. Foremost among these has been Professor Alan Washburn, who is well-known as a researcher and author in search theory and other areas of naval OR. I am especially grateful to retired CAPT and Professor Wayne Hughes for his insightful and generous foreword and his extremely helpful critiques; his book *Fleet Tactics: Theory and Practice* exhibits a depth of naval knowledge, analytical perception of operations, and literacy that I have long admired and envied. Others include Professor David

Schrady, former NPGS Provost, who is undertaking promising initiatives for an at-sea logistics TDA linked to combat requirements; Professor Ferdinand Neider, whose OEG/CNA field experience, particularly with JOTS, was very helpful; and Professor James Eagle, whose prowess in operations research is enriched by his experience as a submariner. Among the more helpful students, I am pleased to cite LCDR Richard Chase, LT Carl Plumley, LT Craig Steffen, LT Fred Buoni, LT Craig Goodman, LT Robert Rubin, and CDR Bernabe Cuberos Carrero of the Venezuelan Navy.

For discussions in depth of TDA models and historical questions and for critiques, I am very grateful to Drs. W. Reynolds Monach, Robert Lipshutz, Michael Monticino, Walter Stromquist, Robert Overton, Robert Buemi, Bernard McCabe, David Kierstead, Barry Belkin, James Weisinger, and Joseph Discenza of DHWA; Drs. Lawrence Stone, Henry Richardson, Thomas Corwin, and William Stevens of Metron, Incorporated; Dr. David Bossard of DCBossard, Inc.; Dr. William Barker of Tiburon Systems; Richard Handford of Atlantic Analysis Corporation; Vincent Aidala of the Naval Underwater Systems Center, Newport; Michael Sierchio of the Naval Environmental Prediction Research Facility; and Lawrence Hermanson and Dr. Mark Shensa of the Naval Ocean Systems Center.

The Naval Air Development Center provided me with valuable help from Walter Leyland and Patricia Beach by critiques of the Integrated Tactical Decision Aids (ITDA) discussions, and from Kathleen Stempeck by advice on operation of ITDA programs. Drs. David Engel and Frank Engel of the Inter-National Research Institute were very helpful on the history of the Joint Operational Tactical System (JOTS).

For the history of submarine target motion analysis I leaned heavily on Gerald Hill, and Dr. Adrianus Van Woerkom of the Naval Underwater Systems Center; David Ghen, Thomas Downie, A. Theodore Mollegen, and Harold Jarvis of Analysis and Technology, Incorporated; William Berry of Raytheon Corporation; Cort Devoe of Sonalysts Incorporated; Joseph Faulkner of Mandex Incorporated; Lyle Anderson of Mitre Corporation; Richard Abate and James Herring of the Electric Boat Division, General Dynamics Corporation and Dr. William Queen, formerly of that organization; Dr. Wouter Vanderkulk, retired from IBM; and retired CAPTs John Fagan, Arthur Gilmore, Frank Andrews and Charles Woods. CAPTs Andrews and Woods were among the foremost leaders in naval tactical analysis in the 1960's, as Commander Submarine Development Group Two and in other capacities. Ronald Thuleen of the Naval Ocean Systems Center and LCDR John Oakes of the Surface Warfare Development Group were my principal sources on surface ship target motion analysis.

Very helpful documents and review comments on submarine TDAs were received from LCDR Alan Richardson, LT Paul Ruud, and James Seaton of the staff of Commander Submarine Development Squadron Twelve.

CPT Alan Womble, USMC, of the Naval Strike Warfare Center gave Professor Washburn and me a very instructive demonstration of the Tactical Aircraft Mission Planning System.

Dr. Samson Brand, Lawrence Phegley, and others at the Naval Environmen-tal Prediction Research Facility were excellent sources and reviewers on the Tactical Environmental Support System. AGC Daniel Boucher of the Geographic Technical Readiness Laboratory helped by operating this system for my needs.

Robert Miller, retired from the Office of Naval Research, and CAPT Andrews substantially expanded and corrected my recollections of the origins of the OPNAV Tactical Development and Evaluation Program.

William Thompson of the NPGS War-Gaming Laboratory and its director, CDR Thomas Halwachs, were very helpful with hardware and software problems.

The Research Reports personnel of the NPGS Library were very effective at unearthing aged documents from various naval archives.

Hania La Born prepared the typescript and computer graphics with enormous dedication, patience, and expertise in desk-top publishing software.

For all of this help, I am profoundly grateful.

Daniel H. Wagner,
Adjunct Professor

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CHAPTER I

INTRODUCTION

This text is intended to provide instruction in the development and evaluation of tactical decision aids (TDAs). The application areas that we consider are predominantly in naval combat operations. Many of the principles involved should have applications in other military operations.

1.1. Background

A TDA should assist a decision-maker by (1) assimilation and convenient presentation of data (on targets, own assets, and the environment) which of themselves are useful to the decision-maker, and/or (2) analysis of the tactical problem beyond what is feasible by humans in timely fashion. Needless to say, none of this obviates thought, insight, or judgment on the part of the decision-maker, who by definition bears the responsibility for the course of action resulting from the decision.

TDAs can have the form of various types of design products, including nomographs, manuals, etc. The noted naval author W. P. Hughes suggests that the most useful TDA is the maneuvering board. However, our main focus will be on TDA programs resident on desk-top calculators (DTC's). These started to have use in Fleet operations in the mid-1970's and have burgeoned in power and applicability in the 1980's. Adoption by the Navy of the HP 9020A in July 1984 as its standard DTC was an important advance in at-sea computer assistance to operations, particularly as a vehicle for TDAs.

User-friendliness problems in TDAs quickly come to the fore. The power and broad scope of computer assistance *may* be accompanied by complexities and time demands on the user. These can burden the user's attention and time schedule in competition with various demands on the user from other duties and requirements for mastery of technology. Hopefully, (1) above will result in a net saving of staff time in TDA use. When a TDA requires a net *increase* in staff effort, that should be weighed against increase in combat effectiveness as a result of (1) and (2) combined.

Advice on user-friendliness in TDA design is offered in Appendix A, by LCDR John Yurchak of the NPGS computer science faculty. User-friendliness in TDA user's guides and TDA training needs are addressed in Appendix E.

TDAs are closely associated with the applied science operations research (OR), which is usually defined as providing a scientific basis for executive decision. While OR results do not *need* to be associated with computers, as applied to Fleet operations in the 1980's they usually have been. When the type of decision problem addressed recurs somewhat repetitively *in form*, TDA implementation usually results. It was these observations that provided the main impetus for this text and the NPGS seminar course in which it was initiated.

Reference [a] is a justly acclaimed text on tactics at the level of a numbered fleet commander. It is highly readable and is particularly strong on historical themes in tactics at that level. The present work is generally on tactics at the *unit* level, i.e., for a ship, an air squadron, or an aircraft. This is largely true even in our discussion of integrated TDAs for a battle group commander. The following remarks from reference [a] about the role of TDAs in C^2 are very relevant to our present topic:

> "To develop a C^2 system, including command responsibilities, staff activities, and hardware and software to support them, the tactical content of operations must be envisioned in more detail. From the outset the difficulty of agreeing on tactical goals and the style of effective command has plagued the necessarily detailed design of systems for a navy tactical flag center. *Where there is no agreement, the alternative is to design the command center and all other C^2 support in the absence of tactical content; by default tactics will be dictated by C^2 support-system designs and locations.* [Emphasis added by the author of reference [a].]
>
> A commander and his staff synthesize information, using decision support systems when they will help do the job better. Today modern displays, geographic and alphanumeric, assist in this process. So does artificial intelligence, which emulates the thinking process and (when it surpasses that process) automatically makes decisions. I do not have an example of a military command decision aid that unequivocally decides better than the human mind. But there are many that do part of the job better. Some weapon fire-control systems assign priorities to threats, lay guns, and fire missiles without human modification, and they have existed since World War II. At least one AAW missile system, while still subject to human intervention and override, is designed to operate on a preprogrammed tactical doctrine."

Ensuing remarks in reference [a] discuss the importance of *time*-to-decision, which can be, but not always is, saved by TDAs and the importance of *timing of* decisions.

Reference [b] addresses TDAs at the level considered here, but does so entirely with the objective of identifying needs for better mathematical methods as such. Its scope is less than originally intended.

The approach taken here is to review the methodology underlying various naval TDAs and their functionality and to seek methods, preferably methodological themes, which potentially apply to future TDAs. Beyond finding *techniques* which apply to future development, we hope to enhance development capabilities by conveying *ideas* involved.

1.2. Summary by Chapters and Appendices

Chapter II addresses search TDAs, predominantly ASW computer-assisted search (CAS). This is a well-developed TDA area. Monte Carlo methods are extensively discussed, with emphasis on representing target motion as a bundle of sample tracks, each with probability of occurrence. These probabilities may be easily updated to reflect, e.g., unsuccessful search, thereby revising (by Bayes' rule) one's earlier assumptions on target motion as well as position.

Analytic approaches are also discussed, mainly via a contemporary development. Integration of search with tracking in TDAs via likelihood estimation from contact/no contact histories is described for both Monte Carlo and analytic CAS systems. We distinguish between CAS and SSN search TDAs in that the latter, although very well developed, do not produce probability maps of target position and updating of same. COMSUBDEVRON TWELVE is the long-standing seat of SSN tactical development and evaluation and has put considerable emphasis on search and target motion analysis methods.

Target motion analysis (TMA) TDAs are reviewed in Chapter III. The problem is to find target position, course, and speed by passive means. Methods of doing this are vital to SSN missions, and accordingly this TDA area is also well developed. In fact, TMA is probably the TDA area of greatest Fleet acceptance and use. The main general approaches reviewed are bearings-only ranging with non-redundant bearings, adjustment of a trial solution to make its implied bearings match observed bearings, hyperbolic ranging with towed arrays, and, in over-the-horizon TMA against maneuvering targets, Kalman filtering based on target motion modeled as an IOU process. All four of these approaches have been used aboard SSNs both in DTC programs and/or embedded software.

Integrated TDAs to serve a battle group commander and his subordinate warfare commanders are taken up in Chapter IV. Here "integrated" refers to serving the separate warfare areas with a common data base, data management, and executive functions to call any of numerous special-purpose programs through a hierarchy of menus. The integrated TDAs of main interest are JOTS, developed at sea in initial prototype form September 1982, sponsored by COMNAVAIRLANT and later CINCLANTFLT, and the later ITDA sponsored by OP-73 and NADC. Both JOTS and ITDA are on the HP 9020A DTC.

JOTS has afforded major advances in C^3 by providing connectivity between shipboard DTC's and Fleet digital data links. This has given convenient access to link information by any ship with a Navy standard DTC. Use of JOTS for transmission of contact data, status boards, and other formatted communications has become widespread. These C^3 functions have overshadowed the warfare-specific TDAs in JOTS, in development and applications, but they have also made JOTS an excellent receptacle for such TDAs by affording data access, transmission of decided courses of action, and frequent attention by senior officers to JOTS outputs. ITDA is also very attractive as a receptacle for TDAs, having excellent environmental data bases and well-developed warfare-specific TDAs in place. Paradoxically, the C^3 activity of JOTS has crowded the access to HP 9020s at sea by ITDA, which since 1985 has received much more warfare-specific TDA development than JOTS, and by other TDAs. Plausibly this will be overcome by adapting JOTS to UNIX in the prospective new Navy standard DTC, thereby affording user time-sharing, but space for terminals will still be a problem.

Some environment-dominated TDAs are discussed in Chapter V. These are selected from TESS, the Tactical Environmental Support System, on the basis of involving tactical analysis along with the environmental inputs. TESS is sponsored by the Oceanographer of the Navy through CNOC, NAVOCEANO, NORDA, and NEPRF.

Appendix A addresses user-friendliness in TDA design. Appendix B reviews some fundamentals of stochastic processes that are relevant to TDAs. Appendix C presents (λ,σ) approaches to modeling cumulative detection probability. A description of the IOU process and types of motion thus modeled is given, without use of mathematical formulas, in Appendix D, by W. R. Stromquist of DHWA. Appendix E addresses TDA training and user's guides.

1.3. Some Observations on Modeling in TDAs.

We make some observations on modeling in TDAs which should be borne out as the reader goes through the remaining chapters. We want to stress the point that the mathematics in modeling in useful TDAs is sometimes elementary, sometimes rather deep, and often at various shades in between. (These relative terms are in the eye of the beholder.) We generally do not go much into mathematics in this text although we try to convey what is going on in the more important models.

Indeed, a great deal of service to operational decisions can be rendered by convenient descriptive presentations based on straightforward calculations on deterministic kinematics and other familiar phenomena. This is particularly demonstrated in several of the warfare-specific TDAs and "support" functions in JOTS and ITDA. Considerable use is made in TDAs of elementary probability concepts, notably the probability maps of target position in computer-assisted search. Still other TDA modeling uses deterministic methods which are not so elementary, such as the orbital mechanics underlying the satellite vulnerability program in JOTS and ITDA.

Many tactical analysis problems and related TDAs involve target motion, which must be regarded as both uncertain and dynamic. The natural tool for treatment of dynamic uncertainty is a stochastic process. Here again the methods range from elementary to deep. An easily understood representation of a stochastic process is a bundle of sample tracks, each assigned a probability, noted above for Monte Carlo CAS and elaborated upon in Chapter II. Analytic methods tend to be more mathematical. For some useful tools, such as Poisson processes and Markov chains, the mathematics is relatively easy to explain. Probably the most mathematically challenging tool employed in TDAs is the IOU process (see next paragraph). However in 3.5 we present this tool in discretized form, as it is implemented in computers, avoiding the more difficult stochastic differential equation methods usually employed. In general, stochastic process methods are sufficiently useful in TDA development that we need to describe them, but we will try to avoid technical details and to use intuitive descriptions as feasible.

A common basis for a perhaps surprising amount of stochastic process methods in TDA modeling is the random tour, treated by A. R. Washburn in 1969 (see Appendix B and reference [c]). The IOU process in VPCAS and PACSEARCH historical analysis (Chapter II), in SALT buoy search optimization (Chapter II), in MTST tracking on maneuvering targets (Chapter III), and in ocean current modeling and chaff dispersion prediction (Chapter V) are all motivated as gaussian approximations to a random tour. Also, the Markov chain motion models in SALT target tracking (Chapter II) and in SCREEN EVAL in ITDA (Chapter IV) are discretizations of a random tour. The approximations lend themselves better to modeling and computation of desired outputs than does the random tour. The random tour basis is both easily described and physically realizable by operating vehicles (an IOU process is neither), and one can give operational meaning to IOU model parameters by identifying them with random tour parameters.

These preliminary remarks about stochastic processes are made because of their frequent use in development of (very pragmatic) TDAs, and also to observe the degree of commonality exhibited by random tours. It is not suggested that mathematics per se should have primary emphasis in a student's approach to TDA development.

The qualities that should be at the fore in the study of TDA methods are those needed for study of OR in tactical development and evaluation: tactical insight and a desire to bring disciplined quantitative methods, with user-friendly computer implementation, to bear on tactical decision problems, and thereby to assist tactical decision-makers to achieve more effective combat operations.

1.4. Main Ideas in TDA Modeling

We endeavor to summarize here in outline form several useful ideas found in past TDA development work that are contained in the remaining chapters and appendices. The attempt is to list these concepts in a logical sequence, not necessarily in order to importance:

Probability map representation of target position (2.2.1); easily understood basis for search planning.

Adaptive use of negative information, on target position and motion, from unsuccessful search (2.1.3, 2.2.3, others); valuable information that should not be ignored.

Multi-scenario priors of target initial position and motion (2.1.2, 2.4.3); well-tried means of utilizing information known before a search begins.

Target motion models:

probability-labeled alternative tracks (2.3.1, 2.4.3, B.2); very flexible, facilitates Monte Carlo analysis, easily understood; information and motion updates via track probabilities;

random tour and generalizations (B.5, 2.8.3, 2.4.3, 4.2.9); realizable by ship targets, computable by Markov chains;

IOU; approximates generalized random tour (B.7, Appendix D, 3.5.2, 2.5, 2.8.4); unlike latter leads to gaussian positions and velocities; robust re ship motion; facilitates capture of historical data base (2.5); has also modeled ocean drift (5.2) and atmospheric turbulence (5.5).

Cumulative detection probability (cdp) models (Appendix C); needed, e.g., for negative information updating; achieve sequential glimpse dependence via process representing deviation of actual from causally predicted signal excess:

(λ,σ); useable analytically (unimodal formulas (C.4, C.5)) and by Monte Carlo (2.4.5, 2.7); intuitively plausible, relatively simple model with sequential dependence; modest empirical basis;

time-independent contributions to deviation process; can enhance realism in (λ,σ); generally requires Monte Carlo;

random search formula (2.1.5, 4.2.3); simple; classic; generally pessimistic;

independence/dependence weighting; crude, apparently effective treatment of sensor *group* cdp (C.7, 2.4.5).

Optimal search planning:

optimal placement of uniform rectangular effort (2.4.6, 2.8.4, 5.2.4);

exposure time maps to approximate optimality by stationary target allocations (2.4.7);

Lagrange multipliers (reference [d] of Chapter II);

transformation of target motion to relative motion space to facilitate stationary allocation (4.2.2, 2.8.4);

evaluation of search effectiveness by acoustic sweep width (4.2.2, 2.8.4);

Brown/FAB recursive algorithm to allocate optimally in time and space (2.4.6);

SSN search planning by sequential choice of sonar lineup, depth plan, speed plan, and track plan, according to anticipated target tactic (2.1.14).

Integration of search with low-data-rate tracking:

likelihood of target state from contact/no contact history via

conditional independence, recursive computation (2.8.5),

independent inter-jump intervals, tunnel method (2.7.1);

Bayesian generalization of Dempster's rule heuristic (proposed, 2.7.2);

transitioning of course, speed, and scenario distributions during rescaling (2.6);

credibility estimation based on false target assumptions (proposed, 2.7.2).

High-data-rate tracking:

by Kalman filtering against constant course and speed targets (3.1);

by Kalman filtering against IOU model of maneuvering target motion, with forward-backward filtering, and extension via long-term/short-term velocities (3.5, Appendix D);

localization by maximization of Fisher information to minimize area of uncertainty (2.8.7).

Target motion analysis (TMA):

by adjusting trial solution to make implied bearings match observed bearings (3.3);

time correction: estimate range as of best range time, controlled by choice of tactic, to minimize error from target speed in line of sight (3.2); recognition of conflict between range accuracy and course/speed accuracy in four-bearing TMA (3.2);

Ekelund ranging: ratio of difference between pre-turn and post-turn own speeds to corresponding difference in bearing rates (3.2);

ranging from towed array hyperbolic loci of position (3.4);

wave front curvature (3.1).

Centralized integration of TDAs (Chapters IV and V):

common data bases for hostiles, friendlies, environment;

executive programs to manage TDA integration;

support functions: maps, formation and track builds, status boards, navigation, etc;

program organization per CWC organization.

Serving decision-making by elementary models:

deterministic kinematics (4.4.1, 4.4.2, 4.4.4);

convenient library retrieval and display (4.6);

elementary simulation (4.2.3, 4.2.5, 4.2.8).

ASW screen evaluation by simulation in depth (4.2.9).

Modeling complex rapid sequences (notably in ASMD) via deferring service of events until service is available (4.3.5).

Scheduling (of airborne refueling) by rule-based expert system (4.4.4).

Display of environmental constraints on ASM launch (5.3).

Optimal route planning to minimize multi-type costs by dynamic programming (5.4).

1.5. Lessons Learned in TDA Training

We close this introduction with emphasis on needs for training in use of TDAs. This topic is discussed further in Appendix E, and is accompanied by discussion of needs in TDA user's guides. The lessons learned in TDA training, from E.1, are summarized as follows:

(1) User communities must expect that TDA training needs will be commensurate with the depth of the TDA's functionality, which is the basis of the TDA's contribution to the mission.

(2) The main key to good TDA training is for the *importance* of the TDA to mission success to be recognized by the leadership, instructors, and trainees in the user community.

(3) Training in TDAs can be greatly enhanced by knowledgeable training initiative inside the user community.

(4) Training in TDAs, as all forms of combat readiness, must be maintained in the absence of immediate need for the TDA.

(5) Training which is confined to TDA operators training their reliefs has inadequate durability.

(6) A TDA which integrates subsidiary TDAs deserves separate training in those parts of the TDA that are of interest to a particular user community; training in support functions will be common to most user communities.

Training in a TDA must be supported by a user's guide which (a) has physical attributes that enhance readability; (b) has good guideposts to help a user find particular desired content; and (c) has content which describes *why* various steps are taken by the user.

References in Chapter I

[a] W. P. Hughes, *Fleet Tactics: Theory and Practice*, Naval Institute Press, 1986.

[b] L. D. Stone, D. D. Engel, and G. P. Pei, *Analytical Problems Related to Battle Group Decision Aids*, DHWA Report to Navy Tactical Support Activity, April 1984.

[c] A. R. Washburn, *Probability density of a moving particle*, Operations Research, Vol. 17, No. 5, September-October, 1969.

CHAPTER II

SEARCH TDAs

In this chapter we will review methods used in TDAs for search problems, which is a rather well-developed TDA area. Most search TDA applications are in ASW. Applications to search and rescue (SAR), ocean bottom search, and search for orbiting objects are also noted.

Most of this chapter will address computer-assisted search (CAS). As the term CAS is used here, it refers to a program that outputs a probability map of target position at any chosen time, suitably updated for unsuccessful search (negative information), target contacts of uncertain position and credibility (positive information), and target motion. The more advanced CAS programs also produce search plan recommendations.

To convey some of the basic concepts, we begin in 2.1 with an elementary example of search for a *stationary* target. Construction of a prior distribution of target position, updating for negative information, and optimal allocation of search effort are illustrated.

The main elements of a CAS system for a *moving* target are outlined in 2.2: a prior probability map of target position; a model of target motion; updates of the probability map for target motion, negative information (requires a model of cumulative detection probability), and positive information; and search plan recommendations.

A target motion model must represent motion as a probabilistic process, i.e., "stochastic process" (see Appendix B). In most CAS systems, this is done by Monte Carlo methods, as we will describe as part of a detailed review of the prominent CAS system VPCAS. Motion modeling can also be done by analytic methods, as we will see in discussing a new CAS development, SALT. Monte Carlo affords more flexibility in types of target motion, while analytic methods afford higher resolution in treatment of motion, which can be valuable in tracking. (This is not a full statement of relative merits.)

In a Monte Carlo approach, target motion is usually modeled as a "bundle" of tracks, each labeled with probability of occurrence. Updating of geographic cell probabilities for negative and positive information is performed via updates of the *track* probabilities. Thus the new information is used to revise our a priori assumption about target *motion* as well as initial position. This updating method is also very important to computational efficiency and to the power of Monte Carlo in CAS; it dates from 1972.

This Monte Carlo approach to CAS is illustrated in 2.3 by an idealized elementary example in which probabilistic target motion is represented by a bundle of only 16 tracks. The probability of occurrence of each track is derived from simple assumed distributions. The probabilistic behavior is quite visible, and the reader is urged to understand this example thoroughly as a prelude to 2.4.

In 2.4 we describe extensively how the ideas in 2.3 are implemented in VPCAS and its successors the COMTHIRDFLT/COSP program PACSEARCH (also in ITDA 2.02--see Chapter IV) and the CAS system going into the P-3C Update IV. The target motion bundle has 500 tracks rather than 16. Building blocks are described which afford a substantial variety of prior distributions of target position and target motions, from which to choose. We further describe the methods of optimal allocation of search effort used in VPCAS.

An historical analysis method usable with VPCAS to provide target motion assumptions is discussed in 2.5. This is illustrated in its PACSEARCH implementation.

In 2.6 we describe how VPCAS was enlarged as PACSEARCH to apply to fixed and towed arrays. Importantly, this included conversion of VPCAS to the HP 9020A, the Navy Standard Desktop Calculator. The long-term and short-term trackers in the P-3C Update IV search system are described in 2.7. The long-term tracker resembles VPCAS.

The recent CAS development SALT, using analytic rather than Monte Carlo methods, is described in 2.8. Differences are noted between SALT and VPCAS and successors, both inherent and as implemented. Estimates of target state likelihood are formed from complete histories of contact/no contact, by the Update IV short-term tracker using Monte Carlo and by SALT using analytic methods. SALT assumes conditional independence to permit recursive information updating. Neither Update IV nor SALT in general is able to retain *all* the information in the "complete histories."

CAS systems addressed to USCG SAR, ocean bottom search, and orbiting object search are noted in 2.9, 2.10, and 2.11. A CAS system for USN SAR will be reviewed in Chapter V.

Evaluation of CAS is discussed in 2.12. The history of CAS dates from 1972, in SAR and ASW. This is reviewed in 2.13.

SSN ASW search methods are discussed in 2.14. These are important, although they are not considered to be CAS, because they do not produce probability maps. They are concerned with sonar lineups, search depth schedules, speed schedules (constant or sprint-drift), and search track plans to oppose various target tactics.

Reference [a] is an article on the principal methods used in Monte Carlo CAS. An excellent tutorial on CAS, with very modest mathematical prerequisites, is given in reference [b]. References [c], [d], and [e] are texts on general methods in search analysis. Reference [f] is an update of reference [c]. Reference [g] is a manual for analysis of deep ocean search. Reference [h] is a review of search planning methods. The doctrinal publication on SSN ASW search is reference [i], which is the basis of the Submarine Fleet Mission Program Library (SFMPL) search programs.

2.1 Stationary Target

In this section we treat an elementary example of search for a stationary target, to illustrate some basic concepts which are very useful in CAS, for moving as well as stationary targets. Multi-scenario construction of a prior distribution, i.e., prior probability map, of target position; Bayesian updating for negative information; and optimal allocation of search effort are illustrated. Map discretization is discussed first.

2.1.1. Map discretization. In CAS applications, geographic positions in a search region are always shown by dividing the region into a rectangular array of discrete cells. A simple example of a 3 x 3 array of such cells is shown in Figure II-1 Here the cells are indexed 1, 2, 3 in latitude and the same in longitude. They could just as well be indexed by mid-latitudes and mid-longitudes of the cells.

FIGURE II-1. MULTI-SCENARIO CONSTRUCTION OF PRIOR DISTRIBUTION OF TARGET POSITION (STATIONARY TARGET)

(a) **Scenario I**
Weight = .7

Latitude Index \ Longitude Index	1	2	3
1	.1	.3	0
2	.3	.3	0
3	0	0	0

(b) **Scenario II**
Weight = .3

Latitude Index \ Longitude Index	1	2	3
1	0	0	0
2	0	.25	.25
3	0	.25	.25

(c) **Composite Scenario**

Latitude Index \ Longitude Index	1	2	3
1	.027	.21	0
2	.21	.285	.275
3	0	.075	.075

A CAS program usually chooses cell size, but it is desirable also to let the user change this choice, as is done in VPCAS and successors. The main factors influencing this choice are accuracies in placement of search effort and in estimation of positional probabilities. See reference [g].

2.1.2. Multi-scenario construction of a prior. In Figure II-1, two scenarios, I and II, are assumed. Each scenario is a postulation as to what caused the target to be wherever it is. Associated with each scenario is a distribution of target position which has been causally derived from that scenario. The distribution is given by assigning a number between 0 and 1 to each cell, with these numbers adding to 1. Each assigned number is the probability, before the search begins, that the target is in that cell, *providing* that scenario is valid. Also associated with each scenario is a number between 0 and 1 called the "scenario weight." The various weights (here two) also add to 1. Each weight is an estimate of the probability that that scenario is valid. It is usually arrived at by expert opinion and may be regarded as a "subjective probability."

The composite distribution is obtained by combining the single-scenario cell probabilities according to the scenario weights. E.g., the composite probability for latitude index 2 and longitude index 2 is

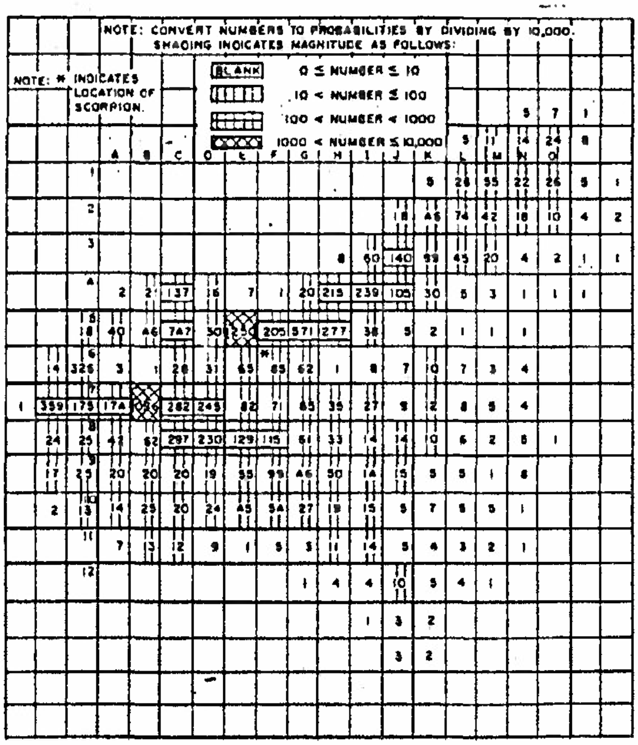
$$.3 \times .7 + .25 \times .3 = .285.$$

The distribution is also called the "probability map of target position" or "probability map" for short. In particular, it is the "prior probability map," further abbreviated as the "prior."

Figure II-2 presents a real-life prior, from the 1968 SCORPION search (reference [j]). It is constructed as a weighted composite of nine single-scenario

FIGURE II-2. PRIOR DISTRIBUTION OF TARGET POSITION IN THE SCORPION SEARCH

This prior was formed as a weighted sum of nine single-scenario priors, each causally derived, and computed by Monte Carlo simulation. The computation (stateside) was performed about six weeks into the five-month search, because of slow communications with the search scene.



priors, as above, and of course is much more complicated than Figure II-1. Among the scenarios were (I) SCORPION struck a sea mount and glided to the bottom, and (II) a torpedo turned active in a tube and SCORPION was unsuccessful in her maneuver prescribed for that emergency. For each of these and various other scenarios, a position distribution on the ocean bottom was causally derived, and scenario weights were obtained by expert opinion. Figure II-2 ensued. The remains were found within a submarine length of the highest probability cell, after a five-month search. Also, a distribution of bottom time of search effort was derived from this prior, and the actual bottom time was within reasonable confidence limits of the mean of this distribution.

2.1.3. Negative information update. We now illustrate an update for negative information. Suppose search effort is applied as in Figure II-3 to the above 3 x 3 array of cells. Figure II-3 is indicative only of quality and amount of search effort, and tells nothing about target presence. The latter remains as in Figure II-1(c).

Suppose this effort is unsuccessful. What is the new, i.e., posterior, probability map? We know that the target is now less likely to be in the cells searched than it was before, and consequently is more likely to be in the other cells. That is valuable information and should not be ignored, but how do we adjust the prior probability map accordingly? The answer, of course, is to apply Bayes' theorem. It is recommended that this be done and learned in spread sheet fashion as follows (of course, a CAS program would do this for us):

[1]	[2]	[3]	[4]	[5]=[4]/S
Cell lat/lng index (i,j)	Pre-search (prior) probability target is in (i,j)	Search *failure* probability *if* target is in (i,j)	[2] x [3]	Posterior probability target is in (i,j)
(1,1)	.07	1.0	.07	.085
(1,2)	.21	.7	.147	.179
(1,3)	0	1.0	0	0
(2,1)	.21	1.0	.21	.255
(2,2)	.285	.6	.171	.205
(2,3)	.075	1.0	.075	.091
(3,1)	0	1.0	0	0
(3,2)	.075	1.0	.075	.091
(3,3)	.075	1.0	.075	.091
	1.000		Total = S = .823	1.000

Column [4] is proportional to the posterior distribution. We normalize it by dividing it by its sum, S, resulting in the posterior, column [5], shown geographically in Figure II-4. This completes the Bayesian update for negative information.

2.1.4. Optimal allocation of search effort. The probabilities in Figure II-3 depend on the amount of search effort applied to the various cells. Usually a search planner can choose among various allocations of effort, cell by cell, and would prefer to so optimally.

FIGURE II-3. APPLICATION OF SEARCH EFFORT (STATIONARY TARGET)

Conditional probabilities that effort applied will detect target, *if* target is in the cell.

Longitude Index

Latitude Index	1	2	3
1	0	.3	0
2	0	.4	0
3	0	0	0

FIGURE II-4. PROBABILITY MAP UPDATED FOR NEGATIVE INFORMATION

Probabilities that a given cell contains the target given that the effort in Figure II-3 did not succeed in detection.

Longitude Index

Latitude Index	1	2	3
1	.085	.179	0
2	.255	.208	.091
3	0	.091	.091

To illustrate this, suppose the search is by an aircraft looking for a liferaft regarded as stationary. Suppose the nature of the search is such that the cumulative detection probability through search time t, cdp(t), is given by the random search formula (see reference [c]):

$$\text{cdp}(t) = 1 - \exp(-wvt/A),$$

where w is sweep width, v is search speed, and A is the area of the cell searched. Assume w = 30 nm, v = 200 kts, and A = 20,000 sq nm. Then

$$\text{cdp}(t) = 1 - \exp(-.3t).$$

(It might be that w, and accordingly the coefficient .3 in cdp, change from cell to cell, but let us assume here that they do not.)

Referring to Figure II-1(c), it is clear that initial effort should be applied to cell (2,2), since it has the highest probability of containing the target, .285. The question is how long should the search remain in (2,2) before putting effort into (1,2) and (2,1), which have the second highest prior probability of containing the target, .21? One might apply the Bayesian algorithm of 2.1.3 to find the value of t which drops the posterior probability in (2,2) to .21. However, that would ignore the fact that as the posterior probability falls in (2,2), it rises in (1,2) and (2,1). The solution, of course, is to find the t where these falling and rising posterior probabilities meet. Noting further that cumulative *failure* probability is exp(–.3t), from the spread sheet algorithm of 2.1.3 we have

$$.285 \exp(-.3t)/S = .21/S,$$

$$t = -.3 \ln(.21/.285) = 1.02 \text{ hrs.}$$

Thus after 1.02 hours the effort should be divided equally among (2,2), (1,2) and (2,1), since all three have the same probability (which we have not calculated) at that point.

This procedure can be continued until all cells which had initially non-zero probability of containing the target have equal probability, and accordingly subsequent search is divided equally among them.

Note that we have proceeded "myopically," i.e., we always search in the current highest probability cell. This optimizes the *immediate* effort without regard to what happens thereafter. Suppose we were initially allowed 4 hours of search effort and planned accordingly by the above method. Then suppose we are allowed an additional 3 hours of effort. Might we then wish we had used the first four hours differently in light of having a total of 7 hours available? The answer is no--myopic search is optimal. Moreover it is optimal both in the sense of minimizing mean time to detection and maximizing the probability of detection within an allowed time T.

The statements in the preceding paragraph depend very much on the target being stationary. If the target is moving, myopic search need not be optimal and the two MOE's, mean time to detect and probability of detection in time T, may lead to different optimal plans.

2.2. Principal Requirements for Moving Target CAS

As a lead-in to CAS for *moving* targets, we note succinctly the requirements for such a system and means by which these requirements can be met.

2.2.1. Prior map. A CAS analysis begins with a prior map (probability map of the target's position). This may be constructed as a weighted sum of single-scenario maps, each causally derived. Typically it begins with a single report of a target's approximate location. Alternatively it may be derived from historical analysis of past target habits.

2.2.2. Target motion model. Target motion must be described in probabilistic terms. This inevitably means that it is given as a stochastic process--see Appendix B. Generally speaking, when this is done by Monte Carlo means it need not be difficult to understand. An analytic model of motion might be fairly elementary, but some analytic motion models have considerable mathematical depth.

Most CAS systems have used Monte Carlo target motion models consisting of a bundle of (typically 500) target tracks, each labeled with the probability that it is (approximately) the actual track. A method is needed for the CAS user to construct this bundle and the associated probabilities from a menu of building blocks and the user's knowledge or assumptions of target behavior. Alternatively, the bundle of tracks may be constructed from historical analysis, and this may be done simultaneously with construction of the prior map.

The track probabilities in a Monte Carlo model are converted at any time to geographic cell probabilities by adding for each cell the probabilities of the tracks with positions in that cell.

2.2.3. Updated maps. The main object of CAS is to produce a probability map of target position *at a user-chosen time* and to do so from time to time. To do this updates are needed for target motion, negative information, and positive information.

Target motion is updated in Monte Carlo modeling simply by moving the target deterministically along each track in the bundle (speeds differ from track to track), without changing any probability labels. An analytic model update for motion follows the mechanism of the model.

Updating for negative information is done by application of Bayes' theorem, and updating for positive information is preferably also Bayesian. In Monte Carlo modeling this is best done by updating the *track* probabilities, and going from there to geographic cell probabilities.

Negative information updating also requires an estimate of the effectiveness of the (unsuccessful) search effort applied. This in turn requires a model of cumulative detection probability (cdp), i.e., the probability of at least one detection in an interval of opportunities, which might be a continuum of glimpses. The problem is to allow for statistical interdependence. A (λ,σ) approach may be taken--see Appendix C.

2.2.4. Optimal search plans. For a CAS system to compute optimal search plans may be considered highly desirable rather than as requirement. If the user is provided with good probability maps, guidance to search planning is at hand--search in the cells of highest detection probability (myopic search). However, it may not be practical to place the next increment of search effort on *just* the high probability locations, so an optimal *practical* plan is desired also. It is also often possible to improve significantly on myopic approaches. More recent CAS systems provide methods of doing both of these things. These include selectively exhaustive examination of a reasonable set of alternatives, optimal placement of a rectangular application of search effort (references [m] of Chapter V and [aa]) and more sophisticated algorithms to compute optimal allocation of effort in time as well as space (references [k], [l], [e], and [m]). Note that the theory of optimal allocation of effort is much better developed than the theory of optimal choice of path by which to deliver that effort. References [n] and[o] are progress in the latter problem.

2.3. Simplified Illustration of Moving Target Monte Carlo CAS

In this section we illustrate the principal method used in Monte Carlo CAS against moving targets. We do so by a simplified example of target motion, application of which appears to capture the main principles involved. From the standpoint of learning from past TDA development to prepare for future developmental work, this simplified case is an excellent example in that the modeling ideas and computer implementation are intimately and effectively intertwined. This point applies in particular to updating track weights rather than cell position probabilities, as described below.

2.3.1. Construction of target motion model. In Figure II-5 we give assumptions from which we can quickly build a model of target motion in a simplified search example. We suppose there are two scenarios, I and II, representing two principal courses of action by the target. These have respective probabilities of occurrence .6 and .4. For each scenario we make assumptions of target initial position, course, and speed. For each of these there are four possibilities, but for each scenario and each of position, course, and speed, only two of these have non-zero probability. We assume here that course and speed remain fixed once chosen. Realistic implementations provide for

FIGURE II-5. INPUTS TO TARGET MOTION ILLUSTRATION

Scenario		Position at Time 0				Course				Speed (kts)			
#	Probability	A	B	C	D	060T	075T	090T	105T	8	9	10	11
I	.6	.7	.3	0	0	0	.8	0	.2	.4	0	.6	0
II	.4	0	0	.6	.4	.5	0	.5	0	0	.7	0	.3

Track	Scenario	Position at Time 0	Course	Speed	Initial Track Weight (Probability)
1	I	A	075T	8 kts	.134
2	I	A	075	10	.202
3	I	A	105	8	.034
4	I	A	105	10	.050
5	I	B	075	8	.058
6	I	B	075	10	.086
7	I	B	105	8	.014
8	I	B	105	10	.022
9	II	C	060	9	.084
10	II	C	060	11	.036
11	II	C	090	9	.084
12	II	C	090	11	.036
13	II	D	060	9	.056
14	II	D	060	11	.024
15	II	D	090	9	.056
16	II	D	090	11	.024
					1.000

course changes and much richer choices of sample values of initial course, speed, and position and of scenarios than the two-point distributions assumed here.

Each choice of scenario, initial position, course, and speed, all four being deemed independent, determines a sample target track. There are 16 such tracks, and they are tabulated in Figure II-5 along with probability of occurrence in the last column. For example, the probability that track 5 occurs is

$$.6 \times .3 \times .8 \times .4 = .058,$$

as seen from the four two-point distributions.

A geographic plot of these 16 tracks is given in Figure II-6, which identifies the four possible initial positions A, B, C, and D. For each start point and course, there is a track for each of two speeds, and these are plotted close to each other as dashed and solid lines.

Each track is labeled with probability of occurrence. The 16 tracks together with the probability labels constitute a "stochastic process." Specifically the process definition is of type III as discussed in Appendix B.

A CAS user would not *see* the bundle of tracks--in VPCAS the bundle would contain 500 tracks, possibly more in the successors to VPCAS at the user's choice, each generally having more complexity than the 16 illustrated here.

What the user does see on request is a probability map pertaining to a given time, e.g., as in Figures II-7 and II-8, pertaining to times 0 and 3 hours. To find the probability that the target is in a given cell of a map, the program determines which tracks have the target position in the chosen cell *at the map time* and simply adds the probabilities of those tracks to obtain the cell probability. In Figure II-7 the prior distribution of the target is given, taken directly from the scenario weights and initial position distributions of Figure II-5. In Figure II-8 the map is derived from moving the target along each track at the speed of that track for 3 hours.

In reference [b] a similar example is given using eight tracks instead of 16, but showing only what the user would see and not the tracks themselves.

2.3.2. Updates for new information. Now we illustrate updating for negative and positive information. We suppose that from time 3 hours to time 6 hours search effort is applied uniformly over the square shown in Figure II-9 as EFGH. Suppose that as of time 6 hours no detection has been made, and we wish to update the probability map to reflect this negative information. First we need an estimate of the effectiveness of the search effort cell by cell, and we must combine that with our assumptions of target motion track by track. I.e., we must find a curve of cumulative detection probability (cdp) *for each track*. This is illustrated in Figure II-10. In VPCAS this is done by a (λ,σ) model (Appendix C).

The negative information update is now applied to the *track* probabilities as shown in Figure II-11. This again applies Bayes' theorem in analogy to 2.1.3, where the updating is on *cell* probabilities. Column [2] is obtained from the 3-hour track positions and track probabilities in Figure II-9 (needed previously to

FIGURE II-6. ILLUSTRATIVE MONTE CARLO TARGET MOTION MODEL

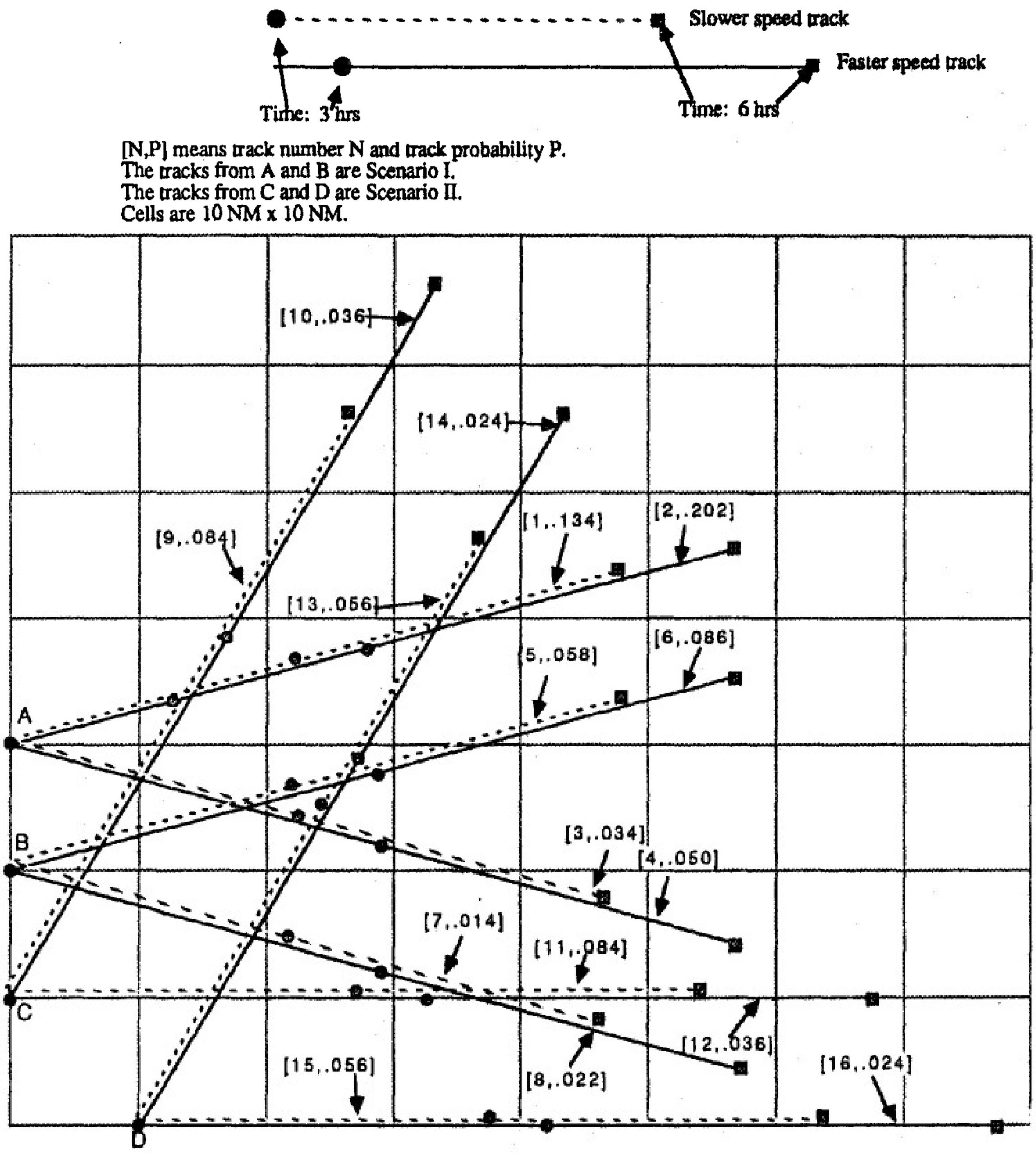


FIGURE II-7. TARGET POSITION PROBABILITY MAP (TIME=0)

Convention: A cell boundary point is considered in cell above or to right of boundary. Cells are 10 NM x 10 NM.

0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
.42 A	0	0	0	0	0	0	0
.18 B	0	0	0	0	0	0	0
.29	0	0	.0	0	0	0	0
C 0	.16	0	0	0	0	0	0

D

FIGURE II-8. TARGET POSITION PROBABILITY MAP (TIME=3 HRS)

Convention: A cell boundary point is considered in cell above or to right of boundary. Cells are 10 NM x 10 NM.

0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0 A	.12	.336	0	0	0	0	0
0 B	0	.308	0	0	0	0	0
0 C	0	.120	.036	0	0	0	0
0	0	0	.056	.024	0	0	0

D

FIGURE II-9. APPLICATION OF SEARCH EFFORT

FROM TIME 3 HRS TO 6 HRS SEARCH IS APPLIED UNIFORMLY TO SQUARE EFGH.

[N,P] means track number N and track probability P.
The tracks from A and B are Scenario I.
The tracks from C and D are Scenario II.
Cells are 10 NM x 10 NM.

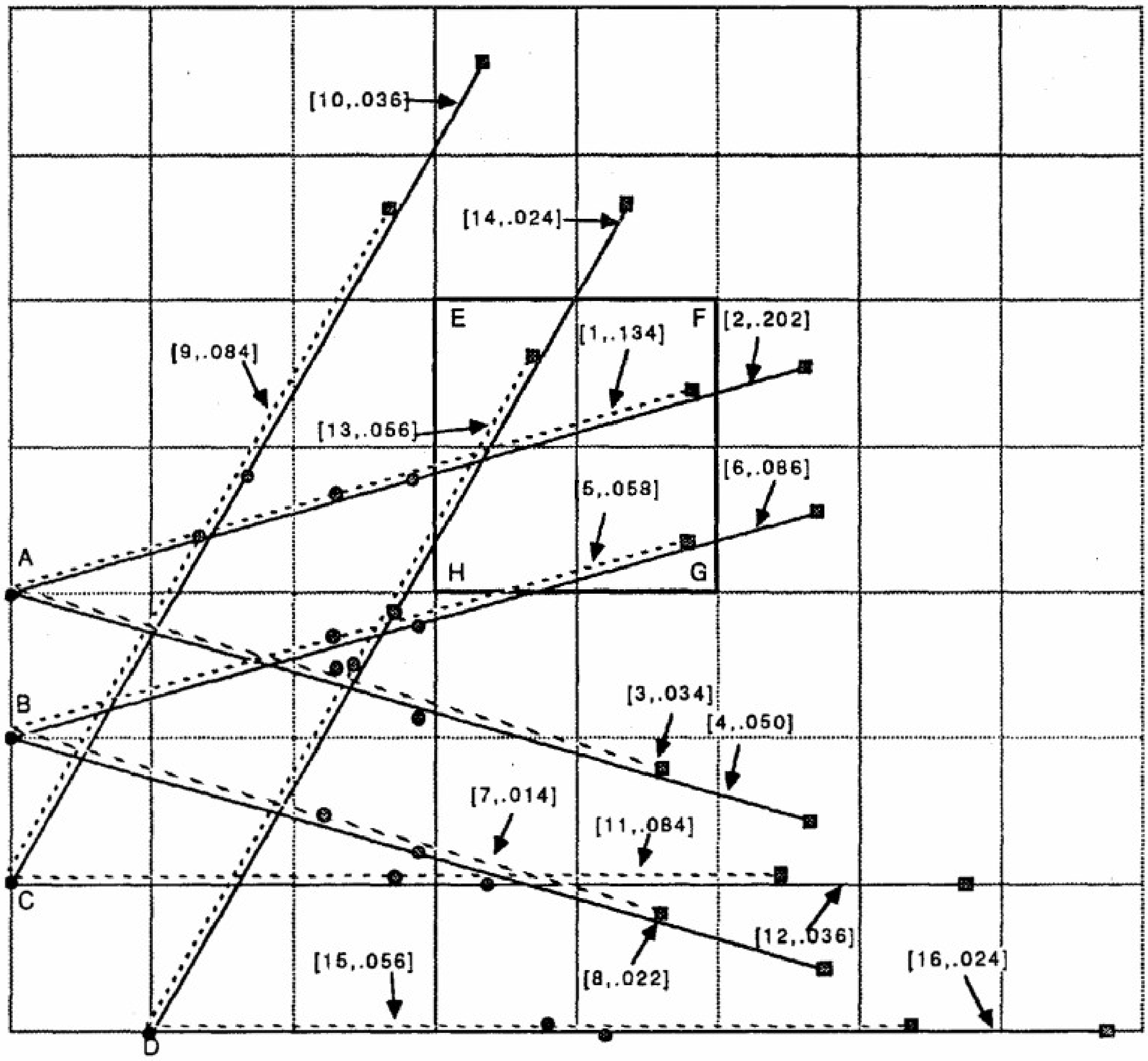


FIGURE II-10. CUMULATIVE DETECTION PROBABILITY

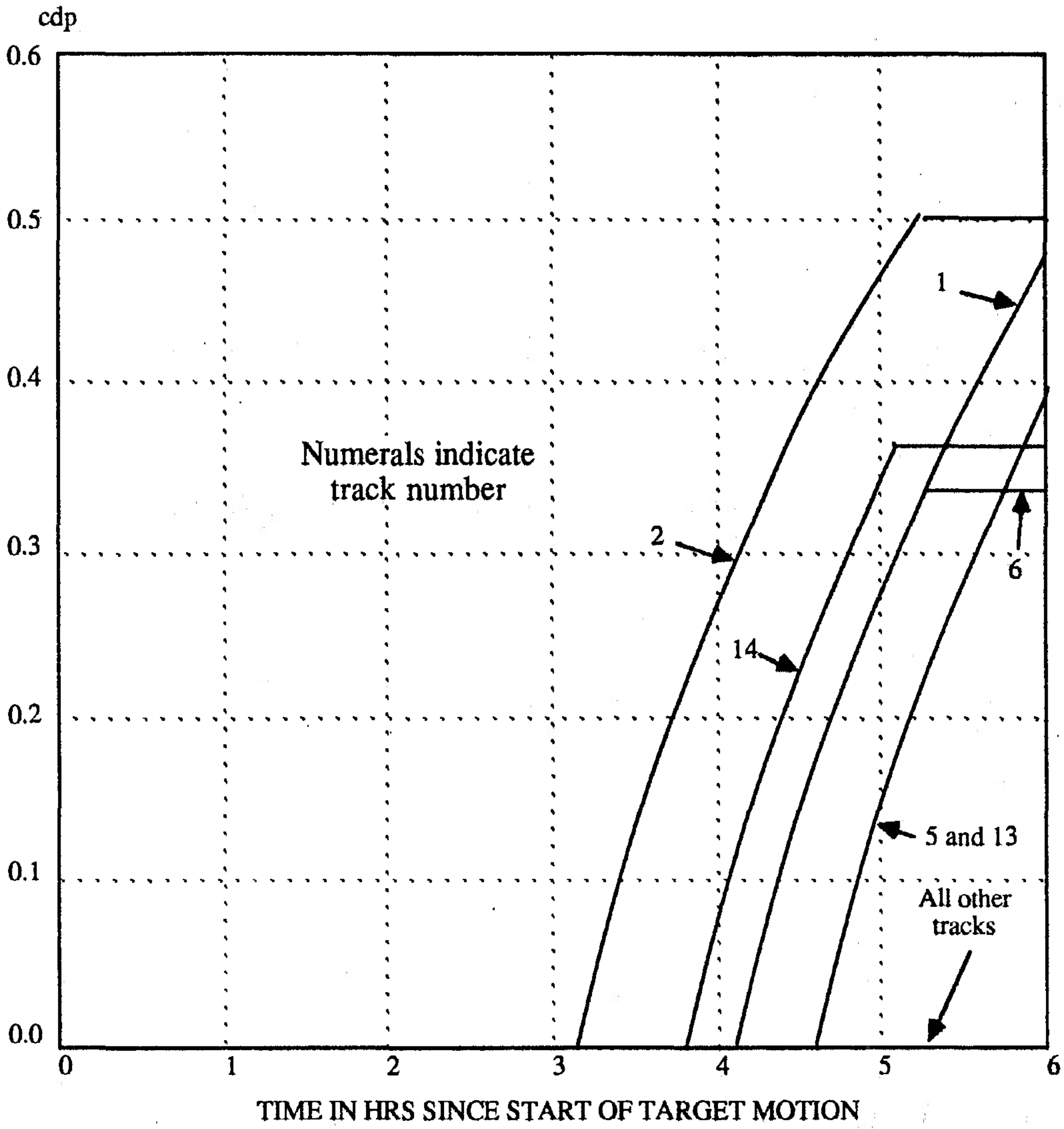


FIGURE II-11. UPDATE FOR NEGATIVE INFORMATION

Search effort is applied uniformly over rectangle EFGH from time 3 hrs to time 6 hrs. No detection occurs. What are the inferred new (posterior) track weights?

[1] Track #, i	[2] Pre-Search (Prior) Track Weight (Normalized)	[3] Search Failure Probability if Track i is Actual	[4] [2] x [3]=Posterior Track Weight (Unnormalized)	[5] Normalized Weight [4]/S
1	.134	.52	.070	.093
2	.202	.50	.101	.134
3	.034	1.00	.034	.045
4	.050	1.00	.050	.066
5	.058	.60	.035	.046
6	.086	.67	.058	.077
7	.014	1.00	.014	.019
8	.022	1.00	.022	.029
9	.084	1.00	.084	.112
10	.036	1.00	.036	.048
11	.084	1.00	.084	.112
12	.036	1.00	.036	.048
13	.056	.60	.034	.045
14	.024	.64	.015	.020
15	.056	1.00	.056	.074
16	.024	1.00	.024	.032
	1.000		S=.753	1.000

obtain Figure II-8), and column [3] is from complementing 6-hour probabilities in Figure II-10. Column [4] is the product of columns [2] and [3] and is proportional to the posterior track probabilities at time 6 hours. The latter are obtained in column [5] by normalizing column 4 and reflect the 3 hours of unsuccessful search as desired.

The posterior distribution over the tracks is translated into the posterior distribution over the cells by the method used to produce Figure II-8. This results in Figure II-12 which is the probability map for time 6 hours, reflecting the 3 hours of unsuccessful search.

Suppose a new contact report is received at time 6 hours, as the probability map in Figure II-13. Suppose also that this report is given credibility .6, meaning that it has .6 probability of being on the correct target. This report may be incorporated into the probability map by the method shown in Figure II-14.

The resulting probability map updated for this positive information is shown in Figure II-15.

FIGURE II-12. TARGET POSITION PROBABILITY MAP (TIME = 6 HRS, AFTER NEGATIVE INFORMATION, BEFORE POSITIVE INFORMATION)

Convention: A cell boundary point is considered in cell above or to right of boundary. Cells are 10 NM x 10 NM.

0	0	0	.048	0	0	0	0
0	0	.112	0	.020	0	0	0
0	0	0	.045	.093	.134	0	0
0 A	0	0	0	.046	.077	0	0
0 B	0	0	0	0	0	0	0
0	0	0	0	.045	.178	.048	0
C 0	0	0	0	.019	.029	.074	.032

D

FIGURE II-13. NEW CONTACT

At time 6 hrs a contact report is received which says the distribution of target position is as below. It is given credibility .6.

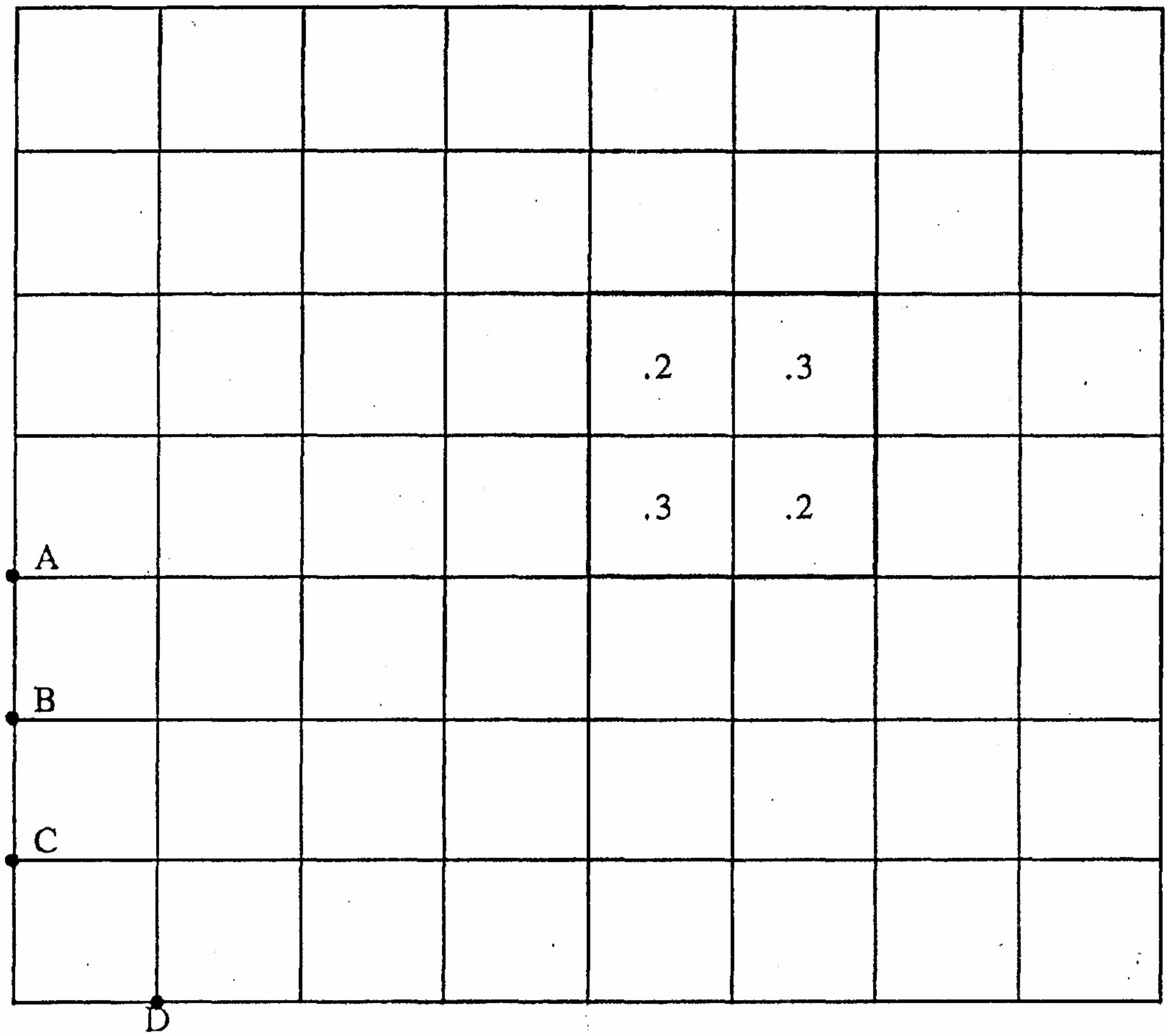


FIGURE II-14. UPDATE FOR POSITIVE INFORMATION

This is the positive information algorithm used in VPCAS applied to the contact report with credibility .6 at time 6 hrs.

[1]	[2]	[3]	[4]	[5]
Track #, i	Latest Track Weight (Normalized)	Track Weight Given by Contract Distribution	[2] x [3]	New Track Wt (Normalized) $[2]\text{x}(1\text{-}.6)\text{+}.6\text{x}\frac{[4]}{S}$
1	.093	.2	.0186	.164
2	.134	.3	.0402	.328
3	.045	0	0	.018
4	.066	0	0	.026
5	.046	.3	.0138	.112
6	.0077	.2	.0154	.136
7	.019	0	0	.008
8	.029	0	0	.012
9	.112	0	0	.045
10	.048	0	0	.019
11	.112	0	0	.045
12	.048	0	0	.019
13	.048	0	0	.018
14	.020	0	0	.008
15	.074	0	0	.030
16	.032	0	0	.013
	1.000	1.0	S=.088	1.000

M. G. Monticino and A. R. Washburn have independently pointed out that this method of updating for positive information which is in VPCAS and reference [a] is questionable, at any rate not Bayesian. This method follows "Dempster's rule" for combining information from separate sources, where one has no knowledge of statistical dependence between the sources. (Some versions of Dempster-Shafer belief functions are based on this rule.) The method in Figure II-15 is indeed heuristic. However it can be argued that in the absence of knowledge which relates the new information to the prior information it is as good an heuristic as another. There is the further problem that the new information is usually a distribution of measurement errors rather than a distribution of target position. We shall return to the problem of positive updating in 2.6.

FIGURE II-15. TARGET POSITION PROBABILITY MAP (TIME = 6 HRS, AFTER POSITIVE INFORMATION)

Convention: A cell boundary point is considered in cell above or to right of boundary. Cells are 10 NM x 10 NM.

0	0	0	.019	0	0	0	0
0	0	.045	0	.008	0	0	0
0	0	0	.018	.164	.328	0	0
0 A	0	0	0	.112	.136	0	0
0 B	0	0	0	0	0	0	0
0 C	0	0	.0	.018	.071	.019	0
0	0	0	0	0	.012	.030	.013

D

We again emphasize the power of updating for negative and positive information via the track probabilities, to revise the prior assumption on motion as well as position and to make the computation more efficient.

2.4. VPCAS

In this section we show how the ideas of 2.3 are expanded upon and implemented in the important CAS system VPCAS. Further expansion will be seen in 2.5 and 2.6.

VPCAS was developed in 1980-83 (see 2.13 for history) to assist mission planners in ASW Operations Centers (ASWOCs) in planning ASW search by VP aircraft, i.e., P-3s. It culminated a decade of CAS development and was a major advance in user-friendliness and scope of methods. It was installed in all LANT and PAC ASWOCs. The modeling methods in VPCAS (other than historical analysis) are rather fully described in references [p], [q], [r], and [s]. The user's guide and program performance specification are references [t] and [u].

The most important decisions served by VPCAS are listed as follows in the form of questions an ASWOC mission planner is called upon to answer:

(1) Should P-3 assets by committed to a search?

(2) How many P-3s should be committed?

(3) What type of sonobuoy patterns should be used?

(4) Where should these patterns be placed?

(5) When should the search be stopped?

The principal inputs to and outputs from VPCAS are shown as follows:

Inputs to VPCAS:

Acoustic data--propagation loss curves, FOM's

Past contacts--ellipse, bearing box, LOB, omni-directional, AOP

Target motion assumptions--fleeing datum, constrained random walk, front motion, historical habits

Unsuccessful search

New contact reports

VPCAS outputs:

Probability maps of target location

Probability of detection, given search plan

Recommended search patterns

Updated distributions of target scenarios, course, and speed

The most important outputs are the probability maps, which help to answer all of the preceding questions. The program generates search plan recommendations, which answer questions (3) and (4) directly.

VPCAS uses the Monte Carlo methods of 2.3, with a bundle of 500 tracks instead of the 16 illustrated there. To describe it our principal task is to describe the "building blocks" available for the user to model probabilistically a target's initial position and subsequent motion, in place of the two-point distributions used in 2.3.

2.4.1. Geographic grids. The probability maps produced by VPCAS are shown in a grid of rectangular cells of user-chosen size or program-chosen size by default. An example is Figure II-16, where the cells are 10 nm x 10 nm. Cell entries are single digits. The highest-probability cell is denoted by *, its probability is shown in the legend, and each single digit represents a fraction of the highest probability as a multiple of .1. Successor CAS programs use color coding instead, which presents less conflict with informative background that may be on the screen.

2.4.2. Initial target position. The initial probability map of target position may be chosen to be any of the various forms of distributions termed ellipse, bearing box, LOB (line of bearing), omni-directional, AOP (area of probability), rectangular, and convex region. See Figures II-17 to II-23. (The "ELLIPS" in the headers of these figures is an arbitrary name of a problem.)

An ellipse is a bivariate normal distribution characterized by an ellipse with two-sigma semi-axes.

A bearing box has a normal distribution in width and a uniform distribution in length, the two being independent.

An LOB has a normal distribution in bearing and a uniform distribution in range, the two being independent.

An omni-directional distribution is uniform in bearing over 360 degrees. Its (independent) distribution in range is derived from own sensor's capabilities. (PACSEARCH permits similar use of own sensors for an LOB distribution in range.)

An AOP, a rectangle, or a convex region is a uniform distribution over the interior of a circle, a rectangle, or a convex polygonal region respectively.

Note that the user is *not* given the option of forming a multi-scenario prior for target *position*, which would parallel the method described for stationary targets in 2.1.2 and the motion prior in VPCAS described below. ASW applications ordinarily begin with a target contact (perhaps an assumed port departure if an historical analysis approach is used). The above list of forms of distribution provide considerable flexibility for such a single-contact prior for the position. It should not be hard to program an extension of this (developmentally) to a weighted sum of such priors.

2.4.3. Target motion models. We summarize the target motion model construction, given more fully in reference [q].

A target motion scenario indicates the target's general course of action. The user may build up to five scenarios and choose a scenario weight for each, indicating relative likelihood of occurrence.

Of the 500 tracks, the numbers assigned to the respective scenarios are such that each has at least 100, and subject to that they are proportional to scenario weights. This is to provide appropriate richness of structure in the motion model for each scenario. Initial weights are assigned to the 500 tracks, uniformly for a given scenario and such that the scenario track weight totals are proportional to the scenario weights.

FIGURE II-16. ILLUSTRATIVE PROBABILITY MAP, I.E., DISTRIBUTION OF TARGET POSITION

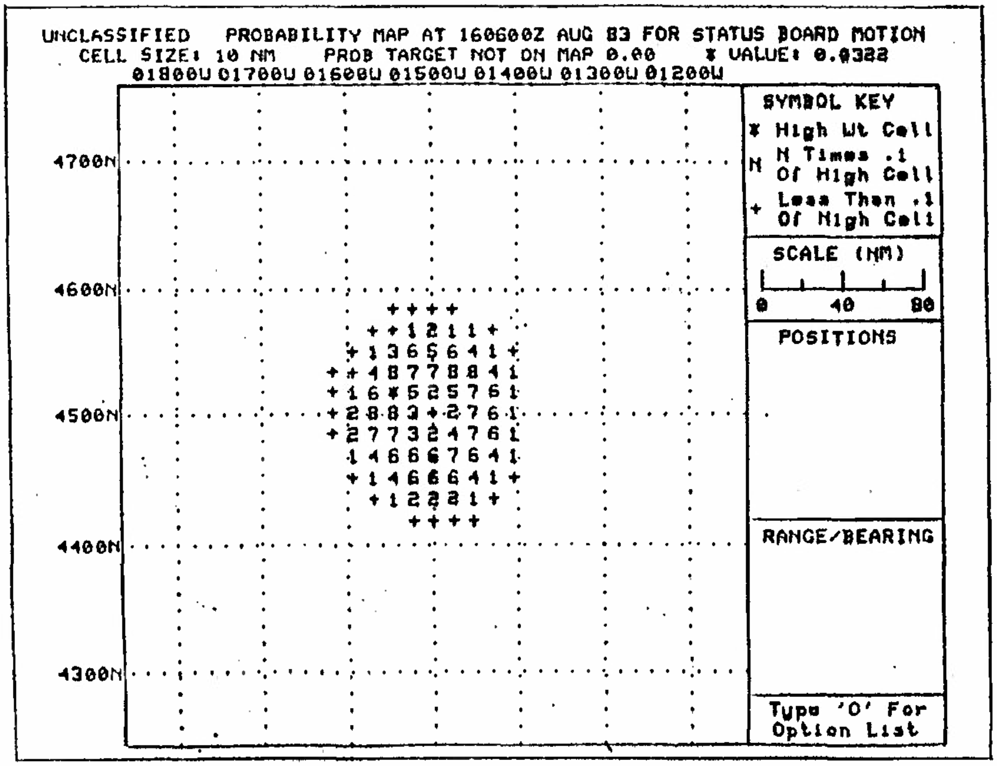


FIGURE II-17. ILLUSTRATIVE ELLIPTICAL INITIAL DISTRIBUTION

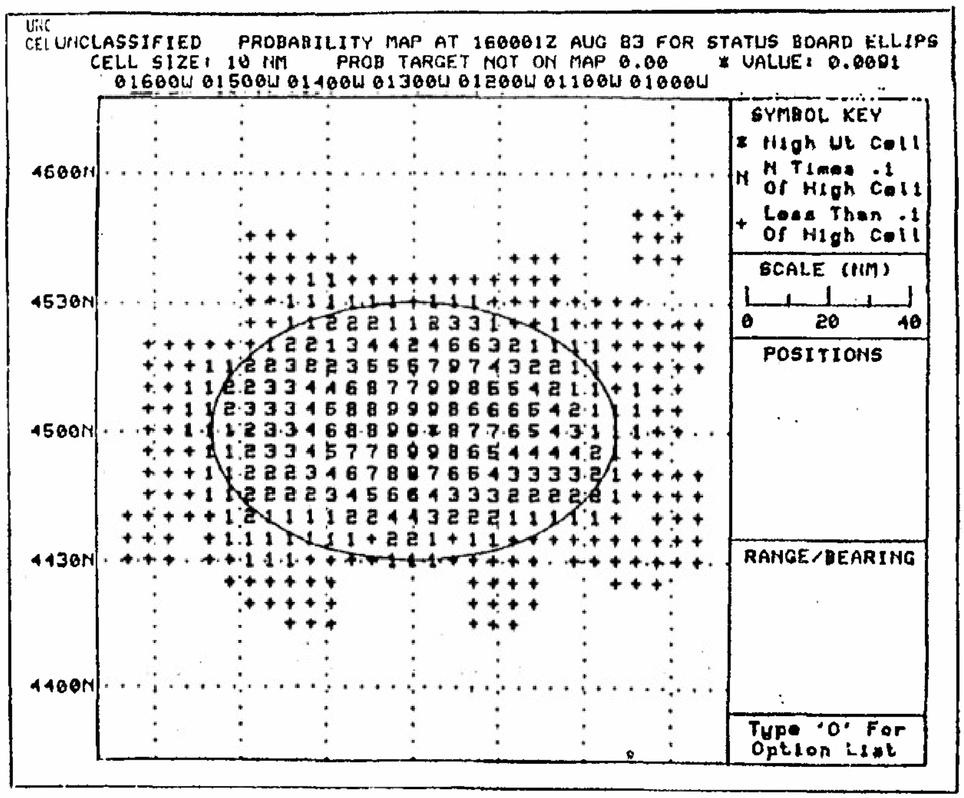


FIGURE II-18. ILLUSTRATIVE BEARING BOX INITIAL DISTRIBUTION

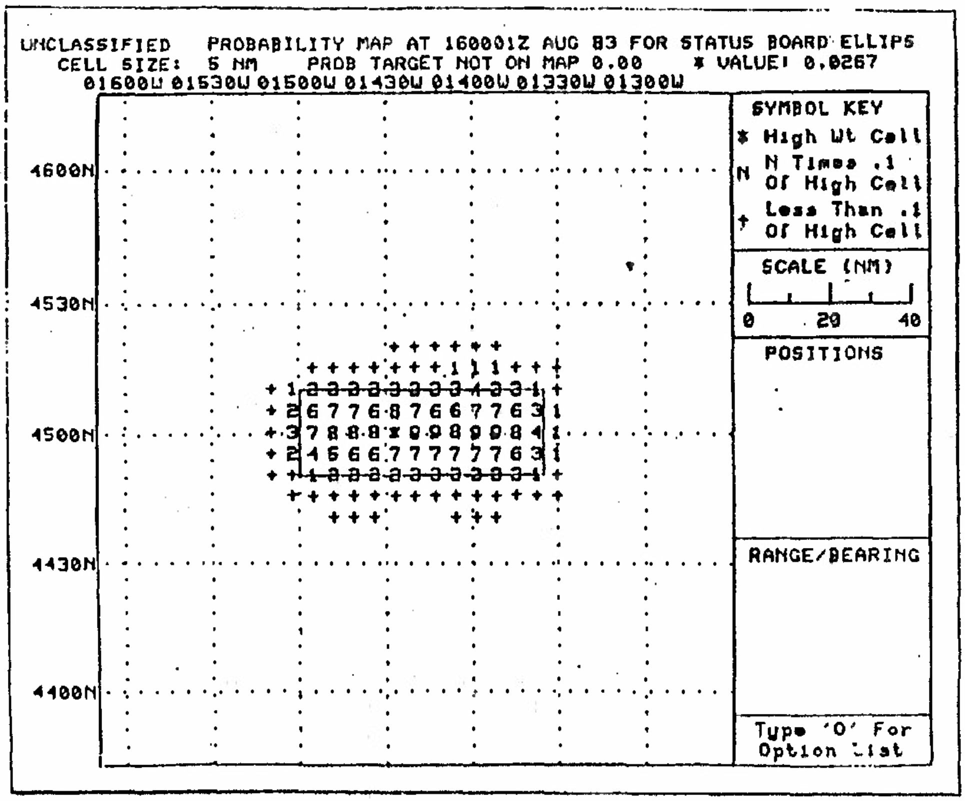


FIGURE II-19. ILLUSTRATIVE LOB INITIAL DISTRIBUTION

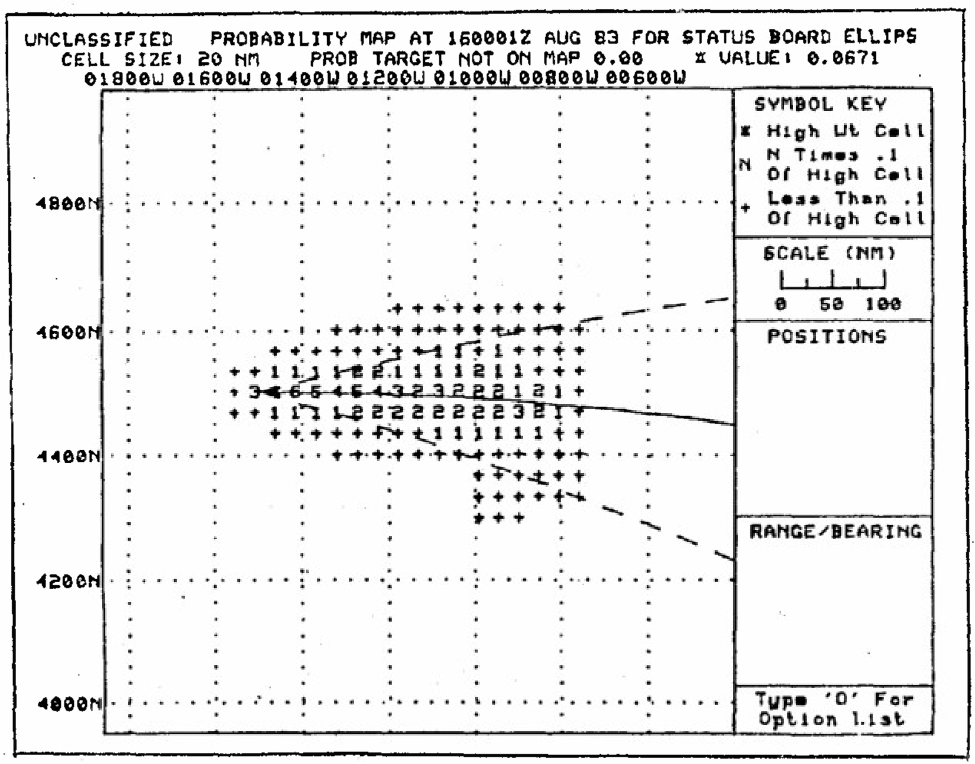


FIGURE II-20. ILLUSTRATIVE OMNI INITIAL DISTRIBUTION

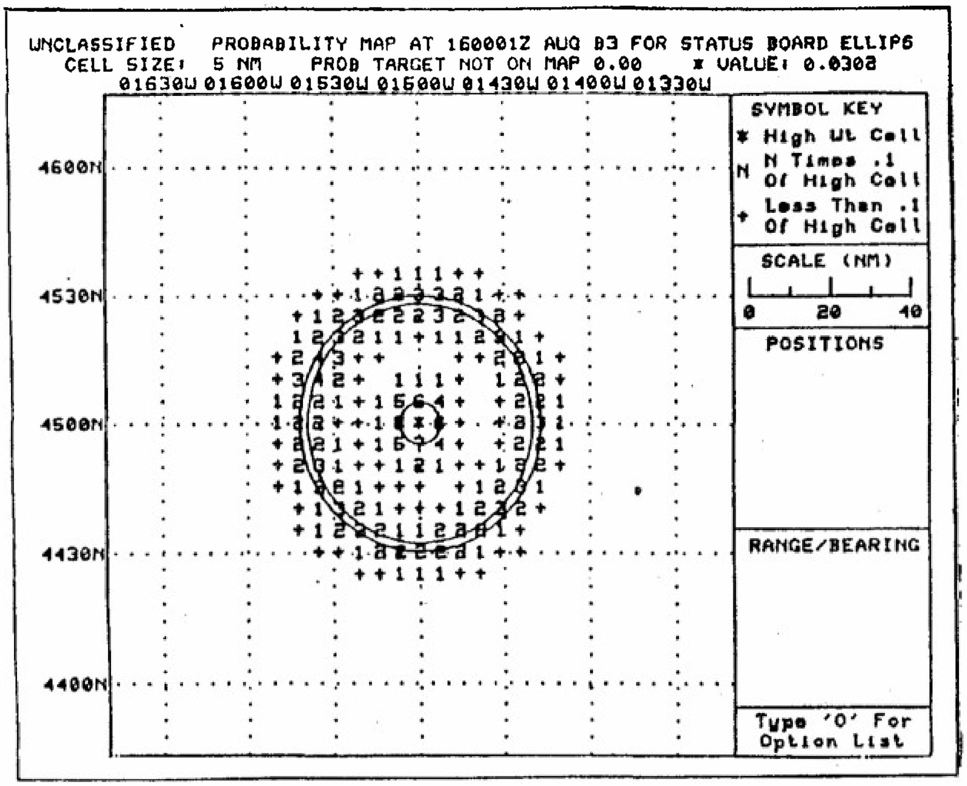


FIGURE II-21. ILLUSTRATIVE AOP INITIAL DISTRIBUTION

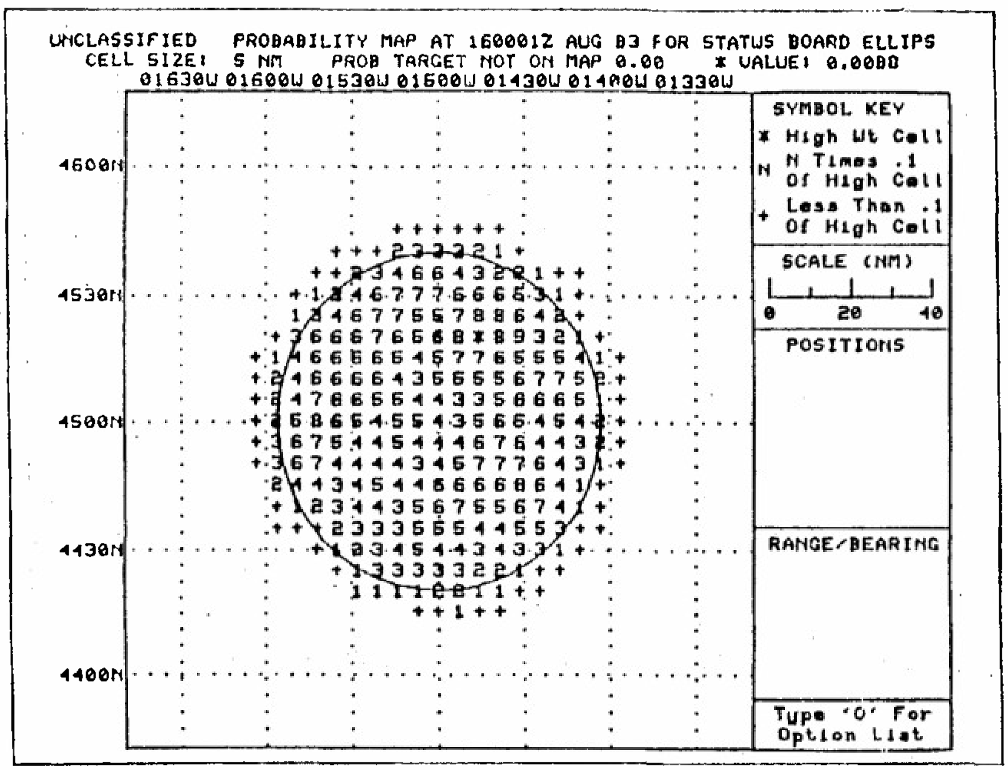


FIGURE II-22. ILLUSTRATIVE RECTANGULAR INITIAL DISTRIBUTION

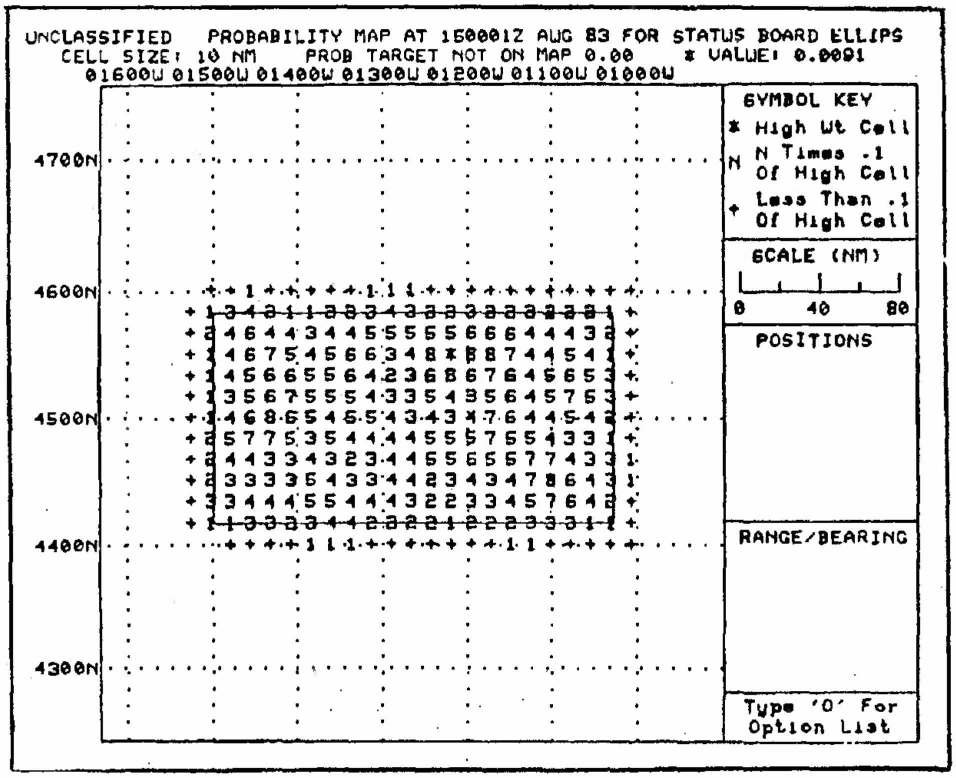
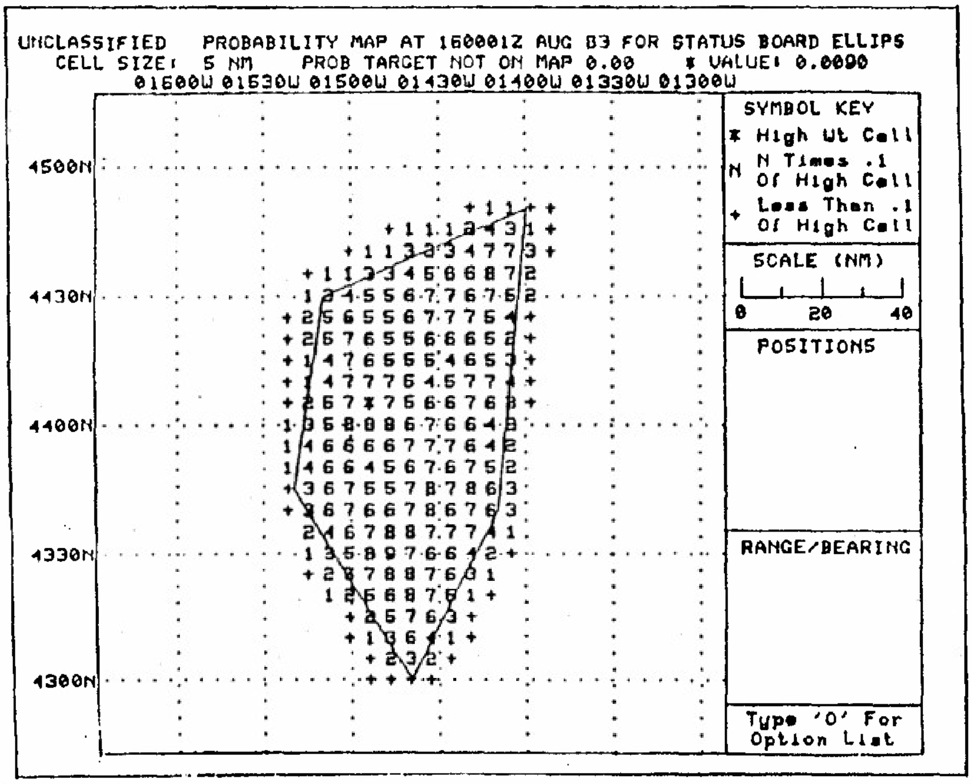


FIGURE II-23. ILLUSTRATIVE CONVEX REGION INITIAL DISTRIBUTION



Each scenario may be divided into up to five intervals. The motion model *for a given interval* either is based on historical analysis or is a destination-constrained random tour (DCRT) as defined in B.5 of Appendix B. A destination distribution is chosen from the following alternatives:

Motion type for the interval	**Destination distribution**	**Parameters specified by user**
Constrained random walk	Ellipse or uniform over a rectangle	Position, size, and orientation of ellipse or rectangle
Front motion	Uniform over a line segment	Line segment end-points
Fleeing datum	Uniform over a circle of very large radius	Nothing

The destination constraint in fleeting datum is negligible as a constraint; it is described as above to include it in the DCRT description.

The start point distribution is as in 2.4.2 for the first interval, and for any subsequent interval it is the destination distribution of the preceding interval. Thus fleeting datum may be used only in the last interval of a scenario.

The base speed for the interval is necessarily non-negative and drawn from a distribution chosen by the user to be uniform, triangular, or normal with user-chosen parameters.

The interval is composed of legs, and time-on-leg is exponentially distributed with user-chosen mean.

The course and speed variation distributions (e.g., Figures II-24 and II-25) are normal with mean zero and user-chosen standard deviations, except that each distribution is then truncated by the program. The speed variation distribution is truncated below at minus the drawn base speed. The course variation is truncated (for reasonableness) in a more complicated way described in reference [q].

These choices are combined as described in B.5. Base speed is added to the speed variation drawn for each leg and necessarily is non-negative. To the course variation drawn for a given leg is added the course from the start of the leg to the originally drawn destination for the interval.

Once the various distribution parameters for track construction have been chosen, the 500 tracks are computed and stored. This burdens memory but greatly facilitates computation of the updates discussed below--the program has put Monte Carlo draws behind it, unless the user changes or adds to the inputs.

Figure II-26 illustrates motion under two scenarios, showing two intervals for scenario 1 and one interval for scenario 2. Figure II-27 illustrates the composition of SOA and base course plus variations of a track for a given interval, under constrained random walk, front motion, and fleeing datum assumptions.

2.4.4. Update for target motion. When the user specifies a time for a probability map (map time), it is necessary to update each of the 500 tracks for target motion. This simply requires computation of the position of each track at the map time according to the motion information stored for that track.

2.4.5. Update for negative and positive information. An increment of search effort, including start and end times, that has been entered in the status board is considered activated by designating it as "included." For each included search the cumulative detection probability (cdp) is computed for each track for the search duration and stored (see references [q] and [r]). Single-buoy cdp's are computed by the (λ,σ) unimodal formula (see Appendix C), with $\lambda = 1$ per hour and $\sigma = 8$ db. To compute the probability that at least one buoy of a pattern detects, the single-buoy cdp's are combined into a pattern cdp, first assuming buoy-to-buoy independence, call it PIND, and second assuming buoy-to-buoy complete dependence, call it PDEP, and taking .45PIND + .55PDEP (this is from the CNA SPAM model) as an estimate of the pattern cdp. If the search produces no detection prior to a given map time, the probability map is updated for this negative information quite analogous to the method of 2.3. An example is Figure II-28--the initial distribution is indicated by the ellipse, from the target motion assumptions the distribution has moved eastward and spread out, and from unsuccessful search applied to the rectangle, the distribution has largely been suppressed in the rectangle and accordingly has increased in its exterior.

Note that if a map time is chosen before completion of an included search, the map will still reflect negative information based on non-success in the *entire* search and thus will include negative information arising *after* the map time. If it is desired to include negative information arising only from search up to the map time, this is done by modifying the duration of the included search to terminate it

FIGURE II-24. ILLUSTRATIVE TRIANGULAR SOA DISTRIBUTION

NOTE: This figure shows the distribution of possible SOAs for a triangular SOA distribution with low SOA 4 kts, high SOA 12 kts, best SOA 9 kts and ratio of best to low or high equal to 2.

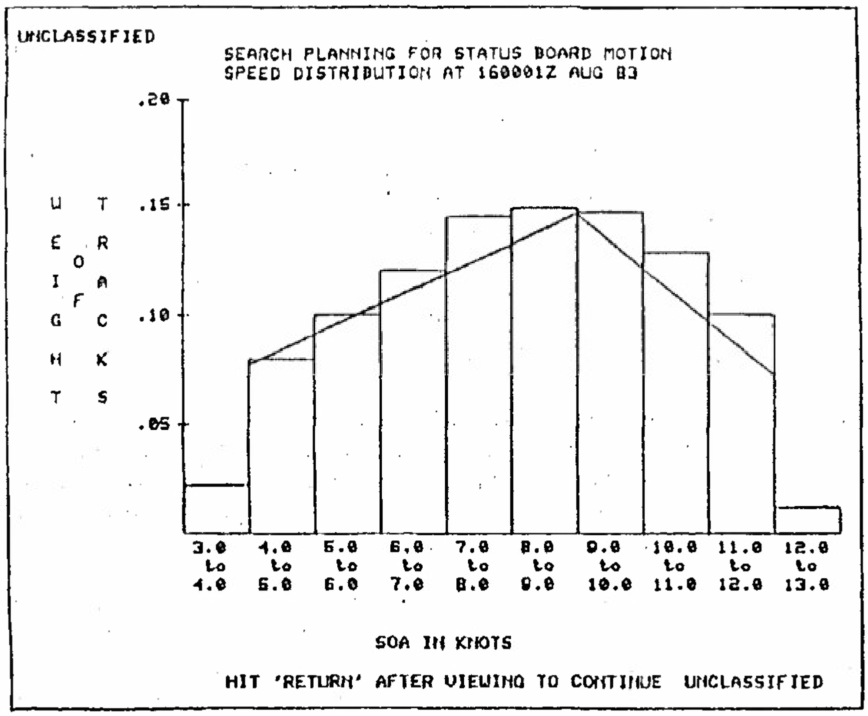


FIGURE II-25. ILLUSTRATIVE COURSE DISTRIBUTION

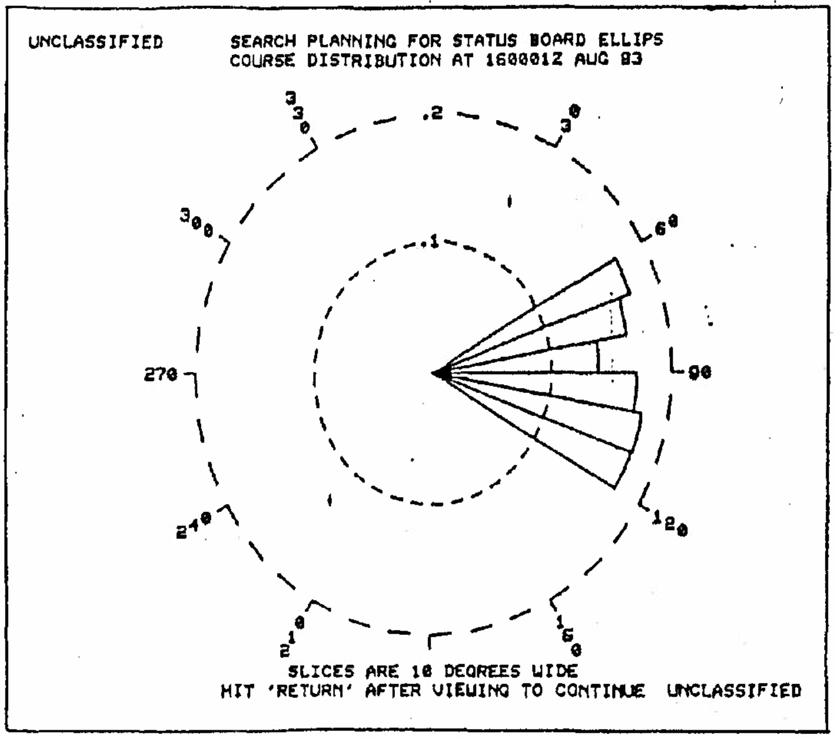


FIGURE II-26. ILLUSTRATIVE TWO-SCENARIO MOTION MODEL

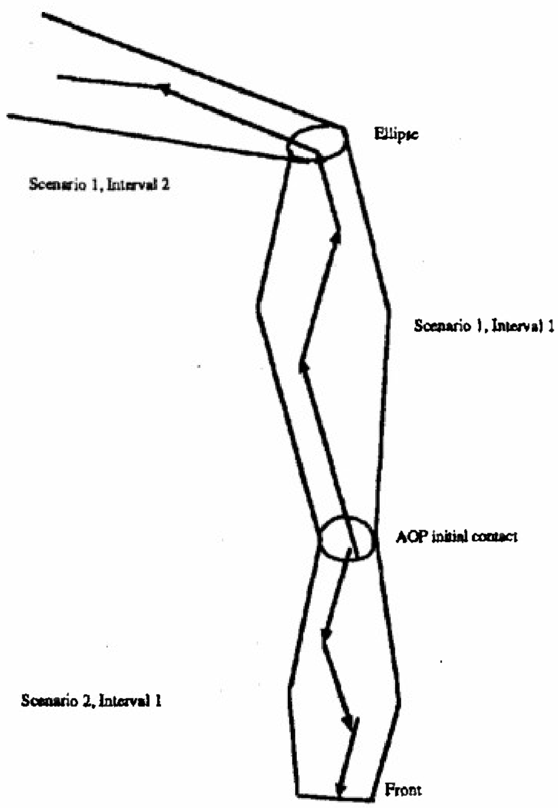


FIGURE II-27. THREE TARGET MOTION MODELS: CONSTRAINED RANDOM WALK, FRONT MOTION AND FLEEING DATUM

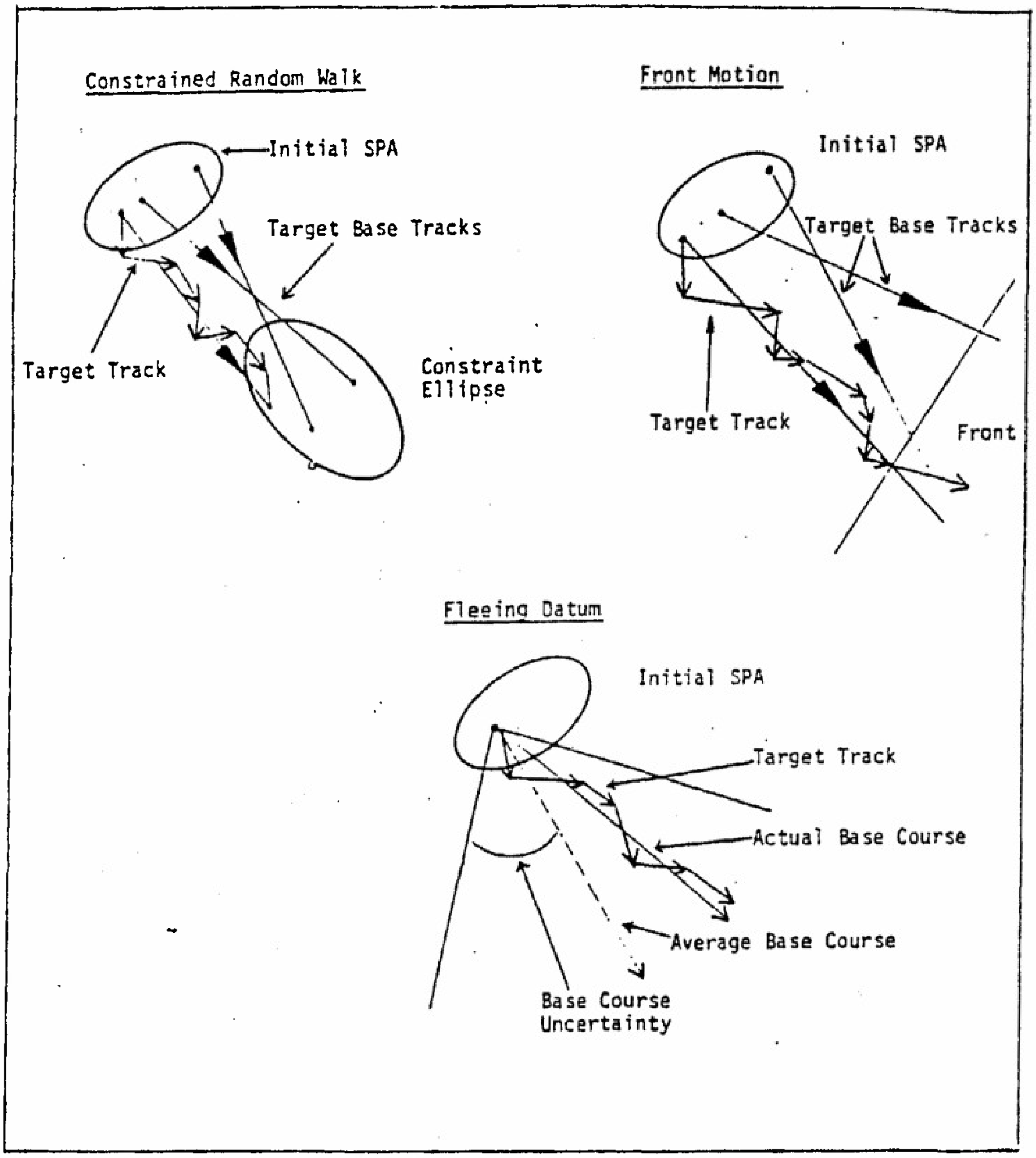
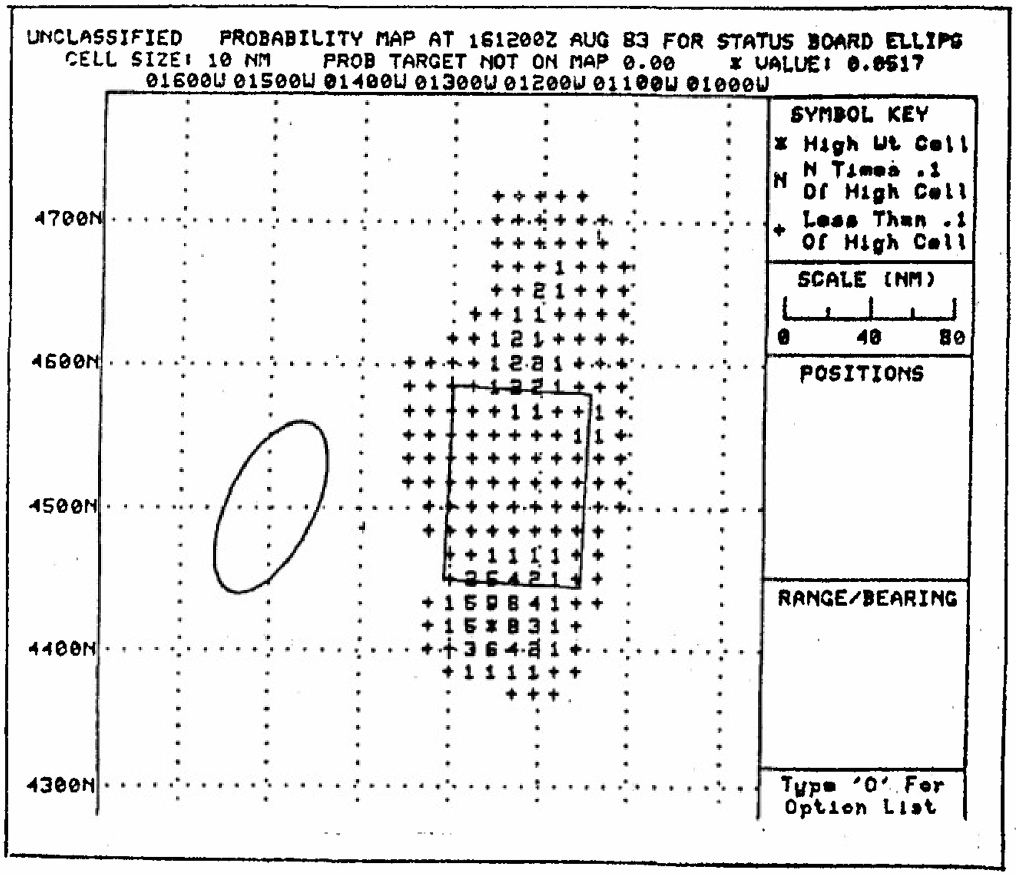


FIGURE II-28. ILLUSTRATIVE PROBABILITY MAP UPDATED FOR NEGATIVE INFORMATION



at map time. Note that if this is done more than once, one should always go back to the beginning of the included search and update from the track weights at that time rather than from an intermediate time (if only motion updating were involved this remark would not apply). This is because combining negative updatings by time segments would treat the separate segments as independent and would lead to a different result, under (λ,σ) cdp, than if the updating were over the total of the time segments. VPCAS does treat separate included searches as independent, whether simultaneous or sequential. A recent feature of PACSEARCH semi-automates such modifications.

Updating for positive information (a new contact report, partially credible) is also analogous to 2.3.2--note the caveat there and further discussion in 2.6 and 2.7 below. The prior which begins this positive update is the negative update to the end of the included search during which the positive information is obtained, unless it is modified to an earlier time as above. Figures II-29 and II-30 illustrate addition to an ellipse type distribution of a new contact report (positive information) in the form of an AOP, with credibilities .2 and .8 respectively. Note that with credibility .8, the new contact dominates the distribution.

FIGURE II-29. THE EFFECT OF AN AOP DETECTION OF CREDIBILITY .2 ON AN ELLIPTICAL DISTRIBUTION

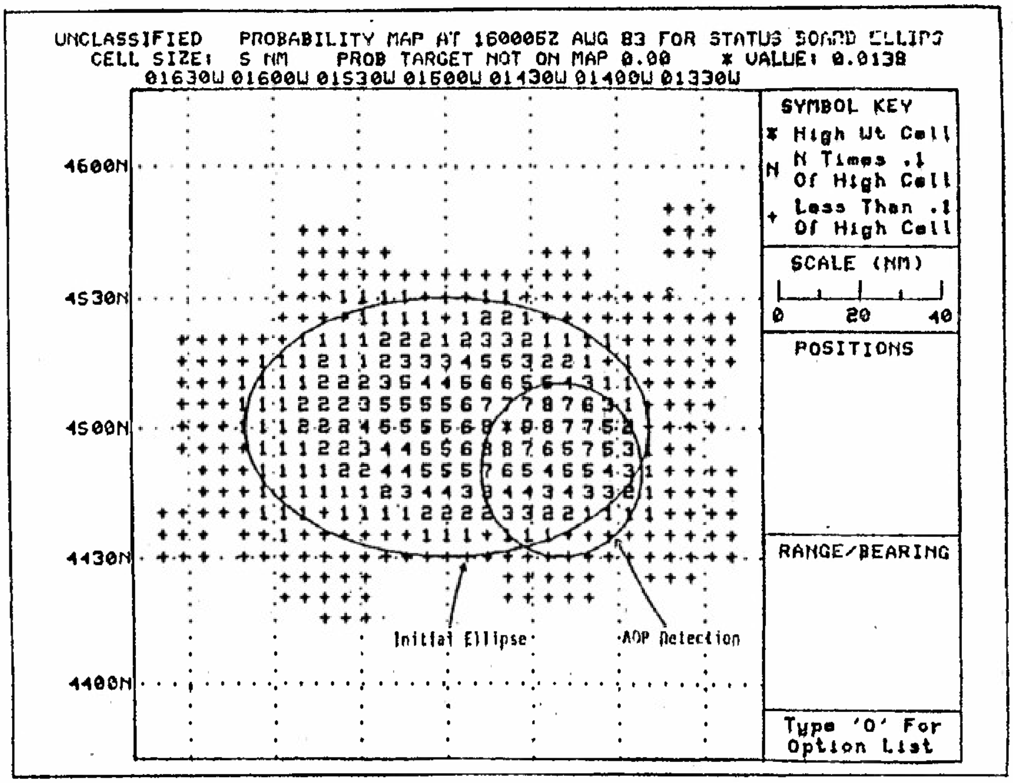
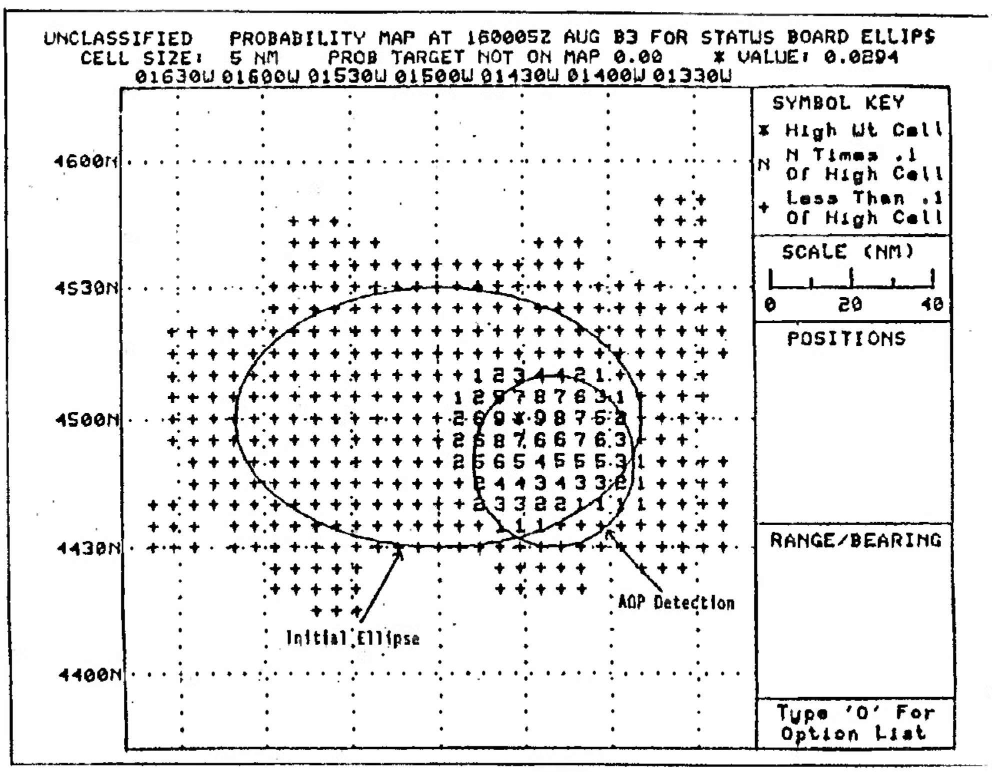


FIGURE II-30. THE EFFECT OF AN AOP DETECTION OF CREDIBILITY .8 ON AN ELLIPTICAL DISTRIBUTION



2.4.6. Probability map. When a probability map is to be displayed, the probability of a given geographic cell is taken to be the sum of the probabilities (normalized weights) of the tracks whose map-time points are in that cell. However, first each point (i.e., track) weight is smoothed as follows with respect to location *within* its cell. Let d_i be the distance from the point to the *center* of the cell, where i runs over the cell containing the point (call it cell 1) and its eight neighboring cells. Let k be the (uniform) cell width and w be the point weight being smoothed. Then the smoothed weight is

$$w \exp(-.1\ d_1/k)/\sum_{i=1}^{9} \exp(-.1\ d_i/k).$$

The cell probabilities formed from the smoothed point weights are output as scaled single digits as in 2.4.1.

2.4.7. Search plan recommendations. On user request, VPCAS computes recommended placement of search effort. A plan extending over up to five sorties may be requested. The MOE is probability that detection occurs at some point during the specified aggregate of sorties.

For a single sortie, the program recommends (see reference [s]) a location of a buoy pattern, a pattern type, a pattern orientation, and buoy spacing. The pattern type and buoy spacing are from among user-entered options. Rather than rely on an *instantaneous* probability map, the program considers target behavior over the pattern's monitor period, specified in advance, and goes back to the 500 tracks. From these it constructs an "exposure time map." This map shows for each cell the mean time, reflecting track weights, that the target spends in that cell during the pattern's monitor time. For this calculation, each track is approximated by a track with course and speed constant at the track's average course and speed over the monitor period. Each cell is smoothed with its eight neighbors, as is done for probability maps. Based on the exposure time map, the program selects two pattern locations, each with a pattern orientation. Now the program tests all pattern types and buoy spacings for each of the two locations and thereby chooses the best among these combinations of location, orientation, type, and spacing for that sortie.

For the 16-track example of 2.3, an exposure time map is illustrated in Figure II-31 for monitor time 3 hours to 6 hours.

For multiple sorties, the program iterates according to Brown's algorithm described in references [l], [k], [e], and [jj]; the latter calls it the FAB algorithm. Each iteration goes through all sorties. For each sortie in each iteration, the procedure is as above except for modification of the exposure time map. In the first iteration, after the first sortie each exposure time map is updated *at the track weight level* for non-success of the prior sorties. A tentative plan is thus obtained for each sortie according to the first iteration. In subsequent iterations, the track weight updating is conditioned on non-success on sorties *before* the sortie of the exposure time map using the tentative plan of the current iteration and also is conditioned on non-success on sorties *after* the same sortie using the plan of the *prior* iteration. This is the essence of the Brown/FAB algorithm. The iterations usually converge rapidly--often two suffice.

FIGURE II-31. ILLUSTRATIVE EXPOSURE TIME MAP

0	0	.008	.02	0	0	0	0
0	0	.05	.003	.02	0	0	0
0	.06	.08	.14	.30	.15	0	0
0	.07	.19	.36	.13	.06	0	0
0	0	.14	.20	0	0	0	0
0	0	.04	.16	.19	.11	.02	0
0	0	0	.02	.10	.09	.05	.02

2.5. Historical Analysis Modeling of Target Motion

Sometimes in applications the best available basis for modeling target motion is historical knowledge of target habits rather than recent contact reports. For example it may be that a target is believed to have left port in some time interval and no other information is available for a substantial time thereafter. We now describe how VPCAS and successors apply historical analysis to deal with this situation.

The principal idea in this historical analysis method is to capture the most useful information in a large data base on target habits by a gradient field of stochastic differentials. It is assumed that target motion can be given an IOU process with velocity drift--see Appendices B and D. This means that it can be characterized by assigning to each geographic cell a quadruple of numbers: average steady-state velocity in two components, the rate at which the actual velocity moves toward the average (a damping coefficient), and the standard deviation of speed.

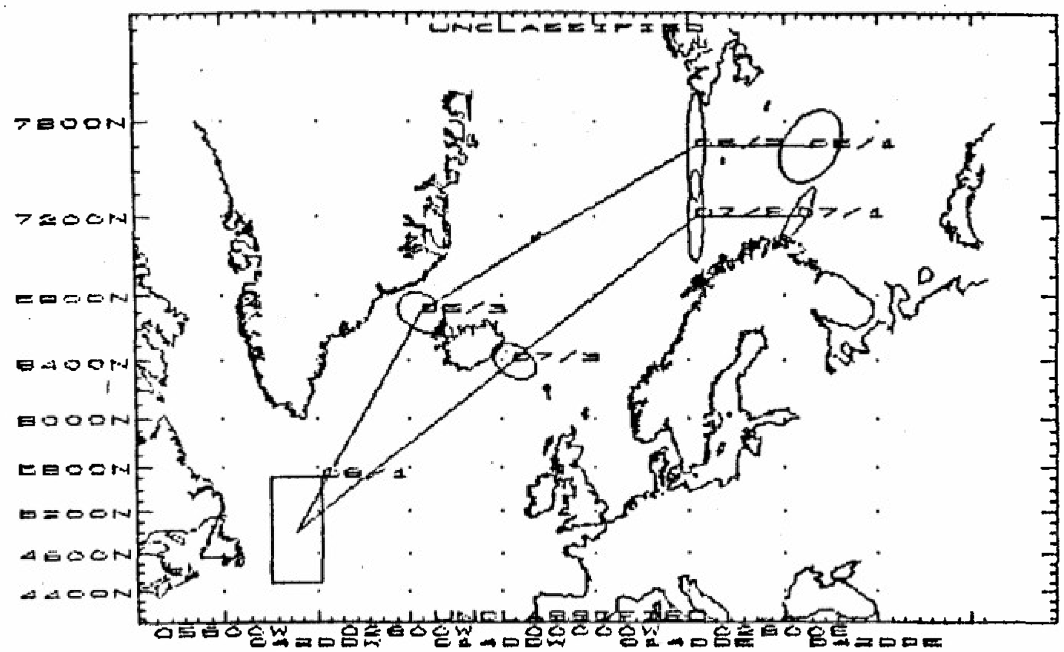
For the LANT and PAC theaters, these quadruples were in fact estimated from a CINCLANTFLT data base. The estimation used Kalman filtering and smoothing in forward-backward fashion. Interpolative smoothing was important in part because the target tracks often had substantial data gaps. This combination of methods is reminiscent of MTST (see Chapter III), but the drift term in the IOU process is an added complication.

The estimated quadruples were then disc-stored for access by VPCAS, and machinery was added to VPCAS to afford such access. An historical motion model in LANT and PAC is thereby available for VPCAS calculations. In the PACSEARCH successor to VPCAS, parameter estimation is included in an historical subsystem of PACSEARCH which produces motion models.

In Figure II-32 we illustrate application of historical analysis with a fictitious example taken from the PACSEARCH user's guide, reference [w]. This is an exit from a fictitious North Cape port, transit to a North Atlantic patrol area, and return to port.

FIGURE II-32. ILLUSTRATION OF MOTION MODEL BY HISTORICAL ANALYSIS

The upper track is scenario 6, intervals 1, 2, 3.
The lower track is scenario 7, intervals 1, 2, 3.
Motion in the rectangular patrol area is scenario 8, interval 1.



The user enters lat/long of the port, a radius (say, 20 nm) of an AOP centered on the port as an initial position, a distribution of port exit time (normal, triangular, or uniform), exit scenarios (here two standard exit lanes), and scenario weights (say, .5, .5). This initiates a target motion model which is carried forward according to the historical information as described above. The subsequent stages could be motion into the patrol area (the "BOX" motion model), motion within the patrol area (the "PAT" motion model), motion out of the patrol area, inbound transit, and port arrival. This requires about 16 seconds of computing on the HP 9020 per day of motion.

2.6. PACSEARCH

PACSEARCH was developed at COMTHIRDFLT and COSP for Pacific area ASW use and is addressed to best use of fixed and towed array assets in ASW search. It includes an HP 9020 version of VPCAS. This affords to begin with much better graphics, e.g., shaded-color-coded probability maps, and much better speed and memory than were available in the NOVA 820 version of VPCAS. Since PACSEARCH potentially offers a much improved CAS capability to the ASWOCs, it was provided by COSP to ASWOC Barber's Point, with a user's guide and minimal training.

We illustrate in Figures II-33 through II-37 some key displays of PACSEARCH. The main differences between PACSEARCH displays and those of VPCAS are the form of the probability maps and references to arrays.

The main menu structure consists of the Status Board menu, Figure II-33, and the Search Planning menu, Figure II-34. The former presents status and the latter is used to activate production of desired outputs.

Figure II-33 shows the status, at some stage of a problem, of inputs pertaining to detections, searches, target motion, and acoustics, and it offers options to select a menu to modify any of these. The sole "detection" listed, "RED1," is the initial distribution of target position. A search, "SRCH1," is listed for consideration; it need not have been enacted and it would be reflected in a probability map only if the user so elects. A single target motion assumption is listed; more, with weights, could be added. Under acoustics, a proploss file, "ACOU," is listed. To remind oneself of details of any of these, one follows menus to modify, not necessarily carrying out a modification. The name of the status board, "EXAMP1," is the user-chosen name of the problem being worked.

By choosing option 5 in Figure II-33, one comes to Search Planning, Figure II-34. The user has elected not to include a search plan from what was listed under search status. At this point one might choose to look at the probability map at a chosen time, without search effort. Instead, suppose the user asks the program for a sonobuoy search plan recommendation, option 5. After the user specifies number of sorties (assume it's one), number and type of buoys, the start and end of monitoring, and some alternatives as to types of pattern, buoy spacing, and row spacing, the program outputs the recommended plan shown in Figure II-35. If this 4-hour search is enacted without a detection, the resulting probability map is as in Figure II-36; at the user's choice, the pattern location is also shown. Note the probability reduction in what was the high probability area, resulting from the negative information.

If instead the user had requested a 3-sortie plan, the program would have worked for two minutes and produced, by the Brown/FAB algorithm, the plan in Figure II-37. Note that there is a difference, although not major, between the 1-sortie plan and the plan for the first sortie of the 3-sortie plan (bearing out the last paragraph of 2.1). The patterns are 4 x 4 versus 5-6-5, the kingpins are 12 nm apart, and the cdp's are .4 and .39 (quite close).

FIGURE II-33. PACSEARCH STATUS BOARD

```
                STATUS BOARD FOR EXAMP1

                      DETECTIONS
         ID          DTG             TYPE     CRED
         --          ---             ----     ----
         RED1   091534Z NOV86        AOP      1.00

                       SEARCHES
         ID          DTG             TYPE     INTEG
         --          ---             ----     -----
         SRCH1  110500Z NOV86 LINE PATRN 1.00

                     TARGET MOTION
WGHT TYPE
---- ----
1.00 /CONSTRAINED/FRONT/

                      ACOUSTICS
         ID
         --
             ACCU

                                      UNCLASSIFIED

      OPTIONS
        1- ACOUSTICS        5- SEARCH PLANNING
        2- DETECTIONS       6- COPY SCREEN TO OUTPUT FILE
        3- TARGET MOTION    7- EXIT
        4- SEARCHES
```

FIGURE II-34. PACSEARCH SEARCH PLAN MENU

```
     SEARCH PLANNING

     SONOBUOY SEARCH PLAN ALTERNATIVES

 ID      START TIME      STOP TIME        TYPE
 --      ----- ----      ---- ----        ----
                 NONE AVAILABLE

                                          UNCLASSIFIED
     OPTIONS
 1-  PROBABILITY MAP
 2-  CUMULATIVE PROBABILITY OF DETECTION
 3-  COURSE AND SOA DISTRIBUTION
 4-  SCENARIO WEIGHTS
 5-  PACSEARCH SONOBUOY SEARCH PLAN RECOMMENDATION
 6-  ENTER/DISPLAY SONOBUOY SEARCH PLAN ALTERNATIVES
 7-  EVALUATE SONOBUOY SEARCH PLAN ALTERNATIVES
 8-  TRANSFER SONOBUOY SEARCH PLAN ALTERNATIVES TO STATUS BOARD
 9-  LIST/CHANGE DATA FOR CALCULATIONS
 10- ARRAY SEARCH COVERAGE
 11- OPTIMIZE ARRAY SEARCH COVERAGE
 12- OPTIMIZE TOWED ARRAY SEARCH COVERAGE
 13- RETURN TO STATUS BOARD OPTION TABLE
```

FIGURE II-35. PACSEARCH SINGLE-SORTIE BUOY SEARCH PLAN RECOMMENDATION

```
        COMPUTE SONOBUOY SEARCH PLAN

PACSEARCH RECOMMENDS THE FOLLOWING SONOBUOY SEARCH PLAN

  BEST PATTERN FOR EVENT MT001  AT 110500Z NOV86 TO 110900Z NOV86
    PATTERN IS A       4X4
    KINGPIN LAT         3912N
    KINGPIN LNG        14745W
    ROAD                  343 DEG
    WALK                   73 DEG.
    BUOY SPC              9.0 NM
    ROW  SPC              7.8 NM
    CUMULATIVE PD THROUGH THIS EVENT IS  .40

  CUMULATIVE PD FOR RECOMMENDED PLAN IS  .40
```

FIGURE II-36. PROBABILITY MAP AFTER UNSUCCESSFUL SINGLE-SORTIE BUOY SEARCH

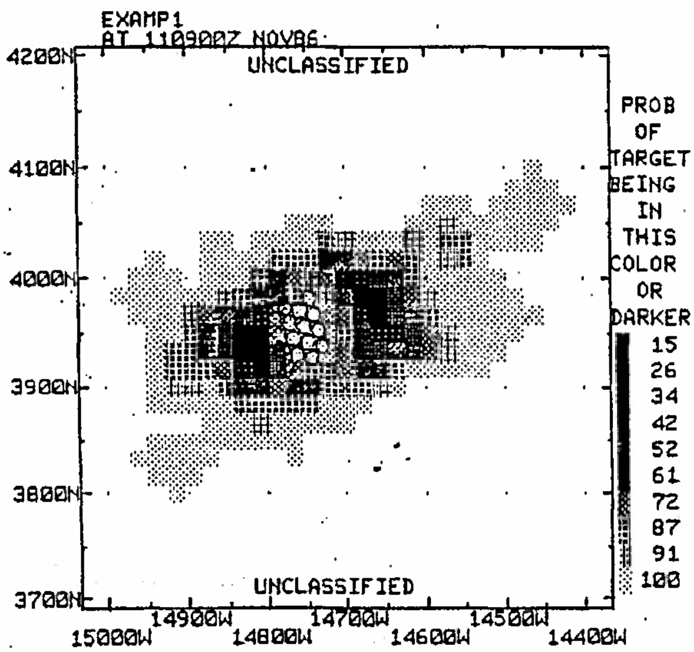


FIGURE II-37. PACSEARCH RECOMMENDED PLAN FOR THREE-SORTIE BUOY SEARCH

```
                COMPUTE SONOBUOY SEARCH PLAN

PACSEARCH RECOMMENDS THE FOLLOWING SONOBUOY SEARCH PLAN

  BEST PATTERN FOR EVENT BS001  AT 110500Z NOV86 TO 110900Z NOV86
     PATTERN IS A      5-6-5
     KINGPIN LAT        3908N
     KINGPIN LNG       14736W
     ROAD                344 DEG
     WALK                 74 DEG
     BUOY SPC            9.0 NM
     ROW  SPC            7.8 NM
     CUMULATIVE PD THROUGH THIS EVENT IS  .39

  BEST PATTERN FOR EVENT BS002  AT 110900Z NOV86 TO 111300Z NOV86
     PATTERN IS A      4X4
     KINGPIN LAT        3907N
     KINGPIN LNG       14813W
     ROAD                343 DEG
     WALK                 73 DEG
     BUOY SPC            9.0 NM
     ROW  SPC            7.8 NM
     CUMULATIVE PD THROUGH THIS EVENT IS  .56

  BEST PATTERN FOR EVENT BS003  AT 111300Z NOV86 TO 111700Z NOV86
     PATTERN IS A      5-6-5
     KINGPIN LAT        3936N
     KINGPIN LNG       14608W
     ROAD                346 DEG
     WALK                 76 DEG
     BUOY SPC            9.0 NM
     ROW  SPC            7.8 NM
     CUMULATIVE PD THROUGH THIS EVENT IS  .73

  CUMULATIVE PD FOR RECOMMENDED PLAN IS  .73
```

Finally we note some advances in PACSEARCH over VPCAS. We have already noted that the historical analysis capability in PACSEARCH is more self-contained than in VPCAS. Also, PACSEARCH can store 100-interval historical models versus five intervals in VPCAS. Other additions include fixed and towed arrays with beamformer characteristics; evaluation and optimization (largely by selective exhaustion) of array sensor detection capabilities including optimal rectangles; range-dependent proploss curves (not included in the ITDA version discussed in Chapter IV); an additional motion type called intercept, which has a moving destination; directional ambient noise; maps of area clearance (SEP as in 2.13.1 below applied to moving targets for towed arrays); sensor coverage maps; and a tracker.

The tracker works as follows: A new contact is obtained with credibility c (probability that the contact is on the correct target) and a geographic distribution Q which is treated as a distribution of target position even though it may be really the distribution of sensor measurement error. Let P be the contact-time prior distribution of target position. It is desired to create a new bundle of 500 tracks which appropriately combines Q, c, and P.

Draw 500c position points from Q and 500(1− c) position points from P, the latter being chosen as prior track points. The number of points from P that are in cell i will be proportional to the prior weight of cell i and the number in cell i from Q will be proportional to the probability of cell i under Q. All 500 points have the same weight. Also assigned to cell i is a distribution of target speed, which is the distribution of speeds of the prior tracks in cell i, smoothed by weighting with distributions in adjacent cells; a similar remark applies to target course and, without need for smoothing, scenarios. By random draws from these distributions a track is generated emanating from each point. The new probability assigned to each cell is the same as would be assigned by the method used by VPCAS and, e.g., reference [a], for positive updating; this probability is divided uniformly over the tracks in the cell. The PACSEARCH tracker has the advantages over VPCAS of better map rescaling and a smooth transition in distributions of scenarios, course, and speed. These advantages entail the disadvantage that one cannot look back for revision of inputs any earlier than the last positive update. This methodology and related topics are discussed in reference [x].

The map rescaling has this significance: When a probability map crowds the probability into a small region, it is usually advisable to reassign tracks lest there not be enough probabilistic detail in the important part of the map. In VPCAS this can be done by restarting the problem. In PACSEARCH the tracker accomplishes this rescaling.

Thus in PACSEARCH target tracking is integrated naturally with the time sequence of probability maps which form the basis for search planning. Positive updating is subsumed under tracking. These remarks apply also to the later P-3C Update IV search software and to SALT. Both the Update IV short-term tracker and SALT provide Bayesian updates, for negative and positive information alike, via likelihood estimates based on the observed sequence of detections and non-detections. We will review these methods in the next two sections.

We note a proposed TDA which could be an adjunct to PACSEARCH, or could operate (at a different level) without PACSEARCH. This is a TDA to help allocate resources of a NAVFAC, serving COSP or COSL. It has been proposed by the NPGS thesis of LT R. L. Rubin (reference [y]) with participation of his advisor, G. G. Brown. A decision is a zero-one vector of high dimension which indicates assignments of beams to processing stations and beam focusing. This is evaluated by a priority-weighted sum *over various targets* of mean signal excess received by a beam, multiplied by contribution of the processing stations assigned to the beam, and summed over the beams. Reasonable solutions to this large-scale mixed-integer linear programming problem have been obtained, and are believed computable on, e.g., a Sun Work Station. This addresses an important TDA need, which is especially difficult in terms of multiple targets, and appears to merit exploration.

2.7. Trackers in the P-3C Update IV

The search software under development for the P-3C Update IV contains two trackers, one short-term (STT) and the other long-term (LTT). The LTT is a derivative of VPCAS in updating for target motion and negative and positive information. The STT finds a likelihood estimate of the target track, at low data rates, based on all observed detections and non-detections during detection opportunities. When high quality tracking is achieved, a Kalman filter tracker takes over from the LTT and STT.

Both of these trackers merge search processing with tracking processing via positive information updating, which, at the same time, is treated in parallel with negative information updating. This is also true of PACSEARCH (see 2.6) and SALT (see 2.8) and is an important contemporary evolution in search and surveillance planning software.

The search and tracking software in Update IV is in the Monte Carlo framework of a weighted bundle of 500 (or more) sample target tracks discussed in much of this chapter. The target motion model in the LTT is the same as in VPCAS (see 2.4); the STT uses a generalized random tour. Both use a (λ,σ) process to model deviation of *actual* signal excess from the *mean* signal excess which is predicted causally. The values of λ and σ are fixed in the program. In the LTT, cumulative detection probability is computed by the discrete-glimpse unimodal formula (see Appendix C); in the STT, the Poisson part of the (λ,σ) process is simulated and the gaussian part impacts without simulation.

The LTT initiates with the first external contact report, presumably at the start of the ASW mission part of the flight. Upon first buoy contact, the STT initiates and the display switches to its output. The LTT continues to operate, invisible to the user. The STT operates and displays until the earliest of (1) mission completion, (2) tracking becomes good enough that it transitions to a Kalman filter tracker, and (3) contact is lost and the first reacquisition attempt thereafter is completed unsuccessfully. Upon (3), the LTT is again displayed instead of the STT. Meanwhile the LTT has included the negative information but not the positive information used by the STT (the positive information is deemed false if the display reverts to the LTT).

We review the STT and LTT in turn. The 500 or more sample target tracks are generated separately from what follows.

2.7.1. Short-term tracker. First note that the target state is 4-dimensional position-velocity. At an arbitrary time instant after STT initiation, during search by a field of buoys, various buoys were in contact part of the time and not at others. We wish to make a new estimate of target state, which is based on our prior assumptions and the contact/no contact information.

Pick a sample track. Take a sequence of independent draws from the exponential distribution whose mean is $1/\lambda$. Each of these simulates the time between jumps of the (λ,σ) process for the chosen track, and *applies to all buoys* in the field. It is assumed that inter-buoy statistical correlation is complete. What we have done is to identify the inter-jump time intervals within which the *signal excess deviation is constant* (and is the same for all buoys). Note that we have not *drawn* these constant values, which would come from the normal distribution with mean zero and variance σ^2.

We also specify that all buoys will be observed as to contact/no contact status at discrete times which are, with exceptions, one minute apart. However, whenever a buoy begins contact, that starts a new sequence of one-minute intervals between observations, for all buoys. (The buoys are monitored at times additional to the STT observation times.) Note that λ is on the order of one per hour, so the observation times average about 60 per inter-jump interval.

Pick one of these inter-jump intervals, and pick a buoy. For the chosen sample track and this buoy we have a history, over the interval, of range to target and accordingly of *mean* signal excess, both of which change from the motion of the track.

Such a history of mean signal excess is illustrated in Figure II-38. Also shown are the observation times, and these are annotated C or N according as the buoy is or is not in contact. Let m_i be the mean signal excess at observation time

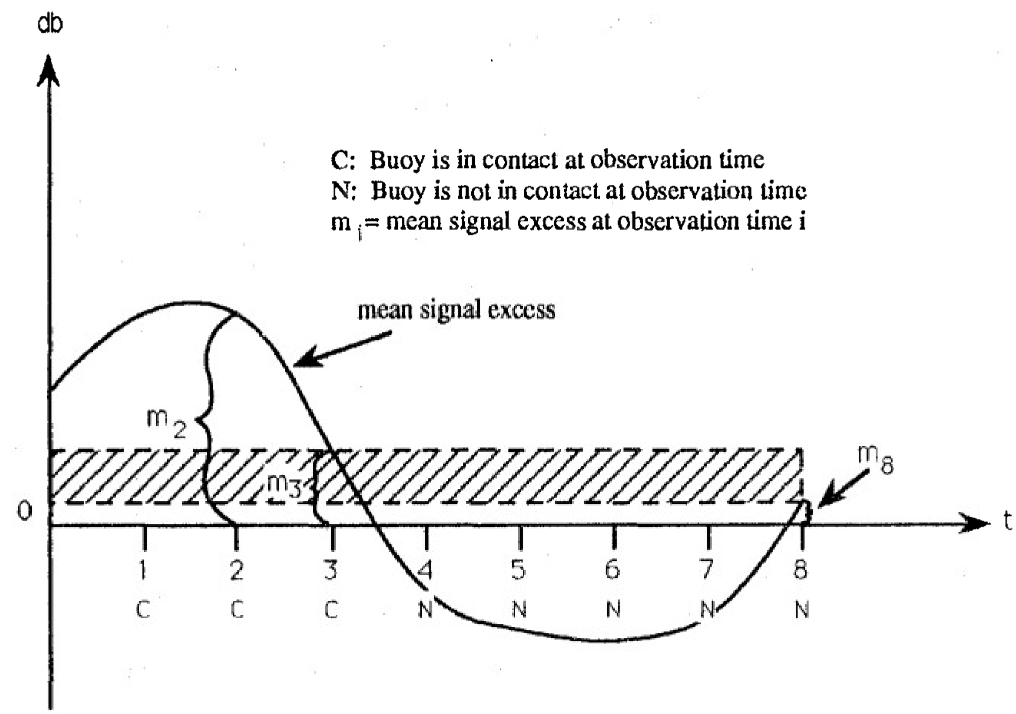
i. Consider time 2. Since the buoy is in contact at time 2, its *actual* signal excess is positive. Hence the as yet unknown draw of the signal excess deviation, call it x (constant over the interval), must be at least $-m_2$, *providing* our various other assumptions, notably the hypothesis that the chosen target track is actual, are correct. Similarly, since the buoy is *not* in contact at time 5, *actual* signal excess of the buoy is negative at that time, so we must also have $x < -m_5$. We have shown $-m_2 \le x < -m_5$, i.e., $m_5 < -x \le m_2$. To narrow down further the possible choices for x, we see that we need only consider the time of *least* mean signal excess among those when contact *is* held, i.e., time 3, and the time of *greatest* mean signal excess among those when contact is *not* held, i.e., time 8. Thus the set of values of x which are consistent with the observations on this buoy for this interval and track is given by the condition $-m_3 \le x < -m_8$, i.e.,

$$m_8 < -x \le m_3.$$

This set is shown as the shaded strip in Figure II-38, which is called the "tunnel" for this track, interval, and buoy. We care only about the projection of this tunnel on the vertical axis, and our interest is in the probability of this set. Hence it does not matter whether this is a condition on x or –x; they both have the same distribution.

FIGURE II-38. STT TUNNEL CONSTRUCTION

NOTE: Buoy, target track, and inter-jump interval are fixed, tunnel is shaded.



Similarly, we find the tunnel for each buoy for this track and interval. The set of values of x which is consistent with the contact/no contact histories and mean signal excess histories of *all* of them, again with our other assumptions, is the *intersection* (because of inter-buoy complete dependence) of all the single-buoy tunnels. The probability that x (or –x) is in that intersection is taken as the *likelihood* of the chosen track during the chosen interval. Again, the distribution of x is normal $(0,\sigma^2)$ so this probability is easily found.

Now suppose the inter-jump interval we chose contains the *present* time, so we can treat only part of the interval, from the start of the interval to the present. This is handled the same way. Previously we found and stored the likelihood of the track for the entirety of each of the previous inter-jump intervals. From the definition of the assumed (λ,σ) process, the statistics for separate inter-jump intervals are independent. Hence, the product over the inter-jump intervals, including the partial current interval, of the single-interval likelihoods is taken to be the likelihood of the chosen track; it is also the track weight.

The same is done for each track. When track probabilities are needed, the track weights are normalized, as usual. To perform this entire processing to update for a new observation time requires typically two seconds on a Sun 3/60 Work Station for about 20 buoys.

Let's return to Figure II-38. Note that the likelihood for that buoy, interval, and track is governed by just two observations, at times 3 and 8. However, time 2, for example, has a higher mean signal excess than time 3, so it is less surprising that contact is held at time 2 than at time 3. A symmetric remark applies to no-contact times. Thus the main (but not all) information content is in the observations at times 3 and 8, the "most surprising" events, from which we have inferred likelihood in this part of the problem.

Also, suppose a tunnel is vacuous, i.e., in Figure II-38, $m_8 > m_3$. Then the chosen track is given likelihood, i.e., weight, zero. That is another way of saying there is *no* draw from the assumed normal distribution with which that track (out of the 500 or so) is consistent.

If it should turn out that each track has at least one interval for which the numbers corresponding to $m_3 - m_8$ are small compared to σ, the ratios of track weights would be rather sensitive to small errors in the numbers such as m_3 and m_8. This kind of problem should be affected by the time between observations (one minute above). As designed that is adjustable pre-flight but not in-flight. Simulation evaluation is under way (and the method was reported to MORS June 1989). It will be interesting to see if such a sensitivity problem arises, and more generally how well the STT outputs realistic tracks.

2.7.2 Long-term tracker. The LTT is modeled much the same as VPCAS with a few differences.

One significant difference is that the probability map is displayed continuously rather than upon user request. For that reason, the map is updated every 15 minutes, and accordingly buoy information is incorporated at discrete times 15 minutes apart. The discrete-glimpse (λ,σ) unimodal formula (Appendix C) is used for cdp; each cdp runs from search inception but that is easily done by multiplicative adjustment to 1–cdp from 15 minutes earlier.

Another significant difference is that actual buoy positions are used as monitored in the aircraft. This obviates discrepancies between intended and actual positions at buoy launch and effect of drift after water entry.

Among planned improvements is inclusion of the PACSEARCH intercept motion model.

The LTT maps reflect all information received from external sources, negative information from buoys monitored by own aircraft (some or all of which could have been laid externally) and the contact from the latter which triggers handover to the STT. Just prior to the handover, the LTT updates its track weights and hence its map for the positive information of this contact. As it stands, it does so by the VPCAS (Dempster's rule) heuristic (also in PACSEARCH and reference [a]). The remainder of this section gives a ***Bayesian*** approach when one can relate the positive information to the prior, and which also reduces to the heuristic method when one cannot do so. This approach is contemplated as a future improvement to the LTT. Through (II-2) it is due to M. G. Monticino, and the remaining derivation of (II-4) is due to W. R. Monach; A. R. Washburn provided a simplification.

Suppose we have a target position distribution, i.e., probability map, P that has been updated for all known information except for a new contact report. This report states that contact has been gained by one or more sensors, the contact credibility is c, i.e., the probability that it is on the correct target (same meaning as in 2.3.2), and may include a position distribution Q. We wish to update the weight of each sample track to account for this information.

Let D, DF, and DV be the events that, respectively, a detection (i.e., contact), a false detection, and a valid detection occur after the last update (the prior). Assume DF and DV cannot both occur and D is equivalent to the event: DF or DV. Let T_i be the event that the ith track correctly represents the target motion. Denote by P[E] the probability of the event E (in the Appendices we use Pr{E}). Assume $P[D] > 0$ and for some j, $P[T_j|D] > 0$. Observe that by Bayes' rule the posterior probability of T_i, given that D is observed, is (we denote summation over all tracks with respect to j by Σ_j)

$$P[T_i|D] = \frac{P[T_i]P[D|T_i]}{\Sigma_j P[T_j]P[D|T_j]} = \frac{P[T_i]P[D|T_i]}{P[D]}$$

$$= \frac{1}{P[D]} \{P[T_i]P[DF|T_i] + P[DV|T_i]P[T_i]\}$$

$$= \frac{1}{P[D]} \{P[T_i]P[DF] + P[DV|T_i]P[T_i]\}. \qquad \text{(II-1)}$$

The last step follows because T_j and DF are independent for all j. Also,

$$c = P[DV|D] = P[DV]/P[D],$$

so

$$P[DV] = cP[D] \quad \text{and} \quad P[DF] = (1-c)P[D]. \qquad \text{(II-2)}$$

Note further that for all j,

$$P[DV|T_j]P[T_j] = P[T_j|DV]P[DV]. \qquad \text{(II-3)}$$

Hence

$$P[T_i|D] = \frac{1}{P[D]}\{P[DF]P[T_i] + P[T_i|DV]P[DV]\} \text{ by (II-1) and (II-3)}$$

$$= (1-c)P[T_i] + cP[T_i|DV] \quad \text{by (II-2)}$$

$$= (1-c)P[T_i] + c\frac{P[DV|T_i]P[T_i]}{\Sigma_j P[DV|T_j]P[T_j]}, \tag{II-4}$$

by Bayes rule applied to $P[T_i|DV]$. Since the $P[T_j]$'s come from the known prior and we know c, to compute (II-1) we need only the $P[DV|T_j]$'s.

In cases where the contact report is such that nothing is known about sensor effectiveness or any knowledge of target position which led to the contact, one may take $P[DV|T_j]$ to be the probability assigned to track j by the position distribution Q in the contact report. With that assumption, (II-4) becomes exactly the positive update formula used in VPCAS (Figure II-14), which goes back at least to reference [a]. In fact VPCAS and PACSEARCH use this same method for all positive updating. As noted in 2.3.2, this is a reasonable heuristic in the absence of a probabilistic relationship.

Suppose on the other hand that a probabilistic relationship is known between the reported contact and the prior, as should be the case if the contact arises from search being planned and monitored. Then one wishes to choose the $P[DV|T_j]$'s by relating the contact to the known detection processes and making (II-4) a Bayesian posterior. One method suggested is to let $P[DV|T_j]$ be the cdp for the aggregate of buoys, conditioned on the event T_j, while also removing from the prior the negative information from the search that led to this contact.

Monach has recently proposed an approach which utilizes (1) probabilities that if a target is detected in cell j it will be reported to be in cell i (which is what the distribution accompanying a contact report usually means and (2) postulated false target probabilities in each cell. He shows that this leads to a natural definition of credibility c_i, of a report whose mean position is reported in cell i, as $v_i/(f_i+v_i)$, where v_i and f_i are the probabilities of obtaining a contact report whose mean is in cell i and which is respectively valid or false. Such c_i could be used in (II-4).

A motivation for including credibility in a positive updating model is that in operations contact reports are typically accompanied by a credibility. Our belief is that it would be better to postulate false target behavior instead of credibility and to derive a Bayesian posterior from that.

2.8. SALT

The Search and Localization Tactical Decision Aid (SALT) is a contemporary *analytic* approach to CAS by Metron in contrast to the Monte Carlo methods reviewed thus far. At present it exists in four versions as follows:

(1) Air SALT is a prototype and the first version of SALT, developed on an Apollo DN-3000 under a Phase I contract with Lockheed for the P-3C Update IV. It is intended for inflight use in buoy search. Although it is

not going forward in P-3s, our review is primarily of this version because it has good technical documentation available, reference [z].

(2) Surface SALT is an advanced development model for NOSC on an HP 9020 for search by surface ships using towed and hull-mounted arrays and buoys. It has been used at sea by COMDESRON THIRTY-ONE.

(3) Sea SALT is a prototype for tracking by SSNs, developed for NOSC on an HP 9020 and for NAVSEA on an Apollo DN 3000.

(4) Parallel SALT is a multi-static application developed as a prototype for DARPA.

Our subsequent reference to SALT will mean Air SALT, but most of what is said applies to all versions.

For an arbitrary number of buoys SALT recommends a pattern customized to the problem at hand; prior to localization search, this is uniform over a rectangle or a line segment. Probability maps are displayed continually (color-coded), and when positive information is added a new pattern recommendation may be generated. It has a natural transition to localization and tracking. The localization objective is minimization of area of uncertainty rather than maximization of detection probability.

2.8.1. SALT inputs. Following are basic inputs to SALT:

Theater--LANT, PAC, or Indian Ocean

Target tactic--transitor (preferred course), patroller (no preferred course), or fleeing datum (constant course and speed once drawn)

Two target depths and probability of each

Course and speed distribution parameters

Initial position as a *bivariate normal distribution*

Two frequencies and target source levels for each

Barrier parameters

Chevron localization parameters

Acoustic fluctuation parameters

Numerous user-chosen proploss curves are in memory and depend on depth, frequency, and theater. The target course distribution is uniform or triangular, and the speed distribution is triangular.

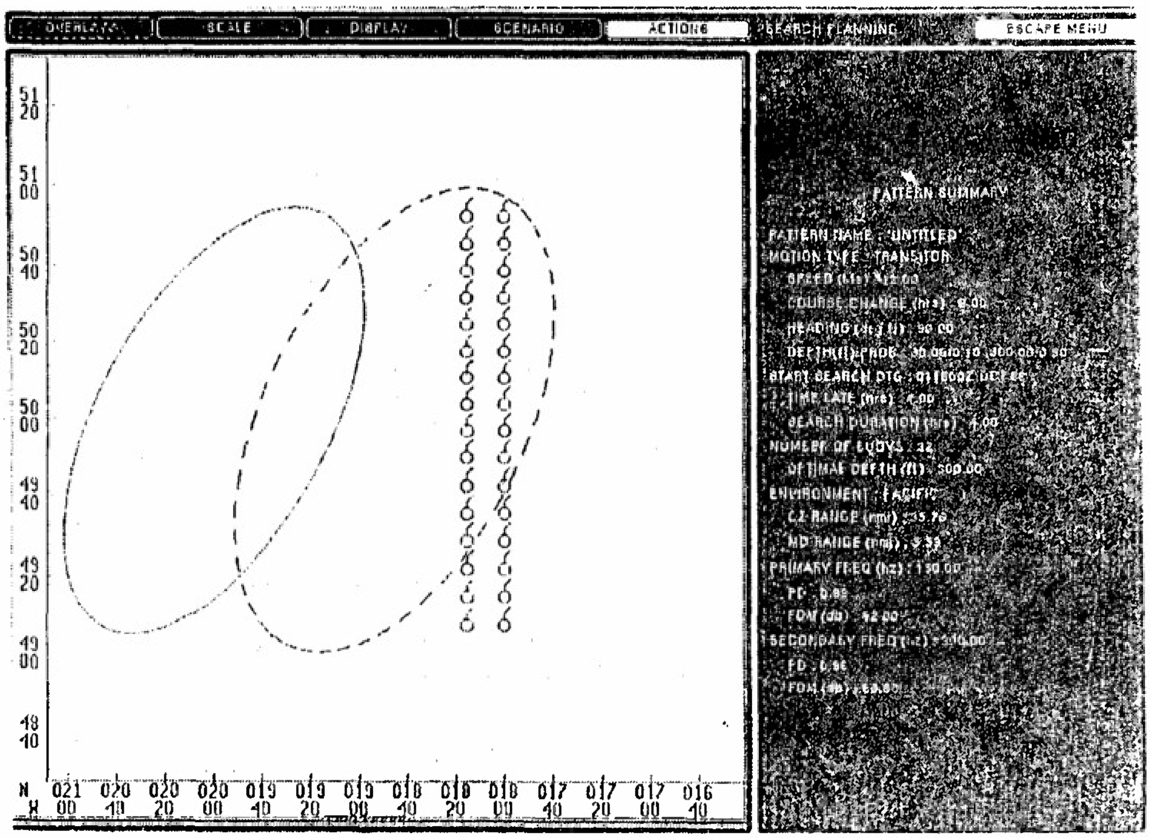
2.8.2. Operation of SALT. After the inputs are entered, the program recommends an initial search plan as in 2.8.4 below. A user-chosen plan may be substituted. When the first buoy enters the water, the Likelihood Ratio Tracker (LRT) is initiated and displays a probability map continually. Each buoy is plotted when dropped. The map is updated about every 20 seconds for motion and negative and positive information. When a buoy detects, it is highlighted.

The search is replanned on user request, again as in 2.8.4, presumably when buoy detections indicate that the previously planned remaining effort is no longer optimal.

The LRT map is rescaled as the distribution contracts. Upon sufficient contraction, localization begins and a chevron pattern is recommended.

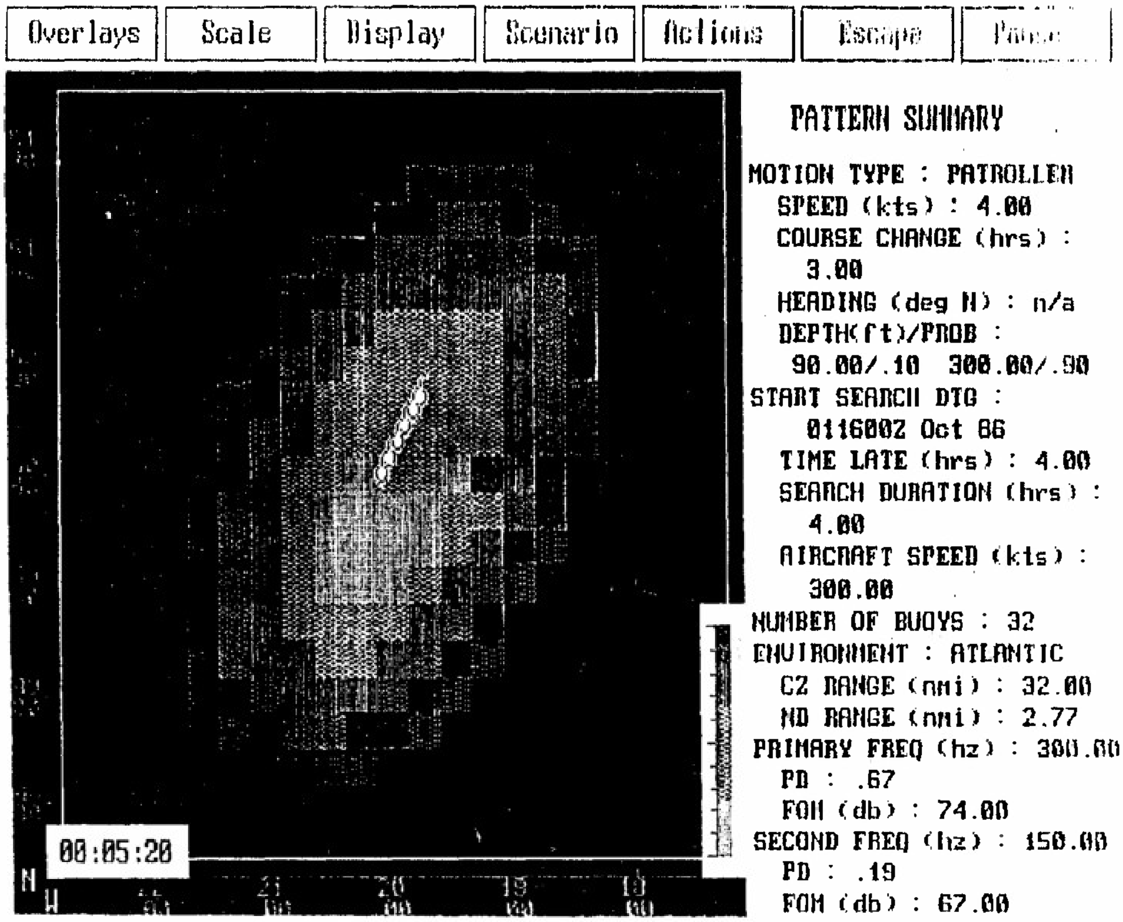
Some SALT displays in buoy search are shown in Figures II-39, II-40, and II-41; color originals are more informative. Figure II-39 shows an initial search plan recommendation. An LRT map prior to buoy contact is shown in Figure II-40. A similar map after contact by two buoys (darkened) is shown in Figure II-41. (Figure II-40 is from an example different from II-39 and II-41.)

FIGURE III-39. SALT INITIAL BUOY SEARCH PLAN RECOMMENDATION



2.8.3. SALT motion modeling overview. The approach to motion modeling in SALT is to regard as an "ideal" model a generalization of Washburn's random tour, reference [v]: Velocity changes occur as events in a Poisson process, and when a change occurs a new velocity is drawn from a fixed distribution independent of the previous velocity. (See B.5.) To the horizontal motion under this process, SALT adds a two-valued depth state. Transitions between the two depths follow a separate Poisson process. Then the 5-vector state, (position, depth, velocity), is Markovian and remains so under discretization of time and state. Resolution requirements govern the number of discrete cells in state space. At the 1-dimensional level, SALT typically uses 21 cells for each of the two position coordinates, eight cells each for course and speed, and two depth cells. Thus there are 21 x 21 x 8 x 8 x 2 = 56448 5-dimensional cells in the state space.

FIGURE II-40. SALT LRT MAP PRIOR TO FIRST BUOY CONTACT

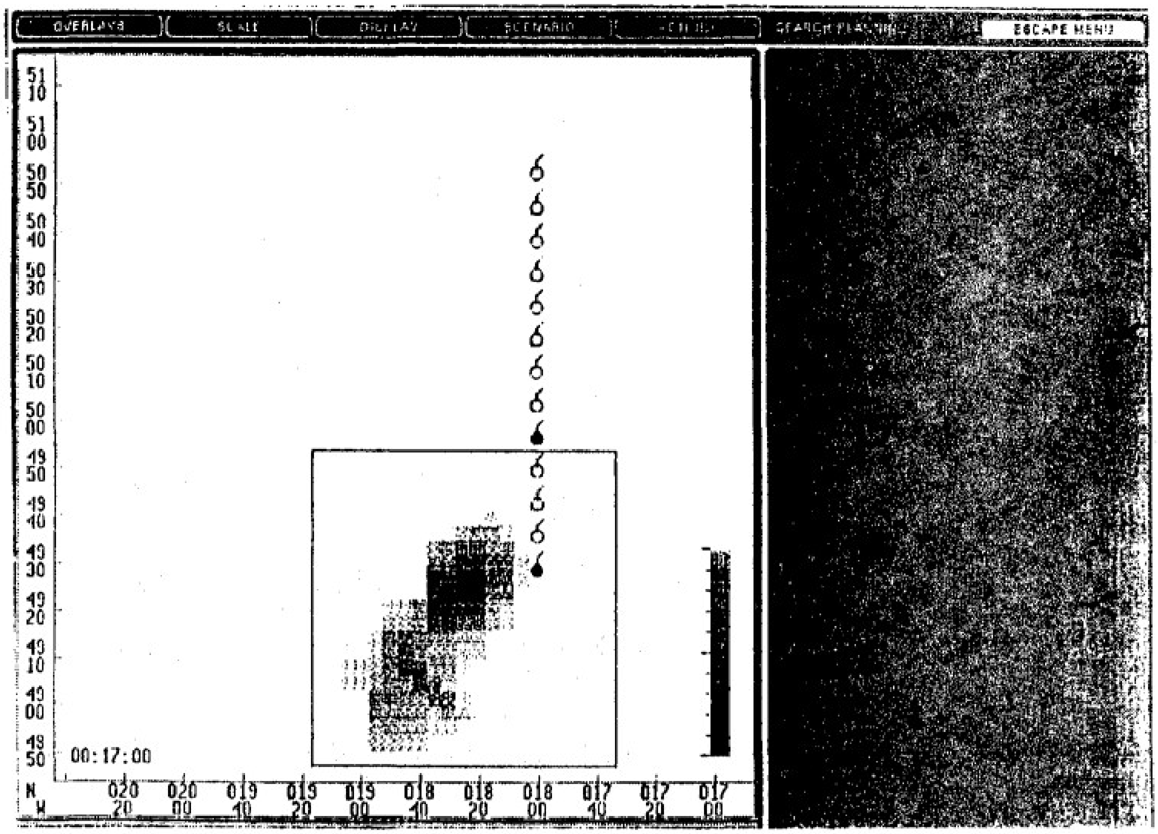


The distribution over the states is a 56488-vector of non-negative numbers totaling one. The transition matrix which maps this distribution at time n into the corresponding distribution at n+1 has 56448 x 56448 entries, mostly zeroes. At time zero, this matrix is constructed in effect from the motion model, and thereafter it is altered by new inferences of course and speed, associated with the various position and depth states, from the information updates. Of course these matrices aren't stored--computation focuses on keeping track of the non-zero entries. Nevertheless, this method is computation intensive, but evidently contemporary chips make it feasible on, say, a Sun Work Station.

In search planning, discussed next, an IOU process is used as an additional motion model.

2.8.4. Search planning by SALT. Calculation of a search plan recommendation by SALT always begins with a bivariate normal distribution of target position. If the position distribution given by the information available, from the LRT or an initial external source, is not normal, it is approximated by the normal distribution with the same mean and covariance.

FIGURE II-41. SALT LRT MAP AFTER CONTACT BY TWO BUOYS



For patroller or transitor motion, the distribution is moved and expanded according to an IOU process through the time late from initial datum to search start plus half the planned search duration. (This has no effect on motion modeling in the LRT or the LRT map.) The IOU preserves normality, but as reference [z] notes this normality restricts the distributions of target velocity and initial position to bivariate normality, and in particular precludes a uniform distribution of speed. SALT then finds an optimal rectangular placement of the available effort as a stationary search problem using the mid-search position distribution. This follows reference [aa] (see also reference [m] of Chapter V which treats this problem for a *sequence* of rectangles). Search effectiveness is gauged by acoustic sweep width (reference [bb]). In the case of transitor motion the problem is transformed to relative motion space (an earlier idea of H. R. Richardson), where the optimization is performed, and then transformed back to geographic space. These usages of acoustic sweep width and relative motion space bear resemblance to modeling in Buoy Search in ITDA and FASTAD (see 4.2.2).

Buoy placement is planned in a sequence to approximate uniform search effectiveness over the chosen rectangle.

In the case of a fleeing datum, target motion is modeled by the Markov chain used in the LRT. This loses normality, as it should--the probability tendency is annular rather than centralized. The start distribution is still bivariate normal and is updated to mid-search time. The updated distribution is obtained by following a classic result of Koopman's (reference [f]). Now a pair of rectangles, concentric with the datum ellipse, is obtained to maximize detection probability via uniform search over the annulus between them. This is new to search theory. Search effectiveness is again gauged by acoustic sweep width.

To place buoys for approximate uniform search over the rectangular annulus, a rectangle is chosen with the same area as the annulus, a buoy placement sequence over this rectangle is chosen as for a patroller or transitor, the rectangle is mapped naturally onto the annulus, and the buoy positions are mapped accordingly.

SALT also generates barrier search plans, in a fairly straightforward way.

2.8.5. Likelihood Ratio Tracker. The LRT is used in the search, localization, and tracking phases of SALT operation. As with most trackers, it alternates between motion and information updating. The entity being updated, typically every 20 seconds, is the distribution over the, say, 56448 5-vector states.

At time n–1, which could be zero, calculations are made which have the effect of multiplying the state distribution at time n–1 by the transition matrix at n–1 to obtain the state distribution at n. Again, the full matrices themselves are not actually used or stored. This constitutes the motion update.

Updating for negative and positive information is by Bayesian inference. We first review inference from observations on one buoy of those monitored. (We do not discuss SALT's treatment of *external* positive information, except for its initial bivariate normal position distribution.)

At time i, denote the observation (contact or no contact) by y_i and the 5-vector state by θ_i--for brevity we use the same symbol for a random variable and the event that it takes a particular value. (The methods could also apply to observations of *amount* of signal excess.)

Here we treat only dependence of y_i on range from buoy to target, i.e., on position state. In practice, depth state affects proploss and a doppler sensor is affected by velocity; the methods adapt accordingly.

Underlying the probability of contact is a (λ,σ) model of deviation of actual signal excess from mean (causal) signal excess.

We use shorthand $Q_i=P[y_i|y_{i-1},\theta_i]$ and $R_i=P[\theta_i|\theta_{i-1}]$ for $i>1$, $Q_1=P[y_1|\theta_1]$, and $R_1=P[\theta_1]$. Since $(\theta_1, \theta_2, ...)$ is a Markov chain,

$$P[\theta_1, ..., \theta_i] = R_1 \cdots R_i, \text{ for } i = 1, 2, ... \qquad \text{(II-5)}$$

SALT also assumes *conditional independence* as follows:

$$P[y_1, ..., y_i|\theta_1, ..., \theta_i] = Q_1 \cdots Q_i, \text{ for } i = 1, 2, ... \qquad \text{(III-6)}$$

From (II-5) and (II-6), at time n (D and D' depend only on $y_1, \ldots, y_n$),

$$\begin{aligned} P[\theta_n|y_1, ..., y_n] &= P[y_1, ..., y_n, \theta_n]/D \\ &= \int P[y_1, ..., y_n|\theta_1, ..., \theta_n]P[\theta_1, ..., \theta_n]\, d\theta_1 \cdots d\theta_{n-1}/D \end{aligned}$$

$$= \int Q_1 \cdots Q_n R_1 \cdots R_n d\theta_1 \cdots d\theta_{n-1}/D$$
$$= Q_n \int R_n \left\{ \int Q_1 \cdots Q_{n-1} R_1 \cdots R_{n-1} d\theta_1 \cdots d\theta_{n-2} \right\} d\theta_{n-1}/D$$
$$= P[y_n | y_{n-1}, \theta_n] \int P[\theta_n | \theta_{n-1}] \, P[\theta_{n-1} | y_1, ..., y_{n-1}] \, d\theta_{n-1}/D'. \qquad \text{(II-7)}$$

Of course the integrals are treated as discrete sums. The integral in the last line of (II-7) is the probability of the state θ_n motion-updated to time n; multiplication by the factor before the integral accomplishes the information update at time n.

This (II-7) result is multiplied by corresponding quantities for the other buoys, regarded as independent, for the same state, each buoy having its own D' (the same for all states). The product of the D' values is the sum over the state values θ_n of the products over the buoys of the numerators (normalization). We thus obtain for each state its posterior probability at time n given all observations on all buoys. Note that (II-7) uses only information known at times n and n-1. The sums (integrals) with respect to θ_{n-1}, being univariate, are manageable. In the absence of either (II-5) or (II-6), the (n-1)-variate sums would be prohibitive to compute.

Computation of $P[y_n | y_{n-1}, \theta_n]$ involves the current and immediate predecessor observations jointly. From the current state one back-steps position to the predecessor state although for a 20-second increment that would not be a significant change.

This completes the information update.

How valid is the conditional independence assumption which is necessary for recursive computability? It would hold if the contact/no contact process is Markovian, more precisely if conditioned on each particular state sequence (θ_1, ..., θ_n), the observation sequence (y_1, ..., y_n) is a Markov process. Under the (λ,σ) model that is not true in general. (This is apart from the assumed Markov *motion*.) By examining various cases of contact/no contact under monotone increasing and monotone decreasing contact thresholds, one can find consecutive time triples when the Markov property holds and others where it does not hold. Non-monotonicities further run counter to the Markov property. The degree to which departures from the Markov property disturb likelihood inferences evidently is not known as such. Thus although the recursive computations at time n retain some, perhaps most, of the inference from observations earlier than n–1, an unknown amount of this earlier inference is left behind. The SALT developers assert some degree of overall model validation from operational trials.

The updates for positive and negative information are done at the times of motion updates, typically every 20 seconds. The sensor could be electromagnetic as well as acoustic.

The issue of whether a given contact is on the correct target is treated in a later version of SALT, but not in Air SALT. The method assumes that a credibility c, representing the probability that the contact is on the correct target, is obtained from a source external to SALT, as in VPCAS/PACSEARCH. The latter uses c to weight two probability maps under the alternate assumptions that (1) the prior is correct and the new contact is not or (2) the reverse is true. SALT instead uses c to weight two likelihood functions under the same alternatives. It then finds a Bayesian update of the combined likelihood function.

2.8.6. Localization in SALT. When the LRT map is essentially unimodal with sufficiently small variance, localization planning is initiated. The approach is to minimize area of uncertainty rather than maximize detection probability. For this tactic, the program restricts to chevron patterns with 120 degrees apex angle. It chooses apex position, orientation, and buoy spacing by minimizing a measure which has the effect of maximizing Fisher information (see reference [z]).

2.8.7. Some comparisons between SALT and Monte Carlo CAS. We state some differences between SALT and Monte Carlo CAS as typified by VPCAS and its successors PACSEARCH and the Update IV CAS (under development). A comparison by equivalent time era would be between Air SALT and CASPER, the prototype predecessor to the Update IV CAS.

Some of the differences are inherent in analytic versus Monte Carlo approaches. Other differences pertain to development choices and could be plausibly eliminated by redevelopment. We do not attempt an overall comparative evaluation.

The principal inherent differences are that Monte Carlo has more flexibility in modeling target motion, and SALT has finer resolution (e.g., over 50,000 target states and an astronomical number of tracks in SALT versus 500 tracks in VPCAS and PACSEARCH) in motion modeling, within the family of motions considered. (The user can increase the number of tracks in PACSEARCH--running time increases roughly proportionally.) The resolution comparison can be important in tracking. Also inherent is that the 500-track representation and associated updating which are typical of Monte Carlo CAS are more readily explained to and understood by CAS operators than the Markov chain methods and associated updating used in SALT. The IOU process used in both SALT search planning and VPCAS historical analysis is more difficult to understand than either of these methods.

A Monte Carlo approach generally has an advantage in that it can postpone smoothing until the final stage of processing, e.g., in converting the output to a probability map. An analytic approach generally involves smoothing in initial stages, and any errors thereby introduced propagate through the processing.

Both the SALT LRT and the Update IV STT attempt inference from full observational histories, in quite different ways. Not surprisingly, both fall short of that ideal, and it appears to require substantial investigation to discern which approach has greater inferential power.

It is also hard to say which approaches produce better search plans, *given* an instantaneous position distribution. Most CAS systems make heavy use of optimal placement of rectangles. The SALT search planning method requires a normally distributed initial position, whereas VPCAS has fairly general choices of initial distribution. VPCAS can accept a target motion based on historical analysis and optimizes over a sequence of sorties by Brown's algorithm, whereas SALT does not. Plausibly all of these disadvantages in SALT could be overcome with effort, e. g., later versions of SALT do accept historical motion models.

SALT is currently unique in modeling target depth changes.

2.9. CASP

CASP is the USCG search and rescue (SAR) program Computer-Assisted Search Planning, reported in reference [cc]. It is the first CAS program, having been operational since 1972 and updated in the 1980's. It is used by USCG Rescue Coordination Centers (RCC's) in planning their more difficult SAR problems, especially by the Miami RCC where proximity to the Gulf Stream makes prediction of drifting objects more difficult. It has been instrumental in saving numerous lives over the years since it was introduced.

CASP is a Monte Carlo program and originated some of the more important features of Monte Carlo ASW CAS discussed above: updating of weights on sample tracks, multiple-scenario priors (generalizing from stationary targets in the H-bomb and SCORPION searches to moving targets), and use of motion building blocks. The methodology in reference [a] is illustrated by CASP.

2.10. SMS

SMS is the Search Management System to assist planning of search for stationary objects on the ocean bottom. A prototype version was used on the search for a Pershing missile lost off Cape Canaveral and, at sea, in the search for a Titan missile lost off Vandenberg AFB. A customized version is on board the NR-1 deep ocean exploration nuclear submarine.

SMS outputs probability maps with Bayesian updating, optimal allocation of search effort (without regard to search track coherence), a search rectangle to best approximate the optimal allocation, a track to search the best rectangle or any chosen convex polygon, and cumulative detection probability.

All single-scenario priors in SMS are bivariate normal. They are combined in weighted fashion as usual.

2.11. SPACECAS

SPACECAS was developed to assist in planning search for lost satellites and other orbiting objects by the GEODSS electro-optical telescopes. It was installed at the Space Command in Cheyenne Mountain, Colorado. The telescopes are in White Sands, Hawaii, and South Korea.

The MOE in SPACECAS is the probability that at least one telescope detects at least once in a given time window. An orbit is characterized by six elements. A prior distribution on this six-tuple is constructed by choosing for each element upper and lower bounds and a nominal value and by choosing the distribution as uniform, truncated normal, or a 50-50 combination of these.

A search plan is chosen as a box spiral with zoom or no-zoom as a function of time. Optimization in time is myopic.

2.12. Evaluation of CAS

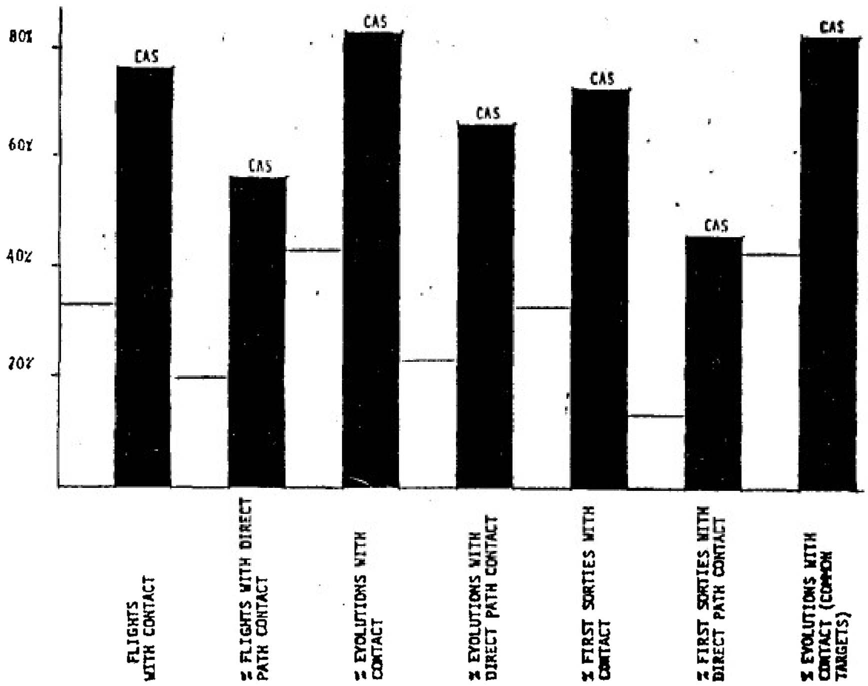
To illustrate how CAS systems can be usefully evaluated, in this section we describe some evaluation methods used on CAS in the past. This material is largely taken from a seminar talk at NPGS on CAS evaluation by S. J. Benkoski.

The strongly preferred method of evaluating a CAS system, or any other TDA, is to conduct trials in a realistic operational setting which reflect the mission effectiveness when using the TDA versus the absence of the TDA or versus some alternative TDA. An evaluation of this sort was conducted on the CAS program OASIS in 1978.

OASIS was used often by Benkoski on assignment to CPWP to plan VP ASW search out of Moffett Field and Barber's Point from 1977 to 1979. During this period many missions were also planned by Naval personnel without using CAS. Questions were raised at CPWP as to degree of success with and without using OASIS and as to what MOE(s) should be used to measure this success.

To answer these questions, Benkoski reviewed the detailed data that had been maintained on all operational flights over the period 1 January 1977 to 30 April 1978. The results were reported in reference [dd], the principal result of which is Figure II-42. For each of seven MOE's, success percentages are shown for use of CAS (OASIS) and non-use of CAS. This figure shows that by any of these MOE's, use of CAS mission effectiveness was roughly doubled or more compared to non-use of CAS. The strength of this conclusion is mitigated by the fact that the use of CAS was by a civilian scientist developer, as was the case with numerous striking ASW CAS successes since 1972.

FIGURE II-42. CAS (OASIS) EFFECTIVENESS



Partly as a result of reference [dd], use of OASIS became standard procedure, and was used *by naval personnel*, so in the subsequent experience one no longer had a data base of non-use of CAS to compare with use of CAS in the same operating environment. The next stage of progress was to develop a new CAS program, SEQUENCER, which gave the user search plan recommendations in addition to the probability maps previously provided. SEQUENCER replaced OASIS, but unfortunately its host was the ASWOC mainframe, the aged NOVA 820, and its use was considerably hampered by hardware problems, including crowded access to the machines. Thus good data bases for comparisons parallel to reference [dd] were not at hand in the latter part of the OASIS era or the SEQUENCER era for different reasons. Possibly a parallel comparison of use of CAS versus non-use of CAS could have been done later in the first year or so of VPCAS use, but this was not done.

Early use of VPCAS did produce examples of an easier but less convincing method of evaluating a TDA: Subjective evaluation of this sort was the following excerpt from an ASWOC Lajes message in June 1984 to CPWL: "ASWOC Lajes has extensively used VPCAS in all ASW planning and prosecutions with outstanding results. It is a tremendous aid to the mission planner and performs extremely well. In several cases, the target would not have been found without the use of VPCAS. VPCAS is an extremely efficient and easy-to-operate mission planning program and has contributed to a high prosecution success rate in the Lajes ASW sector." Probably there were also some unfavorable subjective reactions, but records of such are not at hand.

Subjective evaluations by fleet users of new TDAs (and other systems) are frequently employed. They have the advantages of being relatively easy and reflecting a realistic environment. Systems which are badly deficient can be eliminated reasonably by this means if the evaluation is made with a degree of receptiveness and training that a new system deserves by virtue of its newness. However, as a basis for a TDA acceptance decision which is to be durable, subjective evaluation leaves much to be desired compared to comparative operational trials (as above with OASIS) or by simulation comparisons as illustrated next.

A simulation of CAS was conducted by Boeing as part of its proposal effort for the P-3C Update IV. The CAS system was a prototype called CASPER, a modification of VPCAS for airborne use. Naval TACCO personnel (airborne search planners) were used in parallel with CASPER. See reference [ee] for the comparisons.

The approach was to feed scenarios and input data to both the TACCOs and CASPER and to evaluate the sonobuoy search plans separately produced by both. The TACCOs were allowed to choose the number of patterns they employed. CASPER was instructed as to this number, which was one, two, or four in a given instance.

The initial MOE used to compare the TACCO results with the CASPER results was probability of detection. Comparative results for each of four scenarios are shown in Figure II-43. The numerals in ( ) refer to the number of patterns CASPER was told to use. By this evaluation, CASPER showed clear superiority over the TACCOs unaided by CAS.

The MOE was then changed to meet a Boeing requirement to make the comparisons in db terms. This was to fit CAS evaluation in with evaluation of other equipment and signal processing algorithms. To define db gain, first define P(A,S) to be the probability that search plan A will detect the target providing the target source level is S. If A and B are search plans and P(A,S) = P(B,S–D), then A provides a D db gain over B. In general D would depend on S--the S values used were accepted values for the targets in question. Comparisons by this MOE are shown in Figures II-43 and II-44.

FIGURE II-43. TACCO WITHOUT CAS VS CASPER (cdp COMPARISON)

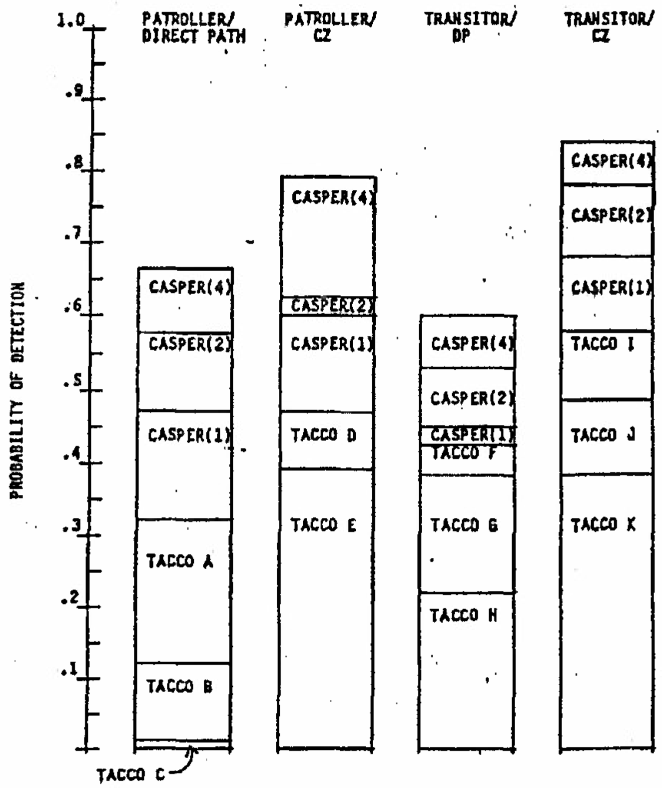


FIGURE II-44. TACCO WITHOUT CAS VS CASPER (DB COMPARISON, TRANSITOR/DP SCENARIO)

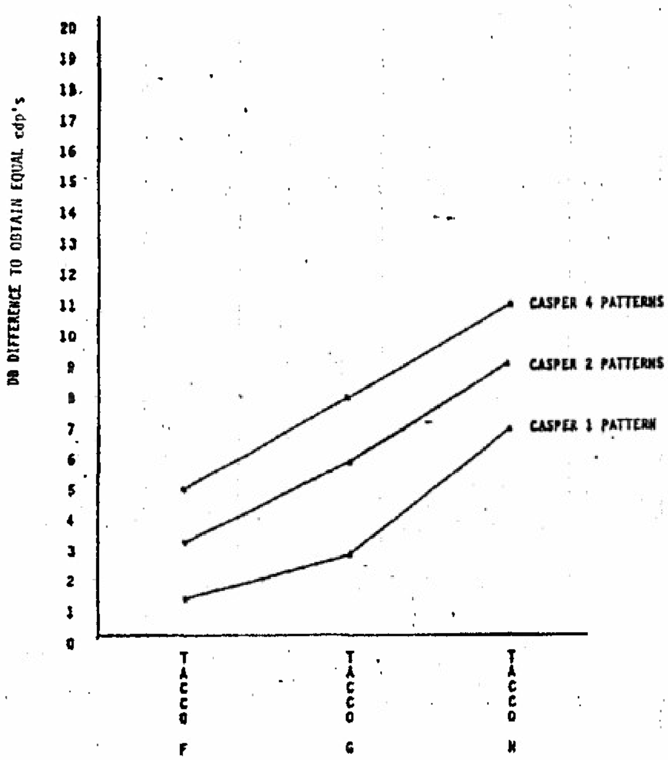
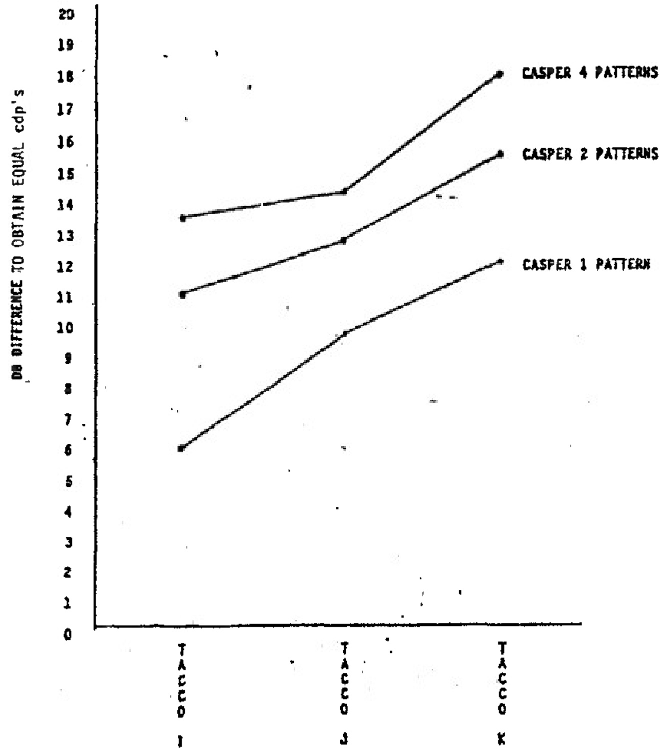


FIGURE II-45. TACCO WITHOUT CAS VS CASPER (DB COMPARISON, TRANSITOR SCENARIO)



It must be noted that in the evaluative comparisons by both these MOE's, the evaluations of the detection probabilities were made by the CASPER program for both the CASPER plans and the TACCO plans. This may be deemed to have favored CASPER. Realizing this and the fact that the evaluations had been done for a marketing purpose, to obtain better credibility Boeing engaged a third party to repeat some of the evaluations and to use the Navy standard simulation program for air ASW, APAIR, to compute the detection probabilities. This was done and reportedly the results favored CASPER even more than the comparisons in Figures II-43 to II-45.

In evaluating user-friendliness of a TDA, even more difficulties are present than in evaluating functional performance. One point is that comparative evaluations of user-friendliness should be made together with performance evaluation. The reason is that if one TDA has useful functions that another does not possess, these added functions may be expected to run counter to user-friendliness: They constitute additional concepts the user must learn, presumably usefully.

An important related point is that *training* needs (see Appendix E) should be evaluated along with functional performance and user-friendliness. It may be expected that a TDA with useful functions will require training of prospective users, and if the TDA is well-conceived, this training will include the learning of concepts which are useful to decision-making even if the TDA were not used. Another difficulty in evaluating user-friendliness is that each individual tends to be his own expert and judges ease of use by his own perception of the user interface. It is very difficult for TDA development personnel and those who make TDA acquisition or acceptance decisions to put themselves in the position of operating users. All of the problems in this paragraph arose, for example, in comparative evaluations for the ASWTDA (intended for an ASWC) in early 1989 (see 2.13).

2.13. History of CAS

Search theory, as a well-developed body of knowledge, may be considered to have originated in WWII, predominantly in the work of the USN Operations Research Group (ORG). The diverse search analyses of this group were organized into a text which has long been considered classic, reference [c], by B. O. Koopman. Koopman was also an important contributor to the theory, notably by his results on optimal allocation of search effort. Koopman credits G. E. Kimball, Deputy Director of ORG, with being the principal pioneer in search theory. Reference [f] is an update of reference [c].

From WWII to the mid-1960's, various somewhat scattered, theoretical contributions were made to search theory. E.g., S. M. Pollock and J. M. Dobbie found optimal allocations of search effort against moving targets under fairly simple target motion. O. Hellman and Finnish colleagues further advanced moving target search.

An era of new advances in analysis, and later computer programs, in direct support of *actual search operations* began with the 1966 Mediterranean H-bomb search and the 1968 search off the Azores for the remains of the submarine SCORPION. The major part of the civilian scientist work on these advances in operational methods was by DHWA. This work served first ocean bottom search for the USN, then SAR for the USCG, and thereafter and most extensively ASW for the USN. It was generally in close association with and at the scene of the operations served. In ASW these developments were usually supported by the Tactical Development and Evaluation Program of the Office of the Chief of Naval Operations (OP-953, now OP-73), via the Office of Naval Research, later via the Navy Tactical Support Agency (see 2.13.5). Alumni of the Operations Analysis and ASW curricula of the NPGS were prominent among the Fleet tactical development officers who oversaw and participated in this work. The ocean bottom search work was sponsored by the Supervisor of Salvage and also in recent years by NAVSEA, PMS-395.

To avoid repetitive identification, we note that, except where otherwise stated, the civilians cited in the rest of 2.13 were on the staff of DHWA.

2.13.1. H-bomb search and SCORPION search. The H-bomb and SCORPION search operations did not involved CAS, but some important principles of CAS took root in those endeavors.

In January 1966 an H-bomb was lost off the Mediterranean coast of Spain as a result of a B-52 collision. The stateside Technical Director of the ensuing search, was J. P. Craven, Chief Scientist at SSPO. At the outset, he formed a prior distribution of target position as a weighted sum of single-scenario priors. Among the issues in forming the scenarios were whether or not the bomb's parachute opened and alternative assumptions as to winds aloft. This originated the concept of a multi-scenario prior, which has been fundamental to use of CAS throughout its history.

Retired CAPT F. A. Andrews (NPGS alumnus and Yale Ph.D. in Physics) was retained as a consultant to the search planning because of his experience as CSDG-2 in command of the successful 1963-64 THRESHER search. At Andrews' recommendation DHWA was enlisted for operations research help.

A USN two-star command afloat off Spain was formed to conduct the search. H. R. Richardson was assigned on scene to render operations research assistance. Stateside he had been chartered by OP-33 and DoD to provide a statistical basis for certifying that the bomb could not be found, but on scene this charter became one of advising on best ways to search.

One of Richardson's contributions was to estimate daily the probability that the effort to date would have succeeded in detection, given that the prior was correct. He termed this search effectiveness probability (SEP). This was of interest to the command as a measure of search progress and an indication of effort remaining. To find SEP, Richardson updated the prior by hand computation using Bayes' theorem to reflect non-success in the search, which he termed "negative information." The revisions to the prior were further used for search planning.

About three weeks after the accident, high credibility was given to a fisherman's sighting of the bomb carried into the water by parachute. This was supported by the fisherman's ability to reproduce his position some five miles off shore by sighting on land features. This credence narrowed the search to something feasible, reflected in revised scenario weights, and some weeks later the bomb was found and recovered.

In May 1968, SCORPION was lost in a westbound transatlantic transit. Classified information put the location some 400 miles west of the Azores in very deep water. A search operation was formed, drawing on the experience of the H-bomb search. Craven, then Technical Director of the Bureau of Ships Deep Submergence Systems Project, was again Technical Director. Richardson went to the search scene for a week to form a plan for search analysis. Over the next five months, at the end of which SCORPION was found, L. D. Stone, S. G. Simpson, and J. R. Rosenberg were successively assigned to do on-scene analysis.

Again the search analysis began with a multiple-scenario prior (some scenarios and uses of the prior are given in 2.1.2). SEP was computed frequently, being complicated by multiple sensors in simultaneous use. Probability maps updated for unsuccessful search were used irregularly, dependent on the approaches of the different commodores and failures of positioning transponders. An important analysis by Stone concluded that a three week investigation of a particular contact should be terminated. Except for stateside computation of the prior, all computation was by hand. Reference [j] is a case history.

Analysis experience in the SCORPION search showed a need for more theoretical research on search problems, which led to considerable basic research in the 1970's, sponsored principally by J. R. Simpson of the ONR Mathematical Sciences Division.

2.13.2. CASP, the first operational CAS. During the latter 1960's, development of computer programs to assist search operations with Bayesian updating for unsuccessful search were known to have been recommended in reports by the Planning Research Corporation and the Cornell Aeronautical Research Laboratory. Apparently these recommendations did not result in operational implementation.

The first operational CAS program was CASP (see 2.9). It was developed in 1970-72 for the USCG to assist its Rescue Coordination Centers in SAR operations. The primary developer was Richardson; some modules were by Stone. Early in the planning of what became CASP, at an ORSA meeting Richardson and Stone met LCDR J. H. Discenza, USCG, whose 1969 NPGS thesis (under Pollock) developed a deterministic SAR program using set and drift data. Discenza then pursued incorporating Markov chain motion and Bayesian updating into his program, which helped to prepare him for an important role in CASP implementation.

CASP went operational in 1972, initially at the RCC in Governor's Island, NYC, which had overseen the development. Prior to that point, Discenza had joined Governor's Island as Operations Analysis Branch Chief. During and after the operational introduction, he was very instrumental as a knowledgeable inside person in overseeing the training and in making the software more user-friendly. The program resided on a CDC 3300 in Washington for remote call by RCC's on either coast, which was a bit cumbersome. Its methods are described in reference [cc].

As noted in 2.9, the more important principles in Monte Carlo CAS originated in CASP.

After CASP had been operational two or three years, USCG people estimated informally that it had made the difference between success and failure in saving about a dozen lives. This was true in some later publicized rescues: in fall 1974 a tuna boat sinking near Long Beach, CA and in fall 1976 a capsized trans-Pacific sailboat resulted in some survivors being found by chance, and by using CASP to work backward to the accident and then forward to current time, additional survivors were found. In fall 1984, the Miami RCC used CASP to vector a helo directly on top of three people adrift 24 hours in cold water in very poor visibility. That required good luck as well as an excellent environmental data base. The Miami RCC has made the most use of CAS, because of the drift effects of the Gulf Stream, and only on the more difficult SAR problems.

In the 1980's, improvements were made to CASP, primarily by J. R. Weisinger and D. D. Engel.

2.13.3. ASW CAS in the 1970's. The birth of ASW CAS was in a "real world" operation labeled an exercise, LANT 1-72, in summer 1972. The initiative came from M. L. Metersky of NADC, VADM F. G. Bennett (NPGS alumnus), COMASWFORLANT (CAPT W. P. Hughes was his ACOS (Analysis)), was the sponsor, and LCDR F. H. Brown of NADC headed the ensuing team. Richardson led the development of a CAS program, following CASP methods with addition of historical analysis and a Koopman optimal allocation of effort. He was assisted by S. J. Bloom of Ketron Corp. and one or two other programmers. The program was applied at Bermuda, by calling a computer at NADC, and its advice to VP search resulted in an operational success. Ironically cognizant officers in Norfolk and Washington were so pleased that they directed that the methods be closely held.

The first DTC CAS, and also the first sea-going CAS was developed by T. L Corwin on field assignment to COMSUBPAC in the first half of 1975. He worked under the direction of CDR O. G. Rutemiller (NPGS alumnus), and had programming assistance from R. Kidani of Pacific Analysis Corp. This program was on a Wang 2200 and was named DENS, later ASP. It was the first CAS program to model target motion analytically (diffusion equation methods), which helped to fit it on a DTC of that era.

Corwin used DENS/ASP with great success at sea in SSN direct support exercises and in operations controlled ashore. He also developed a Markov chain

CAS program, PACSAI, to assist a surveillance-aided intercept (SAI) operation, and the SAI CAS program SASP, using ASP methods. PACSAI was also used in a search for an F-14 crashed in shallow water.

Efforts were made to apply ASP and SASP in the hands of Naval personnel, but these did not succeed. However, success of the program in the hands of the developer did much to elevate the attention CAS received in the Fleet and in Washington. For this work, Corwin was awarded the Navy's Distinguished Public Service Medal by VADM C. H. Griffiths, DCNO (Submarine Warfare), formerly COMSUBPAC.

In fall 1975, B. J. McCabe developed a Monte Carlo SAI CAS program called MONTE on a DTC, an HP 9830, while on field assignment to COMSECONDFLT. It had notable descendants.

In April 1976 an important ASW operation, UNION SURF, was directed out of Norfolk under CINCLANTFLT, ADM I. C. Kidd. CAPT R. C. Austin (NPGS alumnus and currently as RADM, Superintendent NPGS) as COMSUBDEVGRU TWO assigned the Director of his Tactical Analysis Group, LCDR W. J. Hayne, who had a Ph.D. in OA from the NPGS, to assist. Accompanying him were S. J. Benkoski, on field assignment to that command, and W. H. Barker, who had converted DENS to "HPDENS" on the HP 9830. After a few days, based on HPDENS work and their other analyses, this team recommended a shift in a VP barrier from what had been planned. This was implemented over some objections and resulted in a dramatic success. The CSDG-2 team was warmly commended in a message from VADM J. Williams, COMSUBLANT.

UNION SURF led to serious interest in CAS by CTF-24, the flag plot part of CINCLANTFLT, and to development over the next year, principally by Stone and S. J. Bloom, of the CAS program COMPASS as an enlargement of LANT-72. Its host was the, even then, antiquated WWMCCS computer. Training courses in COMPASS were given to CTF-24 officers and enlisted personnel by Stone and F. P. Engel, but the training was not durable. COMPASS was usefully applied by Engel on field assignment to COMSECONDFLT and COMSUBLANT and by D. Jordan and other Planning Research Corp. personnel on assignment to CTF-24. Other versions of COMPASS were developed, principally by Stone, Bloom, and J. R. Weisinger, for COMTHIRDFLT in 1978-79, for the ARPANET in 1977-78, and for use on CV NOVAs (intalled on SARATOGA) in 1977-78.

During the year beginning summer 1976, Richardson developed the CAS program MEDSEARCH on field assignment in Naples to CTF-66/69, RADM J. H. Nicholson. This assignment arose in part out of a CAS initiative of Metersky of NADC. MEDSEARCH was somewhat in the spirit of LANT-72, but was specific to MED geography, with emphasis on historical analysis. Its host was another aged computer, the NOVA 800. It was developed further by Richardson's successors, Barker, M. C. Brennan, S. S. Brown, and W. R. Monach through 1983, and all of them applied the programs very successfully to sensitive operations. Successive CTF-69/66 admirals put considerable emphasis on use of MEDSEARCH, but this pertained to assistance to current operations rather than development of a turnkey tool usable after departure of the civilian developers. These analysts received informal flag commendations, and Monach received the Navy's Meritorious Public Service Citation.

In 1976-77, Engel undertook further development of MONTE, evolving it into TARDIST, notable mainly for its descendants.

Development of CAS intended primarily for ASWOC planning of VP ASW search began at COMPATWSINGSPAC (CPWP) in 1977 and at COMPATWINGSLANT (CPWL) in 1978. Directors of this work through 1983 included CDRs P. M. Harvey, D. L. Stromberg, T. J. Sullivan (NPGS alumnus), and J. Taggert (NPGS alumnus), of CPWP and CDRs G. T. Martinsen (NPGS alumnus), CDR J. Hall, and LCDR W. W. Holland, and CDR R. Johns of CPWL. LT C. S. Gross and LCDR W. Snyder of the Moffett ASWOC were also instrumental. G. Marin of CNA filled the director role temporarily at CPWP early in this period.

In 1977, T. McCoy of SCI at CPWP converted COMSUBPAC's PACSAI to OASIS, further developed by Benkoski, with contributions by Marin. After the comparison of use of OASIS versus non-use of CAS discussed in 2.12, OASIS was much used by Naval personnel in the Moffett Field ASWOC, in contrast to prior CAS programs.

There followed at CPWP development of SEQUENCER and SEQUENCER II mainly by Benkoski and J. A. Byrne. These were the first CAS programs to optimize over a *sequence* of VP sorties--Brown's algorithm (the FAB algorithm) was used, as it was later in VPCAS.

On assignment to CPWL, R. P. Buemi developed ASWOCCAS, in part a descendant of TARDIST, 1978-79. It outgrew the ability to fit on the available DTC.

A project to standardize the input/output of the various CAS systems in use by CTF 66/69, COMSECONDFLT/COMSUBLANT, CPWL, CPWP, COMSUBPAC, and COMTHIRDFLT was carried out in 1979-80 by on-site work at these commands by Brennan, under direction of Corwin.

2.13.4. VPCAS and later CAS. VPCAS was conceived by Benkoski and Buemi during a meeting February 1979. Their approach was to embody the best of SEQUENCER II and ASWOCCAS into a more user-friendly program. This was embraced by both CPWP and CPWL, who jointly sponsored and oversaw development of VPCAS through its completion at the end of 1983. Additional contributors to VPCAS development included T. L. Richardson assigned to CPWL and K. E. Trummel and D. D. Engel assigned to CPWP. The oversight roles by Sullivan at CPWP and Holland at CPWL were especially important.

The historical analysis adjunct to VPCAS was developed off-site. The approach using a gradient field of stochastic differentials, noted in 2.5, was conceived by Corwin. Reference [ff] was a significant antecedent. D. P. Kierstead and G. P. Pei further contributed to this theory. Corwin and Buemi visited four LANT ASWOCs in March 1980 to gather scenario descriptions for development of an historical analysis module. Using an extensive classified data base obtained from CINCLANTFLT, parameter estimation ensued, principally by Buemi, M. C. Brennan, and R. H. Clark. At CPWL, T. L. Richardson wrote VPCAS software to Monte Carlo target tracks through the gradient field using these parameter values based on history.

VPCAS was installed in most LANT and PAC ASWOCs in late 1983 and early 1984. This was accomplished with brief training and delivery of the user's guide, reference [t], in visits of about two days each by T. L. Richardson, D. D. Engel, and Trummel.

With only this brief training, VPCAS use varied quite a bit among the ASWOCs from the start. Lajes was a particularly active user, and from there and some other ASWOC users very promising reports on VPCAS were fed back to CPWP and CPWL. However, despite later preparation of training videotapes by the developers under NAVOCEANO sponsorship, the only training subsequent to initial introduction has been from trainee to relief. That is not durable, and VPCAS use has waned accordingly.

VPCAS was further handicapped by its hardware host, the NOVA 800, whose technology was of the 1960's and in 1989 is still the ASWOCs' main computer. That has been overcome by conversion of VPCAS to the HP 9020, by Analysis & Technology under NAVSEA sponsorship and separately as part of the development of PACSEARCH. The former conversion has been given to ASWOCs without training.

PACSEARCH was developed at COMTHIRDFLT and COSP by Monach over three years beginning November 1984. Its expansion on VPCAS is described in 2.6. The active interest of COSP commodores, CAPTs R. S. Fitch, I. H. Coen, and A. R. More (NPGS alumnus), was instrumental to this development. This can further be said of CDR P. J. Sedun, CDR W. W. Holland (formerly on VPCAS at CPWL), LCDR M. P. Mosier (her NPGS thesis on application of VPCAS to SOSUS contained ideas adopted by Monach), and CDR V. J. Nigro of the COSP staff and, two NPGS alumni, CAPT R. D. Reeves and CDR M. R. Etheridge of COMTHIRDFLT N-7.

PACSEARCH is in active use by COSP. A civil servant maintains the data bases and performs most of the program operation, whose output is used by watch personnel.

A further modernization of VPCAS, including some PACSEARCH improvements, is under development for use in th P-3C Update IV as embedded software, under a DHWA subcontract to Boeing Aircraft.

The motion models algorithms in VPCAS were verified in the NPGS thesis, reference [gg], of LCDR R. E. Chase under R. N. Forrest.

SMS (see 2.10) was developed as a prototype by Monach in 1984 and was developed further during at-sea application to the Titan search November 1985 to February 1986 by Discenza, R. J. Lipshutz, and Monach. Its further development for the NR-1 was principally by Discenza and T. L. Olaisen.

SPACECAS was developed for Lincoln Laboratory in 1983 by H. R. Richardson, J. R. Weisinger, and R. H. Clark. An additional SAR CAS program, NAVSAR, was developed by R. J. Lipshutz and Trummel for NEPRF in 1981 and will be reviewed in Chapter V.

SALT (see 2.8) was developed in prototype form in 1986 by L. D. Stone, D. A. Trader, M. E. Davison, and T. L. Corwin of Metron Corp. for Lockheed under its Phase I contract for the P-3C Update IV.

A very recent CAS program, CASE, was developed by Sonalysts for NUSC and is the basis for ASWTDA. The target motion is a Markov chain discretization of a random tour (as in SALT) in which one-step target movement is constrained to a neighboring cell (compared to a state dimension over 50,000 in SALT). Probability maps are generated and updated for negative information, but not positive information. There is no updating of prior assumptions on motion. It appears to have roots in the SFMPL (see 2.14 and the introduction to Chapter IV).

2.13.5. Washington sponsorship of CAS and other TAC D&E. Most of the Washington sponsorship of ASW CAS came from the Tactical Development and Evaluation (TAC D&E) Program of the Tactical Readiness Division in OPNAV, OP-953 (now OP-73), as implemented at the time by ONR. This program sponsored considerable Fleet tactical development more broadly than CAS, much of it leading to TDAs. We will review some of the history of TAC D&E in this more general context and will conclude with a review of sponsorship of VPCAS after its initial TAC D&E sponsorship. The principal TDA work under TAC D&E that is reviewed in other chapters, predominantly in the 1980's, was on MTST, OTH-T, most of SURTAC, Kalman filtering on a sphere, and ATTAC in Chapter III, and ITDA, pre-ITDA SASHEM, pre-ITDA FASTAD, pre-JOTS TSS, and the 1982 inception of JOTS on AMERICA in Chapter IV.

The origins of the formal TAC D&E Program in OPNAV may be traced to three activities in 1972-73, which began independently and later joined forces: (1) R. J. Miller, Director, Naval Analysis Programs, ONR, convened a working group May 1972 to investigate making more effective use of naval analysis funds to support Fleet activities in tactical development; (2) retired CAPT F. A. Andrews (see 2.13.1) on sabbatical leave from Catholic University, assisted by CDR J. J. Kronzer (NPGS alumnus) formed a USNA research project in summer 1972 on ASW data collection and tactical development, sponsored by OP-095 and Manager, ASW Systems Project; and (3) CAPT W. S. Whaley (NPGS alumnus), OP-326E, undertook initiatives in OPNAV to develop better organization of Fleet tactical development. At Miller's invitation, the USNA group joined the ONR group and Andrews chaired the combined team. Others working with this group of some 23, which met seven times, included E. Kapos of Ketron (former Director, OEG), CAPT W. P. Hughes, ACOS Analysis COMASWFORLANT, and H. R. Richardson, DHWA. The designation Tactical Development & Evaluation (TAC D&E) for what was sought was proposed by Andrews and in less than a year became part of the Navy lexicon.

In latter 1972, the leadership of the ONR/USNA group began working with Whaley. On 16 January 1973, the CNO Executive Board, headed by ADM M. F. Weisner, VCNO, directed OP-03 to convene an OPNAV Steering Group on tactical development. On 20 February 1973, this group, headed by Whaley, submitted an influential memorandum to OP-03 with specific organizational recommendations to establish a TAC D&E program. The ONR/USNA group submitted its report to RADM W. N. Small, OP-95B. Favorable action led to Small becoming the first flag officer in charge of TAC D&E. He delegated authority to OP-953, CAPT D. M. Simon (NPGS alumnus). The program was chartered to be ASW/AAW/ASMD and to be *inter*-type, principally because the submarine community perceived the prospect of interference with the excellent ongoing tactical development by CSDG-2. What ensued was predominantly in ASW and in due course included considerable intra-type as well as inter-type work. The Whaley group had recommended that implementation be through what became NTSA with contracting through NOL. However, these roles were filled by ONR, one reason being that Miller had funds available to support this work. These ONR funds continued to be a key factor during the 1970's. Kapos is credited with an influential role, along with Andrews and Miller, in selling this program to OPNAV and the Chief of Naval Research. OPNAV Instruction 5401.1 formally initiated the program July 1973.

Reference [hh] prepared by Andrews at the conclusion of his sabbatical, contains an excellent compilation of articles and other documents, with editorial comment, which record this evolution of the TAC D&E program. Included are various discussions of earlier history of tactical development and needs for what became the

TAC D&E program. In their history of the 1960's these discussions put particular favorable emphasis on the work of CSDG-2 and the COMASWFORPAC (later COMTHIRDFLT) VASSEL and UPTIDE exercise programs, the latter being primarily under VADM E. P. Aurand. These historical notes generally do not go back to the 1950's. In that era COMOPDEVFOR was the lead Fleet activity in tactical development, before it was renamed COMOPTEVFOR and rechartered to do operational testing and evaluation of equipment rather than tactics. Prominent units were VX-3 (carrier air group tactics) at NAS Atlantic City, VX-5 (tactical nuclear delivery) at NOTS China Lake, and VX-1 (air ASW) at NAS Key West. The author was privileged to be OEG representative to VX-3 in the early 1950's during an especially productive period in tactical development under CDR N. A. M. Gayler (later, as VADM, Director NSA and, as ADM, CINCPAC), his first mentor in the subject.

TAC D&E was headed by Miller until 1980, during which all the above-mentioned CAS programs after LANT-72 into the beginnings of VPCAS were developed in the Fleet under this sponsorship. Miller's acting successor was his deputy, retired CAPT A. E. White (NPGS alumnus), who was succeeded by R. Nagelhout until 1984. Others in ONR who had been prominent as scientific officers of TAC D&E projects included A. F. Andrus on leave from NPGS, J. B. Rimmington, and three NPGS alumni: CDR S. J. Bailey, CDR B. D. Foster, and CDR R. E. Nelson. Research on search theory sponsored by J. R. Simpson was also important to CAS. In 1984, the ONR role in TAC D&E was transferred to NTSA under A. M. Letow, and to NSWC for contracting. Among the products under NTSA aegis and reviewed in later chapters were SASHEM, late stages of FASTAD and ATTAC, and reference [o] of Chapter IV (also reference [b] of Chapter I).

Most of the technical work in this program was by civilian contractor personnel, including several Ph.D. scientists, on site for one to three years, often longer, at headquarters of various Fleet commands engaged in tactical development. These civilians worked closely with staff officers and often went to sea with them on exercises. The officer roles were essential of course to provide knowledge of operational needs and capabilities, to keep the analyses realistic, and to provide user viewpoints to the input/output, especially in the TDA work. NPGS education in OR greatly enhanced these roles. Several such civilians and officers are cited earlier in 2.13 and in histories in later chapters.

Under these arrangements in the 1970's there was considerable productivity in tactical development, including CAS and other TDAs. On the other hand, Fleet activities found ways to utilize some of this effort in modes outside the intents under which the effort had been assigned to them, i.e., to alleviate their perennial staff shortages. Apparently partly in reaction to the latter problem and partly out of a desire to attain a stronger institutionalization of TAC D&E, the TAC D&E Master Plan was put into effect about 1981. This was generated by CAPT R. E. Carlson (NPGS alumnus), OP-953C, who directed TAC D&E about 1979-82. This plan substantially tightened OP-953 control over establishment (not necessarily the conduct) of Fleet TAC D&E projects, and had the effect of greatly reducing contractor on-site support in favor of on-site support by naval laboratory personnel. CNA had always been, and under the Master Plan remained, in a favored position for tactical development in the Fleet.

One of the stipulations of the Master Plan was that development of software for use in an opcon (ashore) was considered outside of TAC D&E. That excluded then current CAS development, notably VPCAS. However, Carlson found another sponsor, viz. OP-951, the ASW Division in OP-095. RADM J. V. Josephson, who was then OP-951 (and formerly sponsored OASIS as CPWP) assigned development cognizance to PM-4(his other hat). CAPT J. Siembieda (NPGS alumnus), OP-951C, his successor CAPT W. L. Vincent (NPGS alumnus), their assistant CDR D. S. Weisbrod, CAPT D. J. Wolkensdorfer, Deputy PM-4 (and later a user of VPCAS as CPWP), and his successor, CAPT D. A. Cox, provided Washington oversight of VPCAS through its completion December 1983. Cognizance was then transferred to the NAVSEA Acoustic Performance Prediction office under P. R. Tiedemann. It came under the ICAPS program, and NAVOCEANO (L. Webb cognizant), contracted DHWA to prepare videotapes for training. NAVSEA contracted Analysis and Technology to convert VPCAS to the HP 9020.

2.14. SSN Search.

Tactical doctrine for SSN ASW search has evolved over some 25 years, primarily through extensive investigative and developmental work by COMSUBDEVRON TWELVE (formerly COMSUBDEVGRU TWO) assisted by on-site representatives from private industry and NUSC assigned to that command. A 1963 manual contained too much complication for at-sea use, primarily from treatment of diesel targets. Efforts at a new and more user-friendly manual in the early 1970's were only partly successful. Present doctrine, reference [i], evolved from these efforts and has been simplified, in part by emphasis on presenting advisable courses of action without quantitative evaluations of these actions. Importantly, it is supported by an HP 9020 package, NWP-73 Assist, which helps in assembling inputs and in making needed calculations. Reference [ii] provides an overview.

As noted earlier, although SSN search tactics are well developed, they do not include adaptive search in response to Bayesian updating, which is why they are reviewed here separately from CAS.

Tactics are presented in reference [i] for area search, barrier search, SOA-constrained search (in transit and direct support), datum search (moving area and expanding datum), and search for a patrolling target. Tactics against diesel targets are generally given separately.

Search planning begins by defining the problem. For each of the above tactical areas, the planner proceeds through the following stages.

Data sheets are completed for needed own ship, target, and environmental inputs. NWP-73 Assist is used to compute sound velocity profiles (SVPs) (possibly merging a shallow in situ SVP with an historical deep SVP), proploss versus range using the RAYMODE model for various frequency and environmental inputs, FOM and its components including power summation of self noise and in situ ambient noise, and sonar lineups (a particularly complicated part of the problem) for various own speeds, search times, and sound channels. The program further assists the ensuing tactical choices.

A depth plan, alternating or fixed, is chosen, beginning with SVP identification of layer depth. Further guidance depends on whether hull-mounted or towed hydrophone arrays or both are used, existence and location of sound channels, and frequencies.

A speed plan is chosen as either constant-speed or sprint-drift, with parameters. This depends on kinematics, detection ranges, and counterdetection ranges. (In the early 1960's, detection and counterdetection were combined probabilistically into a single MOE, secure sweep width, but later practice has treated counter-detection separately and in conservative cookie-cutter fashion.)

A track plan is chosen to accomplish the objectives, consistent with the depth and speed plans. Attention is drawn to efficiencies such as minimizing the overlap that occurs from making sharp turns.

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CHAPTER III

TARGET MOTION ANALYSIS (TMA) TDAS

In this chapter we discuss TDAs which assist decision-making in ASW and ASUW approach and attack situations by performing target motion analysis, i.e., they output target range and, either directly or indirectly, target course and speed. We confine attention to *passive* inputs, primarily target bearings. This has long been vital to submarine ASW and has become important to surface ship ASW and to ASUW by all platforms. We describe several TMA methods that have been in operational use over the years, but we avoid identifying which methods are used in current submarine operations.

Passive TMA began to be important to submarine operations in the early 1950's. It was in this era that ASW began to evolve as an important submarine mission. To preserve the submarine's basic advantage, its stealth, required primary reliance on passive sensors. The primary information gained from passive sensors was target bearings. Methods were needed to deduce target position and target motion from bearings only. This was the basic TMA problem. Its solution was quite vital to the submarine ASW mission and accordingly the problem received considerable attention. As time went on, other passive information, in addition to bearings, was also used.

Submarine acoustic capabilities, in signal processing, hydrophone arrays, quieting, detection ranges, and bearings accuracies had a long way to go as of the early and mid 1950's. Great US progress in all of these areas over the years has been accompanied by great progress in TMA methods and by Soviet submarines. The TMA progress has been particularly important because as detection ranges and effective weapon ranges substantially increased, the TMA problem became inherently harder (range errors are proportional to the square of the range). As detection ranges have decreased more recently, as a result of Soviet quieting, the TMA problem becomes conceptually easier, but with increased needs for speed of solution.

Computers have, of course, played important roles in TMA advances. For filtering methods using many bearings, computers are quite necessary. Other methods which can be done manually are greatly facilitated by computerization. Embedded hardware/software systems serving TMA needs are the FCSs Mk 113, Mk 117, and Mk 118 on submarines and the FCS Mk 116 on surface ships. An SFMPL package of TMA programs resides on the Navy Standard DTC, the HP-9020A, as does the ATTAC TMA package on a few surface ships. Both the embedded and DTC programs include most of the TMA methods discussed herein. Also both submarines and surface ships have hand-held programmable calculator (HHPC) TMA packages. These compute Ekelund range, D/E range, and related quantities such as own speed in and across line of sight, target speed across line of sight, surface sound velocity, ping-steal range, etc.

Most bearings-only TMA methods, possibly all of them up to the 1970's, confine attention to targets with constant course and speed (CCS). If *both* own ship and target are CCS, it is impossible to obtain target range, course, or speed from bearings only, no matter how many and accurate they are, but a solution for the direction of *relative* motion is possible. Given an own ship course or speed change during the bearings, in theory three bearings suffice for target range and four suffice for a complete TMA.

We begin with a lengthy history of passive TMA, 3.1. Four prominent SSN TMA TDA methods, time-corrected Ekelund ranging, MATE, towed array ranging, and MTST are discused in 3.2, 3.3, 3.4, and 3.5 respectively. In 3.3, we further discuss a generalization of MATE to automation of the recursive adjustment and to doppler ranging; this is reviewed in the context of the principal *surface* ship TMA program, that in the FCS Mk 116. Regarding surface ship TMA, we also note the surface version of PUFFS and the ATTAC system in the history given in 3.1. We do not go beyond those discussions in surface ship TMA, because except for the Mk 116 they appear to be contained within submarine methods. ASUW TMA is usually over-the-horizon targeting, and we simply note that that has been the principal application of MTST.

3.1 History of TMA

TMA history begins well before the 1950's, in early WWII, when the first bearings-only TMA method, the Lynch Plot* , was devised by LT F. C. Lynch. Lynch was serving in Panama as the third officer (of three) aboard the re-commissioned WWI submarine R-1. The R-1's first sonar had just been installed and Lynch was assigned to find a method to conduct "sound-only" submerged approaches to torpedo firings (on surface ships). This was needed for some trials of the new sonar two days or so later. Apparently it was not known how this could be done without use of periscope.

Through intense pre-sail effort and excellent geometric insight, Lynch found a pivotal relationship among bearings, bearing rate, and target relative motion. In the ensuing weeks he perfected the Lynch Plot by working evenings plotting submarine attack geometries. He used this method throughout the war as XO HARDER, under Medal of Honor winner CDR S. D. Dealey, and as CO HADDO. After the war the Lynch Plot was introduced to the Submarine School curriculum where it was used well into the 1960's. It is mentioned in reference [a]. We recall that it was very elegant mathematically, and that our efforts to use it in a 1961 SS exercise floundered on a crowded plot, albeit this was on a much longer range problem than Lynch contemplated in WWII.

During the 1950's, various human plot methods and nomographs were used for TMA. One of the oldest of these was the strip plot, later called geographic plot TMA. This utilized transparent strips scored with bearing lines and a template to be fitted to bearing line plots on a dead-reckoning tracer. Each strip was keyed to a target speed, and the speed indicated by a fit, when combined with the bearings and a course change by own ship, yielded a TMA solution. This method has often been used to provide upper and lower bounds on target range, based on bounds on speed. An additional much used nomographic device has

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* We are indebted for this account to D. C. Ghen of Analysis and Technology, who based it on conversations with the late retired CAPT Lynch and recently with his widow, and to retired CAPT F. A. Andrews. Andrews also observed that a creditable (non-original) command thesis on the bearing rate slide rule was written around 1950 by LT Jimmy Carter, Chief Engineer on the K-1, while Andrews was CO.

been the bearing rate slide rule. An early TMA computer was the the Position Keeper, which was a carryover from WWII use as an aid to approach and attack against surface ships.

In 1953, F. N. Spiess showed in reference [b] how to use four bearings on a CCS target with an own ship course change, to compute target course and speed as well as range. Thus this was a complete TMA. His method is known as the Spiess Plot and is thoroughly analyzed in reference [a]. It remains in use in surface ship TMA. "Unstable" solutions arise in some situations, as they will in any four-bearing TMA method--see the end of 3.2. Spiess is a distinguished oceanographer and for 22 years directed the Marine Physical Laboratory, Scripps Institution of Oceanography. His TMA interest derived from his 13 combat patrols as a submarine officer in WWII. He is a CAPT USNR (ret.) and a pre-Monterey NPGS alumnus; his 1946 M.S. in ordnance engineering from Harvard was under the School's program and followed study at the School at Annapolis as was typical of the postgraduate program at the time.

The cxcellent 1954 command thesis of LT J. F. Fagan (NPGS alumnus), reference [c], derived a four-bearings TMA solution which was a transcendental system of three equations in three unknowns. To reduce this to computability by slide rule, he assumed that own ship motion during the first three bearings was approximately zero, which was probably satisfactory for diesel operations. Fagan later had more important influence on TMA progress as an analyst and as a commander.

One of the most famous TMA methods, Ekelund ranging, was devised in 1958 by LT J. J. Ekelund while an instructor at the Submarine School, New London. As RADM, he was Superintendent of the NPGS, 1980-83. The Ekelund method is to measure bearing rates before and after a turn and to divide their difference into the difference between own speeds across line of sight before and after the turn. This is exact if exact bearing rates are obtained immediately before and after an instantaneous turn. Obviously that ideal cannot be obtained.

After deriving his method theoretically, Ekelund tested it by simulation on the school's attack teacher during lunch hours with the help of LT R. E. Goldman, a fellow instructor. Concluding that the method would be operationally useful, he endeavored to report it to COMSUBLANT through his chain. After his draft was returned some four times for revision, he submitted it directly to the COMSUBLANT Quarterly Information Bulletin, where it was published in 1958 as reference [d].

The amazing thing is that this dissemination was sufficient for Fleet personnel to pick it up and use it. Nowadays this would be unheard of--because of the heavy technological load under which Fleet officers work, it is difficult to get their attention to new innovations. Perhaps partly for this reason, this Bulletin is no longer published.

Ekelund ranging has seen considerable use on US SSNs and surface ships and in various foreign navies. After 1970 or so its US use has been primarily in time-corrected form, as discussed in 3.2.

There were three particularly important centers of TMA activity in Groton and Newport in the 1960's and 1970's, interacting with each other: COMSUBDEVGRU TWO (CSDG-2, later COMSUBDEVRON TWELVE (CSDS-12)), the Naval Underwater

Weapons Research and Engineering Station (NEWRES, later NUSC/Newport), and the Electric Boat Division, General Dynamics Corp. (GD/EB). The first two of these remain prominent in TMA.

The era when TMA had its greatest emphasis at CSDG-2 was 1967-73 under the successive commands of CAPT W. M. Pugh, CAPT C. W. Woods, and CAPT Fagan. These commodores were all NPGS alumni as were the following of their staff officers who were prominent in TMA: LCDR L. R. Magner, CDR A. H. Gilmore, CDR M. C. McFarland, and LCDR J. M. Conway. CDR D. R. Hinkle contributed to TMA as Weapons System Director. ENS L. A. Anderson played an important special role. Important civilian contributors to TMA on site at CSDG-2 included D. C. Bossard of DHWA and M. M. Fox, founder of Analysis and Technology. Hinkle later founded Sonalysts, Inc.

The NUWRES/NUSC TMA group was concerned primarily with development of the submarine fire control systems Mk 113, Mk 117, and Mk 118. The group was led by E. L. Messere (currently Technical Director, NUSC) and later G. M. Hill. Reference [e] is a bibliography of over 100 documents on TMA produced by this group through 1988. Among the major contributors have been, alphabetically, V. J. Aidala, J. S. Davis, J. J. DiRusso, K. F. Gong, B. W.Guimond, H. W. Headle, E. J. Hilliard, A. G. Lindgren (consultant), D. J. Murphy (consultant), and S.C. Nardone.

The GD/EB TMA activity was within the R&D group headed by A. J. Van Woerkom, who was also its lead TMA contributor. It evolved from an earlier operations research group headed by Lynch after retirement and from GD/EB's prime contract on the ONR project Submarine Integrated Control (SUBIC), sponsored initially by CDR C. C. Brock (NPGS alumnus). Its other contributors included, alphabetically, R. A. Abate, W. S. Berry, C. R. DeVoe, T. M. Downie, J. W. Herring, H. F. Jarvis, J. S. Krikorian, and W. C. Queen. C. H. Knapp of the University of Connecticut, Spiess, and W. Vanderkulk of IBM contributed as consultants. This group dispersed in the early 1970's.

Another important center of TMA activity from the late 1950's to the early 1980's was the Naval Ordnance Laboratory (NOL--now the Naval Surface Warfare Center) at White Oak. We cite a group under R. Kogge who worked on an early version of the FCS Mk 113; H. E. Ellingson, C. B. Brown, and J. C. Munson, who originated and developed the theory of the PUFFS concept in a research group; A. T. Jaques in the latter group, who devised and effcctively employed the SPAR system to gather bearing accuracy data at sea; and a group under J. A. Faulkner, in which J. B. McQuitty was prominent, which did the engineering development on PUFFS and later conducted a wide aperture array (WAA) program.

PUFFS did passive ranging by measuring the curvature of a wave front arriving from the target. This has the advantage of not requiring a (time-consuming) maneuver. It was a precursor to the present next generation method noted at the end of the section. It was installed on several SSNs, SSs, and DDs. PUFFS was the centerpiece of the NOL TMA work, which, however, extended to a variety of TMA techniques. There exists a bibliography, unfortunately not referenceable, of some 150 NOL documents in the TMA area up to 1983. Reference [f] cites several of these items.

PUFFS went on surface ships as well as submarines. The production contractor for PUFFS, Sperry Gyroscope, designed a micro version for foreign navies combining the sonar and fire control into one equipment. PUFFS later evolved into a WAA program of NUSC, contributed to initially by Jarvis and Downie of GD/EB and later of Analysis and Technology. It was part of the RAPLOC (Rapid Localization) program on TMA techniques which do not require an own ship maneuver.

It is natural to approach range estimation by regression methods using a large number of bearing observations. CHURN was a least squares method of doing so for CCS targets, developed in 1958-59 by Van Woerkom as a consultant to Librascope and later at GD/EB. It used the Spiess plot as a starting point (reference [g] appears relevant). CHURN influenced the advent of the Mk 113 FCS and went to sea with the first Mk 113 aboard THRESHER. CHURN had problems with delta bias (see below).

In 1959, Vanderkulk (reference [h]) was the first of various people (notably Fagan, Bossard, and McCabe--see below) to conclude by analysis that for bearings-only ranging lead-lag is a preferred maneuver. He was addressing a CHURN estimation bias problem. He assumed that bearing rate is approximately constant but different on each of two legs. He showed that for a given total tracking time, standard deviation of range estimation error as a percentage of range is minimized by lead-lag perpendicular to line of sight. He had restrictions on the leg lengths which are satisfied if the second leg is about twice as long as the first.

An analysis of choice of tactics to reduce errors in Ekelund ranging was given in 1967 in reference [i] by Fagan. This included a recommendation in favor of lead-lag as just noted and derivation of a ranging equation similar to what is called the passive ranging equation in reference [a] and is given in 3.2 below. Fagan's formulation had important influence on Bossard's work leading to time correction, described next.

A major CSDG-2 project on passive ranging was initiated by Pugh in 1967 and continued by Woods and Fagan. Under this program, Bossard made a penetrating analysis of the fundamentals of bearings-only ranging and the effect of own ship maneuvers on ranging accuracy. Bossard's principal achievement in this work was development of time correction. This evolved from his examination of Fagan's formulation of a bearings-only ranging equation, in anticipation of testing Fagan's results in an exercise. Bossard observed that ranging errors from the principal source, target speed in line of sight, could be eliminated by judicious choice of the time for which the range was estimated. Also, by judicious choice of ranging maneuvers, this best time could be controlled to be in the past, present, or future, e.g., at roughly the time of own weapon impact. He called this method "time correction" and applied it to various forms of bearings-only ranging, notably Ekelund, Spiess, and CHURN--see reference [a]. He showed that CHURN ranging errors were greatly reduced by time correction, but CHURN was already superceded developmentally. As applied to Ekelund ranging, time correction is discussed in 3.2.

Also under Pugh was possibly the most extensive TMA exercise ever held, LANTSUBASWEX 2-68 in August 1968. This was a thorough comparison of various methods of bearings-only ranging aboard PARGO, whose CO was CDR S. A. White, later, as VADM, COMSUBLANT and, as ADM, Chief of Naval Materiel. At-sea exercise direction was by Hinkle assisted by Magner. Fox was chief scientist on the exercise. Bossard did the principal at-sea analysis on non-automated methods, generally centered on time correction. DiRusso took MATE (see below) to sea for the first time, operating it on a GD/EB computer system. Downie and Ghen worked with automated systems, and GD/EB supplied special instrumentation and other support. Considerable data were taken on digital tape, which by later analysis showed, for example, the effect of delta bias on CHURN. The "quick look" report on this exercise, reference [j], was a compendium of most of the passive ranging knowledge up to that time.

From this work there evolved under Woods the Passive Ranging Manual in three volumes, reference [a], later an NWP. Volume II, on ranging tactics was prepared by Magner and Bossard, and Volume III on theory, with emphasis on time correction applied to various ranging methods, was prepared by Bossard. Time correction is also reported in reference [k]. Some ranging tactics results of Bossard in reference [a] are noted in 3.2.

The TMA program that has probably seen the most active operational use is the Manual Adaptive TMA Evaluator (MATE), discussed in 3.3. MATE was developed at NUWRES around 1968 (see references [l] and [m]), principally by Headle and DiRusso. It was included in the FCS Mk 113 Mod 9 and successors.

The possibility of improving on the CHURN least squares method by recursive least squares in the form of Kalman filtering was explored in the 1960's by Van Woerkom, Jarvis, and Knapp at GD/EB (references [n] and [o]), Davis and D. J. Murphy at NEWRES (references [p] and [q]), and probably others. In particular, Van Woerkom sought smoother bearings for CHURN by such recursive methods, because the bias in CHURN was proportional to bearing variance.

The first Kalman filtering TMA system to be implemented operationally was KAST, the Kalman Automatic Sequential TMA program, which was developed for the Mk 113 by Davis, based on Murphy's 1968 Ph.D. thesis, reference [q]. This implementation at times had a problem often incurred by extended Kalman filters (see 3.5.6), viz., "covariance collapse." Aidala found a cure for that problem, but the result was a biased estimator. These kinds of problems appeared to be prevalent in the 1977 TMA symposium at NPGS, reported in reference [r]. Around 1978, G. W. Johnson of IBM observed that reformulation in polar coordinates was a key to solving the existing KAST bias problem--see reference [s]. This was facilitated by a further reformulation by Aidala--see reference [t].

KAST assumes a CCS target and gaussian bearing errors. It gives a good solution after one ranging maneuver, given high signal-to-noise ratio in broadband and moderate bearing rates. It does not adequately treat discontinuities in input data, or large bearing changes.

One important source of TMA errors is delta bias, referring to a form of errors in relative bearing arising from the fact that the receiving hydrophones are an array rather than at a single point. Specifically, delta bias is the difference in bearing bias error from one leg to another of a TMA maneuver. Ekelund ranging is insensitive to delta bias, in that it primarily uses bearing rates. MATE is sensitive to this source, but operators can compensate for it. Delta bias is a serious problem in KAST and geographic (strip) plot TMA. Ekelund and other methods are sensitive to the standard deviation of random bearing errors, which in turn is sensitive to signal-to-noise ratio. Delta bias is part of a larger class of errors discussed in reference [f].

From the early 1970's into the present era, RANGEX exercises at sea, with associated analysis and development ashore, have been periodically conducted by CSDG-2/CSDS-12 and NUWRES/NUSC. Starting about 1975, to a great extent these exercises were modeled after SUBASWEX 2-68. A key feature has been TMA data collection on magnetic tape. This has been a valuable program for TMA testing, in part by accuracy estimation, and for developing various TMA improvements. Among the methods involved were those which used depression/elevation (D/E) angles of arriving signals, ping stealing with comparison of arrival times by different paths, doppler effects, and wave front curvature, in addition to those discussed at greater length in this chapter. From the CSDS-12 findings in RANGEX and other work has evolved the SSN doctrinal TMA publication, reference [u].

We now describe the evolution of an important TMA method known as FLIT, although we cannot discuss the method itself because it is classified.

In the late 1960's a new type of passive sonar information was becoming available. In 1969, Queen of GD/EB developed TMA algorithms to take advantage of this information along with bearings (see references [v], [w], and [x]). He tested it preliminarily with modest at-sea data. A related development at GD/EB was a phase-lock loop system, led by J. S. Krikorian. This was a generalization of the bearings-only method of steering the sonar in an automatic target follower (ATF) mode. These developments were under Herring, Abate, and, over all, Van Woerkom.

In June 1970, Gilmore, CSDG-2 Weapons System Director under Woods, had available this new type of data from a recent exercise. He assigned Anderson to try to use these data in TMA. Anderson was a new surface Ensign with a B. A. in physics, temporarily at CSDG-2 awaiting nuclear power school. He succeeded in achieving a TMA in two weeks or so by combining these data with bearings data and using (non-recursive) regression. He used a USL computer and received experienced coaching on TMA from Magner. Gilmore was able to confirm that his solutions were good. These results evoked considerable CSDG-2 interest.

In his initial analysis Anderson had not been aware of the GD/EB work. In comparing Queen's references [v], [w], and [x] with Anderson's reference [y] (the latter is more fully developed), one finds much in common, which is not surprising. There also appear to be significant differences, notably regression was important to Anderson's analysis but is at most implicit in Queen's documentation. On the other hand, in reference [y], Anderson cites reference [x] and credits it with an alternative approach which Anderson expressed in regression terms and which used a line-of-sight (moving) coordinate system compared to his own north-east coordinates. Queen left GD/EB and the subject in August 1970. Conversations in 1989 (inhibited by security) with Anderson, Queen, and others involved in 1970 do not shed additional light on the origination of the FLIT concept.

In summary, we credit (1) Queen with the first TMA algorithm using the sonar data central to FLIT, (2) Anderson with the first method of this sort to be implemented operationally, and (3) both Queen and Anderson with doing excellent analytical work on this problem.

Van Woerkom and some associates briefed Woods and others of CSDG-2 on the GD/EG work, notably the phase-lock loop, shortly after Anderson completed his initial TMA work. Thenceforth Anderson and GD/EB joined forces to develop a sea-going prototype system using Anderson's TMA algorithm (related to Queen's), which at a later point Gilmore named FLIT, and GD/EB's phase-lock loop system. Berry was GD/EB's senior engineer on the project. (Woods had Anderson's orders changed to postpone his departure; that came six months later, three months after Fagan relieved Woods. Fagan steered Anderson toward submarine qualification.)

The FLIT prototype went to sea with Berry, Anderson, Gilmore, and Woods in late July on STURGEON (CDR W. L. Bohannon was CO, later CO NUSC) to do TMA against SKATE. Late changes were made while underway, but successful results were obtained. For his work, Anderson received the Navy Commendation Medal. Berry received GD/EB's Engineer of the Year award for his engineering leadership on this prototype.

During the next year or so FLIT was combined with Kalman filtering, by an algorithm developed by Jarvis of GD/EB and modified by Aidala of NUSC, using methods developed in the evolution of KAST. A technical description of the FLIT method is given in reference [z]. For additional documentation see reference [y] and the introductory text of reference [aa]. FLIT has seen considerable important operational use.

Ranging and tracking at long range by Kalman filtering methods on a sphere were developed in the mid and latter 1970's, primarily for COMSECONDFLT, by Bossard, J. B. Oehrle, and L. K. Graves of DHWA. This was motivated by over-the-horizon (OTH) targeting needs.

Kalman filtering on a sphere was employed in 1978 by F. P. Engel of DHWA, on field assignment to COMSUBLANT, to develop the program OTH-T for OTH tracking on CCS targets. OTH-T resided on the Tektronix 4051 DTC and was used by CSDS-12. In 1982 it incorporated MTST (see reference [bb] and 3.5 below) to track maneuvering targets. In this form it was included among the SFMPL TMA programs on the HP 9020. It is also included in the NUSC/Sonalyst search program CASE and hence ASWTDA (see 2.13 and the introduction to Chapter IV).

In 1978-79, McCabe derived a formula in reference [cc] for the variance of a bearings-only range estimate and from this he derived useful tactical conclusions: The range estimate at the end of a lead-lag maneuver was much more accurate than that of a lag-lead maneuver. This preference is consistent with findings of other approaches from different viewpoints. McCabe's work was part of a study of short-range ranging sponsored jointly by the UK and CSDS-12. In recent correspondence, Vanderkulk showed how McCabe's results could be strengthened by using four-parameter likelihood instead of two parameters. His analysis reinforces a contention of A. R. Washburn's (reference [cc]). Vanderkulk, McCabe, and Washburn all reached the same tactical conclusion.

A 1978 DTC Kalman filter TMA TDA was developed at COMSUBPAC on a Tektronix 4051 by S. S. Brown of DHWA under CDR W. J. Hayne, an NPGS Ph.D. in OR. It assumed planar CCS motion and outputted an updated bearing accuracy estimate as well as position.

Some important theoretical advances took place in 1978 at DHWA, which paved the way for TDAs to track maneuvering targets. A keystone was B. Belkin's introduction into ASW modeling of the integrated Ornstein-Uhlenbeck (IOU) process (reference [dd]). This has proved to be a robust model of motion by submarines and other vehicles which maneuver relatively slowly. It was chosen as the best gaussian approximation to the Washburn random tour (reference [ee]). (It was named IOU by R. J. Miller of ONR out of impatience with the larger mouthful during a briefing.) For further discussion, see 3.5.2 and Appendices B and D.

As a further theoretical advance, stochastic differential equations (SDE's) were used to describe target motion updates in conjunction with measurement updates by Kalman filtering; the principal motion process was IOU. This work was led by T. L. Corwin, with later contributions by D. P. Kierstead, G. P. Pei, J. W. Palmer, and M. E. Davison all of DHWA. Among the applications were simulation of submarine tracking as an estimation of Soviet potential against US SSBNs, prior to the development of an operational tracker by this means. Reference [ff] is an excellent summary of the relevant mathematical properties of IOU, as given by stochastic differentials, and generalizations thereof.

In 1980-81 at COMSUBPAC, W. H. Barker of DHWA employed IOU/SDE/ Kalman methods to develop the Maneuvering Target Statistical Tracker (MTST). This TDA was the first operational program to take this approach. Barker improved the earlier algorithms and importantly added a smoother by forward-backward filtering to eliminate outliers. MTST has been extended further by Barker, Kierstead, W. R. Stromquist, N. L. Gerr, and others of DHWA. Its methodology, discussed in 3.5, is believed to be state-of-the-art in maneuvering target tracking. It has been incorporated in submarine combat control systems. It is also used in automated reconstruction by NTSA.

The Generic Statistical Tracker (GST) was developed at DHWA as a PC version of MTST in 1985-87 by Stromquist, Kierstead, J. R. Weisinger, and others. It has been installed at NOSC, NADC, NUSC, CNA, and Boeing.

Excellent expositions of the methodology in MTST and GST respectively are given in references [gg] (6.1 and 6.2, prepared by Barker at Tiburon Systems) and [hh] by Weisinger. Briefer discussion is in 3.5 and Appendix D.

Concurrent with Barker's work on MTST, Engel, J. W. Stopple, W. R. Monach, and L. E. Hollowood of DHWA also developed for COMSECONDFLT (CDR R. L. Starck) and NUSC (M. J. Pastore) a Kalman/IOU ASUW tracker, known as SURTAC (reference [ii]). SURTAC had (1) a CCS tracker taken from OTH-T, (2) a maneuvering target tracker using IOU and Kalman filtering (forward filtering only--see 3.5.4), (3) a turn-detector as a basis for choosing between (1) and (2), and (4) a Harpoon acquisition model (by MONACH). This program became the basis for the Tactical Surface Surveillance (TSS) program which in 1982 was the initial basis for JOTS--see 4.1.1.

SURTAC had its strengths, but its turn-detector did not work very well and MTST was better developed as a maneuvering target tracker. In 1982, MTST was merged into OTH-T, as noted above, which is a better implementation of the dual CCS/maneuvering target approach and remains in being.

An advanced Kalman filter method using information domain processing (see 3.5.6), multiple data sources such as bearings, doppler, and D/E angles, and CCS motion was developed by Bossard of DCBossard, Inc. in the early 1980's. Working in the information domain is advantageous until enough information is acquired for non-singular covariance. This work was for Applied Mathematics, Inc. under a US/UK contract and was accompanied by displays developed by W. J. Browning of that firm. It has been used on UK submarines. A prior version had been developed for CPWL for VP TMA on hand-held calculators.

Towed array ranging (reference [jj]) came into being at CSDG-2 in the early 1970's. This centers on hyperbolic methods discussed in 3.4. The aids to *hand*-computed hyperbolic ranging noted there were developed by A. T. Mollegen (current CEO of Analysis and Technology), while on the staff of CSDG-2, 1972-75. The french curve approach is due to W. Follette of CNA.

Finding target depth is also part of the TMA problem. Little contribution to this problem has been made by TMA TDAs to date, but the NUSC MRADE system shows promise under some environmental conditions. Evidently multiple path methods must be used.

The bibliography of reference [kk] contains references to several additional contributions to TMA and related physics, by industry and government.

In reference [ll] Van Woerkom discusses experience factors in TMA. He emphasizes the need to deal with multiple maneuvering SSN targets.

The principal computerization of *surface* ship TMA is that which is contained in the FCS Mk 116, which is a fairly comprehensive weapons control system. The heart of its TMA is a generalization of MATE, so we review it under the discussion of MATE in 3.2. The algorithms for this approach had their roots in mid 1970's work by W. B. Adams (reference [mm]) of General Electric and S. T. Chou (reference [nn]) of NOSC and were developed further in 1979-80 by C. N. Burgis and P. B. Houser of Librascope and later by M. J. Shensa (reference [oo]) and J. D. Pack of NOSC. The Mk 116 was developed by NOSC under R. D. Thuleen, Code 62. L. A. Hermanson has been responsible for most of the implementation of the TMA algorithms since about 1980. Evaluations at sea began 1982, and the production versions of the system began shipboard installation in 1985. It is operational on a few Aegis cruisers and DD 963s and is scheduled for all ships of these classes.

In 1983-84, the Automated TMA Tactical Aid to Commanders (ATTAC) was developed for SWDG for surface ship use by DHWA, principally L. B. Whitt, and IDEAS Inc., principally C. Shortledge (reference [qq]). This work was primarily under LCDR J. R. Oakes, an NPGS alumnus. ATTAC computerized various doctrinal methods (see reference [rr]) in a single program and is included in FFISTS. (FFISTS is intended for non-NTDS DE 1052s. It contains JOTS and requires four HP 9020s and some HP 9836s.) These methods include MATE, geographic plot, Ekelund, KAST, and D/E, all adapted from SSN methods.

There also exist various surface ship TMA programs on hand-held calculators.

An SSN bearings-only TMA method has been recently proposed by LT P. K. Peppe on LA JOLLA, an NPGS alumnus. It is under evaluation as an NPGS thesis project by CDR B. Carrero Cuberos of the Venezuelan Navy, under his advisor J. N. Eagle. The method is as follows: Take about 12 bearings about 20 seconds apart on a lead leg followed by the same on a lag leg. Make a linear fit to each of these sequences of bearings versus time. Use these linear functions to extrapolate bearings forward in time from the first leg and backward from the second leg. Cross the forward extrapolations of the first leg with the actual bearings of the second leg to obtain an estimate of target track, call it T_1. A second estimate, T_2, comes from crossing the backward extrapolations of the second leg with the actual bearings of the first leg. It is believed that this idea has been tried in the past with two bearings on each leg, but not with as many as 12. Preliminary simulation evaluations indicate the T_1 is generally very good, and T_2 is usually not a good estimate. Also, the conflict between range accuracy and course and speed accuracy, discussed at the end of 3.2, appears to be confirmed by these simulations.

A still more recent bearings-only TMA method has been proposed by CDR H. R. Bishop, PCO ALEXANDER HAMILTON (GOLD), an NPGS alumnus. He has derived an exact expression for range, involving first and second derivatives of bearings, in an effort to avoid the Ekelund idealizations. As yet his method has not been tested at sea or by simulation.

Among the notable facts in this lengthy history of TMA is that on at least three occasions quite innovative methods were found by young officers and put to use in Fleet operations: the Lynch plot, Ekelund ranging, and FLIT. (Much of the theory of Anderson's innovation on FLIT was done earlier by Queen.) The recent proposals by Peppe and Bishop indicate that Fleet interest in innovation in TMA remains alive.

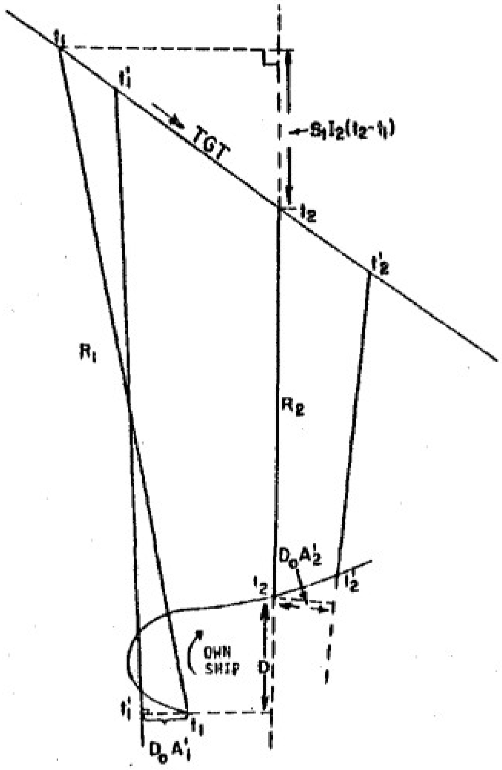
Probably the most important TMA TDA methods from past experience are MATE, FLIT, time-corrected Ekelund, hyperbolic towed array ranging, and MTST. Except for FLIT, these are reviewed in turn in the next four sections. Possibly the most important TMA method in the visible future is planned for the SEAWOLF and uses wave front curvature, taking advantage of longer base-lines afforded by towed arrays, in a system called TARP, and by wide aperture hull arrays.

3.2. Time-Corrected Ekelund Ranging

In this section, we describe the marriage of two important ranging concepts discovered a decade apart, Ekelund ranging and time correction. At the end of the section we note the Spiess four-bearing TMA method and a TMA accuracy conflict disclosed by time correction theory.

The tactical situation is shown in Figure III-1. Target course and speed are constant. Own ship records its position and bearing to target at times t_1 and t_1' before a turn and at time t_2 and t_2' after the turn. The recorded bearings are denoted by B with corresponding subscripts and primes. The subscripts o and t refer to own ship and target, and A and I refer to "across line of sight" and "in line of sight." The D's, with and without annotations, refer to certain distances moved by own ship as shown in Figure III-1.

FIGURE III-1. GENERAL RANGING MANEUVER



Referring to Figure III-1, as in reference [a] we make the following definitions:

$$\hat{B}_1 = \frac{\sin(B_1'-B_1)}{(t_1'-t_1)} \frac{\cos(B_2'-B_1')}{\cos(B_2-B_1)},$$

$$\hat{B}_2 = \frac{\sin(B_2'-B_2)}{t_2'-t_2},$$

$$\hat{S}_1 = D_oA_1' \frac{\cos(B_2'-B_1')}{t_1'-t_1},$$

$$\hat{S}_2 = \frac{D_oA_2'}{t_2'-t_2}.$$

The first two definitions are approximate bearing rates and the other two are approximate own ship speeds across line of sight. (These and other formulas can usually be simplified by the approximations $\sin x \approx x$ and $\cos x \approx 1$, for x in radians less than, say 1/3.)

With these definitions, it is shown in reference [a] that the range at time t_2 is given exactly (providing measurements are exact) by

$$R_2 = \frac{\hat{S}_2-\hat{S}_1}{\hat{B}_1-\hat{B}_2} - D\,\frac{\hat{B}_1}{\hat{B}_1-\hat{B}_2} - S_tI_1{}'\,\frac{\sin(B_2'-B_1')}{\hat{B}_1-\hat{B}_2} - S_tI_2\,\frac{(t_2-t_1)\,\hat{B}_1}{\hat{B}_1-\hat{B}_2}.$$

In reference [a] this is called the passive ranging equation. Its first right-hand term is the Ekelund estimate. It is simply the ratio of the difference between own speeds across line of sight before and after the turn to the corresponding difference in bearing rates. In the idealized situation where the turn is instantaneous and these speeds and bearing rates are exactly measured immediately before and after the turn, the Ekelund estimate would be exact. The remaining right-hand terms represent the error in the Ekelund estimate in a non-idealized situation, apart from the effect of measurement errors. Fagan in reference [i] and others addressed some tactical choices which in effect reduce these error terms.

Reference [a] went further by observing that the two terms containing target speeds in line of sight, the major contributors to error, can be eliminated by judicious choice of the time at which the range estimate is to apply. Define

$$\bar{t} = t_2 - \frac{(t_2-t_1)\hat{B}_1}{\hat{B}_1-\hat{B}_2}$$

$\bar{D}$ = distance moved by own ship between t_2 and $\bar{t}$ in the direction of bearing B_2,

$$t^* = t_2 - (t_2-t_1)\frac{\hat{B}_1}{\hat{B}_1-\hat{B}_2} - \frac{\sin(B_2'-B_1')}{(\hat{B}_1-\hat{B}_2)}\,\frac{\cos(B_1'-\bar{B})}{\cos(\bar{B}-B_2)}, \text{ and}$$

D^* = distance moved by own ship between $\bar{t}$ and t^* in the direction of bearing B_1'.

It is shown in reference [a], with the help of Figure III-2, that at time t^*, called the "best range time,"the range is R^* given by (B^* is the bearing at time t^*)

$$R^*\cos(B^*-B_1') = \left(\frac{\hat{S}_2-\hat{S}_1}{\hat{B}_1-\hat{B}_2} - D\,\frac{\hat{B}_1}{\hat{B}_1-\hat{B}_2} - \bar{D}\right)\frac{\cos(B_2'-\bar{B})}{\cos(\bar{B}-B_2)} - D^*.$$

Note that target speeds in line of sight have been eliminated, which has the effect of minimizing range error. All quantities in the formula for R^* can be measured on own ship. Finding t^* and R^* thus defined is the time correction method.

When time correction was developed, desktop computers were unavailable, so the graphical method described next and simplified versions of the above equations were obtained using the small angle approximation, to facilitate hand computations. With desktop computers, these simplifications are largely unnecessary.

We describe a neat graphical method taken from reference [a] for finding the best range time t^* for an Ekelund range estimate. This is illustrated in Figure III-3, which is based on a time-bearing plot. Now strictly speaking for the first right-hand term in the above formula for R^* to represent an Ekelund estimate, we should let t_1' come close to t_1 and t_2' come close to t_2. Then in effect we are dealing with bearing rates at t_1 and t_2. Let these bearing rates be estimated by the slopes of the straight lines fitted to the points near t_1 and t_2 respectively. Let $\hat{t}$ be the time coordinate of the intersection of the extensions of these two lines. Now let B_1 be the bearing at time t_1 and draw a line through (t_2, B_1) parallel to the fitted line at t_2; let $\bar{t}$ be the time at which this line intersects the line fitted at t_1. Then t^* is the time whose distance below $\bar{t}$ equals the distance by which $\bar{t}$ is below $\hat{t}$.

FIGURE III-2. TIME CORRECTION OF THE RANGE

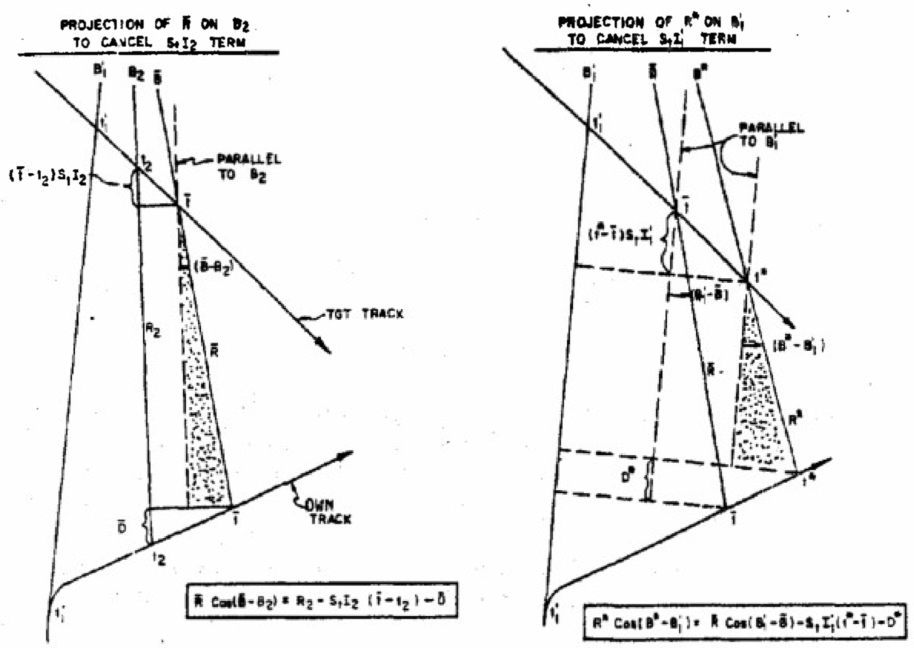
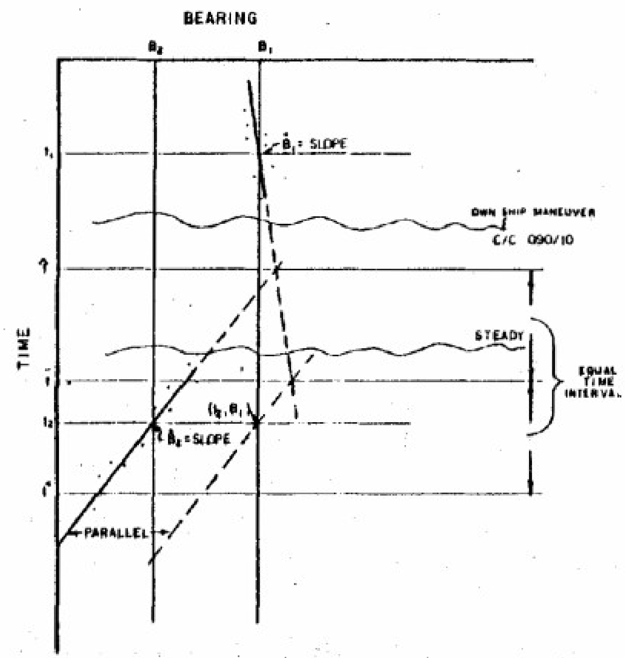


FIGURE III-3. TIME-BEARING PLOT CONSTRUCTION TO FIND EKELUND BEST RANGE TIME, t*



An additional step by reference [a] was to observe that the occurrence of the best range time could be controlled by judicious choice of the ranging maneuver by own ship. As general guidance it states as follows:

"(1) The best range time usually lies on the same side of the turn as the leg with larger (magnitude) bearing rate.

(2) If the bearing rates on both legs are in the same direction, then the best range time lies outside of the maneuver."

If for example, the ranging maneuver is a leg which points or leads the target followed by a lag leg, then t^* will usually be in the future which confirms findings of others as to preference for lead-lag over lag-lead. Additional guidance of this nature is given in reference [a].

We close this section with a brief statement of the Spiess four-bearing TMA method and a discussion of an accuracy conflict inherent in four-bearing TMA. This conflict was revealed by the time correction analyses of reference [a].

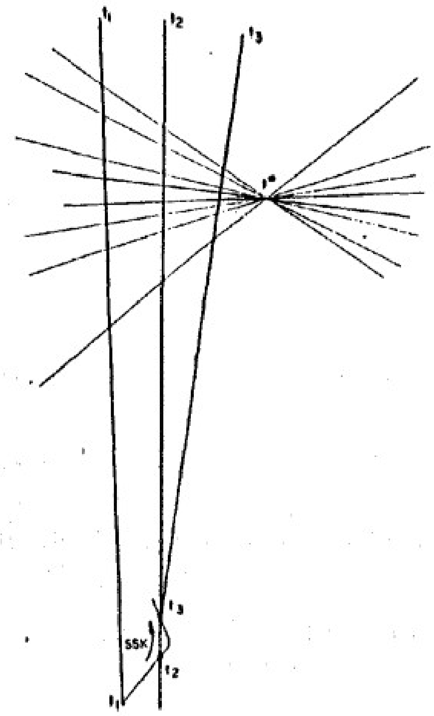
The Spiess four-bearing method is based on the following fact cited in reference [a]: Given bearings on a CCS target at times t_1, t_2, and t_3, the locus of target positions at a chosen time t_4 is a computable straight line. Crossing that locus with the bearing at t_4 yields target position, the mirror image of the procedure yields position at t_1, and these two positions yield course and speed.

If in the preceding construction it should happen that t_4 is so chosen that it is close to the best range time t^* corresponding to (a) t_1, t_2, t_3, and t_4, (b) the bearings at these times and (c) own ship's track, then we have a highly unstable situation. This is illustrated in Figure III-4. To explain Figure III-4, we first note that for small bearing changes the small angle approximations are assumed.

In Figure III-4, each of the family of lines shown converging at time t^* is a locus of target positions at t^* corresponding to bearings at times t_1, t_2, and t_3 and own ship track. The approximate convergence is shown in reference [a]. The various converging lines correspond to *small* changes in one or more of the bearings at t_1, t_2, and t_3. Now these small changes in bearings introduce changes in t^*, but *not very much*. Thus the substantial variation in direction of the converging lines illustrates the fact that small errors in bearings lead to very large errors in course/speed estimation, *providing* $t_4 \approx t^*$. We do not obtain relief from the mirror image of the procedure leading to a position estimate at t_1, because that is well removed from the best range time and inherently entails a substantial error in range, so that the track between the positions at t_1 and t_4 remains sensitive to bearing errors.

We thus have the following accuracy conflict in four-bearing TMA: If range estimation accuracy is paramount, then use lead-lag and choose the bearing observation times so that one of them is (1) at the estimation time desired and (2) at the best range time; this will entail a serious degradation of course/speed estimation accuracy. If the latter is important, then use lag-lead-lag and *avoid* the best range time, accepting a degradation of ranging accuracy for better accuracy of course and speed. We have presented these findings in the context of Spiess ranging, but they are inherent in *any* TMA method by four bearings only. These findings in reference [a] also explained previously unpredictable instabilities in the Spiess plot.

FIGURE III-4. CONVERGENCE OF FOUR-BEARING TMA SOLUTIONS



To overcome this accuracy conflict, use additional information beyond four bearings, e.g., additional bearings.

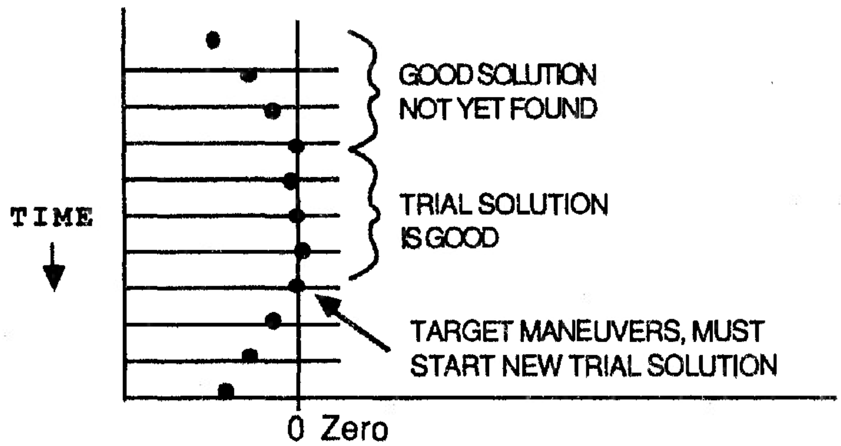
3.3. MATE

The Manual Adaptive TMA Estimator (MATE) is in effect a computerization of geographic (strip) plot TMA. MATE can be used to *evaluate* a TMA solution obtained by some other method or to *generate* a solution. In either case one begins by entering a TMA solution into the computer.

In the evaluation mode, target bearing, range, course, and speed are entered as of a given time. This CCS target track implies the bearing that should be observed by own ship at any given time, in particular at the actual times at which bearings were observed. Over a time interval on which it is presumed that the target is CCS, MATE generates a plot, illustrated in Figure III-5, of time vertically and as horizontal coordinate the difference, called the residual, between each observed bearing and the implied bearing at that time. If (1) the displayed bearing differences are close to zero, i.e., if they are distributed roughly symmetrically as "white noise" about zero (known colloquially as "stacking the dots"), and if (2) own ship changes course or speed during the time sequence plotted, the trial solution is a good one.

FIGURE III-5. MATE DISPLAY

NOTE: Trial solution consists of range and target CSE/SPD.



Difference between observed bearing and bearing predicted by trial TMA solution

To generate a TMA, MATE employs this evaluation principle. If the solution is not a good one, i.e., if the dots are not stacked or are stacked at a value away from zero, then the solution is adjusted, the adjusted solution is evaluated, and the procedure repeats until a good solution is obtained or new data are observed. However, for solution generation, the input procedure is modified compared to the evaluation mode.

The modification is called "end-point" MATE. A time interval of bearings is chosen as above (during which own ship changes course and speed), and the observed bearings at the end-points (start and end) of the interval are entered. Additionally, *estimated* target course and speed are entered. These four values suffice to imply the bearing sequence as before, and the residuals are displayed. If the dots do not stack on zero, the course and speed are adjusted, while keeping the end-point bearings fixed. If repetition of this procedure does not produce a good solution, the end-point bearings are adjusted and then held fixed while course and speed are adjusted, and the procedure reiterates. Thus the MATE operator ultimately has a four-parameter choice, but at a given stage he is adjusting only two parameters, which can be done more effectively than with four. Nevertheless, the adjustment methods are considered to be an art learned by operator experience.

It is worth noting that a key to the usefulness of MATE is the *visual display* of the residuals, as a guide to solution adjustment.

Of course, if own ship maintains CCS as is assumed for the target, it will be impossible to estimate range from bearings only, by MATE or any other means. The geographic plot method illustrates that a given bearing sequence can be produced by a broad family of CCS target motions in that circumstance.

MATE accuracy is enhanced by high bearing rates and large own ship maneuvers. Also, the MATE display clearly shows delta bias, so an alert operator can remove this effect, which is not possible with other statistical methods.

A MATE solution will be disrupted if the target maneuvers, as also illustrated in Figure III-3. However if a good solution had been obtained before the target maneuver, the solution effort on the new target leg will begin with a good estimate of range, so a good new solution should be obtained more quickly.

We now turn to the central TMA method in the surface ship FCS Mk 116, which generalizes MATE as described above, in two important directions: In addition to bearings it utilizes received frequencies to compute doppler ranges, and it automates the adjustment of trial solutions. This method is called "maximum likelihood estimation (MLE)," based on the fact that its recursive improvement is by reduction of mean squared error. As before, a CCS target is assumed. The bearing and frequency histories are recorded at 32 second intervals and are smoothed.

First let us describe the basic doppler ranging principle. Let f_0 be a "base" frequency emitted by a target under the assumption that it is motionless but creating its actual acoustic noise. This frequency is received by own ship as f and has undergone the doppler shift due to both own and target speed in line of sight, denoted S_0I and S_tI as in 3.2. If refraction is ignored and sound travels at a constant speed c, then the relation among these quantities is

$$f = f_0 + [S_0I - S_tI]/c.$$

If one has an estimate of the base frequency, f_0, and has measured f, then this equation can be solved for S_tI, which with other information available is enough to obtain a TMA. However, since quality of the solution is heavily dependent on accuracy of the estimate of the base frequency, the latter is included as a trial solution component to be adjusted along with TMA.

Thus a 5-dimensional target state is defined: two components each for position and velocity and a component for base frequency. An initial trial solution, i.e., state estimate, is formed by going out the latest and earliest observed bearings (on the target's presumed CCS track) to (arbitrarily) 20,000 yards, which gives two position points and hence a TMA. Base frequency is initially estimated from intelligence or as observed frequency (base frequency equals observed frequency is equivalent to zero relative motion in line of sight).

This trial 5-vector implies the bearing and frequency sequences that should be observed and, by solving the above equation for f_0, a new estimate of the base frequency. The bearing residuals, i.e., observed bearing minus implied bearing at various times, are displayed as in Figure III-5. A similar procedure is separately followed with frequencies.

We now outline how the recursive adjustment is automated. Form the sum S of the squares of the frequency residuals. To normalize this to a dimensionless quantity, find the least squares quadratic fit to these residuals, sum the squares of the deviations of the residuals from the quadratic fit, and divide S by this sum. Do the same for bearings. Let Q be the sum of these two normalized sums. Regard Q as the measure of badness, i.e., cost, of the trial 5-vector. If we can drive Q to zero, that is equivalent to stacking the dots perfectly in manual MATE.

To this end, it is noted that the dependency of Q on the trial 5-vector is a rational function and its partial derivatives can be found analytically. One attempts to zero these derivatives, hoping that achieves a global minimum, in any event not accepting an increase in Q. The indicated direction of adjustment of the last trial solution is the negative gradient of Q at that point, which is analytically computable. The extent of the adjustment is to reach the nearest coordinate hyperplane subject to certain reasonableness constraints. If this reduces Q, the adjustment is complete and one proceeds to the next adjustment by the same method. If not, it is assumed that the adjustment attempt overshot the mark and interpolation is used via a cubic approximation to Q, which can be minimized analytically. If that does not reduce Q, the adjustment is complete. Up to three such adjustments may be made, before reverting to processing new observations.

Although this is called "maximum likelihood estimation (MLE)," this is a bit of a misnomer, as the developers realize. If minimization of Q could be achieved, and if the bearing and frequency distributions were fixed and known in advance, then this would be true MLE.

Technical documentation of this algorithm is given in references [mm], [nn], and [oo] and, in programming language, in the program performance specification, reference [pp]. A technical evaluation was conducted at sea in 1985-86.

3.4. Towed Array Ranging

The distinctive feature of towed array ranging is the fact that a target indication received by a towed array merely indicates that the target is somewhere on a circular cone which is coaxial with the array cable. This is illustrated in Figure III-6. Note that coverage directly forward and aft is truncated by endfire and that a detection directly abeam can be anywhere on a vertical plane.

The intersection of a circular cone with a plane parallel to its axis, e.g., a horizontal plane, is an hyperbola--see Figure III-7. Thus if approximate target depth is assumed, the target location ambiguity is reduced to an hyperbola, which in the case of a target directly abeam reduces to ambiguity between two bearings, the beam directions port and starboard. If source and receiver are at the same depth, the hyperbola becomes a pair of lines.

To resolve the hyperbolic ambiguity, an additional locus of target position is needed. One source of such is for own ship to turn as in Figure III-8 and obtain a new hyperbola of position which may be intersected with the pre-turn hyperbola. This is known as hyperbolic cross-fixing. "Hybrid" hyperbolic cross-fixing uses a direct path bearing instead of the second hyperbola. Hyperbolic methods have been programmed for FCS, DTC, and HHPC use.

Aids to hand-computed towed array TMA have been developed as earlier TDAs. The hyperbolic slide rule known as Towed Array D/E Range Finder computes hyperbolic cross-fixes, and ordinary D/E ranges. Also, hyperbolic lines of position ("hyperbolic bearings") can be superimposed on a geographic plot for fitting by speed strips. Hyperbolic templates with holes have been developed for this purpose. A french curve approach has also been developed. It was first pointed out in reference [ss] that a full solution on a CCS target can be found from hyperbolic bearings only, except for right/left ambiguity, zero bearing rate, and certain special cases.

FIGURE III-6. TYPICAL TOWED ARRAY BEAMS

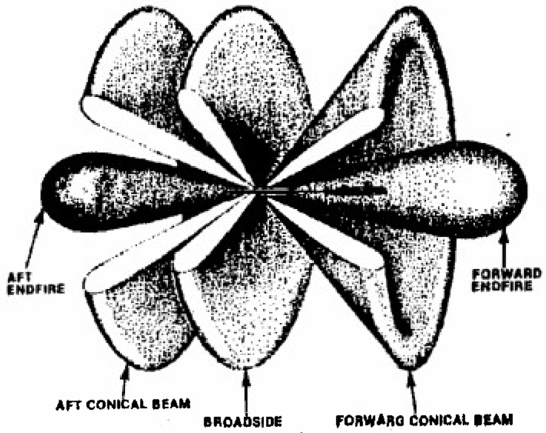


FIGURE III-7. HYPERBOLA FORMED FROM BOTTOM BOUNCE CONICAL BEAM

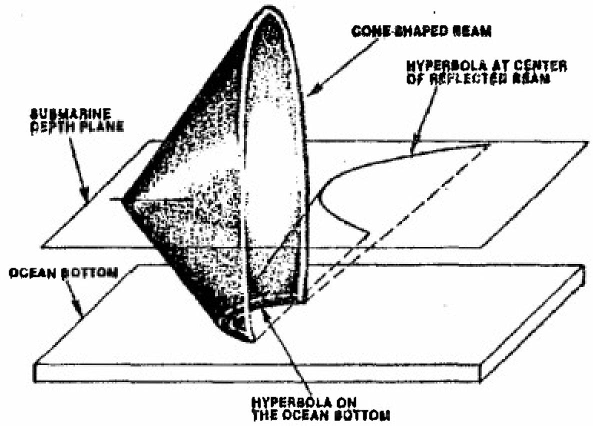
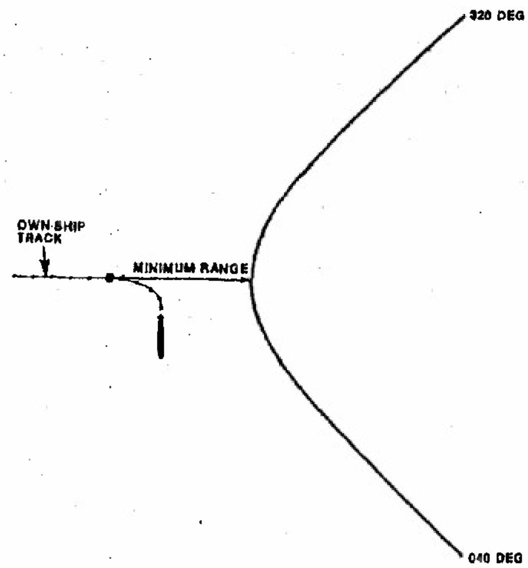


FIGURE III-8. HYPERBOLA PLOTTED ON GEOGRAPHIC PLOT



Ekelund, MATE, and geographic plot TMA methods can be applied with towed array bearings, but they generally take longer than with hull array bearings, depending on signal-to-noise ratio. The longer time makes time correction in Ekelund more desirable than usual, because of greater departure from the instantaneous turn assumption.

3.5. Maneuvering Target Statistical Tracker (MTST)

MTST is an algorithmic method for automatic tracking of maneuvering targets. In common with most contemporary automatic trackers, it employs Kalman filtering. What principally distinguishes MTST from other Kalman trackers is use of an IOU target motion model--see Appendices B and D. In this section we will describe the basics of the MTST method, under some simplifying assumptions and assuming some reader knowledge of Kalman filtering. Specifically, we will describe a simplified version of the forward filter part of MTST. Addition of backward filtering and other important extensions beyond this simplified case are summarized in 3.5.6.

3.5.1. Example and background.

First we will illustrate what MTST can do by giving a tracking example that would ordinarily be considered difficult. This example is given by Figures III-9 through III-13 and was constructed in 1984 by W. R. Stromquist on a Tektronix 4052. MTST is now programmed on more modern DTC's, in fact on PC's.

Figure III-9 shows a target's actual track over four hours. Rather radical changes in course and speed are made. Eleven observations on the target, consisting of gaussian ellipses and lines of bearing are shown in Figure III-10. (Bearing boxes could also be accommodated.) The track constructed by MTST from these observations is shown in Figure III-11. Note that the principal turns by the target are captured quite well, although there is not enough information to reveal the short maneuvers beginning at 1840. Figure III-12 shows the observations superimposed on the reconstructed track. The reader may want to reflect on how the reconstruction could be achieved from the observations without computer assistance--it is possible but difficult. Finally, Figure III-13 shows the sequence of areas of uncertainty (AOU's) given by MTST. These are 95% containment ellipses and form what is often called a "slinky" diagram.

Kalman trackers of ship targets are usually based on CCS target motion. Such a tracker has difficulty maintaining a good track after a target turn. In fact the solution on the new leg cannot be expected to stabilize on the correct track unless the pre-turn observations are ignored, which can be done if the turn time can be recognized. Otherwise the best recovery that can be expected is a CCS approximation to the actual track, which might differ uncomfortably from the current track. It is principally in overcoming that problem that MTST has its greatest value. It does so via the IOU motion model.

Excellent expositions of the MTST method are given in references [gg] and [hh]. They include stochastic differential equation characterizations of the IOU process, more so in [gg] than in [hh]. Even so a reader familiar with Kalman filter methods should find them readable. Note that in [hh], the treatment is in terms of a 6-dimensional target state and motion on a spherical surface (both noted in 3.5.6 below). To relate it to the treatment below, in [hh] drop the last two coordinates and let gamma be zero (spherical parameter).

FIGURE III-9. MTST ILLUSTRATION--ACTUAL TRACK

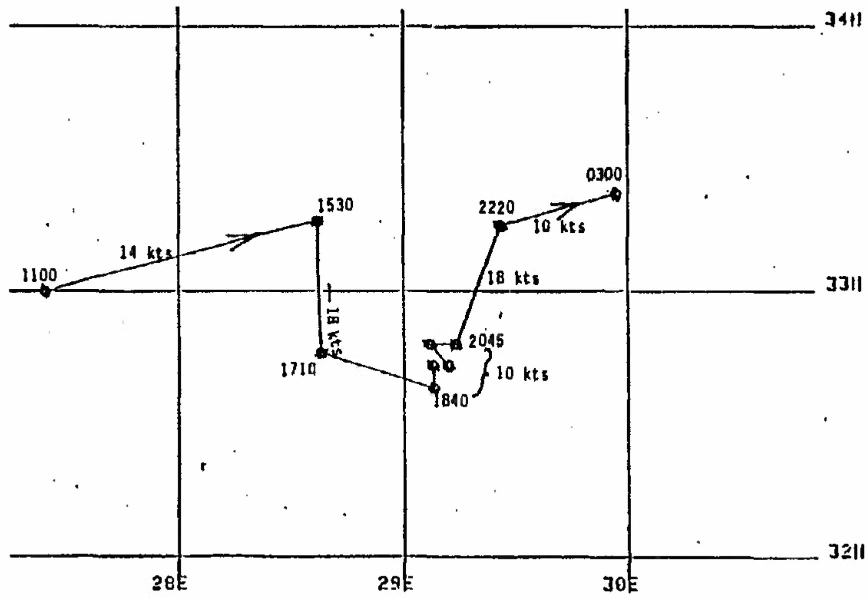


FIGURE III-10. MTST ILLUSTRATION--OBSERVATIONS ON TARGET

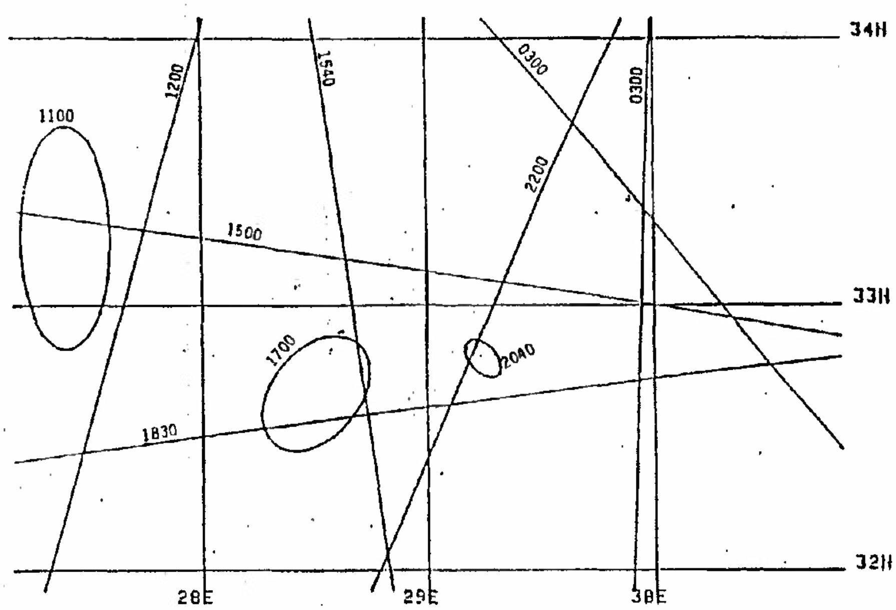


FIGURE III-11. MTST ILLUSTRATION--TRACK PRODUCED BY MTST

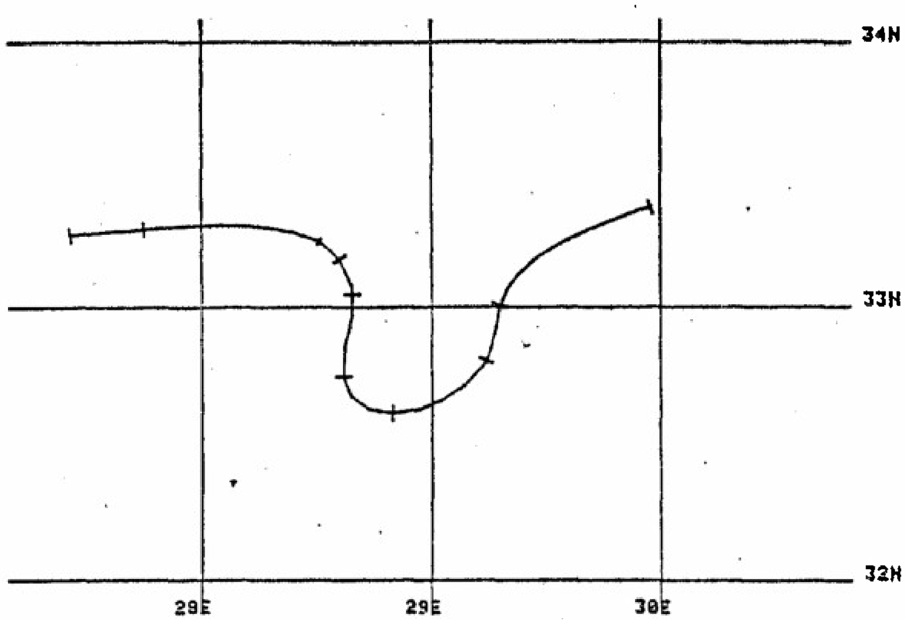


FIGURE III-12. MTST ILLUSTRATION--OBSERVATIONS SUPERIMPOSED ON MTST TRACK

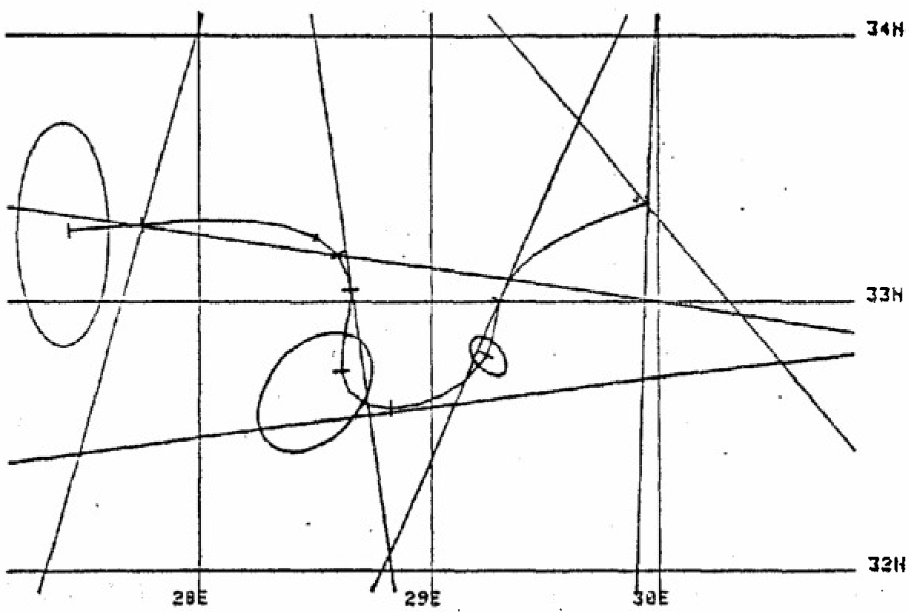
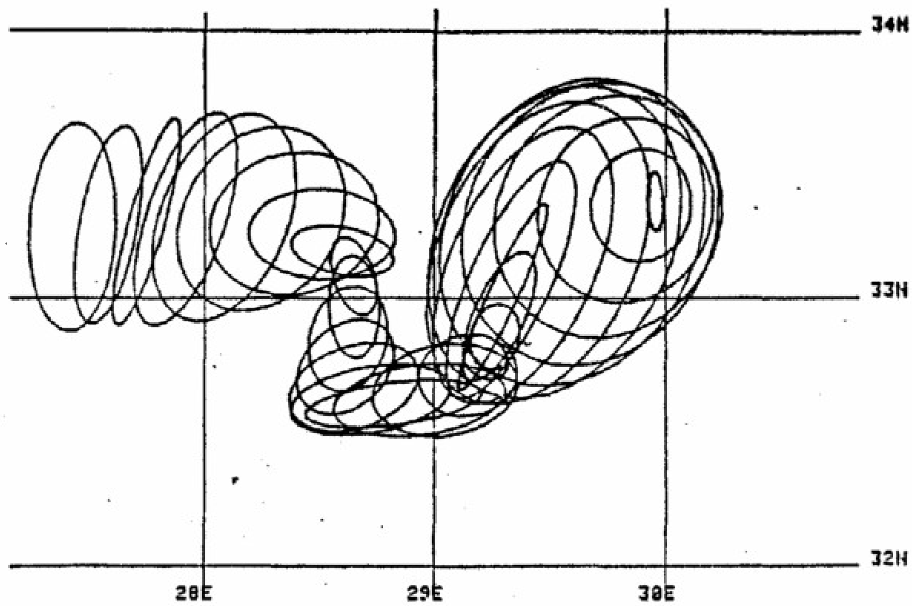


FIGURE III-13. MTST ILLUSTRATION--95% CONTAINMENT ELLIPSES



An excellent primer on Kalman filtering is reference [tt]. Standard more advanced texts are references [uu] and [vv]. For present purposes, an understanding of reference [tt] and Appendix B below should suffice.

3.5.2. Target state and motion model. To begin our description of how MTST works, we define the target *state* at time t to be $S(t) = (x(t), y(t), u(t), v(t))^T$, a 4-vector (we denote a vector by a column matrix and the transpose of a matrix m by m^T). Here $(x(t), y(t))^T$ is target position and u(t) and v(t) are speed components in the x and y directions. We want the tracker to estimate speed as well as position to enable us to make predictions of near-term future target movement. We also want the tracker to indicate degree of uncertainty in these estimates.

Each S(t) is a random variable and S is a stochastic process (Appendix B). To employ the very effective method of linear Kalman filtering to update our estimation recursively, we need S to be a *gaussian* process. This is achieved by assuming that the initial state, $S(0) = (x(0), y(0), u(0), v(0))^T$, is a gaussian random variable and the ensuing process follows an IOU mechanism.

Although the stochastic differential equation characterization of IOU is succinct, it entails considerable underlying technology, so we will bypass it in favor of a *difference* equation, since we must discretize for computation anyway. We fix $\beta \geq 0$ and $\sigma \geq 0$ and assume that for small $h \geq 0$

$$S(t+h) - S(t) \approx h\begin{bmatrix} u(t) \\ v(t) \\ -\beta u(t) \\ -\beta v(t) \end{bmatrix} + \sigma\sqrt{h}\begin{bmatrix} 0 \\ 0 \\ p \\ q \end{bmatrix}, \qquad \text{(III-1)}$$

where p and q are independent gaussian variables with zero mean and unit variance.

Formula (III-1) fully characterizes a 4-dimensional IOU process, given a gaussian initiation. We can give operational meaning to the parameters β and σ by relating them to the parameters of a random tour. It is a striking fact that by suitable choice of β and σ, the first and second order moments of $x(t)$ and $y(t)$ in an IOU process match the corresponding moments of a random tour *for all* t (see references [dd] and [gg]). (From the further fact that a gaussian distribution is fully determined by its first and second order moments we infer that an IOU process is the best gaussian approximation to a random tour.) From this parameter identification it is shown that

(1) β is the effective average rate of target course changes per unit time, and

(2) $\sigma/\sqrt{\beta}$ (if $\beta > 0$) is the rms target speed in the water (think of it as average instantaneous speed), which we denote by V.

Thus we can choose β and σ as inputs to MTST based on our views of target course change rate and speed. In particular, we can reduce an IOU model to CCS by setting $\beta = \sigma = 0$ in (III-1). In Appendix D, it is shown how, in a version with a 6-dimensional state, various types of motion can be obtained by appropriate choices of values of parameters of that model.

We now assume that our observations of the target occur at uniform time intervals of length δ and that $\beta > 0$ and $\sigma > 0$. The target motion information that we need (in addition to initialization) to conduct MTST calculations (short of the extensions in 3.5.6) is given by the following matrices:

$$\Phi = \begin{bmatrix} 1 & 0 & b_1 & 0 \\ 0 & 1 & 0 & b_1 \\ 0 & 0 & b_2 & 0 \\ 0 & 0 & 0 & b_2 \end{bmatrix}, \quad C = \begin{bmatrix} c_1 & 0 & c_2 & 0 \\ 0 & c_1 & 0 & c_2 \\ c_2 & 0 & c_3 & 0 \\ 0 & c_2 & 0 & c_3 \end{bmatrix}, \qquad \text{(III-2)}$$

where

$$\begin{aligned} b_1 &= (1/\beta)[1 - \exp(-\beta\delta)], \\ b_2 &= \exp(-\beta\delta), \\ c_1 &= \tfrac{1}{2}(\sigma/\beta)^2[2\delta - (1/\beta)[3 - 4\exp(-\beta\delta) + \exp(-2\beta\delta)]], \qquad \text{(III-3)} \\ c_2 &= \tfrac{1}{2}[(\sigma/\beta)(1 - \exp(-\beta\delta))]^2, \\ c_3 &= \tfrac{1}{2}(\sigma^2/\beta)[1 - \exp(-2\beta\delta)]. \end{aligned}$$

The significance of Φ and C, beyond their algorithmic use below, is that by regarding them both in terms of their dependence on δ (which we would have to do anyway if we considered observations at non-uniform intervals), they can be used in a natural way to determine the mean and covariance functions of a gaussian process, and the process thus determined can be shown to be a solution to (III-1) as h approaches zero (uniquely so, given a gaussian initiation)--see references [gg] or [hh]. The further significance of Φ and C is the consequence that (since we have discretized time, we denote $S(n\delta)$ by S_n)

$$S_{n+1} = \Phi S_n + w_n, \qquad \text{(III-4)}$$

where the w_n's are independent gaussian 4-vectors with mean zero and covariance matrix C. This is the type of motion description we want in order to do Kalman filtering. We further need a stochastic description of observations of the target, which we give next.

3.5.3. The observation process. For Kalman filtering purposes, we postulate a sequence of observations of the target, given as a sequence of k-vectors $Z_1, Z_2, \ldots$, related linearly to the target states as follows:

$$Z_n = H_n S_n + q_n, \tag{III-5}$$

where the H_n's are k x 4 matrices and the q_n's are independent gaussian k-vectors with mean zero and k x k covariance denoted R_n. Thus q_n is the measurement error in the nth observation. Also the q_n's and w_n's are independent of each other.

For simplicity in our present description, we will confine attention to observations of position in (x,y) coordinates (so k = 2), each observation having a bivariate gaussian error distribution with mean zero and standard deviation r in all directions. I.e., the 1-sigma error ellipses have both semi-axes equal to r.

This further means that the H_n's and R_n's are independent of n, so we denote them H and R, and that

$$H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

and $R = r^2 I$, where I is the 2 x 2 identity matrix.

3.5.4. Kalman filter update formulas and initialization. We now develop estimates of target state formed by a forward Kalman filter as used in MTST, i.e., based on the above assumptions. The estimate prior to the first observation is taken to be an arbitrary 4-vector, typically the zero vector. As of time of each observation, we make a pre-observation update of the state estimate to allow for target motion in accordance with our motion model; we then make a post-observation update to incorporate the information obtained in the observation. It suffices to perform these updates on the means and the covariance matrices of the estimates, since these determine the (gaussian) 4-variate distribution of the estimate at a given stage.

We denote the pre-observation mean and covariance of the state estimate for the nth observation by $\mu_n^{(-)}$ and $\Sigma_n^{(-)}$ respectively and the corresponding post-observation objects by $\mu_n^{(+)}$ and $\Sigma_n^{(+)}$. We initialize as follows:

$$\mu_1^{(-)} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \text{and} \quad \Sigma_1^{(-)} = \begin{bmatrix} 2000 & 0 & 0 & 0 \\ 0 & 2000 & 0 & 0 \\ 0 & 0 & \frac{1}{2}V^2 & 0 \\ 0 & 0 & 0 & \frac{1}{2}V^2 \end{bmatrix}. \tag{III-6}$$

The upper left 2 x 2 corner in $\Sigma_1^{(-)}$ is our initial covariance of target position; choosing 2000 nm^2 as the initial variance of each position coordinate merely indicates that we know very little about position prior to the first observation. The lower right 2 x 2 can be shown to be the limiting covariance of the velocity vector after a long time without observations and is a natural choice for this initial covariance.

We now define the Kalman gain matrix K_n pertaining to observation n by (K_n is 4 x 2)

$$K_n = \Sigma_n^{(-)}H^T[H\Sigma_n^{(-)}H^T + R]^{-1}. \qquad \text{(III-7)}$$

This is instrumental in the post-observation update as follows, defining m_n as the observed position 2-vector (and I as the 4 x 4 identity matrix):

$$\mu_n^{(+)} = \mu_n^{(-)} + K_n [m_n - H\mu_n^{(-)}], \qquad \text{(III-8)}$$

$$\Sigma_n^{(+)} = [I - K_nH)]\Sigma_n^{(-)}.$$

The pre-observation motion update is done as follows:

$$\mu_{n+1}^{(-)} = \Phi\mu_n^{(+)}, \qquad \text{(III-9)}$$

$$\Sigma_{n+1}^{(-)} = \Phi\Sigma_n^{(+)}\Phi^T + C.$$

Kalman filtering theory has chosen (III-7), (III-8), and (III-9) so as to minimize, after observation n, the sum of the diagonal elements of $\Sigma_n^{(+)}$, which is the sum of the variances of $x_{n\delta}$, $y_{n\delta}$, $u_{n\delta}$, and $v_{n\delta}$. This estimate is also the Bayesian update, based on the pre-observation state distribution as the prior and the current observation as the new information.

Formulas (III-7), (III-8), and (III-9) are standard in linear Kalman filtering, somewhat specialized in that under our simplified assumptions H, R, Φ, and C do not depend on n. Again, what makes this forward filter part of MTST different from other Kalman filtering is the particular formulations, which derive from the IOU assumption, of Φ, C, and $\Sigma_1^{(-)}$.

3.5.5. Illustrative forward filter example. We illustrate this forward filter part of MTST by two examples in Figures III-14 through III-17. In these examples, we assume as inputs (not based on observations) that the target's effective course change rate, β, is 2 per hour, the target rms ("average instantaneous") speed, V, is 12 knots, and the time between observations, δ, is 10 minutes. The four rows under each observation in Figures III-14, III-15, and III-16 pertain in order to x, y, u, and v.

Figure III-14 shows the pre-observation and post-observation covariances, $\Sigma_n^{(-)}$ and $\Sigma_n^{(+)}$, and the Kalman gain matrices, K_n. Iteration of these calculations through 12 observations shows only slight changes in these matrices after observation 6. Note that no observation data impact this figure. The entries to Φ and C are, using (III-3),

$b_1 = .1417$, $\quad b_2 = .7165$,

$c_1 = .3489$, $\quad c_2 = 2.8927$, $\quad c_3 = 35.035$.

A reader who is inexperienced in Kalman filter calculations is encouraged to perform some of the calculations in Figure III-14 by hand using (III-7), (III-8), and (III-9) and earlier formulas for their inputs. The matrix inversion in (III-7) is in this case simple, because the matrix being inverted is a scalar multiple of the identity (because our observations are simply the first two coordinates of state and have a circular gaussian distribution).

FIGURE III-14. COVARIANCE AND KALMAN GAIN MATRICES

Assumed target effective course change rate = 2 per hour.
Assumed target rms (average instantaneous) speed = 12 knots.
Minutes between observations = 10.
Standard deviation of observation measurement errors = 1.5 nm.

Pre-observation Covariance $\Sigma_n(-)$				Kalman Gain K_n		Post-observation Covariance $\Sigma_n(+)$			
Observation 1									
2000	0	0	0	.99888	0	2.25	0	0	0
0	2000	0	0	0	.99888	0	2.25	0	0
0	0	72.00	0	0	0	0	0	72.00	0
0	0	0	72.00	0	0	0	0	0	72.00
Observation 2									
4.04	0.00	10.20	0.00	0.64	0.00	1.45	0.00	3.65	0.00
0.00	4.04	0.00	10.20	0.00	0.64	0.00	1.45	0.00	3.65
10.20	0.00	72.00	0.00	1.62	0.00	3.65	0.00	55.45	0.00
0.00	10.20	0.00	72.00	0.00	1.62	0.00	3.65	0.00	55.45
Observation 3									
3.94	0.00	11.14	0.00	0.64	0.00	1.43	0.00	4.05	0.00
0.00	3.94	0.00	11.14	0.00	0.64	0.00	1.43	0.00	4.05
11.14	0.00	63.50	0.00	1.80	0.00	4.05	0.00	43.47	0.00
0.00	11.14	0.00	63.50	0.00	1.80	0.00	4.05	0.00	43.47
Observation 4									
3.80	0.00	10.21	0.00	0.63	0.00	1.41	0.00	3.79	0.00
0.00	3.80	0.00	10.21	0.00	0.63	0.00	1.41	0.00	3.79
10.21	0.00	57.35	0.00	1.69	0.00	3.79	0.00	40.13	0.00
0.00	10.21	0.00	57.35	0.00	1.69	0.00	3.79	0.00	40.13
Observation 5									
3.64	0.00	9.69	0.00	0.62	0.00	1.39	0.00	3.70	0.00
0.00	3.64	0.00	9.69	0.00	0.62	0.00	1.39	0.00	3.70
9.69	0.00	55.64	0.00	1.64	0.00	3.70	0.00	39.72	0.00
0.00	9.69	0.00	55.64	0.00	1.64	0.00	3.70	0.00	39.72
Observation 6									
3.59	0.00	9.58	0.00	0.61	0.00	1.38	0.00	3.69	0.00
0.00	3.59	0.00	9.58	0.00	0.61	0.00	1.38	0.00	3.69
9.58	0.00	55.43	0.00	1.64	0.00	3.69	0.00	39.71	0.00
0.00	9.58	0.00	55.43	0.00	1.64	0.00	3.69	0.00	39.71

FIGURE III-15. TARGET STATE ESTIMATION

Actual target speed = 12 knots.
Actual minutes from 3rd observation to 45 degree turn = 0.

Actual Posit	Observation error Vector	Observation error Distance	Estimated state Pre-Obs $\mu_n^{(-)}$	Estimated state Post-Obs $\mu_n^{(+)}$	Posit est error post-obs Vector	Posit est error post-obs Distance	Radius 2-sigma AOU
Observation 1							
0.00	0.28	1.9	0.00	0.28	0.28	1.9	3.0
0.00	1.84		0.00	1.84	1.84		
			0.00	0.00			
			0.00	0.00			
Observation 2							
2.00	0.23	2.0	0.28	1.53	–0.47	2.0	2.4
0.00	2.03		1.84	1.96	1.96		
			0.00	3.16			
			0.00	0.30			
Observation 3							
4.00	–0.54	0.9	1.98	2.92	–1.08	1.1	2.4
0.00	–0.73		2.00	0.27	0.27		
			2.27	4.94			
			0.22	–4.70			
Observation 4							
5.41	–3.21	3.3	3.62	2.73	–2.68	2.9	2.4
1.41	–0.73		–0.40	0.28	–1.13		
			3.54	1.14			
			–3.37	–1.54			
Observation 5							
6.83	2.52	2.7	2.89	6.88	0.05	0.5	2.4
2.83	0.90		0.06	2.33	–0.50		
			0.82	11.42			
			–1.10	4.93			
Observation 6							
8.24	–0.95	1.0	8.50	7.76	–0.49	0.7	2.4
4.24	–0.07		3.03	3.73	–0.51		
			8.19	6.20			
			3.53	5.41			

In Figures III-15 and III-16, the matrices of Figure III-14 are applied to two examples of six observations each. In both cases the *actual* target motion is CCS for a few observation intervals followed by a 45 degree port turn and then the same speed on the new course. The units are nm and knots throughout these tables. The actual position at time of the first observation as taken as the origin, (0,0), of the position coordinate system (that the actual position isn't known to the tracker doesn't matter). In Figure III-15 the constant speed is taken to be 12 knots (same as assumed in Figure III-14) and in Figure III-16 it is 8 knots. In Figure III-15 the turn time coincides with an observation, the third of the six, and in the other case it is midway between the third and fourth observations. The turn is idealized to be instantaneous in both cases.

The observation data in Figures III-15 and III-16 are presented as 2-vectors of errors in observed position; such a vector is added to actual position to obtain observed position. The 24 coordinates of these error vectors (two each in six observations in each of two figures) are independent draws from a gaussian distribution with mean zero and standard deviation 1.5 nm, the assumed value of r. Each error distance is the length of its error vector.

FIGURE III-16. TARGET STATE ESTIMATION

Actual target speed = 8 knots.
Actual minutes from 3rd observation to 45 degree turn = 5.

Actual Posit	Observation error Vector	Observation error Distance	Estimated state Pre-Obs $\mu_n^{(-)}$	Estimated state Post-Obs $\mu_n^{(+)}$	Posit est error post-obs Vector	Posit est error post-obs Distance	Radius 2-sigma AOU
Observation 1							
0.00	−1.01	1.6	0.00	−1.01	−1.01	1.6	3.0
0.00	−1.21		0.00	−1.21	−1.21		
			0.00	0.00			
			0.00	0.00			
Observation 2							
1.33	1.65	1.7	−1.01	1.55	0.22	0.6	2.4
0.00	−0.16		−1.21	−0.53	−0.53		
			0.00	6.47			
			0.00	1.71			
Observation 3							
2.67	1.41	1.4	2.47	3.49	0.83	0.8	2.4
0.00	0.14		−0.29	−0.02	−0.02		
			0.00	6.47			
			1.22	2.00			
Observation 4							
3.80	−0.05	2.0	4.56	4.05	0.25	1.4	2.4
0.47	−2.00		0.27	−0.86	−1.33		
			5.40	4.03			
			1.43	−1.59			
Observation 5							
4.75	−1.43	1.5	4.62	3.82	−0.93	1.5	2.4
1.41	−0.31		−1.08	0.27	−1.14		
			2.89	0.74			
			−1.14	2.46			
Observation 6							
5.69	0.81	1.4	3.92	5.50	−0.19	0.2	2.4
2.36	1.09		0.62	2.35	−0.00		
			0.53	4.76			
			1.76	6.40			

The estimated state 4-vectors, $\mu_n^{(-)}$ and $\mu_n^{(+)}$, are shown as computed by (III-6), (III-8), and (III-9). Again the reader is encouraged to perform some of these calculations. Note from (III-8) that the nth post-observation state estimate, $\mu_n^{(+)}$, is a weighted sum of the pre-observation estimate, $\mu_n^{(-)}$, and the observation m_n, with the Kalman gain matrix, K_n, providing the weights for each coordinate.

Each 2-vector error in a post-observation position estimate is the position part of the state estimate vector less the actual position vector; the estimation error distance is the length of the error vector. The radius of the 2-sigma area of uncertainty, AOU, is $2\sqrt{g}$, where g is the upper left corner entry of $\Sigma_n^{(+)}$, the variance of each position coordinate estimate. This AOU, centered on the position estimate, is an 86% containment region.

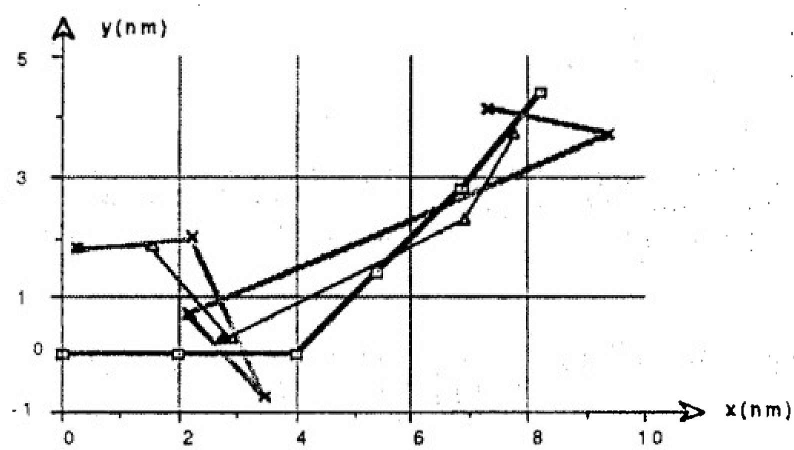
FIGURE III-17. GRAPHICAL DISPLAY OF MTST ILLUSTRATIONS

□ Actual target positions at observation times connected by ▬▬

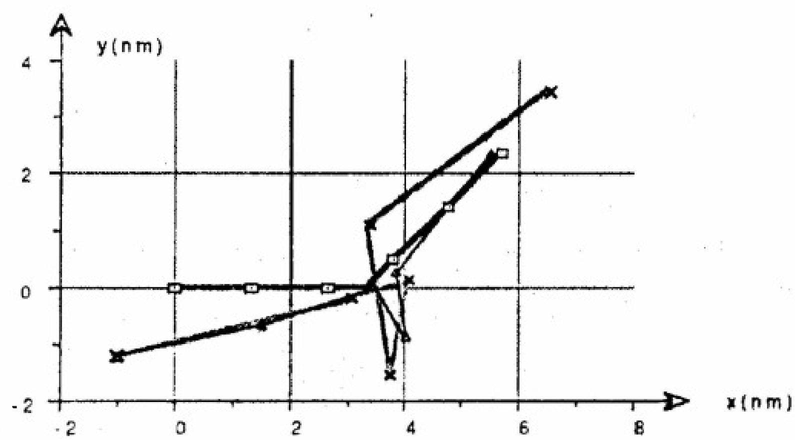
× Observed target positions, connected by ▬▬

♦ MTST estimate of target position, connected by ——

(a) Actual target speed = 12 kts, turn at 3rd observation



(b) Actual target speed = 8 kts, turn midway between 3rd and 4th observations



The purpose of these examples is to illustrate some of the main principles and mechanisms of MTST. It is not their purpose to be evaluative. Evaluations should consider a much broader variety of target motions, assumed and actual, and should use more powerful extensions of the present case as discussed in 3.5.6. However, it is of some interest to compare the MTST estimates with the observations and the actual target states in these examples.

Position estimates may be compared with position observations via the error distances. In this respect MTST does at least as well as the direct observations in all of these cases except observation 3 of Figure III-15. By this comparison the two figures are typical of several computed examples.

To compare velocity estimates with velocity "observations" would require some other definition of velocity derived from the position observations, into which we will not delve.

From velocity estimation vectors one can compute speed as vector length to compare with actual speed. Estimated speed is generally significantly lower than actual speed in both examples. This is explained by the fact that MTST has been led to expect a higher rate of turns (2 per hour) than is actual (one in one hour) in these examples. Note, however, that after observation 6 of Figure III-16, the estimated speed is $(4.76^2 + 6.40^2)^{1/2} = 7.98$ compared to the actual speed of 8 knots. The course estimate from these components is arctan(64/4.76) = 53 degrees which is 8 degrees off from the actual 45 degrees (referring to the original course as 0).

A graphical display of the above position comparisons is given in Figure III-17; parts (a) and (b) show results from Figures III-15 and III-16 respectively.

3.5.6. MTST extensions of the simplified forward filter. We now consider various extensions of the above treatment, which give MTST more power than do the methods discussed thus far. These consist of non-uniformly spaced observations; observations in the form of elliptical SPA's, bearing boxes, and lines of bearing (LOB's) which may change in form from one to the next; backward filtering for smoothing and elimination of outliers; 6-dimensional target states; and treatment of motion on a spherical surface.

Non-uniformly spaced observations are easy. Merely let Φ and C depend on n and let the δ in (III-3) be the time between observations n−1 and n.

The observation error distributions may be elliptical gaussian, e.g., an elliptical SPA, rather than restricted to circular. Then the covariance of observation measurement error, R (r^2I above), becomes

$$R = \frac{1}{4}\begin{bmatrix} a^2\cos^2\theta + b^2\sin^2\theta & -a^2\cos\theta\sin\theta + b^2\cos\theta\sin\theta \\ -a^2\cos\theta\sin\theta + b^2\cos\theta\sin\theta & a^2\sin^2\theta + b^2\cos^2\theta \end{bmatrix}. \qquad \text{(III-10)}$$

Here a and b are the semi-axes of the 1-sigma ellipse and θ is its orientation angle. Also, a, b, and θ and hence R may depend on n.

An LOB observation is harder. One method is to treat an LOB as an ellipse with one semi-axis infinite. The width perpendicular to the infinite semi-axis is constant throughout the length and is treated as the 1-sigma limits of measurement error in that direction. Let r be half this width. How is r chosen? Generally, the advisable choice is to guess the target range (e.g., using previous tracking data) and let r be the width subtended at that range by the standard deviation (presumed known) of bearing measurement errors. Then let $R_n = r^2$ and

$$H_n = \begin{bmatrix} \cos\theta_n & -\sin\theta_n & 0 & 0 \end{bmatrix},$$

where θ_n is the bearing of the LOB observation in question. Note that having defined H_n in this way, we can no longer generate the Kalman gain and estimation covariance matrices independent of the observed data as we did in Figure III-12. More importantly, this also causes us to leave the realm of *linear* filtering and to enter *extended* Kalman filtering, because R_n depends on an estimate of target state. It means that we can no longer assert mean square minimization, Bayesian updating, or gaussian posterior distributions and that $\mu_n^{(+)}$ and $\Sigma_n^{(+)}$ no longer have their meaning as mean and covariance. However, the gaussian distribution determined by $\mu_n^{(+)}$ and $\Sigma_n^{(+)}$ thus generated may be regarded as an approximation to the actual distribution and evidently errors arising from this modeling approximation are generally smaller than those arising from measurement errors. Further discussion of extended filtering is beyond our intended scope.

A bearing box observation is treated in a way similar to that of an LOB, except that the range which determines the cross-bearing standard deviation is taken from the range limits of the bearing box, rather than estimated externally as in the preceding paragraph.

Backward filtering is employed for smoothing and importantly for elimination of outliers. Smoothing is a procedure for retrospective estimation of a state vector at a time intermediate between the start and end of an observation interval. MTST does this by using forward filtering, as described above, from the start of observations up to and including the smoothing time, and using backward filtering from the end back to the smoothing time. The backward recursion is somewhat analogous to the forward recursion but is usually expressed more conveniently in terms of information matrices (inverse of covariance) and information vectors (estimation mean left-multiplied by the information matrix). See references [hh] or [gg]. Such smoothing methods are particularly useful in automated exercise reconstruction.

The power of MTST may be enhanced by treating 6-dimensional states compared to 4 dimensions as above, particularly in tracking transitors. In this mode, velocity in the motion model is the sum of a short-term velocity and a long-term velocity, both stochastic--see Appendix D. This model is a generalization of an IOU process, but it isn't a composite of two IOU's, because both velocity components impact position. To reduce this model to an IOU, set the long-term velocity or the short-term velocity at zero. The description of this model in the first section of Appendix D is, at any rate, particularly recommended reading for its IOU flavor in that it conveys what is going on in an IOU without explicit use of stochastic differentials. Appendix D is also recommended for its description of motion types obtained by parameter choices. Note that the 6-dimensional treatment in reference [hh] uses *acceleration* (in two components) as the 5th and 6th state components--the two-velocity approach is better. Reference [gg] is confined to 4 dimensions.

The final extension is to spherical motion. This again entails non-linear filtering, i.e., extended Kalman filtering. The approach is to linearize the problem approximately by choosing a tangent point near each contact and doing the filtering in the corresponding tangent planes. One must project from the sphere to a plane and back to the sphere in a way which is reasonably faithful and which admits linear filtering in the plane. One clever point is that a covariance matrix is projected by projecting its eigenvectors.

The example in Figures III-9 to III-13 uses elliptical SPAs, and LOBs at non-uniform spacing and forward and backward filtering. E.g., if the first half of the track in Figure III-11 were based only on the first half of the observations, a different result would be obtained, perhaps not much different. The target state was 4-dimensional. Spherical methods were not used, and the distances were not great enough for that to matter.

We have tried to convey the main concepts and algorithmic procedures in MTST, which is a state-of-the-art method for tracking maneuvering ship targets. We note briefly the associated problem of report-to-track correlation. In this problem, multiple contacts occur on multiple targets, in general by multiple sensors whose outputs are treated collectively. Tracks are maintained on the separate targets. When a new contact is reported, with which track should it be associated, i.e., correlated? In recent years considerable work has been done on algorithms to automate solutions to this problem. We will simply refer to NRL as a center of such activity and to reference [ww] as a contemporary text on the subject.

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CHAPTER IV

INTEGRATED TDAS FOR BATTLE GROUP COMMAND

The prototype integrated TDA for battle group command is the Joint Operational Tactical System (JOTS). A derivative of JOTS which has developed in different ways is the Integrated Tactical Decision Aids (ITDA). Both JOTS and ITDA reside on the Navy Standard DTC, the HP 9020A. Both are organized according to the Composite Warfare Commander (CWC) concept, wherein the CWC commands the battle group and delegates authority in the warfare areas ASW, AAW, ASUW, EW, and strike to the respective subordinate warfare commanders, the ASWC, AAWC, ASUWC, EWC, and SWC.

As presently configured, neither JOTS nor ITDA has a strike warfare module. The principal TDA for carrier aircraft strike planning is the Tactical Aircraft Mission Planning System (TAMPS). Although it is not integrated in the sense of JOTS and ITDA, it complements these two systems, so we discuss it at the end of the chapter.

The reference to integration in JOTS and ITDA pertains to use of data bases and executive programs which are common over the separate warfare areas and the separate TDAs. The data bases are on targets, own forces, and the environment. The executive programs manage the data bases, call particular warfare-specific programs and displays for use by the CWC or a cognizant warfare commander, and call various support functions such as navigation computations, map displays, formation builds, track builds and analysis, status boards, etc.

The TDA program menus in JOTS and ITDA are organized in hierarchical fashion. The major categorization is by warfare area. Each of these contains various TDAs, which are integrated in the sense described above, but not in the sense that outputs of one such TDA transfer to another. However outputs of various support functions, pertaining to the environment, dispositions, and kinematics, are stored for convenient access by TDAs. The menu organizations and the various TDAs and support functions of JOTS and ITDA are described in their user's guides, references [a] and [b], which are supplanted by their training manuals, references [c] and [d].

While JOTS was originally designed according to the TDA concepts described above, its great success has been through its C^2 communications functions. JOTS is connected to the principal Fleet data links, notably Link 11 and OTCIXS. This affords connectivity with these systems to any ship with an HP 9020. In particular, JOTS supports exchange among control centers, afloat and ashore, of status boards, contact data, and other formatted communications. ITDA does not have comparable data links and depends on JOTS or other systems to reach Link 11 or OTCIXS. On the other hand, ITDA has much better developed warfare-specific TDAs. Post-1984 JOTS TDA development has been subordinated to its C^2 communications development and implementation. ITDA TDA development has been on-going during this era.

The hierarchical menu organizations of JOTS and ITDA are mainly described in Figure IV-1. Our main interest here is in the functions and models of the warfare-specific TDAs shown for JOTS in the upper right corner of part (a) and for ITDA in the last two pages of part (b). However, the reader is encouraged to peruse the remainder of Figure IV-1 to obtain a feel for the scope of these integrated TDAs and of the communications functions of JOTS.

We remark that the principal difference between the user interfaces of these two systems in appearance to the user is that selection of menu items is made through special function keys in JOTS and through the main keyboard in ITDA (without Return in both cases). Both systems use the main keyboard to respond to prompts under a menu item (followed by Return), and both use the special function keys (without Return) for various support menus.

We further remark that in JOTS and ITDA TDAs, the user is often asked to input an ellipse. That is always the 2-sigma ellipse of a bivariate normal distribution, and hence has 86% containment, *except* that for SASHEM (see 4.3.5) the ellipses have 90% containment. Also, a circle on the earth's surface has an elliptical appearance under great circle or Mercator projections as is evident on many JOTS and ITDA displays and in some figures in this chapter.

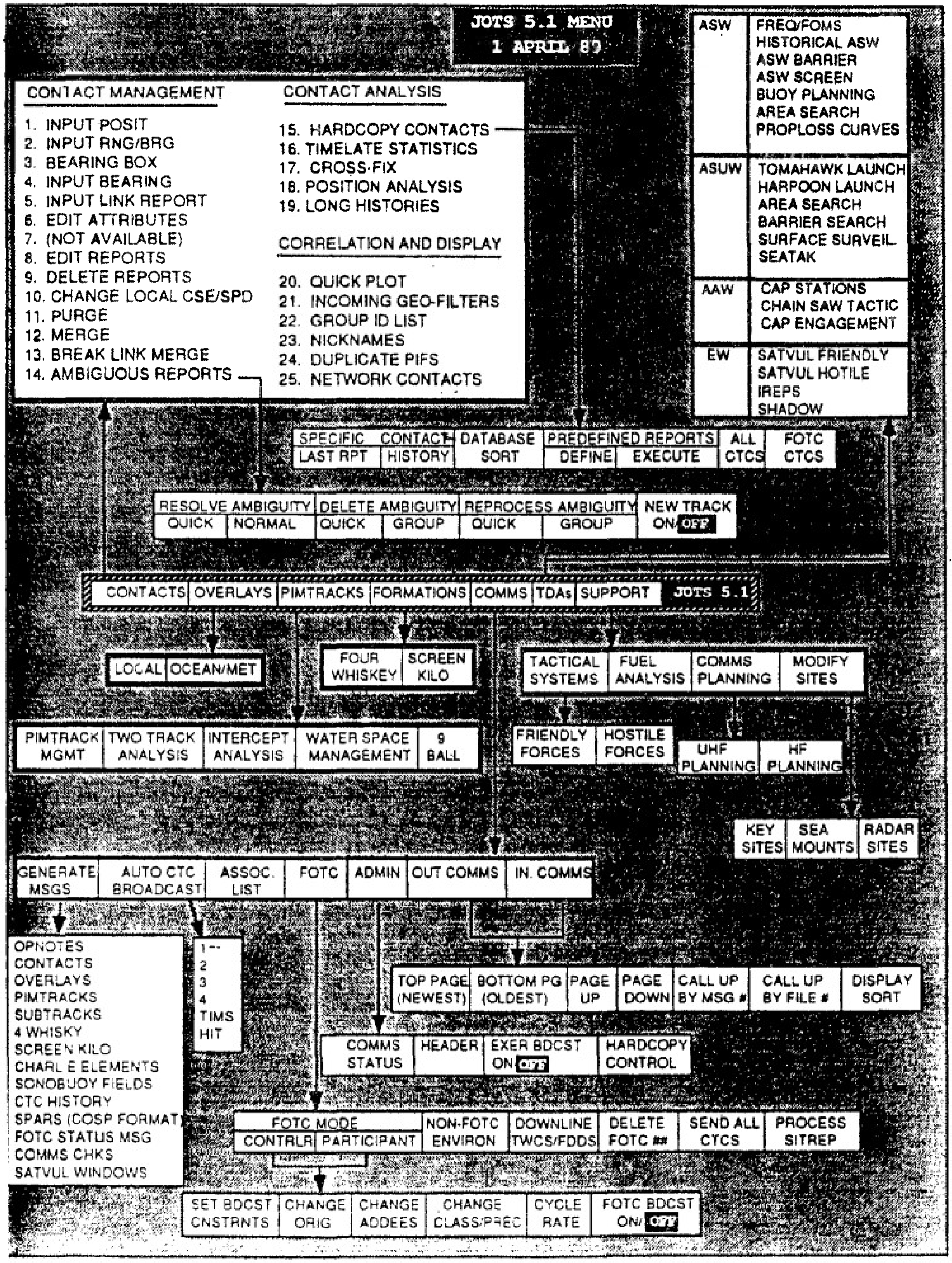
JOTS is programmed in HP BASIC and ITDA is in UNIX/C. Conversion of JOTS to UNIX/C is underway in anticipation of use in the next generation Navy Standard DTC. This conversion has the important implication of affording user time-sharing on JOTS. (ITDA is designed as a multi-user system.) Hopefully, that will overcome a problem ITDA and other at-sea HP 9020 programs have had in terms of limited machine access, because of heavy HP 9020 use by JOTS communications functions. Limited space for terminals will still be a problem and may well be a limiting factor in sea-going use of TDAs for the foreseeable future.

Anticipating the conversion to UNIX/C, JOTS is a potentially excellent receptacle for TDAs, by way of affording access to real time data and a means of rapidly communicating decided actions. Also important to TDA potentiality is the fact that JOTS terminals have frequent attention from commanders and their staffs, because new and useful information frequently appears on the displays. ITDA is also an excellent receptacle for new TDAs in that it affords excellent access to environmental data bases and integrated data management; moreover, TDAs are primary in ITDA, while secondary in JOTS. At the same time, addition of TDAs to an integrated TDA should be planned in an orderly fashion, else a confusing and redundant collection may evolve.

Within the ASW sphere, development of a new integrated TDA, known as ASWTDA, is underway as of early 1989, sponsored by OP-71, RADM J. R. Fitzgerald (NPGS alumnus) . The lead laboratory is NOSC (Code 62) with NUSC performing software development and NADC providing technical support. The APP office of NAVSEA provides additional oversight. The core of this system is the Composite Area Search Evaluation (CASE) methodology developed by Sonalysts for NUSC, with support from the Oceanographer of the Navy (OP-96), RADM R. F. Pittenger (NPGS alumnus). This software is being converted from BASIC to UNIX/C. ASTWTDA/CASE at present has oceanographic displays, the OTH-T tracker from the SFMPL (see 3.1), and a rather limited search planning capability (see the end of 2.13.4). It has excellent graphics. Planned additions to the ASWTDA include

FIGURE IV-1. MENU ORGANIZATION IN JOTS AND ITDA

(a) JOTS Menu Organization



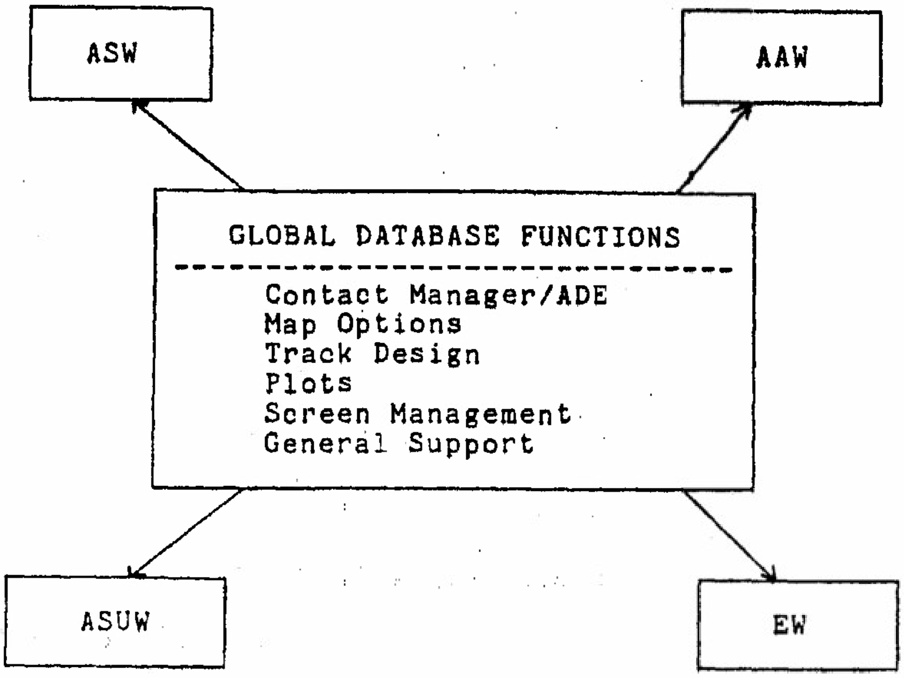
(Continued)

Reproduced from best available copy.

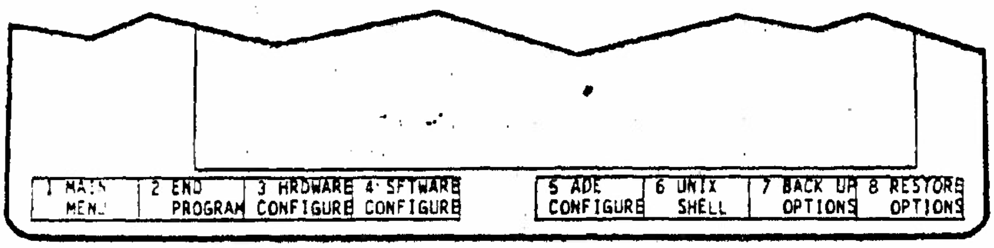
FIGURE IV-1. (Continued)

(b) ITDA Menu Organization

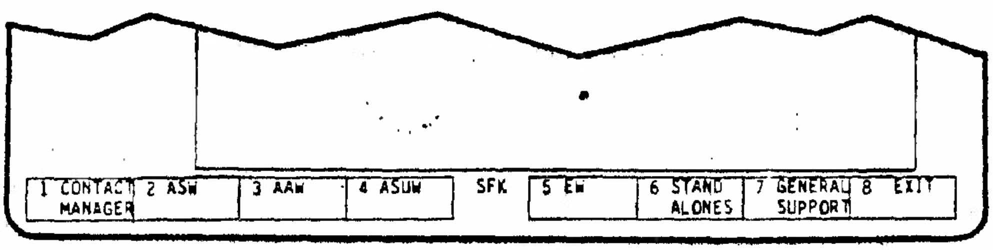
ITDA HIGH LEVEL BLOCK DIAGRAM



ITDA SYSTEM MENU



ITDA MAIN MENU



(Continued)

FIGURE IV-1. (Continued)

(b) ITDA Menu Organization (Continued)

SPECIAL FUNCTION KEY TOP LEVEL HEIRARCHY

- [MAP OPTIONS]
  - [EDIT CNTRAD]
  - [CENTER ON]
  - [ZOOM]
  - [STORED MAPS]
  - [MAP STATUS]
  - [MAP ONLY]
  - [REDRAW GEOPLOT]
- [PLOTS]
  - [PLOT STATUS]
  - [PLOT CONTACT]
  - [PLOT OVERLAYS]
  - [PLOT AIDS]
  - [PLOT TRACKS]
- [TRACK DESIGN]
  - [4W BUILD]
  - [SECTOR BUILD]
  - [TRACK BUILD]
  - [2-TRACK ANALYSIS]
  - [INTRCPT ANALYSIS]
- [TOP OF MENU]
- [HELP]
- [MAP TOGGLE]
- [TIME CHANGE]
  - [MANUAL RESET]
  - [SYSTEM RESET]
  - [AUTO (STATIC) CLOCK]
- [SCREEN MGT]
  - [PRINT TABLES]
  - [PRINT GEOPLOT]
  - [SCREEN STORAGE]
  - [ENABLE (DISABLE) PLOTTER]
  - [START (STOP) LSD]
  - [LSD SNAPSHOT]

(Continued)

FIGURE IV-1. (Continued)

(b) ITDA Menu Organization (Continued)

ITDA PROGRAM TOP LEVEL HEIRARCHY

- [CONTACT MANAGER]
  - [INPUT/EDIT CTC]
  - [DELETE CONTACT]
  - [MERGE CONTACTS]
  - [AMPLIFY CONTACTS]
  - [PLOT CONTACT]
  - [HRDCOPY]
- [ASW]
  - [OCEAN ENVIRON]
  - [GFMPL OE 1.3]
  - [BUOY SEARCH]
  - [PAC SEARCH]
  - [ASW COVERAGE]
  - [SCREEN EVAL]
  - [TAC NUC]
- [AAW]
  - [UNIT PIM]
  - [GRAPHICS]
  - [INTCPT]
  - [TACTICS]-
  - [ASMD]
  - [STORE RECALL]
  - [ACTION FUNCTION]
- [ASUW]
  - [SASHEM]

(Continued)

FIGURE IV-1. (Continued)

(b) ITDA Menu Organization (Continued)

- [EW]
  - [SAT VUL]
  - [SATCAT]
  - [GFMPL AE 1.3]
  - [RADAR SHADOWING]
- [STAND ALONES]
  - [PANDA]
  - [ASODA]
  - [FMOS]
  - [TEPEE]
  - [COPS]
  - [CAPTOR]
  - [FAMP]
- [GENERAL SUPPORT]
  - [AREA SEARCH]
  - [BARRIER SEARCH]
  - [FEATURE BUILD]
  - [MODIFY PORT/ANCH]
  - [FRONT & EDDY PROC]
- [EXIT]
  - [MAIN MENU]
  - [END PROGRAM]
  - [HRDWARE CONFIGURE]
  - [SFTWARE CONFIGURE]
  - [ADE CONFIGURE]
  - [UNIX SHELL]
  - [BACKUP OPTIONS]
  - [RESTORE OPTIONS]

PACSEARCH and a program for building and evaluating an ASW screen, plausibly SCREEN/EVAL in ITDA (see 4.2.9). At this stage, there is insufficient information available on the functionality of ASWTDA to review it further here.

In 4.1 we give a history of JOTS and ITDA. A description of various ITDA 2.02 and JOTS 5.1 TDAs (the current versions) in each of ASW, ASUW, AAW, and EW is given in 4.2, 4.3, 4.4, and 4.5. The strike planning system TAMPS is discussed in 4.6.

4.1. History of JOTS and ITDA

In this section we give a history of JOTS and, separately, ITDA.

4.1.1. History of JOTS. The development and implementation of JOTS has been dominated by the leadership of two individuals: VADM J. O. Tuttle (NPGS alumnus), currently OP-094, the C^3 director in OPNAV, and previously performing the same function for the JCS as J-6; and F. P. Engel, current president of the Inter-National Research Institute (INRI) and until recently head of its Battle Management Systems Division.

In 1982, RADM Tuttle was COMCARGRU EIGHT, based in Norfolk, and Engel managed the Norfolk area office of DHWA. His work for COMSECONDFLT on surface surveillance took him to sea at times with CCG-8 as battle group commander. It was on such a one-month cruise on AMERICA in September 1982, as part of a major NATO exercise, that JOTS was born.

Engel was evaluating an ASUW surface surveillance program, Tactical Surface Surveillance (TSS--see 4.3.2), which had its roots in SURTAC (see 3.1). From his observations of battle group command decision needs, he conceived and partly programmed at sea, on an HP-9845, an enlargement of TSS to include additional TDAs, not restricted to ASUW, e.g., CAP stationing, which were integrated in the sense described above. Also part of the integration were the beginnings of various support functions such as maps, kinematic calculations, etc., that proved to be an important part of JOTS usefulness.

Tuttle was very receptive to this concept. He has given it and its subsequent orientation to C^2 communications very strong support then and in his later capacities as CTF-60 in the MED, Deputy CINCLANTFLT, J-6, and OP-094. As CCG-8, he with Engel presented and demonstrated this concept to CNO war games and tactical symposia at the Naval War College in November 1982, January 1983, and January 1984.

At the second of these three events, Engel converted the programs at Newport to the newly available HP 9020C. This was an important advance over previous DTC's in speed, memory, color graphics, and, in the C version, light pen capability. CCG-8 obtained the first production copy of the HP 9020C in January 1983. Evidently the subsequent success of JOTS on this machine significantly influenced the decision on July 13, 1984 to make the HP 9020A the Navy Standard DTC (the A version does not have the light pen of the C).

The name JOTS was adopted in spring, 1983. Colloquially it was referred to as the "Jerry O. Tuttle System." Engel and his DHWA colleagues M. A. O'Donnell, S. G. Stukenbroeker, W. K. Stevens, and W. R. Monach, further developed the TDAs and support functions in JOTS, supported by COMNAVAIRLANT and COMSECONDFLT, into 1984. The CCG-8 staff, under Tuttle and his successor, RADM J. H. Flatley, importantly contributed to and supported this development, notably CAPT D. G. Hay, COS, and CDR P. D. Frazer, Operations Officer. Much of this work was at sea in LANT, MED, and CARIB. It included five weeks on two carrier cruises by Stukenbroeker, which was unusual for a female contractor employee. In related work, D. D. Engel of DHWA worked on site at the Task Force Command Center (TFCC) project at NOSC, developing an interface between JOTS and NTDS. Under a DHWA subcontract to SEA, Inc., O'Donnell, F. P. Engel, and R. B. Pember developed a JOTS-like system to control range safety for the Mobile Sea Range at Point Mugu. The continuation of this work by INRI in 1985 included an interface with Link 11, which was an important step toward the C^3 prominence of JOTS. This interface was derived from the Tactical Data Acquisition Unit (TDAU), developed by R. Cope and M. Bowman of EDO Corp., partly while their office was part of Software Ideas, Inc.

The TDA development of JOTS continued into the JOTS II version of 1984 and evidently went little beyond the JOTS II Plus of 1985. The current version of JOTS is 5.1, the last version in BASIC. Figure IV-2 is the table of contents of the technical documentation of JOTS II, reference [e] prepared by F. P. Engel, Stevens, O'Donnell, and Stukenbroeker of DHWA. A majority of the programs listed had been in JOTS I in 1983. E.g., O'Donnell derived the program to compute the area of a polygon used in JOTS/ITDA/AREA SEARCH and added the encroached area feature to TSS (see 4.3.2). As noted below, JOTS II became ITDA I. Figure IV-2 is thus a summary of ITDA I as well as JOTS II. Note that this figure lists the programs alphabetically, rather than by warfare commander, even though the programs and user interfaces were organized in the latter form. Evidently reference [e] is the latest technical documentation available on JOTS TDAs, outside of the user's guide, reference [a]. Figure IV-2 identifies programs that survive in the present JOTS 5.1 and ITDA 2.02, possibly revised in the interim.

On 1 May 1984, F. P. Engel joined INRI, and except for Stukenbroeker's conversion to JOTS of the CNA radar shadowing program, and D.D. Engel's TFCC work in 1984, virtually all of the subsequent JOTS development was by INRI and various Fleet personnel. Among the INRI contributors were D. D. Engel, O'Donnell, L. B. Whitt, and D. L. Pressler.

Two notable later additions to the list in Figure IV-2 were the CNA radar shadowing program noted above and the ASW search program called Historical ASW (containing principally TRANSIT SEARCH--see 4.2.5) in JOTS 5.1, both added in 1985. The latter is the transit part of the MEDSEARCH program used very effectively in the MED in 1977-83 (see 2.13). Also SATVUL has been revised to add friendly satellites.

The significance of the Link 11 interface with JOTS, originally in the Mobile Sea Range work in 1985, has been described as "providing phones to a telephone system with few phones." The point is that this potentially gave any unit with a Navy Standard DTC, the HP 9020A, connectivity to Fleet digitized real time data and formatted communications. Realization of this potential led to concentration of JOTS development and implementation on C^3 functions. Interfaces between JOTS and other Fleet data links, and installation of JOTS in control centers afloat and ashore virtually Fleet-wide, evolved starting 1985 with

FIGURE IV-2. JOTS II TECHNICAL REFERENCE MANUAL -- TABLE OF CONTENTS

NOTE: A majority of Section 3 were also in JOTS I in 1983.

* Also in JOTS 5.0, possibly revised
\+ Also in ITDA 2.02, possibly revised

(Continued)

FIGURE IV-2. (Continued)

*Also in JOTS 5.0, possibly revised } NOTED FOR SECTION 3 ONLY
+Also in ITDA 2.02, possibly revised

great success. Although the communications functions of JOTS are very relevant to TDAs, as noted above, we will not endeavor to review them as such. A CNA evaluation of JOTS C^2 is reported in reference [f].

Review of the present JOTS TDAs will be done in subsequent sections in parallel with those of ITDA.

4.1.2. History of ITDA. The birth of ITDA may be traced to a TAC D&E Steering Group meeting, held at the NPGS February 1984 and led by COMO C. E. Armstrong, OP-953 (now OP-73). The agenda included a JOTS presentation by F. P. Engel. OP-953 decided to formalize development of a JOTS-like system within the mainstream of TAC D&E, whereas development of JOTS up to then (and most subsequent JOTS development) was in the Fleet, evolving from rapid prototyping, without Washington sponsorship. Soon thereafter, the Central Development Agency (CDA) was created at NADC to oversee this development and further to have review authority over TDAs in general. LCDR K. A. Kail (NPGS alumnus), a computer specialist and helo pilot, was appointed as the first head of the CDA. Kail was succeeded June 1986 by LCDR R. F. Hudson (NPGS alumnus and a VPCAS user at ASWOC Lajes), who was succeeded by W. A. Leyland in May 1987. M. A. Leonardo participated in technical management 1985-87. OP-953/73 direction has been by CAPT W. J. Gerard (NPGS alumnus), CAPT F. M. Frick (NPGS alumnus), and, since January 1987, CAPT T. E. Ferguson.

In 1984, JOTS II was adopted by NADC as ITDA I (see Figure IV-2), the only version of ITDA in BASIC.

After about a year of processing a procurement competition, contractor work on ITDA 2 began June 1985. Following JOTS, the program was organized into modules corresponding to the CWC's subordinate warfare commanders, and the contractor projects were broken down accordingly. The initial awards were to Metron with Quantics as subcontractor for ASW, DHWA with Delex as subcontractor for ASUW and strike, and Atlantic Analysis Corp. (AAC) with Tetratech as subcontractor for AAW, EW, and system integration. Subsequently, the contractor work was reprioritized, in effect to shift the strike effort to ASUW and the EW effort to AAW. NADC additionally contracted to Pacer to provide software review and support functions.

The ITDA/ASW effort concentrated on FASTAD, the Fleet ASW Tactical Decision Aid, developed at COMTHIRDFLT 1983-85 under the OP-953/ONR/NTSA TAC D&E program, by R. J. Lipshutz of DHWA. See references [g], [h], and [i]. CAPT R. D. Reeves, CDR M. D. Etheridge, and LCDR N. M. Johnson (all NPGS alumni) provided the principal COMTHIRDFLT staff oversight of and participation in this development, which included considerable testing and evaluation in support of an ASWC at sea and in the COMTHIRDFLT opcon.

The main program in FASTAD is SCREEN EVALUATION. It was derived from an earlier DHWA program, CVSCREEN, developed for NADC principally by T. L. Corwin and M. C. Brennan. CVSCREEN was improved by NADC, principally Leonardo, prior to the COMTHIRDFLT development. Target motion modeling is by approximation of a random tour by a Markov chain, an approach used by Corwin in CVSCREEN and later in SALT (see 2.8). NADC converted the Screen Evaluation code to UNIX/C. A new user interface was designed by J. Tseng and P. W. Beach of NADC and was subsequently refined by K. D. Stempack of Pacer and later NADC. SCREEN EVAL will be reviewed in 4.2.9.

A recent contribution to screen optimization for convoy protection is reference [j], the NPGS thesis of LT K. D. Kowalski under W. P. Hughes. It allocates total available sweep width over screen positions to minimize risk from submarine attack, using nonlinear programming. This is programmed as a TDA. It generalizes and updates results in the 1964 NPGS thesis of LT R. E. Cooper and LCDR W. P. Hughes, reference [k], under W.P. Cunningham, who was a co-initiator of the operations research program at NPGS.

Other ITDA/ASW programs of the 1985-87 era include ASW COVERAGE, AREA SEARCH, and BARRIER SEARCH, in the spirit of JOTS programs. The latter two are in GENERAL SUPPORT rather than ASW in ITDA 2.02. Later ASW additions include BUOY SEARCH from FASTAD, adapted by L. W. Lampone of Metron, and PACSEARCH (see 2.6), adapted by W. R. Monach of DHWA. Lipshutz' modeling in BUOY SEARCH (described more fully in reference [i] as Buoy Planning) has in common with SALT (see 2.8) use of acoustic sweep width and relative motion space, which were earlier ideas as noted. Among his useful innovations in this modeling is use of the ellipse-to-circle transformation. The TACNUC program in ITDA/ASW computes effects of underwater nuclear explosions and was developed at the Los Alamos National Laboratory.

The ITDA/ASUW work concentrated on adapting SASHEM, the SAG-Against-SAG Harpoon Engagement Model, developed as an evaluation tool in 1984-86 for SWDG and NTSA by DHWA via Delex. SASHEM will be reviewed in 4.3.5. The original SASHEM development was principally by Stevens and Stukenbroeker of DHWA and D. A. Downey of Delex, under the direction of W. L. Harrison of Delex and CDR D. A. Ehemann (NPGS alumnus) of SWDG. The acquisition modeling mentioned in 4.3.5 is due to R. Bronowitz of CNA (reference [l]). Reference [m] is an interim technical documentation of SASHEM. The adaptation to ITDA was by R. H. Overton and R. D. Samms of DHWA and Downey and D. S. Hawley of Delex, under the oversight of E. Sidewater of NADC.

For ITDA/AAW, NADC oversight was by J. P. Phillips. Most of the TDA development was by R. C. Handford, AAC president, with programming by Tetratech. CAP STA (see 4.4.2) is a modification of a small part of the NOTS China Lake TDA Computer Assisted Stationing Tool (CAST), also used by JOTS in a different modification. CHAINSAW in ITDA/AAW is also different from that of JOTS. It was designed by Handford, based on consultation with CCG-4, CCG-8, COMSECONDFLT, and TACTRAGRULANT. ASMD was developed by J. W. McCollum of AAC, with programming by Tetratech; the SAM engagement modeling was from formulas of the Applied Physics Laboratory/Johns Hopkins University which were approximations to a large model of theirs.

Some review and analysis pertaining to CAST, cited above, can be found in reference [o]. This was a study of needs for mathematical models in TDAs, done for NTSA by L. D. Stone, D. D. Engel, and G. P. Pei of DHWA under A. F. Andrus of NPGS and NTSA.

The NPGS thesis of LT C. W. Plumley under R. N. Forrest, reference [p], provides a tutorial and an evaluation of ITDA/AAW and a verification of the algorithms in ITDA/CHAINSAW.

The refueling scheduling program ITDA/TARS (see 4.4.4) was developed by F. A. Barker and R. F. Kennedy of NADC and B. H. Rhodes of Villanova as a consultant, with most of the modeling by Rhodes. This was in response to a COMTHIRDFLT request.

ITDA/EW TDAs are SATVUL, adapted from a NAVSPASUR program by E. H. Kauffman and Tseng of NADC; SATCAT; and RADAR SHADOWING, developed by M. A. Cala and J. T. Bober of CNA in response to a request from COMSIXTHFLT. JOTS has had counterpart programs from the same sources, but has dropped SATCAT. A former IREPS stand-alone has been replaced in ITDA 2.02 by GFMPL Atmospheric Environment programs and data bases. IREPS remains in JOTS. E. A. Picard of NADC was also active in EW TDAs and in ITDA training.

R. F. Kennedy, G. Groshner, and C. J. Owens of NADC principally developed the ITDA core, and F. E. Hollenbach of NADC, working with INRI, developed the ADE functions.

The principal TDA programs in the current ITDA 2.02 and JOTS 5.1 will be reviewed by warfare area in the next four sections.

4.2. ASW TDAs

In this section, we review various ASW TDAs in ITDA 2.02 and JOTS 5.1. These deal with acoustic support, search (five TDAs), screen evaluation (three TDAs), and nuclear explosion effects in turn.

We begin in 4.2.1 with ASW acoustic support functions. These data bases and programs generate and/or store for future use data on sonar figure of merit (FOM), proploss, ambient noise, and bottom contours. Target source levels are stored within the ITDA/SCREEN EVAL program, but are inputs by the user where needed in other programs.

In 4.2.2 through 4.2.6, we review various ASW search programs, ending with ITDA/PAC SEARCH, the most functional and most important of these (and the most sophisticated internally). JOTS/ITDA/BARRIER SEARCH (in GENERAL SUPPORT in ITDA) in 4.3 applies just as well to ASW as to ASUW under which it is reviewed.

Three TDAs to evaluate an ASW screen are reviewed in 4.2.7, 4.2.8, and 4.2.9, in order of increasing functionality, culminating with ITDA/SCREEN EVAL. As noted in 4.2.6, ITDA/PAC SEARCH can also be used to evaluate a screen, although that was not an application for which it was designed.

We conclude with a brief review in 4.2.10 of ITDA/TAC NUC, which gives effects of underwater nuclear explosions.

4.2.1. Acoustic support functions. JOTS/FREQS/FOMS provides maintenance of data bases on source levels for up to 15 SSNs at up to eight frequencies and on FOMs for up to 50 sonar/target pairs at each frequency stored for the target. All data are input by the user.

JOTS/PROPLOSS CURVES generates, displays, and stores for TDA use, curves of proploss versus range, based on frequency, source and receiver depths, bottom type, sea state, water depth, and sound velocity profile (SVP). SVP may be taken from an historical data base, user entered SVP or bathymetric data, or a com-bination of the two. Evidently proploss is calculated from the Raymode model, although reference [a] is not clear on this. An additional output is a ray trace diagram.

ITDA/OCEAN ENVIRONMENT also provides proploss curves based on Raymode. It further provides ambient noise versus frequency and bottom contours, both based on lat/long. All of these come from Ocean Environment functions of GMPL. Bottom contours are not used directly in TDAs, but can aid decisions in their own right by helping to indicate presence of convergence zones and possible submarine hiding places. Bottom depth and type are of course reflected in proploss calculations.

ITDA/GFMPL 1.3 OE is a stand-alone provided for use by those who are knowledgeable of this substantial oceanographic data base, to whose user's guide reference [b] refers. Ray trace, sensor performance prediction, historical data base analysis, and tides are some of the many functions available in this stand-alone.

4.2.2. ITDA/BUOY SEARCH. This program computes an optimum buoy field to detect a user-entered target and the target AOU at the time of buoy field deployment.

Specifically, the user enters a target AOU as an ellipse, target course and speed with uncertainties, target source level and frequency, and, for active buoys, target strength. The user-entered buoy field constraints are buoy life, type, and depth and number of buoys. A proploss file (in general with multiple frequencies) is specified from OCEAN ENVIRONMENT taken from GFMPL 1.3 OE as in 4.2.1. Evidently source level and target strength are the only inputs to FOM that are utilized.

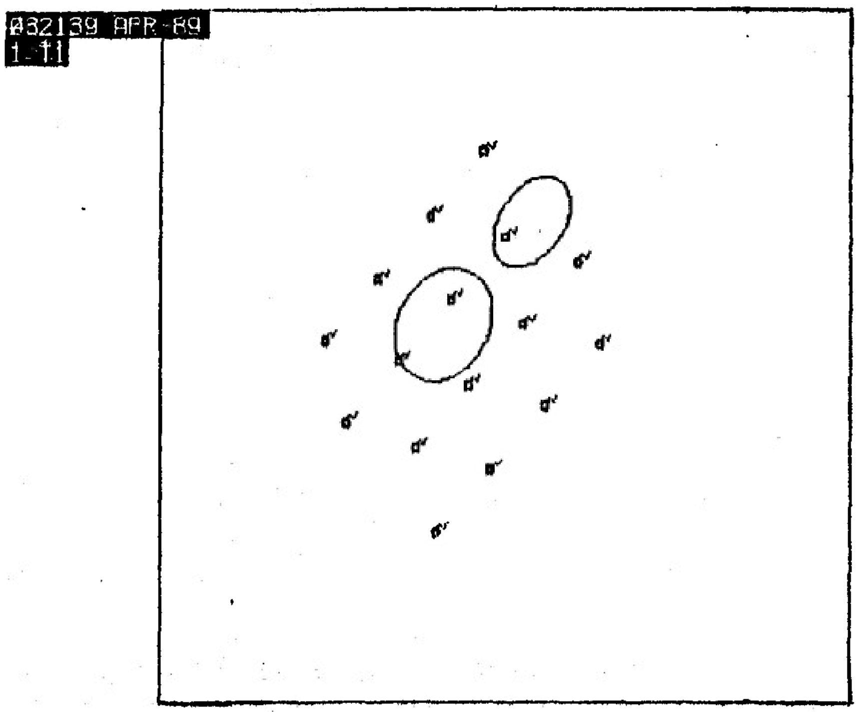
From this information, the program updates the target AOU to the start of the field life and calculates the optimum field from among the patterns single-line barrier, 6x5 distributive field, and n x m distributive field. See Figure IV-3 for an illustration. Some inputs are deleted for security. The ellipses displayed pertain to the initial AOU and the update noted above.

We outline the methodology for finding an optimum field. For further details, see reference [i]. The MOE is probability of detection during the time of search.

We first evaluate a single buoy with a fixed FOM. Given the target course and speed, covered area versus time is computed from the DP and CZ coverages (cookie-cutter at this stage); the covered area versus time goes through transitions reaching a steady state increase from the leading edge of the outer CZ. The covered area is averaged over the distribution of FOM ($\sigma = 8$ db) from which sweep rate versus time is obtained. This is averaged over time to obtain expected swept rate, and that divided by target speed is called acoustic sweep width (see reference [bb] of Chapter II).

A coordinate system is chosen with one axis parallel to target course. The problem is transformed to relative motion space (an earlier idea of H.R. Richardson), but first the coordinates are transformed so that the target position ellipse becomes a circle; an axis is still parallel to target course. The problem becomes one of choosing the position and sides of a rectangle in relative motion

FIGURE IV-3. ITDA/BUOY SEARCH




```
Target:
     DTG          LAT    LNG    SMJ SMN ANG CSE SPD CUN SUN
241630 FEB 89 2300N 07300W  15  10  45 225  12  15   3

Buoy Field Constraints:
     DTG          LIFE #B TYPE DEPTH FREQ FOM
241800 FEB 89     4   16 DIF  XX     XX   XX

Proploss File: PL1

Recommended Buoy Field:
PAT  LAT    LNG    BS RD  WLK RS #R B/R OFF
NXM 2320N 07317W 25 225 135 22  4   4  +12
```

space to maximize detection probability. The circularization enables us to give an analytic formula for detection probability. This function can have local maxima which are not global; a global maximum is found by discrete exhaustion. The solution rectangle is transformed back to geographic space and further by the reverse of the ellipse-circle transformation, which makes it a parallelogram. The allotted buoys are assigned in a uniform array over this parallelogram. A line barrier is treated as a degenerate parallelogram, and a 6x5 field is approximated by a parallelogram.

4.2.3. JOTS/ASW BARRIER. This TDA evaluates by simulation an ASW barrier, composed of ships and/or sonobuoy fields.

Previously entered identities of targets and barrier assets are drawn upon. Detection ranges are either user-entered or are drawn from stored outputs of FREQS/FOMS. They are given as low, mean, and high detection ranges, corresponding to FOM − 8 db, FOM, and FOM + 8 db; direct path and convergence zone ranges and CZ widths are given for all three cases. Barrier kinematics may include sprint-and-drift.

An illustrative scenario using a three-SSN barrier is shown in Figure IV-4. The initial target AOU is shown by the ellipse. Not shown are detection ranges, target course at 225, course uncertainty at 20 degrees, target speed at 12 knots, and speed uncertainty at 3 knots.

The last column in the parameter summary in Figure IV-4 is the advance/recede angle. Here it is zero, meaning that each barrier unit patrols back and forth on its assigned track. If this angle were negative, the barrier would recede away from the target, which might afford a higher detection probability until the barrier runs out of room. A positive angle would have the barrier advance toward the target, which might be used when the acoustics and kinematics favor the barrier, to gain earlier detections or to achieve the coverage with fewer assets.

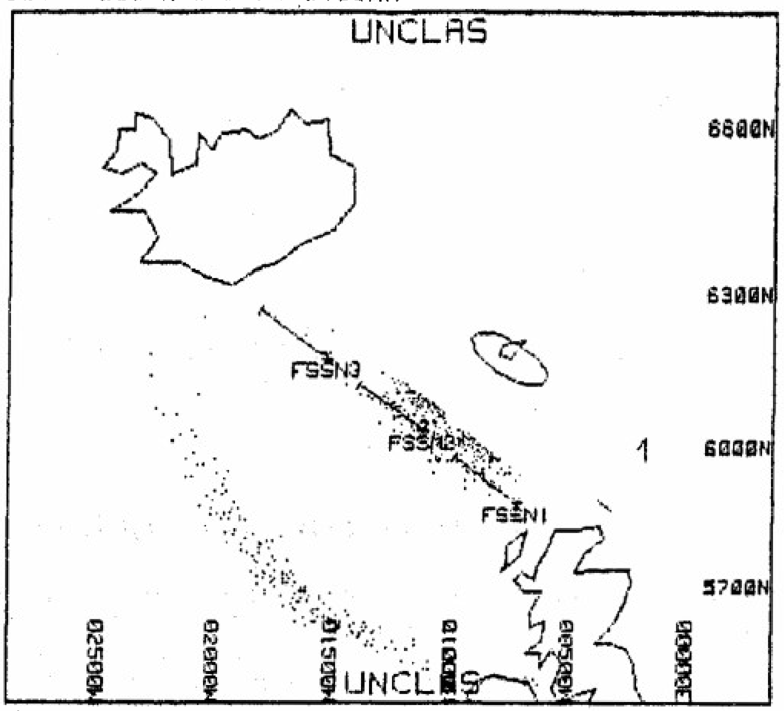
The results of a 24-hour simulation, using 100 sample tracks, are also shown in Figure IV-4. Each dot in the vicinity of the barrier is a sample position at initial detection, color-coded (not shown) by the detecting unit. The dots some 100 nm to the southwest of the barrier are samples which were not detected. About 47% of the samples were detected, most by FSSN2 as expected. On request, the sample target tracks are displayed, which might help the user to envisage the simulation mechanism.

This TDA appears to offer a fairly convenient way of evaluating an ASW barrier with reasonable realism. Suggested improvements include computing cdp by a (λ,σ) model, reflecting the barrier's vulnerability to counterdetection, and inclusion of noise-speed curves of own ship and target to facilitate the tradeoff between acoustic degradation and kinematic enhancement that accompany higher speed.

4.2.4. JOTS/ITDA AREA SEARCH. Both of these TDAs use the classic random search formula (see, e.g., OEG 56, reference [c] of Chapter II and the formula below) to evaluate a search in a convex polygon or an ellipse for a moving target. The speed input, V, to this formula is search speed *relative to the target*, averaged over a uniform distribution of target course over the full compass.

FIGURE IV-4. JOTS/ASW BARRIER

TIME = 01:12:31 28 Feb 1989
MAP CENTER/ RADIUS = 6200N 01200W 0400NM



BARRIER:BAR1\

##	UNIT	START	TIME MON	YR	ONSTA HRS	POSITION LAT	LNG	LEN/ANG NM	DEG	DRIFT KTS	MIN	SPRINT KTS	MIN	A+/R- DEG
XX	XXXXXXXXXX	DDHHMM	MON	YR	XXX	DDMMN	DDDMMW	XXX	XXX	XXX	XXX	XXX	XXX	+XXX
1	FSSN1	272100	Feb	89	72	5904N	00637W	101	306	10	30	25	10	+000
2	FSSN2	272100	Feb	89	72	6034N	01039W	97	306	10	30	25	10	+000
3	FSSN3	272100	Feb	89	72	6200N	01441W	93	306	10	30	25	10	+000

Both programs output the area, A, of a user-built convex polygon. This uses a utility function in an earlier version of JOTS.

JOTS goes further than ITDA in that it accepts a user-built search track of connected straight legs, and computes time on track as an input to the random search formula. This usage of the random search formula, which is a generally pessimistic estimate of detection probability, somewhat follows OEG 56 treatment of parallel sweeps.

Figure IV-5 is a JOTS example. The polygonal search region is entered by hooking the corners; an ellipse would be entered as semi-axes and orientation as usual. The program handles up to three search regions, treating them independently; here we use one. The search region may be given a rate of radial expansion. E.g., in Figure IV-5 the area at map time is about twice the initial value. The target is shown in the figure by a small triangle. It is entered by its identification in the contact manager files, without detectability data. It is given course, speed, and uncertainties.

The search track is entered by hooking waypoints (or typing lat/long's), identifying origin and destination (possibly different), and giving departure time, speed of transit to and from the search region, search speed in the region, and detection range, R. The random search formula for detection probability in time T is

$$P(T) = 1 - \exp(-2RVT/A).$$

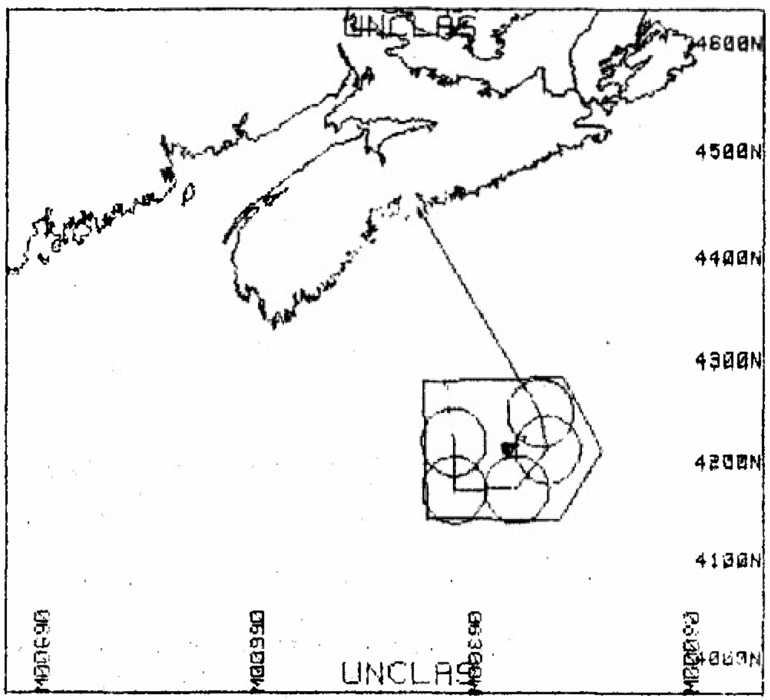
4.2.5. JOTS/TRANSIT SEARCH. TRANSIT SEARCH in JOTS is a CAS program based on part of the CTF-69 program MEDSEARCH (see 2.13). It evaluates search for a target transiting through a network of alternative paths, e.g., in geographically restricted waters. It is accessed under HISTORICAL ASW.

Node locations are inputs as ellipses, and branches between ellipses are designated. Additional target inputs are designation of start ellipse, start time with variations, minimum and maximum speed on each branch, and branch probabilities. The target inputs are amenable to historical analysis, and a companion program by that name provides for building and utilizing an historical data base. Part of the CTF-69 MED data base (evidently as of 1985) has been stored for use. In the absence of historical analysis, the user postulates target inputs based on conjecture and/or current intelligence, as in other CAS.

The search effort is given by placement of one or more barriers. Each barrier is characterized by location of end-points, start time, duration, and probability of detection, given the target crosses the barrier during barrier life. The detection probability is estimated off-line by the user and is the only input that reflects acoustics.

A Monte Carlo simulation of 100 sample transits (the user may choose more or less) is conducted. The stochastic elements are start time (weighted three-point distribution), speeds (uniform distribution), branch probabilities, and detection probabilities. At user-chosen times, a probability map of target

FIGURE IV-5. JOTS/AREA SEARCH



142322:34 Mar 89

AREA #1
Area size :8000
Prob cf Det:.63

SEARCHER
Departure time
101200 Mar 89
Trans spd :350
Search spd :250
Detect rng :20
Sortie time:12

TARGET/AREA
Posit time
101200 Mar 89
Target cse :+180
Target spd :15
TIME LEFT =10.7

position, given no detection, is updated for negative information and displayed. Also displayed are dots showing the sample target positions at update time, color-coded by detection probability at the simulation end time.

The probability map displays are user hostile and illustrate an important point in display design. Cell probabilities are displayed as *two*-digit numbers. This requires grid lines to separate them and these unnecessarily crowd the screen, oppressively so with small cell size. (They also try the user's patience by slow erasure.) If probabilities were gauged on a single-digit scale of 0 to 9, as in VPCAS, the grid lines would not be needed. Better still would be color coding.

Figure IV-6 illustrates pre-simulation inputs, and a simulation-generated probability map. Only node 2 has two branches emanating from it, and these have probabilities .4 and .6. Two barriers, labeled B1 and B2, extend from Africa to Sardinia and Sicily, with detection probabilities .55 and .65 respectively. Speeds are from 9 to 12 knots on all branches except from node 2 to node 5 to node 6, where they are 11 to 15 knots. Start is at node 1. Earliest start time was 010800, best guess was 011200, and latest was 011600, with best guess twice as likely as earliest and latest. Update and simulation end times were 031200. Grid cell size is 60 nm. Grid crowding worsens as cell size decreases. Dots in the post-simulation map show sample target locations, mostly near nodes 3 and 6, at update time. They are color-coded (not shown) by probability of transiting both barriers undetected.

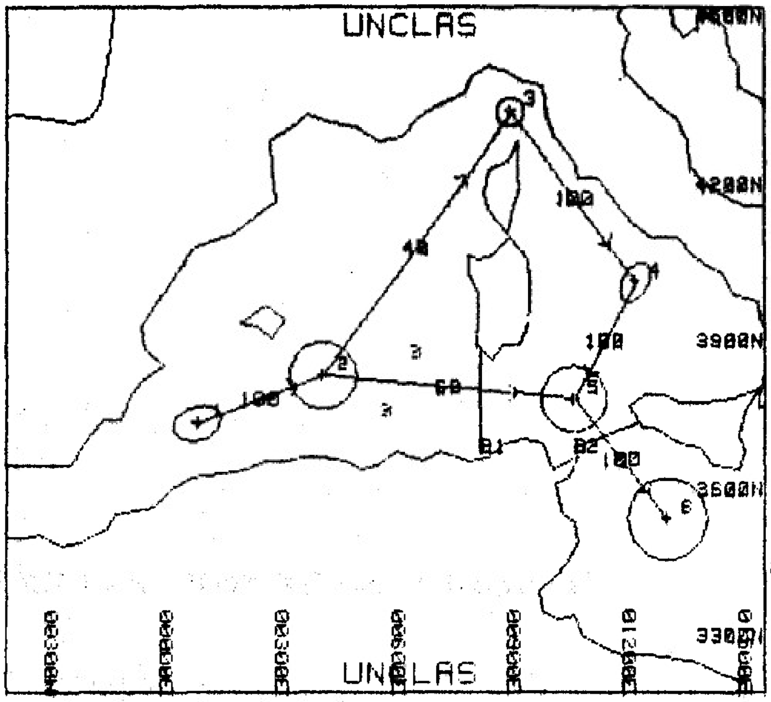
4.2.6. ITDA/PAC SEARCH. PACSEARCH models and use are reviewed in 2.6. It was integrated into ITDA 2.02, where it is called PACIFIC SEARCH and PAC SEARCH. All of these names are unfortunate in that the PACSEARCH program is not peculiar to the Pacific, and it is important to realize that. Most of its use has been at COSP, where it was designed, and an extensive historical PAC data base has been built up for PACSEARCH use. A LANT historical data base could be incorporated into PACSEARCH, more easily than when this was done for VPCAS, but this has not yet been done. Of course, the program can be used without historical data.

The change from the COSP version of PACSEARCH to the ITDA version that is most visible to the user is that the four status boards of a problem, acoustics, detections, target motion scenarios, and searches, are displayed in four quadrants of one screen (because the ITDA screen does not roll), rather than with vertical separation as in Figure II-33. Also, the search planning menu (Figure II-34) is broken up into other groups of prompts. A needed improvement is to provide better separation or delineation among the four status board quadrants.

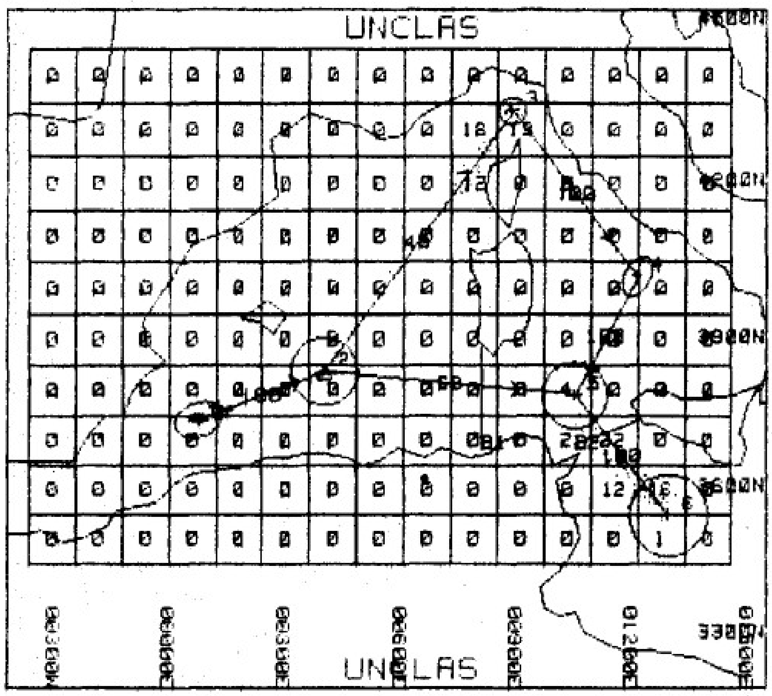
The present ITDA 2.02 user's guide, reference [b], unfortunately omits some important capabilities and a crucial need that are in (all versions of) the PAC SEARCH program. (Evidently this resulted from the press of a deadline for a Fleet exercise.) No mention is made of inputting detections, i.e., target contacts, and one of these is needed to start the problem. The only motion described is fleeing datum motion in a single scenario and the only search sensor described is sonobuoys. On the other hand the program with its menus and prompts provides for all of the types of detections and motions described in 2.4.2 and 2.4.3 and for search by fixed, towed, and hull-mounted arrays. Also, the user's guide should

FIGURE IV-6 JOTS/TRANSIT SEARCH

TIME = 22:09:23 2 Mar 1989
MAP CENTER/ RADIUS = 3900N 00600E 0400NM



TIME = 01:39:11 3 Mar 1989
MAP CENTER/ RADIUS = 3900N 00600E 0400NM



provide some of the underlying reasons for user actions. Hence it is recommended that the PACSEARCH part of reference [b] be supplemented by reference [w] of Chapter II, particularly the latter's illustrated example in its Chapter IV.

A potential application of PAC SEARCH not anticipated in its design (but suggested by its designer, W. R. Monach), is ASW screen evaluation, which is the subject of the next three subsections. To do this, the user would enter into the search status board searches, unit by unit, which constitute a screen design. They can be given motion as is done in a towed array, whether or not towed arrays are in use, or the screen motion could be transferred to the target, whose motion would be modeled relative to the screen. Initial target position distribution may be given as in 2.4.2, which unfortunately for this purpose does not include a distribution along a circular arc, as in 4.2.9 below, although that could be readily added. Evaluation would be by probability maps and associated cdp's.

4.2.7. ITDA/ASW COVERAGE. This program provides an evaluation of an ASW screen which is much simpler than ITDA/SCREEN EVAL (see 4.2.9), but which does not go as far in gauging vulnerability to SSN penetrators. Given a Kilo screen design (as compared to the 4-W screens used in SCREEN EVAL), associated sonars, SSN targets, and proploss, these programs plot contour regions of signal excess, i.e., FOM minus proploss. Also, the user must compute or choose FOM's off-line, whereas SCREEN EVAL computes FOM's from stored data bases on sonars and source levels.

The Kilo design means that each screen unit is assigned a sector defined by a bearing interval and a range interval, both measured from the screen center, presumably an HVU or the PIM.

Targets are characterized purely by their radiated frequencies. Up to 15 targets with up to four frequencies each may be entered.

Sonars are characterized purely by FOM at a given frequency. Up to 15 sonars may be entered. It does not appear that sonobuoys are intended to be included, but in principle buoys could be handled by treating a field or a single buoy as a sonar, duly assigned Kilo coordinates and an FOM.

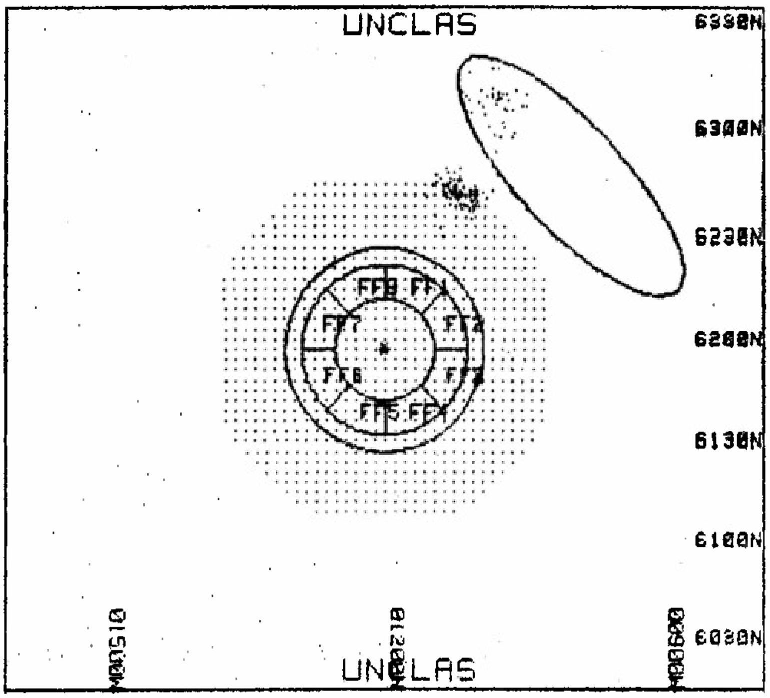
Proploss curves are calculated as in 4.2.1.

From these data, average signal excess contour regions are calculated and displayed in color-coded form (not reproduced here but similar to the contour regions in Figure IV-7 below).

4.2.8. JOTS/ASW SCREEN. In JOTS/ASW SCREEN, the user builds a Kilo screen, as in 4.2.7, and evaluates its detection performance against a simulated target. Detection capabilities and target position and motion are treated as in JOTS/ASW BARRIER (4.2.4).

An illustration is given in Figure IV-7. Eight frigates have Kilo stations uniformly around an annulus 15 nm to 25 nm from screen center. The keep out range is 30 nm, shown as the outer circle. The screen is on course 020 at 15 knots. Sprint speed of 25 knots and drift speed of 15 knots are timed to result in that SOA. The target starts from the normal distribution shown by the ellipse. It is on course 225 at 12 knots, with a speed uncertainty of 3 knots.

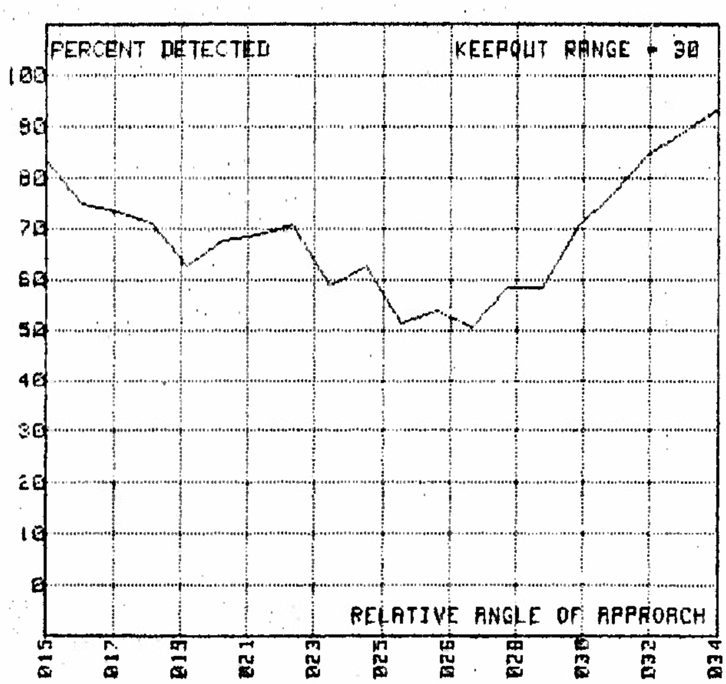
FIGURE IV-7. JOTS/ASW SCREEN



280056:52 Feb 89

CUM DET PROB = .67
TOTAL POINTS = 120

ASSET	PROB
FF1	.54
FF2	.11
FF3	0.00
FF4	0.00
FF5	0.00
FF6	0.00
FF7	0.00
FF8	.02



One evaluation is by a display of contour regions of signal excess, shown in Figure IV-7 by a shaded octagon. Color coding (not shown) indicates four intervals of signal excess, SE: SE < –5 db, –5 db ≤ SE < 0, 0 ≤ SE < 5 db, and 5 db ≤ SE; all points in the octagon are in the latter interval.

The scattered dots in the vicinity of the screen show the sample positions of initial detections. The dots within the ellipse show origins of sample tracks which were not detected. It appears that only sample tracks that intercept the keep out circle are considered.

The primary evaluation is by the screen coverage graph shown in the lower part of Figure IV-7, which gives percent detected versus relative angle of approach track.

This TDA is intermediate between ITDA/ASW COVERAGE and ITDA/SCREEN EVAL in functionality and in complexity of use.

4.2.9. ITDA/SCREEN EVAL. SCREEN EVAL allows the user to build a 4-Whiskey ASW screen and to evaluate the screen against a simulated SSN penetrator. The penetrator's initial position distribution may be given as an ellipse, uniform on a circular arc, normal on a circular arc, a line of bearing, or uniform over a rectangle. The evaluation is in terms of the screen's cumulative detection probability (CDP) and the penetrator's cumulative probability of weapon launch (CLP).

While the outputs of SCREEN EVAL, both graphic and numeric, can be very useful, and the running time is quite acceptable for planning needs, the inputs are time-consuming, particularly the initial acoustic inputs. Also, because the input procedure is rather lengthy, it is susceptible to digression. However, in practice, most inputting can be done pre-sail or at sea prior to ASW vulnerability, and in any event, the outputs can be used to develop policies peculiar to force composition and mission, which may not change much over a matter of weeks.

As prerequisites, the user must enter into data bases one or more candidates of each of own force track, own formation on a 4-W grid, and friendly and hostile units. Each of these is given a short name for easy call during a current or future problem.

Proploss curves are obtained as in 4.2.1. Ambient noise versus frequency is also generated, given input shipping density (high, medium, or low).

Next the user designates battle group inputs by first choosing track, 4-W formation, and search units from the names that have been input to the data bases. The search units are assigned sensors, whose capabilities have been stored in the program from APP data bases. If a search unit mounts VS or HS, the sensors may be sonobuoys. Noisy units are designated, because *the program models mutual interference among search units*. If buoy sensors have been included, field parameters are entered.

The target is designated, by its data base name. The program has stored source levels by class, frequency, speed, and depth, all of which the user enters. Target initial position distribution is specified as above, and rules for target tactics at various stages are chosen, possibly as defaults. A high value unit in the battle group is designated.

The acoustic data menu is then entered to bring together the acoustics relevant to the choices of sensors and target, notably search frequencies and FOMS.

The outputs are now generated by simulation under the SCREEN ANALYSIS menu, illustrated in Figure IV-8. Using the MAP OPTIONS support program, the 4-W formation is added to the lat/long grid, which also displays the PIM track, sensor coverages, and the initial distribution of target position. This is illustrated in Figure IV-8(a), with a CV HVU and a screen of eight frigates (admittedly optimistic), a CG, and a 10-buoy barrier field. The detection coverage against the chosen target is shown by 50% contours. The target position is normally distributed over an arc. In the remaining parts of Figure IV-8, detection coverage is omitted and miles per inch is doubled.

The simulation is run in increments of 15 minutes of real time, each taking about seven seconds of running time. At any time the user may request a current map, which shows updated positions of PIM, 4-W formation, sensor coverages, and, as a distribution, target position. Current CDP and CLP are displayed,but not in the graphics to which Figure IV-8 is confined.

The start disposition is repeated (rescaled) in Figure IV-8(b). Part (c) shows the disposition four hours later. The 4-W formation and the target have advanced toward the buoys from opposite directions. The target position distribution has spread out. It is updated for the negative information from the search, which is presumed unsuccessful; this depresses the probability immediately northeast of the buoys. Part (d) shows the situation eight hours from start--the target distribution has become more circular as the target loiters. Parts (e), (f), and (g) show the situation 12,16, and 24 hours from start. The buoy life was set at 12 hours, so buoys do not show in parts (f) and (g).

Figure IV-9 presents graphs of CDP and CLP versus time. Note that CDP rises sharply during the 12 hour buoy life and rises slowly thereafter. Buoy field renewal is indicated. In this example CLP for the postulated weapon does not rise beyond a negligible value.

Target motion is modeled in this program as a Markov chain discretization of a random tour, which is also done in SALT (see 2.8).

By operating SCREEN EVAL for alternative candidate screens and plausibly alternative targets, an ASWC staff can obtain a good basis for recommending screen disposition in anticipated combat situations.

4.2.10. ITDA/TAC NUC. This TDA illustrates the self damage and collateral effects from employment of underwater detonation nuclear weapons.

Inputs are aim point, yield, depth of detonation, bottom depth, and receiver lat/long for blueout.

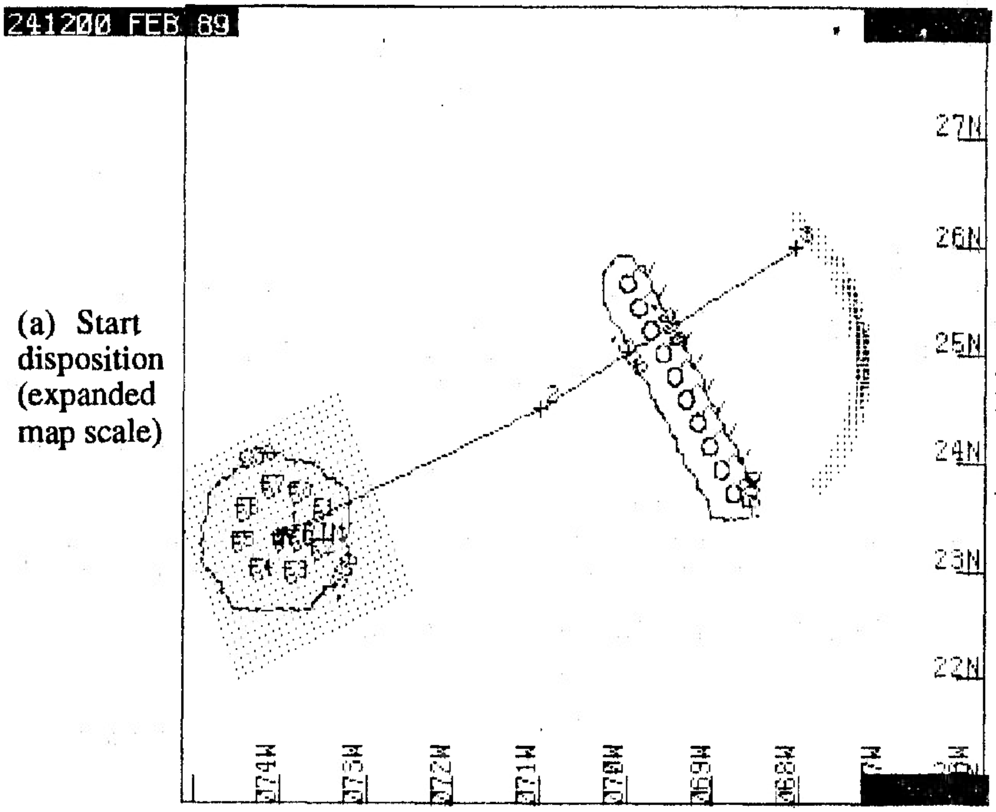
Outputs displayed are (1) a top view of radii of peak velocity components, base surge aerosol and surface radioactivity 30 minutes after detonation, and air shock pressure change at 1 psi; (2) a side view of peak velocities and air shock pressure change; (3) emergency and operational safe standoff ranges; and (4) a chart of blueout lives at 50, 200, and 400 Hz.

4.3. ASUW TDAs

In this section we review most of the ASUW TDAs in ITDA and JOTS. PAC SEARCH is in ITDA/ASUW and AREA SEARCH is in JOTS/ASUW; both are reviewed in 4.2 (PAC SEARCH more extensively in 2.6) and not here.

FIGURE IV-8. ITDA/SCREEN EVAL

(a) Start disposition (expanded map scale)

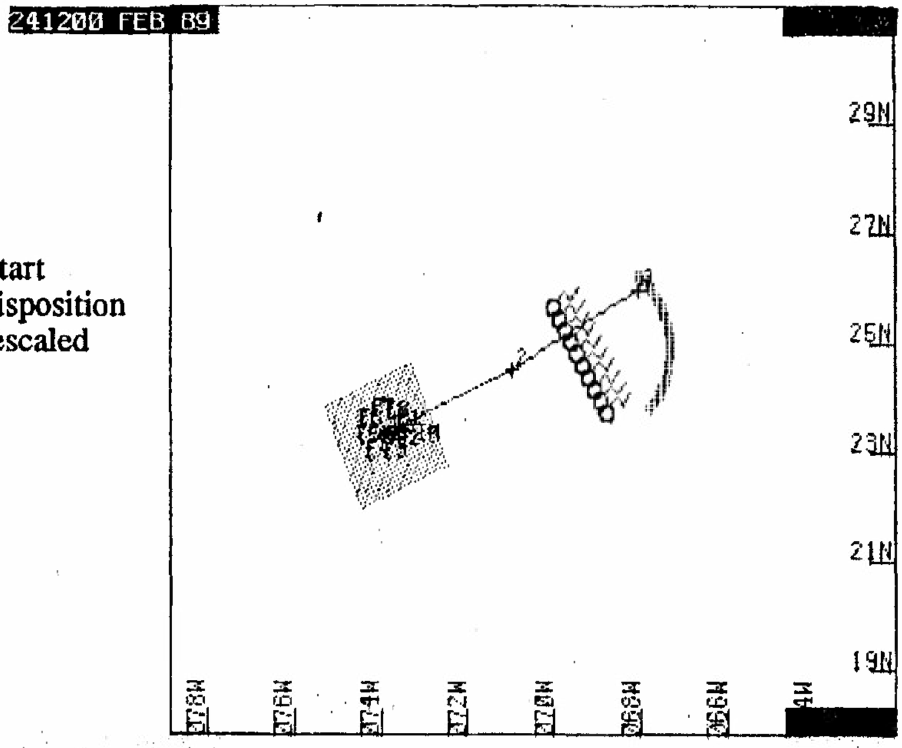


NOTE: The parallelogram of dots is the 4-W grid. The PIM is at the HVU, a CV. The screen is a CG plus eight FFs plus a field of 10 buoys. (The CV and CG are not visible in hard copy.) The PIM track has two legs (slight course change). Target position is normally distributed in an arc. Contours of 50% detection probability are shown around the FFs and buoys. Subsequent displays do not include contours and are rescaled to twice as many miles per inch.

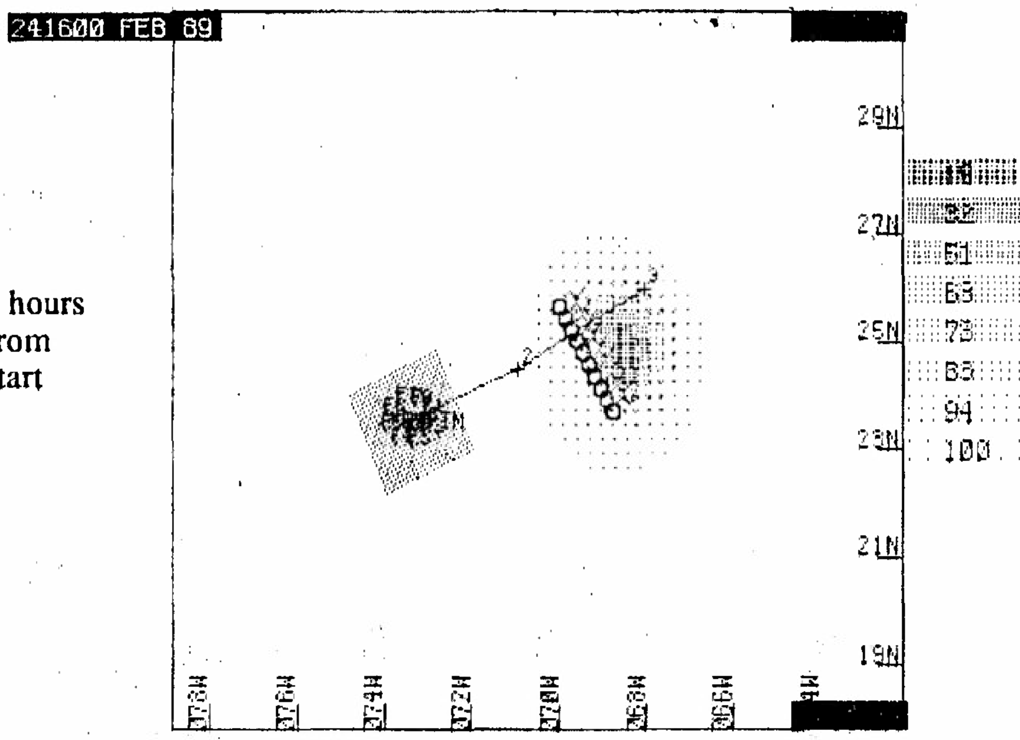
(Continued)

FIGURE IV-8 (Continued)

(b) Start disposition rescaled



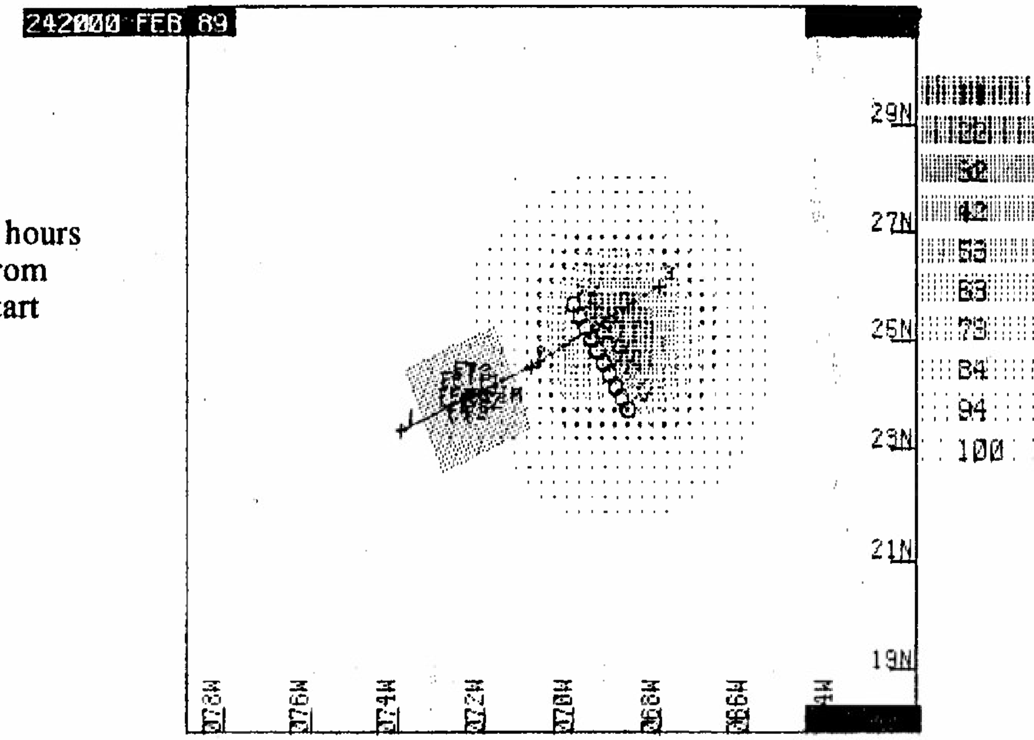
(c) 4 hours from start



(Continued)

FIGURE IV-8 (Continued)

(d) 8 hours from start



(e) 12 hours from start

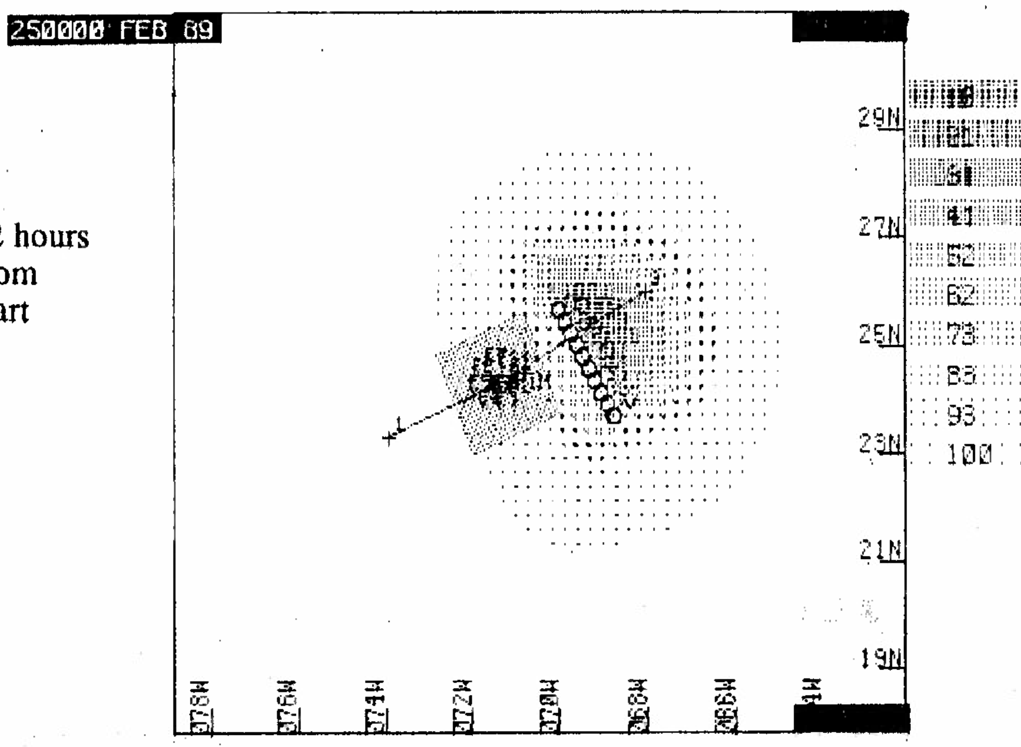
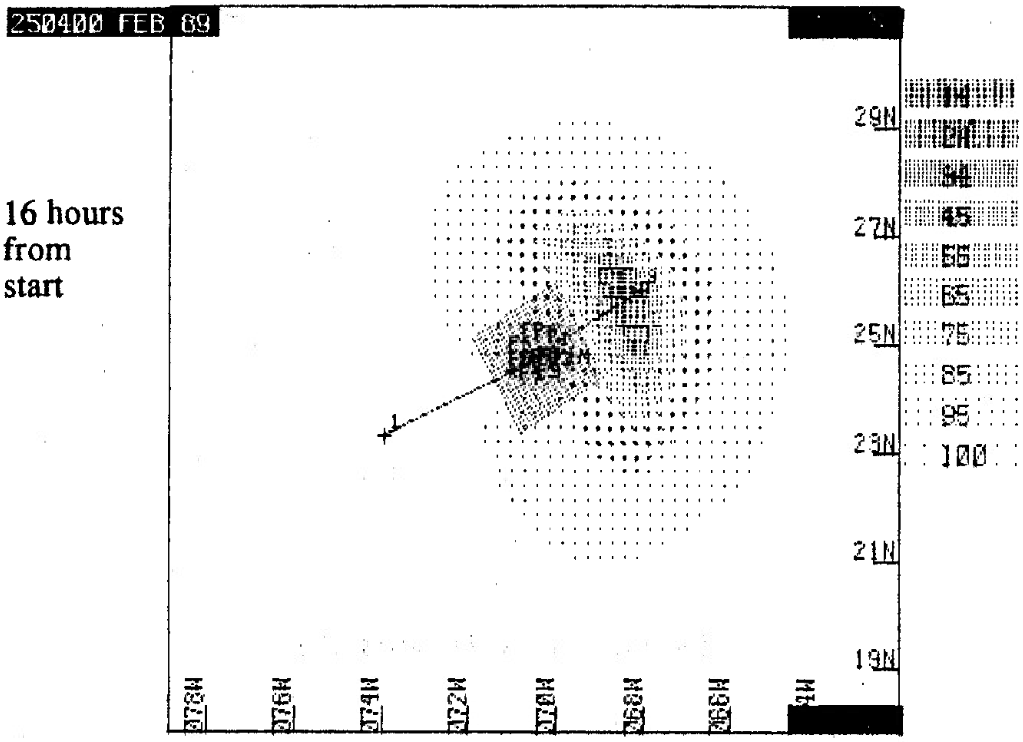


FIGURE IV-8 (Continued)

(f) 16 hours from start



(g) 24 hours from start

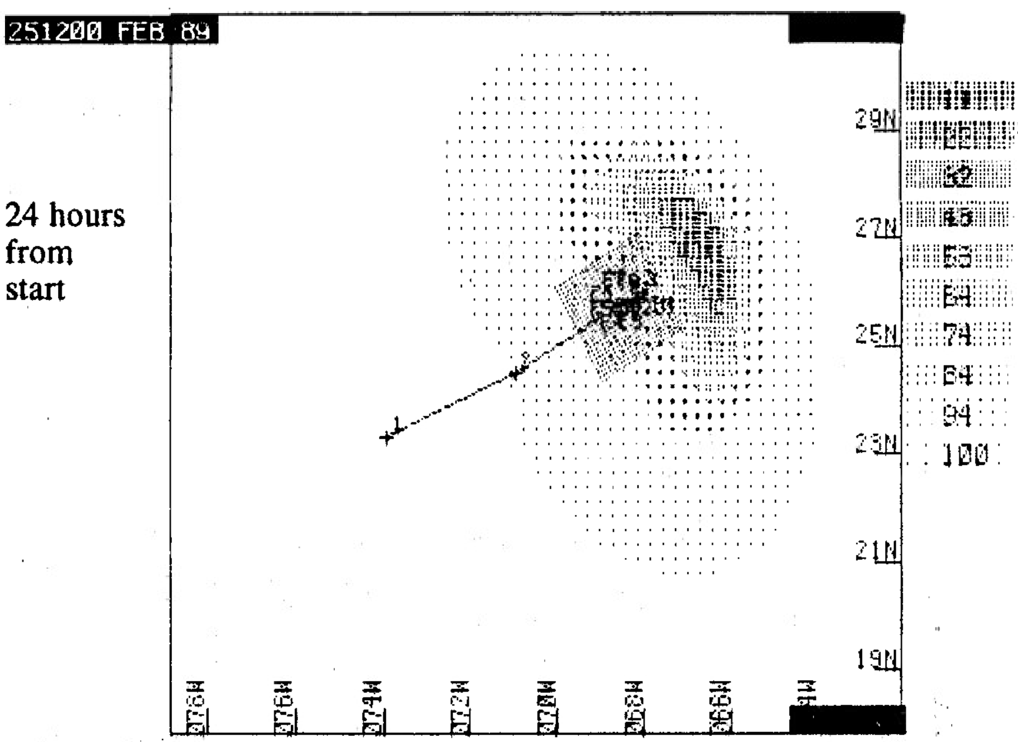
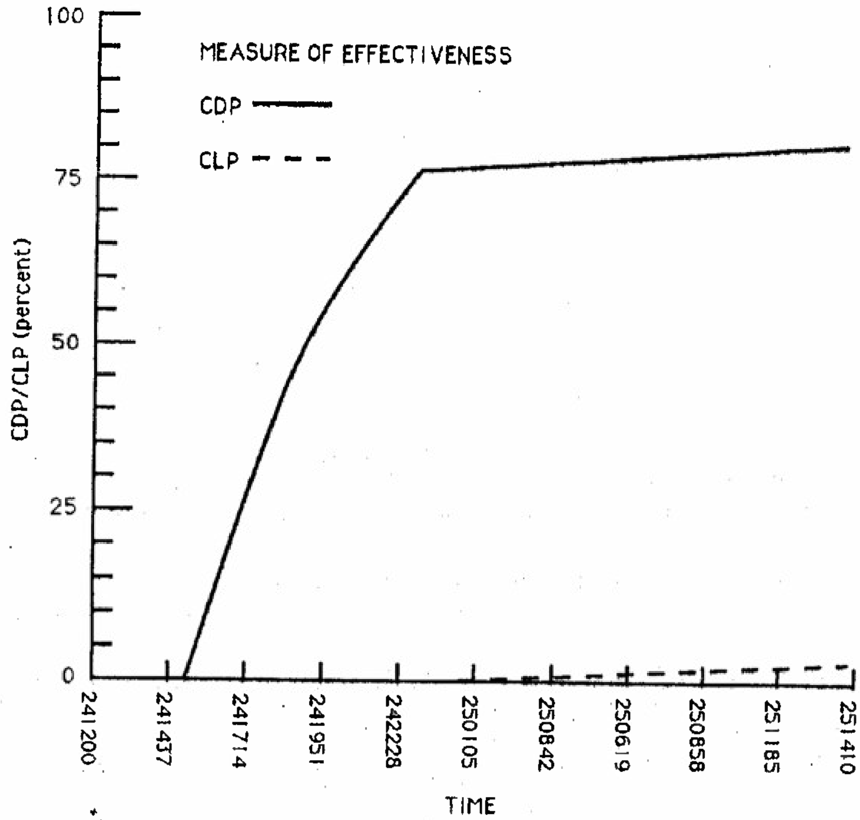


FIGURE IV-9. ITDA/SCREEN EVAL CDP AND CLP



NOTE: CDP is cumulative detection probability by ASW screen against SSN target.
CLP is target's cumulative weapon launch probability.
Both pertain to Figure IV-8.
Note that CDP rises persistently until the buoy field expires after 12 hours.
The time axis ticks are 157 minutes apart (chosen by program).

We begin with two search TDAs from JOTS: BARRIER SEARCH (also in ITDA) and SURFACE SURVEILLANCE. JOTS/SURFACE SURVEILLANCE shows "unencroached" regions at various times after a surface search. We then review TOMAHAWK, and HARPOON from JOTS, and we conclude with ITDA/SASHEM. SASHEM develops outcomes of HARPOON engagements; it treats the targets' antimissile defense, and has much deeper modeling than the other programs in this section. JOTS/HARPOON also analyzes HARPOON engagements; given various inputs, it presents time on top given launch time or launch time given time on top, without hit probabilities or target ASMD. A similar remark applies to JOTS/TOMAHAWK.

4.3.1. JOTS/ITDA BARRIER SEARCH. This program applies equally well to ASW; in ITDA it is under GENERAL SUPPORT. The presentation differs from that of JOTS/ASW BARRIER (see 4.2.3).

A search vehicle is assigned a barrier length, which it patrols back and forth. The barrier window is a bit longer, because of the detection range extension at either end. Detection is definite range, i.e., "cookie-cutter." All points of the window are assumed equally likely as target crossing points. The probability versus window crossing point, and the average of this probability over the window (which is also "kinematic" sweep width divided by window length). The advance/recede angle has the same meaning as in 4.2.3. Figure IV-10 is an example from JOTS.

4.3.2. JOTS/SURFACE SURVEILLANCE. This TDA is the remainder of the TSS program that was the starting point for JOTS in 1982. However, that program had SURTAC tracker and Harpoon acquisition features that are no longer retained and did not have the unencroached region feature described below.

The main idea in this program is to gauge the region, called the unencroached region, in which surface targets could not be present at a given time after a surface surveillance effort (implicitly of high confidence) by aircraft. Up to 50 aircraft may be given search assignments, each specified by start and end times and by search region given as a rectangle, annular sector, or a combination of such.

A simple example is given in Figure IV-11. A search assignment, starting at 1200, is made in each of two rectangles. The map time is 1600, one hour after search completion. Unfortunately, the color-coding to show the unencroached region does not copy. We show it instead by shading. It is a vertical strip about 40 nm wide in the center lower rectangle and one about half that wide in the upper rectangle. This implies that encroachment comes only from east or west and not from north or south, and that search ended earlier in the upper rectangle than in the lower; this is puzzling in that it does not appear in the input assumptions.

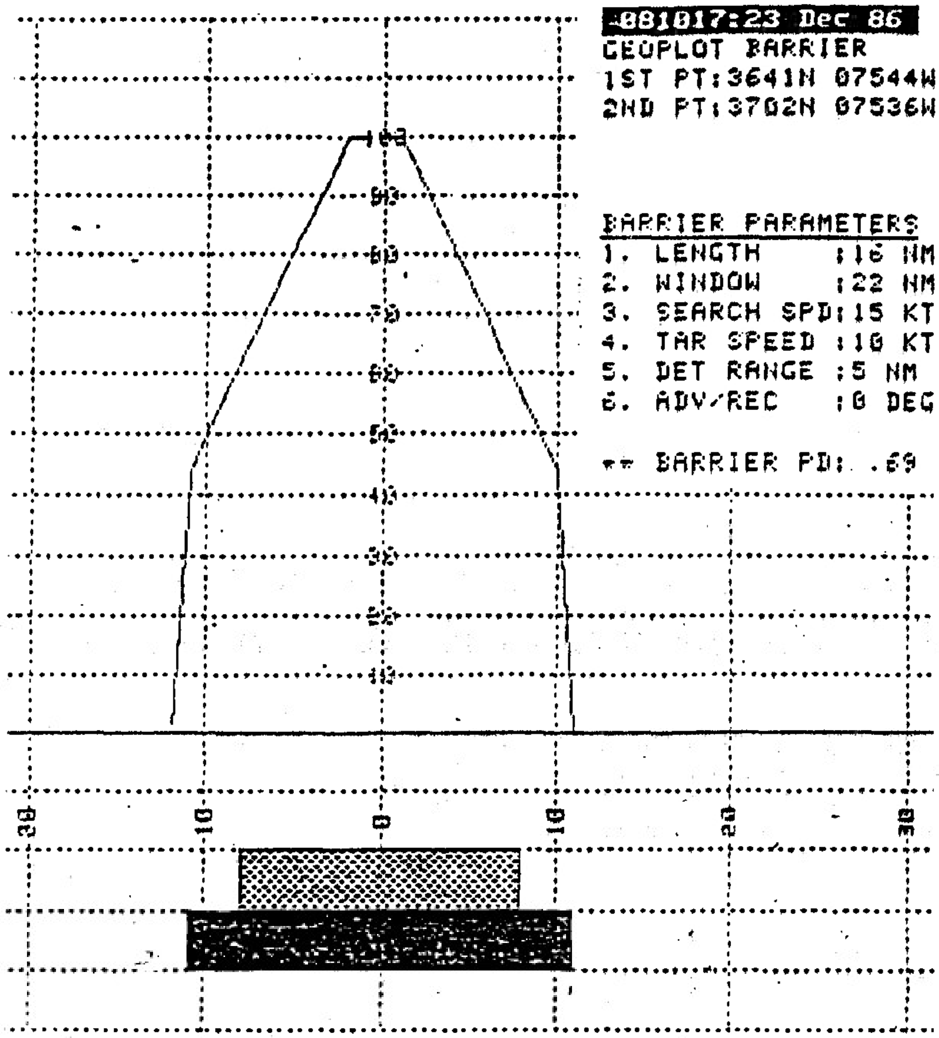
4.3.3. JOTS/TOMAHAWK. The best way to describe this TDA is to go directly to Figure IV-12. Multiple TOMAHAWK shooters (here one) each fire multiple TOMAHAWK (here one) at a single target. Various inputs are accepted to determine TOMAHAWK flight times. If for each TOMAHAWK, launch time is entered, then time on top is computed, and vice versa; these computations appear to be the main service to decision-making. In Figure IV-12, quantities which disclose distances involved have been deleted for security reasons.

4.3.4. JOTS/HARPOON. The remarks in 4.3.3 apply here also--see Figure IV-13. Two shooters are shown.

4.3.5. ITDA/SASHEM. SASHEM is an acronym for SAG-Against-SAG Harpoon Engagement Model. (SAG means surface action group.) It accepts designations of classes and positions of targets, shooters, and Harpoon firings, along with environmental inputs, and computes distributions of acquisitions and hits and related information. Most of the modeling is in the targets' ASMD, defense against air-to-surface missiles. ASMD capabilities have been stored according to target class. Acquisition modeling is also important and is based on reference [1].

The input/output is not automatically linked to real time, so SASHEM must be regarded as a planning TDA.

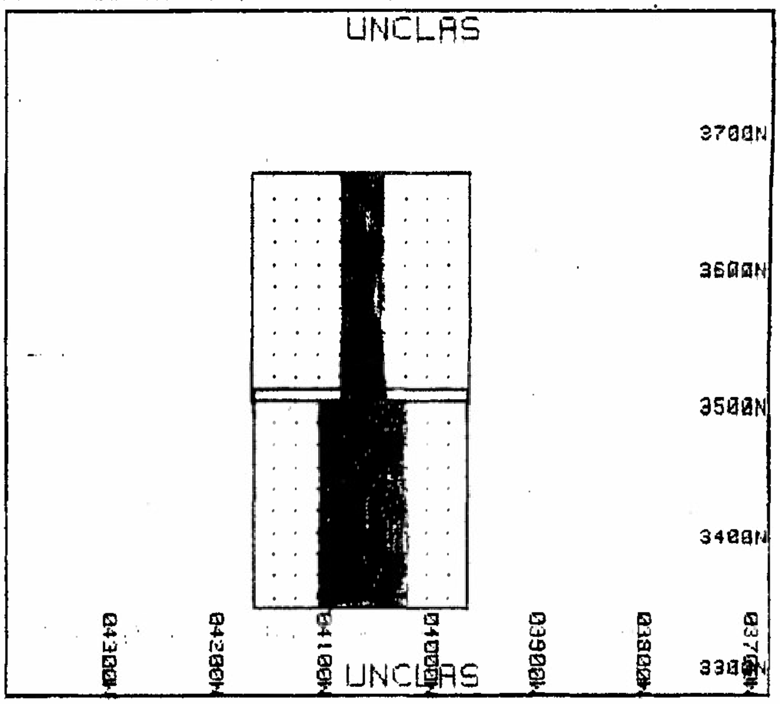
FIGURE IV-10. JOTS/ITDA/BARRIER SEARCH



An example is shown in Figures IV-14, IV-15, and IV-16. Non-zero probabilities and data which imply distance have been deleted for security. Here and later, some of the deletions are shown by xx. In Figure IV-14, we postulate a Soviet target SAG consisting of a CGN and two DDGs. The CGN is shown at the center of the AOU. Three Harpoon shooters are entered (class identification not needed). The postulated sequence of firings and various launch data are shown in the tableau in Figure IV-14; four Harpoons are fired at the CGN and two each at the DDGs, as depicted graphically. More complex firing sequences are readily accepted (and by TOMAHAWK and HARPOON in JOTS, which do rather little by way of evaluation).

FIGURE IV-11. JOTS/SURFACE SURVEILLANCE

MAP CENTER/ RADIUS = 3527N 04017W 0152NM



SURFACE SURVEILLANCE ASSIGNMENTS FOR SCENARIO: SURVSC1
THREAT SPEED: 25 GRID CENTER: 3508N 04032W
LAST SEARCH START: 141201 Mar 89 PLOT TIME: 141600 Mar 89

##	ID	START DTG	END DTG	LAT	LNG	ANG	ANG	RNG	RNG
1	S2	141200 Mar	141500 Mar	3333N	04032W	***	000	100	100
2	S1	141200 Mar	141500 Mar	3508N	04032W	***	000	100	100

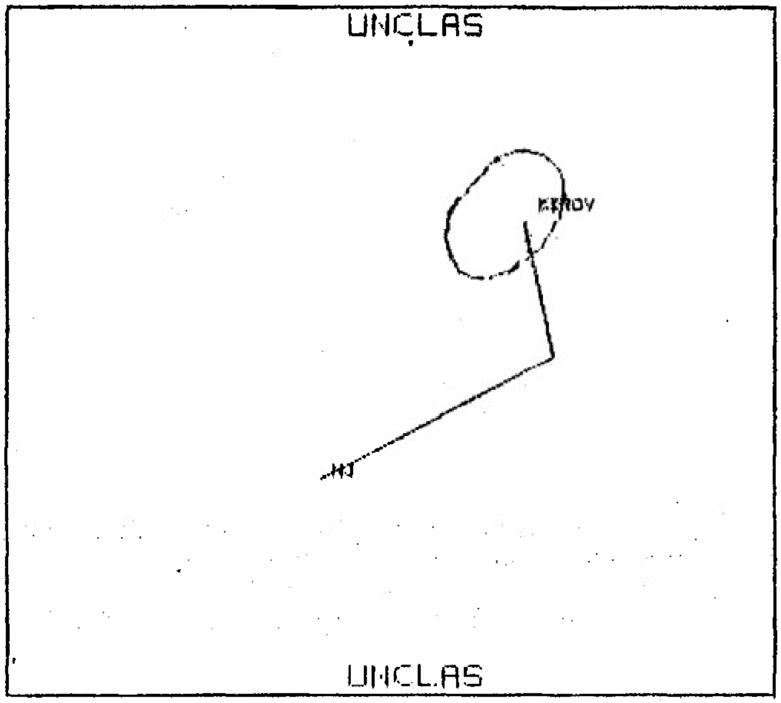
Probabilities of acquisition and hits, called PACQ's and PHIT's, are displayed in the (censored) form shown in Figure IV-15. First is shown the probability of a given Harpoon acquiring a given target, and then is shown the probability distribution of the number of acquisitions on a given target, and similarly for hits. A user who runs such an example may be puzzled by seeing, for example, a probability that all Harpoons aimed at a given target acquire that target which is quite close to the lowest of the single-Harpoon acquisition probabilities (an upper bound). That is because these acquisition events are highly correlated by their geometry. To a lesser degree, a similar remark applies to hits.

An engagement summary is also displayed. Figure IV-16 shows only the first page. This is a time sequence of events at the target scene (again with key output data deleted) which would occur if the CGN were *actually* at the center of the AOU (perfect targeting).

We now describe the modeling in SASHEM, primarily in the targets' ASMD. Much of the methods might have application in other ASMD problems.

FIGURE IV-12. JOTS/TOMAHAWK

MAP CENTER/ RADIUS = 3558N 03819W 'NM

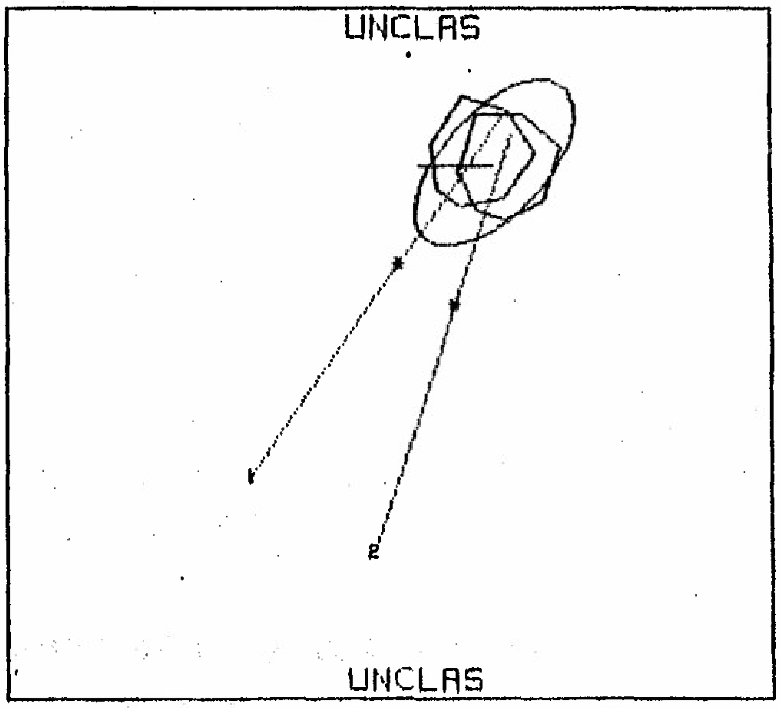



```
TOMAHAWK SCENARIO: THSC1

TARGET        POSIT TIME     LAT     LNG   MAJ MIN ANG CSE SPD CUN SUN
KIROV        121200 Mar 89  XX 'N  XX   W          045 270 015 040 003

SHOOTER       LAT     LNG  CSE SPD  PL PACQI LAUNCH TIME  TIME TO ELLIPSE
NJ              N       W 045 015      .XX  121200 Mar 89  12XXXX Mar 89

TOMAHAWK DATA
RADAR RANGE(NM): XX
LAUNCH PATTERN :PL- XX
CONTAIN ELLIPSE: XX
```

Each Harpoon flight is given a piecewise linear track until acquisition. It has a fixed speed throughout which depends on environmental inputs (although wind is an input, the program no longer uses it). If the Harpoon would lose time turning at launch to its course, that it is not recognized.

FIGURE IV-13. JOTS/HARPOON

MAP CENTER/ RADIUS = 3623N 03726W . NM



HARPOON SCENARIO: HASCI

TARGET	POSIT TIME	LAT	LNG	MAJ	MIN	ANG	CSE	SPD	CUN	SUN
KIROV	121200 Mar 89	XX N	XXX W	XX	XX	045	270	015	030	003

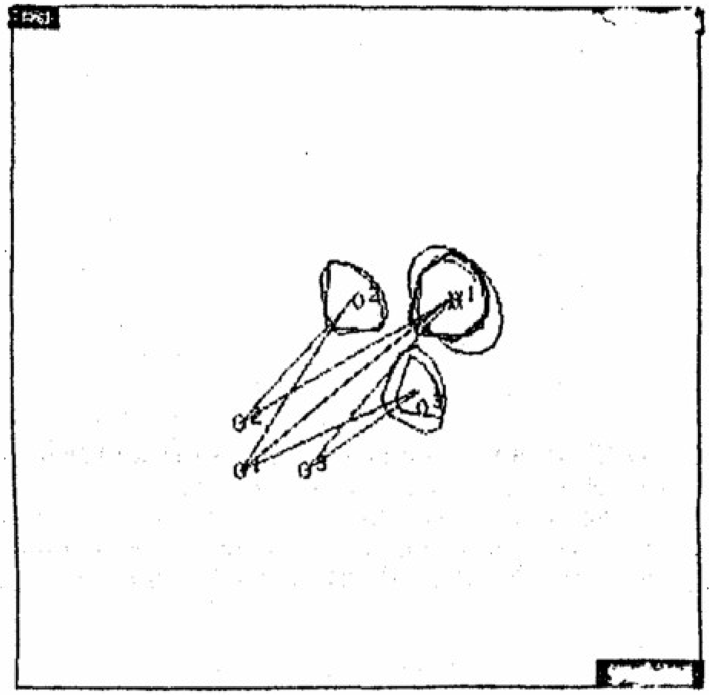
#_SHOOTER	LAT	LNG	CSE	SPD	PAT	LAUNCH TIME	TIME ON TOP	USER FIRE	FIRE BRG	RNG NM
1 1EX	XXXX N	XX XX W	045	015	XX	121200:05	1212 XX		037	XX
2 MD	XXXX N	XX XX W	045	015		121200:02	1212 XX		015	XX
3										
4										
5										

ENVIRONMENTAL DATA

1. TEMP(C) :	25	3. SEA STATE :	2
2. WIND SPEED/DIR:	10 / 270	4. RAIN(MM/HR):	0.0

At the scene of the targets, the SAG formation is advanced according to its input course and speed, and the AOU is expanded linearly at a rate derived from the input course and speed uncertainties. The expansion ceases at mean time of arrival of the Harpoons at their aim points. The expanded AOU is approximated by a 7 x 7 rectangular grid of 49 cells of uniform size, chosen to approximate the 3-sigma ellipse centered on the user-entered 90% ellipse. We suppose that the "center" of the target SAG, we'll call it the CGN following our example, is moved to the center of one of the cells; the target units are moved in formation. We perform a detailed ASMD analysis for that circumstance, repeat for each of the cells in turn, and combine the results over the 49 cells, weighted by the cell probabilities.

FIGURE IV-14. ITDA/SASHEM



ENVIRONMENT	
1.TEMPERATURE(F)	:60
2:SEA STATE	:3
3:RAINFALL(mm/hr)	:4
4:WIND SPEED(nm/hr)	:14
5:WIND DIRECT	:90

FORMATION

DDHHMMSS	MON	YR	DDMMN	DDDMMW	SMJ	SMN	ANG	CSE	SPD
08170000	MAR	89	XX N	XX E	.XX	.XX	135	270	15

##	BRG	RNG	PLATFORM
1	0	0	KIROV 2 CGN
2	270		KASHIN DDG
3	200		KASHIN DDG

HARPOONS

SH	WP	LAUNCH TIME			WAYPOINTS AIMPOINT		RNG	BRG	VAR		OFF AXIS	ENAB RNG	DEST RNG
##	##	DDHHMMSS	MON	YR	DDMMN	DDDMMW	XX.X	XXX.X	XXXX	PATTRN	XXX	XX.X	XX.X
1	1	08170000	MAR	89	XX N	XX E	XX	55.7	XX	XX	0	XX	XX
1	2	08170030	MAR	89	N	E		37.8			0		
1	3	08170130	MAR	89	N	E		59.8			0		
1	4	08170200	MAR	89	N	E		55.4			0		
2	1	08170000	MAR	89	N	E		47.1			0		
2	2	08170100	MAR	89	N	E		53.5			0		
3	1	08170000	MAR	89	N	E		60.2			0		
3	2	08170100	MAR	89	N	E		45.3			0		

FIGURE IV-15. SASHEM ACQUISITION AND HIT PROBABILITIES

SINGLE-SHOT ACQUISITION PROBABILITIES

SHT	HRP	TARGET 1	2	3
1	1	0.XX	0.00	0.00
1	2	0.00	0..	0.00
1	3	0.00	0.00	0..
1	4	0...	0.00	0.00
2	1	0.00	0. .	0.00
2	2	0.:	0.00	0.00
3	1	0.00	0.00	0. :
3	2	0.	0.00	0.00

Distribution of # acquisitions on each target

# ACQ's	TARGET 1	2	3
0	0.XX	0.XX	0.XX
1	0.	0.	0.
2	[illegible]	0..	0..
3	0.	0.00	0.00
4	0.	0.00	0.00
5	0.00	0.00	0.00
6	0.00	0.00	0.00
7	0.00	0.00	0.00
8	0.00	0.00	0.00

PROBABILITIES OF TARGET HIT TABLE

SHT	HRP	TARGET 1	2	3
1	1	0.XX	0.00	0.00
1	2	0.00	0...	0.00
1	3	0.00	0.00	0.
1	4	0..	0.00	0.00
2	1	0.00	0.	0.00
2	2	0..	0.00	0.00
3	1	0.00	0.00	0.
3	2	0.	0.00	0.00

Distribution of # hits on each target

# HITS	TARGET 1	2	3
0	0.XX	0.XX	0.XX
1	0.	0	0.
2	0.	0	0.
3	0.	0.00	0.00
4	0.	0.00	0.00
5	0.00	0.00	0.00
6	0.00	0.00	0.00
7	0.00	0.00	0.00
8	0.00	0.00	0.00

We now describe the engagement analysis conditioned on the CGN being in a particular cell.

Some ground rules are that (a) all Harpoons work as designed, (b) hostiles are fully alerted, (c) there is no coordination of hostile targeting, (d) all hostile weapon systems are free to fire at anything aloft (free fire area defense), and (e) a given weapon system engages a given Harpoon at most once.

Each Harpoon is dead-reckoned along its given track unless and until its seeker pattern contains a target unit. Its seeker scan logic and environmental effects on acquisition are modeled as in reference (l). Upon acquisition that event is scored and thereafter the Harpoon heads toward the acquired target unit at the same speed. It continues even if killed (with some probability) without effect on its absorption of additional ASMD (a model defect), but its hit on the target is diminished by the probability that it was killed en route.

The targets' ASMD assets are long range SAMs, medium range SAMs, and CIWS guns. Their capabilities are stored in memory according to class of USSR surface combatants. Each weapon system has a maximum range and minimum range. Each target platform has a coverage sector for each of its ASMD weapons. A weapon system "bears" on a Harpoon that is in its coverage sector and is between the weapon system's maximum and minimum ranges. However, the engagement modeling also considers whether or not a weapon system which bears on a Harpoon is also free to engage it, i.e., is not engaging another Harpoon.

FIGURE IV-16. SASHEM ENGAGEMENT SUMMARY

ASMD DOCTRINE: SHOOT- XX

SCENARIO TIME	HARPOONS	SHOOTERS	TARGETS	SALVO SIZE
08170000 MAR 89	8	3	3	1

ASMD	TARGET		HARPOON	SHOOTER	TIME	SINGLE SHOT PK	CUM.PK
SA-N-6	1	INTERCEPTING	2	3		0.XX	0.XX
SA-N-6	1	INTERCEPTING	2	3		0.	0.
SA-NX-9	1	INTERCEPTING	2	3		0.	0.
SA-NX-9	1	INTERCEPTING	2	3		0.	0.
SA-N-6	1	INTERCEPTING	1	1		0.	0.
SA-N-6	1	INTERCEPTING	2	3		0.	0.
SA-N-6	1	INTERCEPTING	1	1		0.	0.
SA-NX-9	1	INTERCEPTING	1	1		0.	0.
SA-NX-9	1	INTERCEPTING	2	3		0.	0.
SA-NX-9	1	INTERCEPTING	1	1		0.	0.
SA-N-6	1	INTERCEPTING	1	1		0.	0.
630	1	IMPACTING	2	3		0.	0.
SA-N-6	1	INTERCEPTING	2	2		0.	0.
SA-N-6	1	INTERCEPTING	2	2		0.	0.

Each platform has at most three types of sensors, surveillance radar, fire control radar, and passive electromagnetic intercept. The detection capability of each of these is characterized by detection range and probability that detection occurs. The target use a shoot-shoot-look-shoot firing doctrine, but the look is a long delay, so the third shoot usually occurs only for a long range SAM and a long detection range. There are fixed delays from detection of a Harpoon to assignment of a fire control radar, from that assignment to launch (which frees the launcher), and from launch to launch (for SAMs). There is also a calculated delay from launch to intercept (which frees the fire control radar), based on a constant weapon speed and a hind start to account for initial acceleration.

To handle the complication of whether or not a weapon system is free to engage, the engagement analysis is keyed to a sequence of "engagement events." An engagement event begins when a Harpoon comes within firing range of a given weapon system (meaning that if the weapon were fired at that moment the Harpoon will be within its maximum range at interception) and ends when the Harpoon reaches its CPA on that weapon system, impacts any platform, or comes within minimum weapon range.

The program first generates all possible engagement events without regard to whether a weapon system is *free* to engage. In general these are very numerous. They are ordered by start times, and the program services each in turn.

The servicing begins by calculating when the Harpoon is detected by the weapon system's platform, based on the detection systems on board. A "mean" detection range for the platform is found by averaging the sensor detection ranges with respect to their detection probabilities. A platform detection probability is found by adding the detection probabilities of disjoint events formed by the various combinations of detection by one or more sensors. The averaging of detection ranges is a disturbing model defect. E.g., a low range sensor can decrease the "mean" detection range unduly, in fact below the range obtained by deleting that sensor from the platform's assets! It would be better to obtain a platform cdp by, e.g., treating temporal correlation in individual sensors by a (λ,σ) model and sensor-to-sensor correlation by weighted averaging of cdp under independence with that of complete dependence, in analogy with a field of sonobuoys (see Appendix C). Perhaps inter-sensor independence is a reasonable assumption. At any rate, the model assumes that when a Harpoon comes within a platform's detection range it is detected with the platform's detection probability, denoted P_D.

We now come to a key point in the processing. We take the later of (a) the start of the engagement event being serviced and (b) the time the Harpoon comes within the platform detection range plus the detection-to-assignment delay. At that time a fire control radar is assigned and a launch ensues after the assignment-to-launch delay *providing* (1) a fire control radar is available (not otherwise engaged), (2) intercept is possible, and (3) a launcher is available if needed (a vertically launched SAM does not need a launcher). If (2) fails, the engagement event is canceled. If (1) or (3) fails, the engagement event is rescheduled as a "queue" event with start time at time of earliest possible availability of a fire control radar and a launcher. If at the new start time, another engagement has preempted the anticipated radar or launcher, that will be dealt with in the usual way when the queue event is serviced.

If assignment and launch occur, the probability that the Harpoon is killed at intercept, P_K, is calculated based on the aspect and range, from stored data obtained from NSWES, Point Mugu. The Harpoon's survival probability (initially 1) is decremented by multiplication by the current $1 - P_A P_D P_K$, where P_A is a fixed assignment probability and P_D is omitted after the first firing of a given weapon system on that Harpoon.

This processing continues until all engagement and queue events have been serviced. As time goes on, more and more events will be quickly canceled because of failure of (2) above. Each Harpoon is scored according to whether or not it acquired a target and which one, and according to its probability of surviving all weapon systems in the SAG which could bear on it (platforms are treated independently). If acquisition occurred, a Harpoon survival probability becomes hit probability for that Harpoon on its acquired target.

This completes the processing for the CGN at a given grid cell. We now move the CGN to the next cell and repeat the processing. When all 49 cells have been treated, we combine the acquisitions and the hit probabilities by Harpoon-target pairs over the 49 cells, weighted by the cell probabilities. From these combined results, single-Harpoon acquisition and hit probabilities on a given target and corresponding distributions of number of acquisitions and number of hits on a given target are determined. These resulting probabilities and distributions are displayed as outputs as in Figure IV-15. From the sequences of events with the CGN at the *center* cell, the engagement summary is formed and displayed as in Figure IV-16.

Probably the most important innovation in SASHEM is the treatment of a complex set of events, which happen rapidly in real time, as an ordered sequence, with preservation of the ordered property by the rescheduling of engagement events as queue events, as needed. In other respects also, it appears to be an excellent approach to modeling ASMD and acquisitions by Harpoons. It also might be considered to be overmodeled in light of input accuracies, but we do not consider that a significant criticism if user-friendliness is retained, which we believe is so. We have also noted some defects, notably, in apparent order of importance, (i) a dubious approach to platform cdp, (ii) allowing Harpoons that have been killed to continue to absorb ASMD after being killed (with some probability), and (iii) over-simplification of Harpoon kinematics. These defects are known to the developers and (i) and (iii) have feasible remedies; (ii) appears difficult to overcome.

4.4. AAW TDAs

The first observation on AAW TDAs in JOTS and ITDA (or anywhere else on DTCs) is that they are intended purely for pre-engagement planning and not for real time assistance during AAW combat. Planning versus real time aid may be a debatable point in other warfare areas, but not in AAW, where the action is much too fast for the present DTC/TDA state of the art.

Another observation is that nothing is probabilistic in the AAW TDAs in ITDA or JOTS, with a minor exception in JOTS/CAP STATIONS. The optimizations are generally in terms of choosing an interception parameter to meet certain requirements. There are interior optima in ITDA's computation of keepout range and CAP station range, and possibly in JOTS/CAP STATION. The analyses in the TDAs of this section are essentially descriptive and are based on kinematics and, in TARS, a scheduling algorithm. Models of SAM dynamics in ASMD are taken from specialists in the subject.

The figures for this discussion of AAW are taken from reference [d], except that Figures IV-21, IV-23, and IV-24 are from reference [a] and Figure IV-20(a) is from reference [o].

A useful suggestion in reference [p] with which we concur is that these AAW programs use times which refer to a problem start as zero rather than use date-time groups. At least it would be good to have this as a user option, in both ITDA and JOTS. In planning uses, which are the only uses in AAW, it can be more confusing and harder to remember the time situation when using DTGs rather than time from start. Also, DTGs require more keystrokes for entry, particularly if the program requires month and year for each entry (which PACSEARCH does not). On the other hand, at least one Fleet user has insisted that time entries should be confined to DTGs to help with "sailor-proofing."

Except for ITDA/ASMD, this section deals with detection, interception, and refueling problems involving carrier-based fighters and attacking ("threat") aircraft. Both combat air patrol (CAP) and deck-launched interceptors (DLIs), with or without help from airborne early warning (AEW), are used.

4.4.1. ITDA/INTERCEPT. INTERCEPT in ITDA has three options, INTERCEPT THREAT, AEW STATION, and LONG RANGE INTERCEPT, which we discuss in turn.

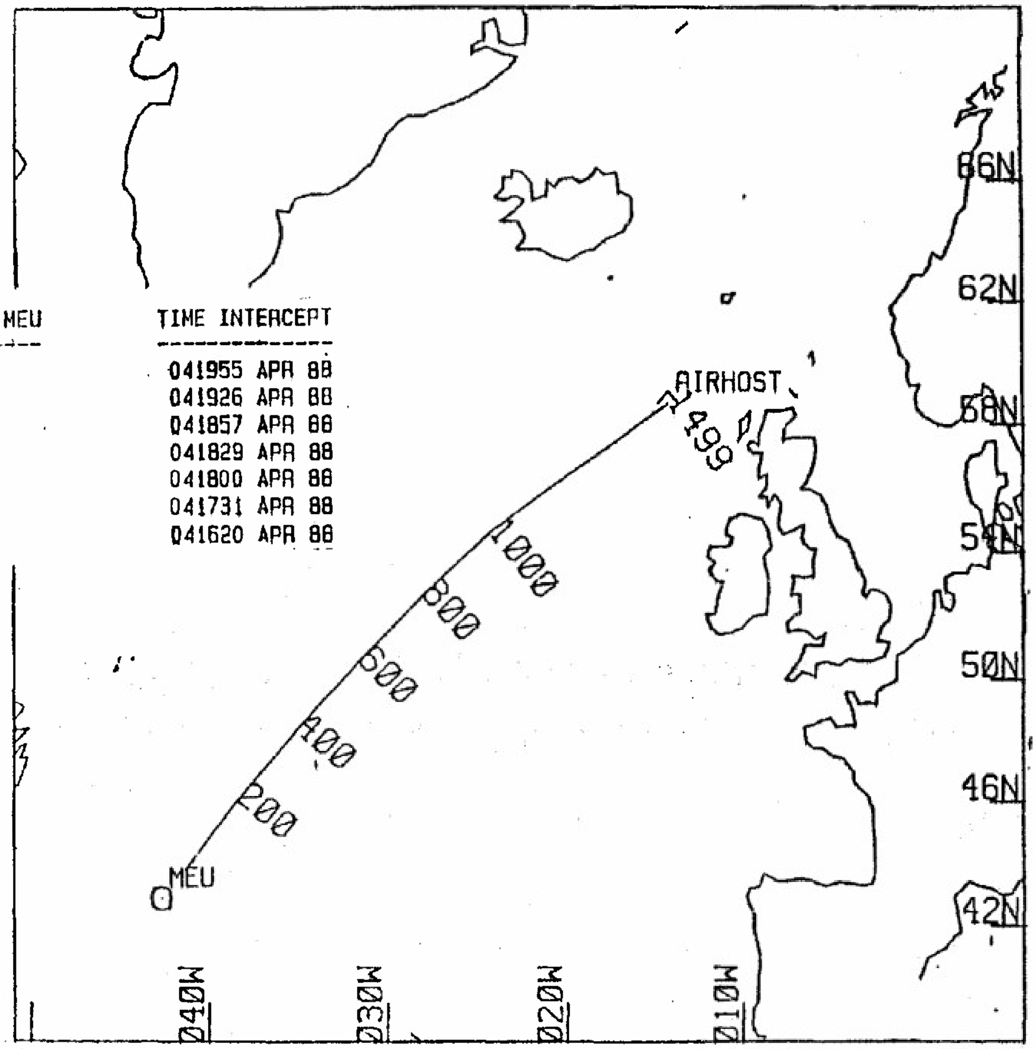
INTERCEPT THREAT deals with a threat aircraft (it would apply also to a threat ship), and computes and displays its track to intercept a friendly ship, denoted MEU for mission essential unit. The user may designate up to nine ranges from the MEU at which the threat arrival times and positions are displayed. An example is shown in Figure IV-17 with illustrative inputs and outputs.

One may apply this option reciprocally to obtain a friendly interceptor's track against a hostile target. Reference [p] anticipates this mode as being usual and suggests a toggle to reciprocate bearings rather than require the user to do so.

There are two support programs in both JOTS and ITDA which are closely related to this option, INTERCEPT ANALYSIS and TWO-TRACK ANALYSIS. These are accessed under AAW ACTION/CPA in ITDA and under PIMTRACKS in JOTS. INTERCEPT ANALYSIS accepts a track to be intercepted, the speed and course of a would-be interceptor, the time the interception is to start, and the interceptor's speed while intercepting; it outputs position of interception and the interceptor's course while intercepting. A waypoint requirement may be imposed on the interceptor. TWO-TRACK ANALYSIS accepts two tracks and outputs range and bearing from one to the other versus time.

We remark that in discussions of interceptions particularly, the user's guides are not as clear as they might be as to who does what to whom.

FIGURE IV-17. ITDA/INTERCEPT THREAT



RANGE FROM MEU	TIME INTERCEPT
ON TOP	041955 APR 88
200	041926 APR 88
400	041857 APR 88
600	041829 APR 88
800	041800 APR 88
1000	041731 APR 88
1500	041620 APR 88

The AEW STATION option either computes an AEW station, under COMPUTE AEW RANGE, or it accepts an AEW position and computes the threat range (keep out range) at which a DLI can intercept, under INPUT AEW RANGE. Various user inputs are required in both cases: for a threat aircraft and an MEU, position at a given time, course, and speed; threat altitude; AEW fly out speed and detection range on the threat; and DLI intercept speed, take off factor, and assurance factor. The take off factor is a time delay, apparently from launch decision to launch, taken as 7 minutes in the examples below. The assurance factor is another time delay, apparently allowing for things to go wrong. Reference [p] observes that there is no provision for AEW climb out speed deficit below its fly out speed (true also for the DLI) and suggests use of the assurance factor as an interim fix. It is further observed in reference [p] that input threat speed is treated by the program as the speed component *in the direction of the MEU*, and the user is not warned that correction is needed if the threat is transiting without approaching the MEU.

Under COMPUTE AEW RANGE, additional inputs are (1) the angle (zero in the example we give) between the desired bearing of the AEW and the threat bearing and (2) the required range from the MEU for the DLI to intercept the threat, uninformatively called the "fighter escort pickup range." The outputs are the minimum range from the MEU on the desired bearing for the AEW to be stationed and the latest AEW launch time in order to meet the requirements. An example is shown in Figure IV-18, with tableaus of inputs and outputs. The AEW detection range and the desired DLI intercept (pickup) range are graphed omni-directionally. Color-coding helps to clarify the display.

Under INPUT AEW RANGE, AEW station range is an input and the main outputs are the pickup range at which the DLI can intercept and the maximum allowed AEW angle off-axis.

By judicious choice of inputs and experimentation, AEW STATION can help the AAW planner-user to obtain a quantitative feel for the relationships between AEW stationing and DLI intercept ranges, for various threats.

The third and remaining option under ITDA/INTERCEPT is LONG RANGE INTERCEPT. Figure IV-19 is an illustration. Unfortunately, neither references [b] nor [d] describes the scenario underlying this problem, which we will try to do. It is the core of the Chainsaw tactic.

Two DLI's, call them F1 and F2, are launched 30 minutes apart, the "search interval." Reference [d] gives position, course, and speed of the threat and the MEU, but only the threat course (toward the MEU) and speed (400 knots) are relevant. When F1 has flown out 350 nm, the "search radius," it returns to the MEU. Thus the maximum detection range on threat axis is 100 nm radar range plus 350 nm fly out range, i.e., 450 nm. Suppose at this point, an on-axis threat is just beyond detection range, 450 nm from the MEU; F2 is .5 x 480 = 240 nm behind F1 so its range is 350 – 240 = 110 nm and its detection range on axis is 210 nm from the MEU. Where does F2 detect the on-axis threat just missed by F1? The distance closed is 450 – 210 = 240 nm at a closing speed of 480 + 400 = 880 knots, which requires .273 hours. In this time, F2's on-axis detection-range advances 130.9 nm to 340.9 nm which is the minimum on-axis detection range shown in Figure IV-19. The rest of the outputs follow easily from this.

If DLI's continue to be launched at the same intervals, an on-axis threat approaching at a random time can be detected at a range from the MEU between the minimum and maximum on-axis detection ranges output by this TDA, and similar remarks apply to the other outputs.

4.4.2. ITDA/JOTS/CAP STA. ITDA/CAP STA outputs a CAP station given interception requirements or alternatively interception coverage given a CAP station. No AEW is involved, so detection of the threat is by the CAP's own radar. JOTS/CAP STATIONS outputs multiple CAP stations and an AEW station, given interception requirements; it has a simple treatment of AAM kill probabilities.

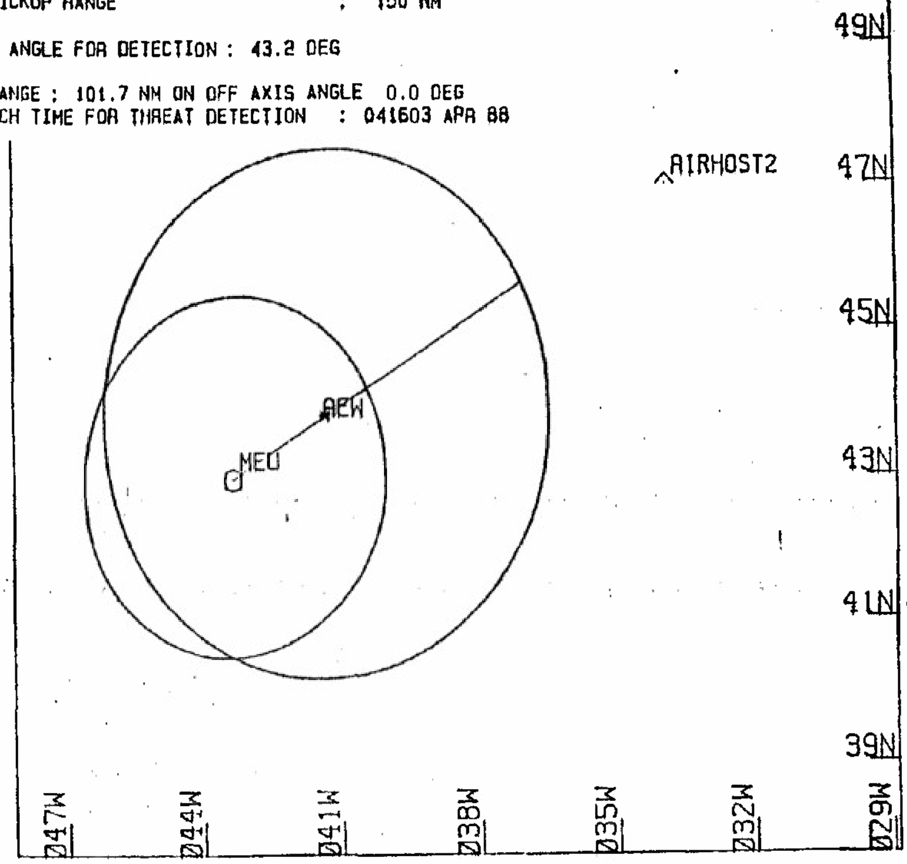
ITDA/CAP STA has three options: FIXED CAP RANGE, COMPUTE KEEP OUT, and COMPUTE CAP RANGE. All three use input tableaus with various inputs in common and produce output tableaus without graphics. The interception geometry is shown in Figure IV-20(a). Examples are shown in Figure IV-20(b). (Radar azimuthal coverage is shown as half angle in Figure IV-20(a) but as full angle in Figure IV-20(b).) The common inputs are threat aircraft speed = 600 knots, CAP intercept speed = 480 knots, and CAP radar has azimuthal coverage = 120 degrees and detection range = 100 nm.

FIGURE IV-18. ITDA/INTERCEPT/AEW STATIONING

AEW STATIONING RANGE ON AXIS : 101.7 NM
THREAT AIRCRAFT DETECTION RANGE ON THREAT AXIS : 321.7 NM AT TIME 041643 APR 88
FIGHTER ESCORT PICKUP RANGE : 150 NM

MAXIMUM OFF AXIS ANGLE FOR DETECTION : 43.2 DEG

AEW STATIONING RANGE : 101.7 NM ON OFF AXIS ANGLE 0.0 DEG
MAXIMUM AEW LAUNCH TIME FOR THREAT DETECTION : 041603 APR 88



1. AEW RADAR SENSOR DETECTION RANGE: 220 NM
2. FIGHTER ESCORT PICKUP RANGE : 150 NM
3. THREAT AIRCRAFT SPEED : 400 KTS
4. FIGHTER ESCORT INTERCEPT SPEED : 480 KTS
5. AEW FLY OUT SPEED : 150 KTS
6. DLI TAKE OFF FACTOR : 7 MIN
7. ASSURANCE FACTOR : 0 MIN
8. OFF ANGLE DIRECTION : CCW

MEU CSE/SPD: 045/18

THREAT CSE/SPD/ALT: 200/400/20,000

FIGURE IV-19. ITDA/LONG RANGE INTERCEPT

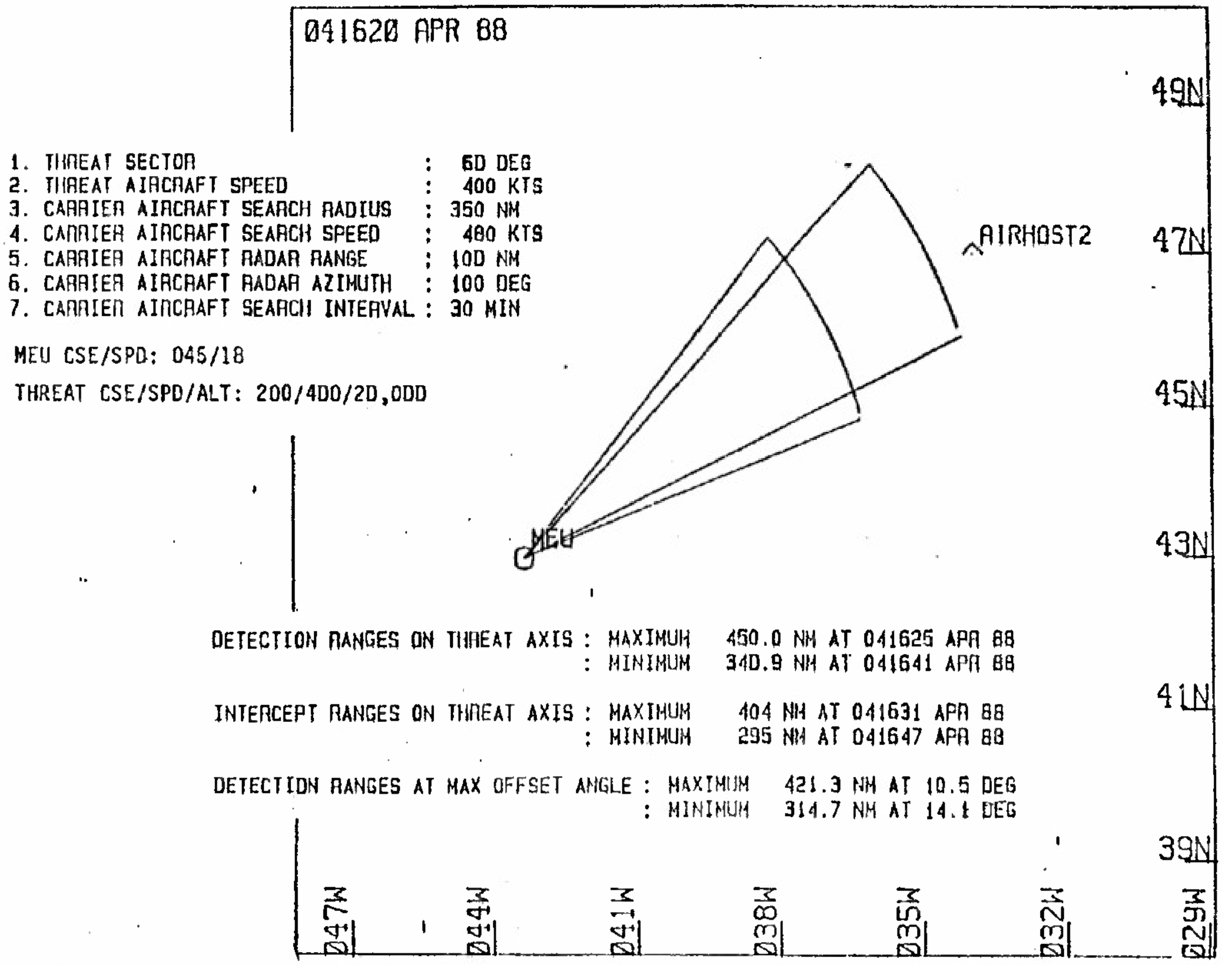


FIGURE IV-20. ITDA/CAP STA

(a) Station/Detection/Intercept Geometry

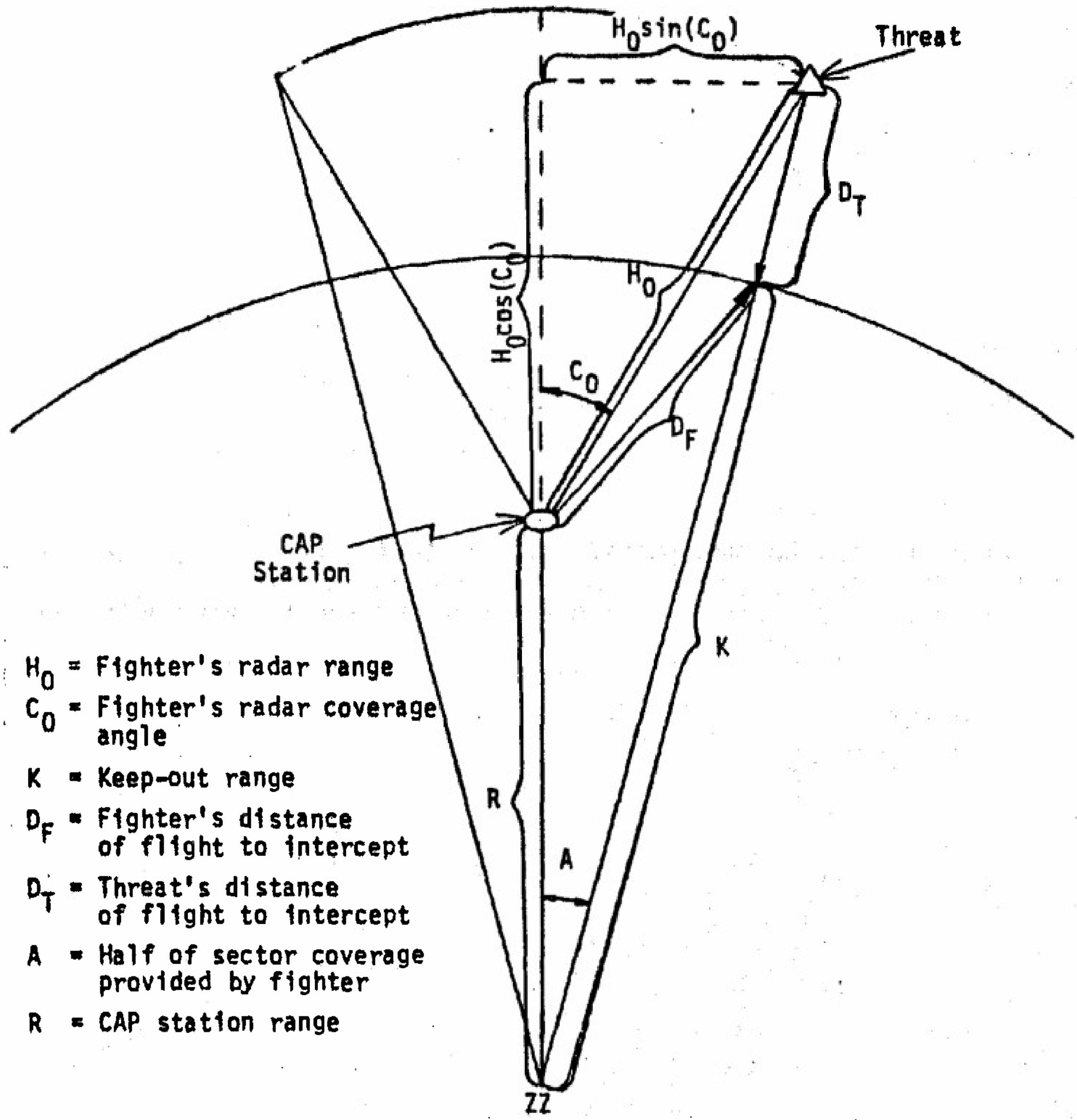


FIGURE IV-20 (Continued)

(b) Input/output tableaus

INPUTS **OUTPUTS**

FIXED CAP RANGE

1. THREAT AIRCRAFT SPEED	:	600 KTS
2. CAP INTERCEPT SPEED	:	480 KTS
3. CAP RADAR MAXIMUM AZIMUTH ANGLE	:	120 DEG
4. CAP RADAR DETECTION RANGE	:	100 NM
5. CAP STATION RANGE FROM MEU	:	100 NM
6. MINIMUM INTERCEPT RANGE FROM MEU	:	125 NM

CAP STATION RANGE FROM MEU: 100 NM
CAP INTERCEPT COVERAGE MEASURED FROM MEU: 42.0 DEG
MINIMUM INTERCEPT RANGE MEASURED FROM MEU: 125 NM

COMPUTE KEEP OUT

1. THREAT AIRCRAFT SPEED	:	600 KTS
2. CAP INTERCEPT SPEED	:	480 KTS
3. CAP RADAR MAXIMUM AZIMUTH ANGLE	:	120 DEG
4. CAP RADAR DETECTION RANGE	:	100 NM
5. CAP STATION RANGE FROM MEU	:	100 NM

CAP STATION RANGE FROM MEU: 100 NM
CAP INTERCEPT COVERAGE MEASURED FROM MEU: 60.0 DEG
MINIMUM INTERCEPT RANGE MEASURED FROM MEU: 106 NM

COMPUTE CAP RANGE

1. THREAT AIRCRAFT SPEED	:	600 KTS
2. CAP INTERCEPT SPEED	:	480 KTS
3. CAP RADAR MAXIMUM AZIMUTH ANGLE	:	120 DEG
4. CAP RADAR DETECTION RANGE	:	100 NM
5. MINIMUM INTERCEPT RANGE FROM MEU	:	150 NM

CAP STATION RANGE FROM MEU: 145 NM
CAP INTERCEPT COVERAGE MEASURED FROM MEU: 41.9 DEG
MINIMUM INTERCEPT RANGE MEASURED FROM MEU: 150 NM

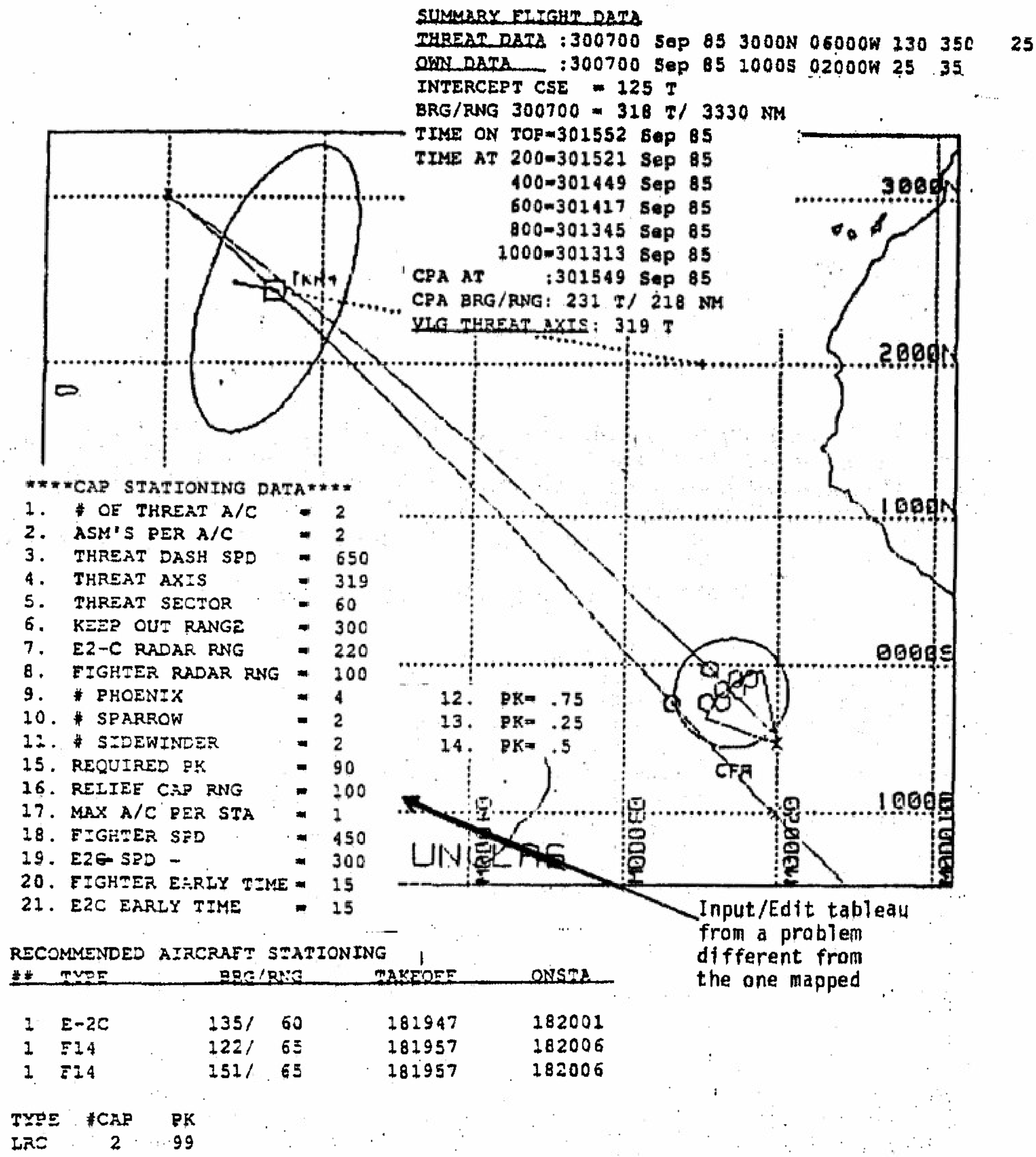
Under FIXED CAP RANGE, the additional inputs are the CAP station range from the MEU, here 100 nm, and a required intercept range from the MEU, keep out range, here 125 nm. The output is a coverage angle, here 42 degrees. This means that with the given inputs, the interception requirement can be met for any threat approaching on a bearing from the MEU within 21 degrees on either side of the CAP bearing from the MEU.

Under COMPUTE KEEP OUT, the same inputs are used as in FIXED CAP RANGE, except for keep out range. The program chooses the coverage angle, measured from the MEU as before, here 60 degrees, to maximize the keep out range, here 106 nm, under the remaining inputs (in the tableau this range is called minimum intercept range measured from the MEU).

Under COMPUTE CAP RANGE, the inputs are the same as under FIXED CAP RANGE, except that CAP station range is omitted and becomes an output instead. The program tries various station ranges, starting at 5 nm less than the keep out range and decreasing in 5 nm steps. For each it finds the coverage angle achieved subject to the keep out requirement. The solution here is a station range of 145 nm and a coverage angle of 41.9 degrees (this example is an end-point optimum, but in general the optimum is interior).

JOTS/CAP STATIONS accepts input data on a threat, fighters, and an AEW similar to ITDA/CAP STA inputs plus some inputs that appear to be redundant for the stationing problem. An illustration from reference [a] of an input/edit tableau, output tableau and geometry is shown in Figure IV-21. (The input/edit tableau is taken from a problem different from the rest of the figure (our juxtaposition).) The outputs are recommended number of CAP stations and recommended CAP and AEW stations. The rationale for the recommendations is not clear. Also output is a threat kill probability, evidently based on independently combining input AAM single-shot kill probabilities.

FIGURE IV-21. JOTS/CAP STATIONS



4.4.3. ITDA/JOTS/VECTOR LOGIC. Vector Logic is a polar coordinate system used by carrier aviation as a convenient means of identifying aircraft stations relative to the MEU or some other reference point. Ranges from origin are coded by A, B, C, ..., every 50 nm and bearings are coded by their first two digits. Thus 25C refers to the position bearing 250 at range 150 nm from the origin.

Both JOTS and ITDA have options which allow the user to enter stations in these coordinates and display them on a Vector Logic grid, as illustrated in Figure IV-22.

4.4.4. JOTS/ITDA/CHAINSAW. Data summary and graphical display illustrations on the Chainsaw fighter defense tactic are shown in Figures IV-23 and IV-24 respectively, taken from reference [a]. As noted above, ITDA/LONG RANGE INTERCEPT treats the kinematics of a given sector chain.

4.4.5. ITDA/TARS. The TARS acronym means Tanker AAW Refueling Schedules. From user-entered dispositions of CAP and tanker aircraft and other data, the program computes and tabulates a schedule of airborne refueling to meet a durability requirement and a summary of the fuel transfers. This program is accessed through ITDA/VECTOR LOGIC, although Vector Logic is not involved in the inputs or outputs. A user's guide with more details than are in reference [b] is reference [q]. The scheduling method, which is a rule-based production system form of artificial intelligence, is described in reference [r].

The program uses the term "grid" to refer to a geographic disposition and an array of inputs in the form of Figure IV-25. The user defines the geographic grid by choosing the number of sectors 30 degrees apart, ranges from the grid origin at which medium range (MR) and long range (LR) CAP are stationed, and any offset between the grid origin and the CV.

A key input is grid duration, i.e., the length of time the CAP stations must be manned. The user also specifies the average times for a CAP to be refueled by a carrier-based tanker and for a shuttle (carrier-based tanker) to be refueled by a land-based tanker, and whether or not each aircraft is initially topped off (ITO).

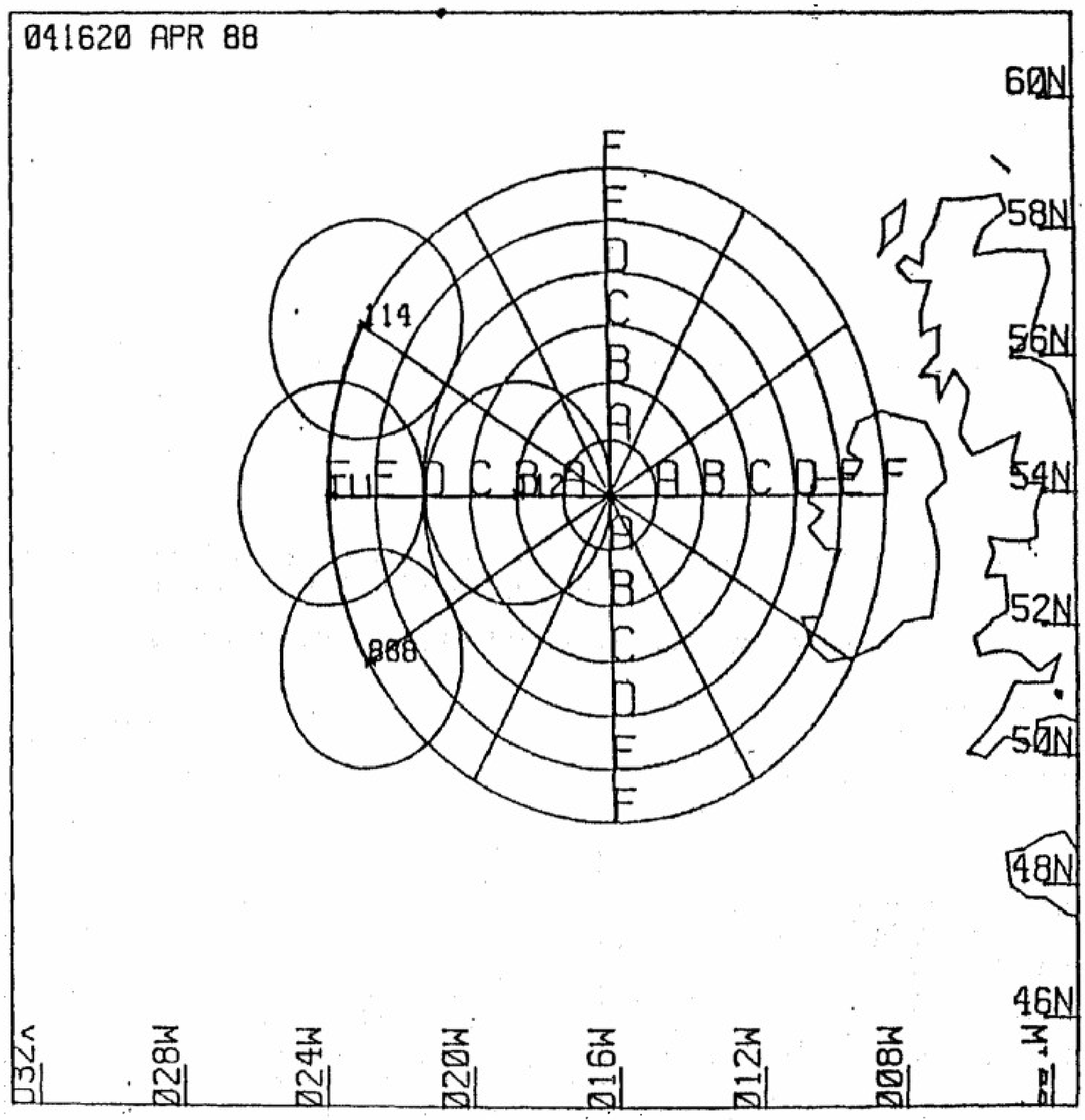
The user chooses a code to identify the various individual aircraft involved, i.e., each MR CAP, LR CAP, carrier-based tanker (CBK), at most one land-based tanker (LBK), DLI, support aircraft (SAC), and shuttle aircraft. If no LBK is used, the user may specify a CBK kingpin in each sector. Using his code, the user enters the aircraft disposition via the grid form in Figure IV-25, which is clarified by color coding.

Further assumptions are that all refuelings occur at MR, MR CAP relieve LR CAP during LR CAP refueling, and a DLI may relieve MR or LR CAP.

As an example, we assume one sector, MR = 150 nm, LR = 200 nm, zero grid origin offset, grid duration = 360 minutes, no LBK, SAC, or shuttle, and 5 minutes average time for CBK to CAP refueling. The aircraft disposition data are partly shown in Figure IV-25: #100 is an F-14 MR CAP and #200 is an F-14 LR CAP, both are ITO; T1 and T2 are KA-6D/300 CBKs, and neither are ITO.

This is a relatively simple refueling example. The solution schedule for CAP 100 and for both CBKs and the activity summary are shown in Figure IV-26. Running time for a problem with some twice as many aircraft is not bothersome, but one suspects that running time could be a problem with numerous aircraft involved (up to 50 are permitted). If a given problem does not have a solution, the message "grid not maintained" is displayed.

FIGURE IV-22. ITDA/JOTS/VECTOR LOGIC



ACTIVE STATIONS

#	STA	SNO	TYP	RNG
1.	30F	114	F14	100
2.	27B	112	F14	100
3.	24F	888	F14	100
4.	27F	111	F14	100

4.4.6. ITDA/ASMD. The function of ITDA/ASMD is to display contours of SAM coverage versus bearing, against an ASM threat of a given profile, based on own ship SAM capabilities. This is new to ITDA in 2.02; JOTS has no ASMD analysis, and previously, ITDA's only ASMD analysis was for hostile forces, in SASHEM.

FIGURE IV-23. JOTS/CHAINSAW--DATA

CHAIN SAW DATA SUMMARY

```
1. VICTOR LIMA                = 2900N 04500W
THREAT DATA                           CAP DECK-LAUNCH-INTERCEPT
2. THREAT AXIS   (000-360)    = 000   15. EGRESS SPEED (KTS/MACH) = 500 KTS
3. THREAT SECTOR  (0-180)     = 60    16. ENGAGE RANGE   (NM)     = 0  NM
4. THREAT ALT HIGH     (KFT)  = 26 KFT
5.        ALT LOW      (KFT)  = 2  KFT  TACTICAL CHOICES
6. THREAT INT RNG HIGH        = 200 NM  17. FLY OUT RANGE (NM)      = 200  NM
7.        INT RNG LOW         = 130 NM  18. LAUNCH DTG          = 181905 NOV 86
   THREAT SPEED                         19. STAGGER LAUNCH  Y/N     = Y
8.   CRUISE    (KTS/MACH)     = 500 KTS 20. LAUNCH INTERVAL  (MIN)  = 45 MIN
9.   DASH      (KTS/MACH)     = 700 KTS 21. R-A-D RANGE   (NM)      = 100 NM
                                        22. RADIALS (DEGT) = 330  350  010  030

 CAP  SURVEILLANCE
10.  ALTITUDE   (KFT)         = 18  KFT SUMMARY RESULTS:
11.  RADAR RNG HIGH (NM)      = 100 NM  DLI  INTERCEPT RANGE         = 56 NM
12.  JAM DET RNG     (NM)     = 230 NM  WORST CASE DETECTION         = 135 NM
13.  SPEED  (KTS/MACH)        = 450 KTS MAXIMUM FIGHTERS AIRBORNE    = 0
14.  FUEL FOR R-A-D  (LBS)    = 2400 LBS MINIMUM FIGHTERS AIRBORNE   = 0
```

*****ACRONYMS********

CAP: Combat Air Patrol

DLI: Deck Launched Intercept

R-A-D: Rope-A-Dope

****

The user builds a threat profile of up to eight legs. The start of the first leg is at time of SAM launch and the final leg is at range zero from own ship and altitude zero. A profile is illustrated in Figure IV-27, by graph and tableau.

The user builds a formation from units identified in the contacts data base (built and maintained in the local contacts manager base). SAMs are assigned to each unit from among the types SM-1(ER), SM-2(ER), and SM-2(MR). A mission essential unit is designated.

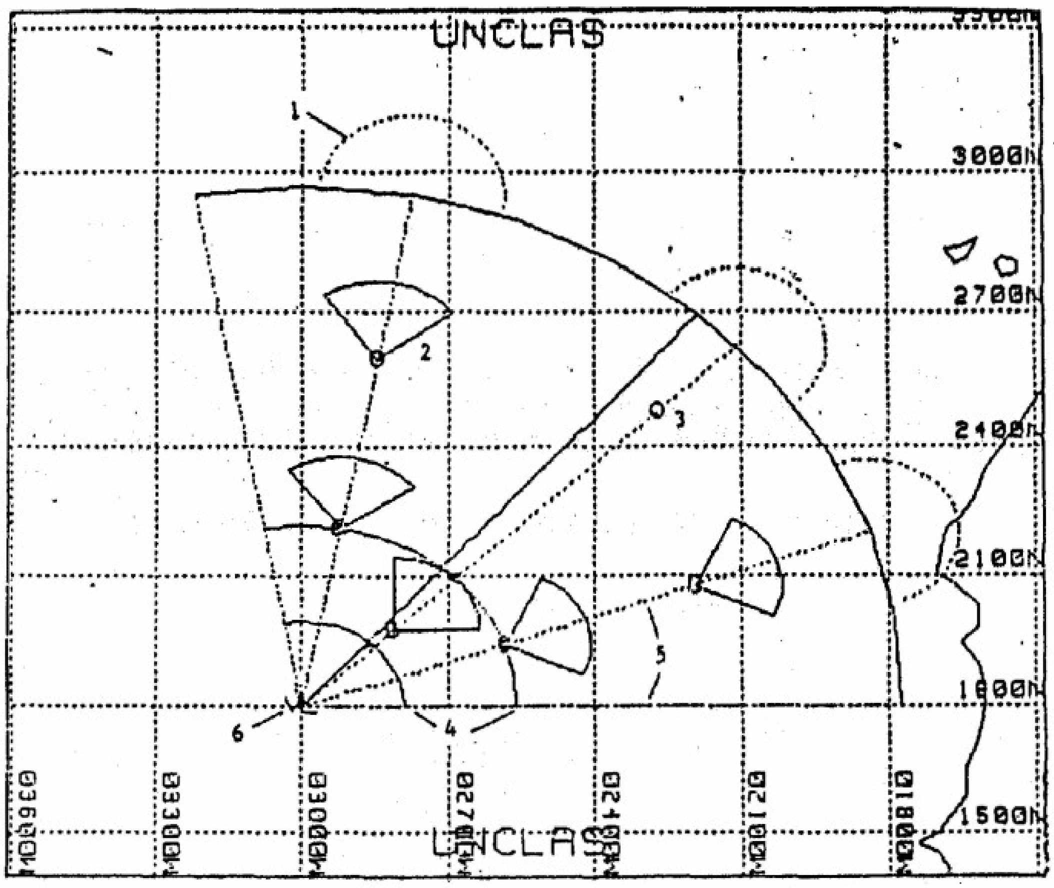
The output is a display of sector coverage contours, as illustrated in Figure IV-28. A contour in this context is a curve, not shown, through the tips of the displayed radials. As noted in 4.1.2, the radials are based on an APL/JHU model. They are indicative of the ASMD provided to the MEU, unit 1.

4.5. EW TDAs

ITDA/EW has three TDAs, SATVUL, SATCAT, and RADAR SHADOWING. JOTS II has had all three, but JOTS 5.0 dropped SATCAT. JOTS has IREPS (atmospheric effects on electromagnetic propagation) as had ITDA 2.01. ITDA and JOTS obtained these programs from the same external sources (see 4.1). ITDA 2.02 has dropped IREPS in favor of the Atmospheric Environment (AE) part of GFMPL. We will review the existing EW TDAs of ITDA and JOTS, but not IREPS or GFMPL-AE, in this section.

FIGURE IV-24. JOTS/CHAINSAW--GRAPHICS

CHAIN SAW TACTIC GRAPHIC DISPLAY



1 Green fly-out range and CAP sensor range beyond fly-out at end of radial

2 Yellow CAP sensor envelope

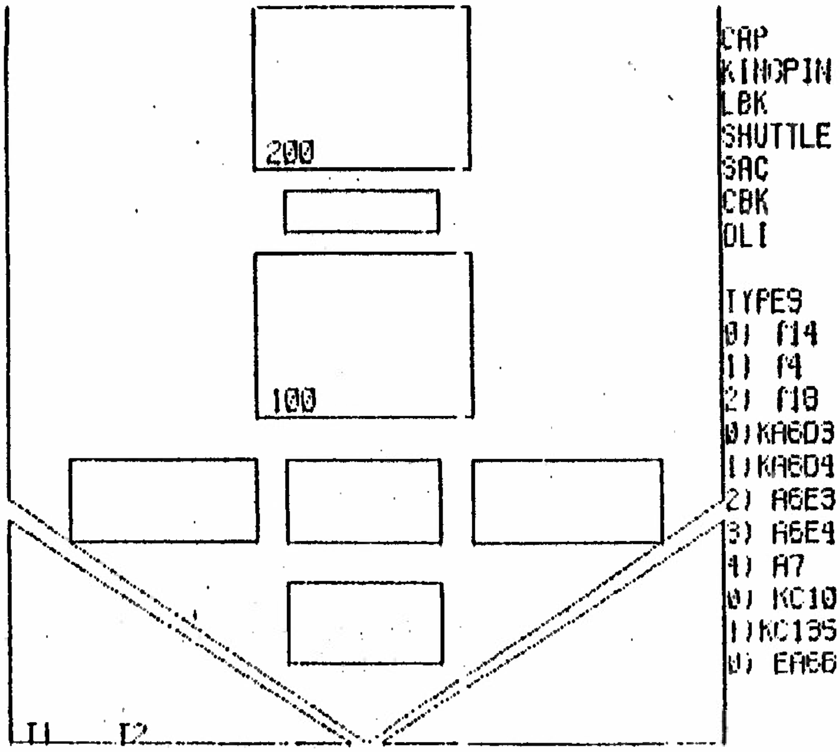
3 Purple returning CAP

4 White DLI intercept range and worst case detection range

5 Red sector limit line and CAP radial

6 VL=VICTOR LIMA

FIGURE IV-25. ITDA/TARS (TANKING AND REFUELING)-- INPUT GRID



It is noteworthy that neither ITDA nor JOTS has TDAs pertaining to jamming, electronic deception, or passive electronic detection and direction finding, which constitute the mainsteam of EW.

A survey of EW TDAs in all the armed services has been conducted by Northrup for the Joint Electronic Warfare Center, San Antonio, and is reported in reference [s]. Bibliographic PC software on three floppy discs has been prepared under the same auspices and includes findings during nine months of additional surveying after completion of reference [s]. Its user's guide is reference [t].

4.5.1. JOTS/ITDA SATVUL. SATVUL depicts the exposure of a ship to entry into satellite "footprints." The footprint of a satellite at a given moment is the locus of points on the earth's surface which are visible to the satellite's sensor(s) at that moment. It is also called effective field of view (EFOV).

Satellite data bases are maintained on satellite missions, orbit characteristics (called "charlie elements" or "orbele" data), and EFOV. These data originate from NAVSPASUR and may be revised from time to time. Friendly satellites are included.

Figures IV-29, IV-30, and IV-31, taken from reference [a], illustrate SATVUL output. Figure IV-29 gives an EFOV plot, showing footprints off Greenland (00147) and west of Ecuador (00116). Figure IV-30 displays future vulnerability of own ship's track--there is one 14-minute period of vulnerability, to 00147. A time line display output showing vulnerability to all satellites in a 112-minute period is given in Figure IV-31.

FIGURE IV-26. ITDA/TARS-SCHEDULES

SCHEDULE FOR 100

time	action	sector	tanker	amount(klbs)	tour	tourtype
53	GET FUEL	1	T1	6.5T	1	2
58	DEPART MR	1			1	2
66	ARRIVE LR	1			1	2
153	DEPART LR	1			2	2
161	ARRIVE MR	1			2	2
161	GET FUEL	1	T2	9.3T	2	2
227	GET FUEL	1	T1	5.7T	3	2
232	DEPART MR	1			3	2
240	ARRIVE LR	1			3	2
327	DEPART LR	1			4	2
335	ARRIVE MR	1			4	2
335	GET FUEL	1	T2	9.3T	4	2

SCHEDULE FOR ALL TANKERS

tanker	time	action	sector	platform	amount(klbs)	tour	tourtype
T1	25	LAUNCH	1			1	2
T1	53	FUEL		100	6.5T	1	2
T1	74	FUEL		200	8.4T	1	2
T1	79	RTN CV	1			1	2
T2	112	LAUNCH	1			2	2
T2	140	FUEL		200	5.7T	2	2
T2	161	FUEL		100	9.3T	2	2
T2	166	RTN CV	1			2	2
T1	199	LAUNCH	1			3	2
T1	227	FUEL		100	5.7T	3	2
T1	248	FUEL		200	9.3T	3	2
T1	253	RTN CV	1			3	2
T2	286	LAUNCH	1			4	2
T2	314	FUEL		200	5.7T	4	2
T2	335	FUEL		100	9.3T	4	2
T2	340	RTN CV	1			4	2

** ACTIVITY SUMMARY **

FUEL RECEIVED

AIRCRAFT	REFS	AMT FUEL
100	4	30.7
200	4	29.0

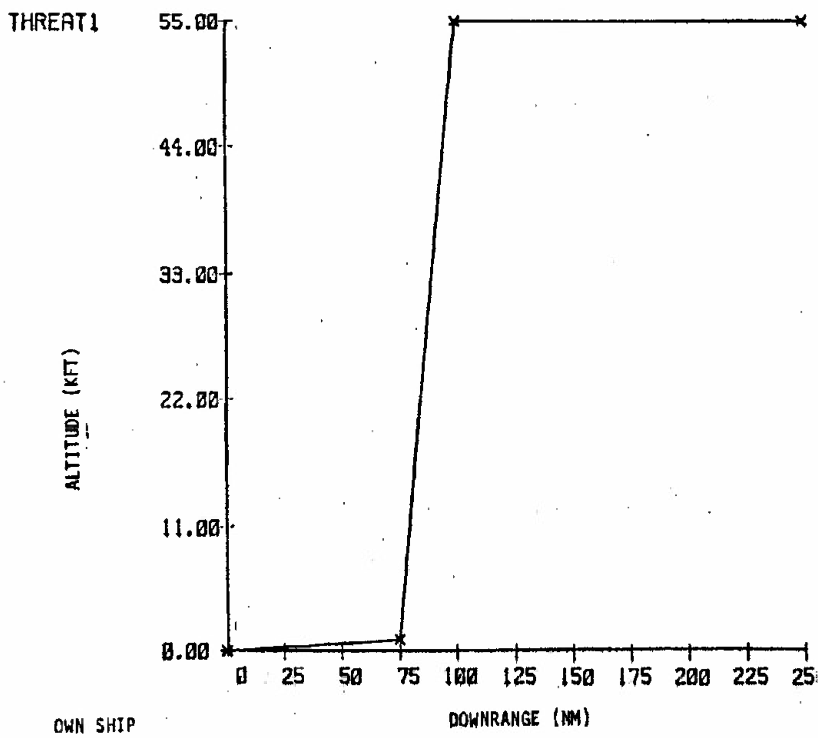
FUEL GIVEN

AIRCRAFT	REFS	AMT FUEL	SORTIES
T1	4	29.8	2
T2	4	29.9	2

TOTALS

NUMBER OF REFUELINGS	8
NUMBER OF CBK SORTIES	4
AMOUNT OF FUEL USED	59.7
NUMBER OF FUEL TRANSFERS	0

FIGURE IV-27. ITDA/ASMD--THREAT PROFILE



THREAT NAME: THREAT1

LEG	RANGE (NM)	ALTITUDE (FT)	SPEED (KNOTS)
1 *	250	55000	1000
2	100	55000	1000
3	75	1000	1000
4	0	0	1000
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0

* Range of Leg 1 = Launch Range

FIGURE IV-28. ITDA/ASMD--SECTOR CONTOURS

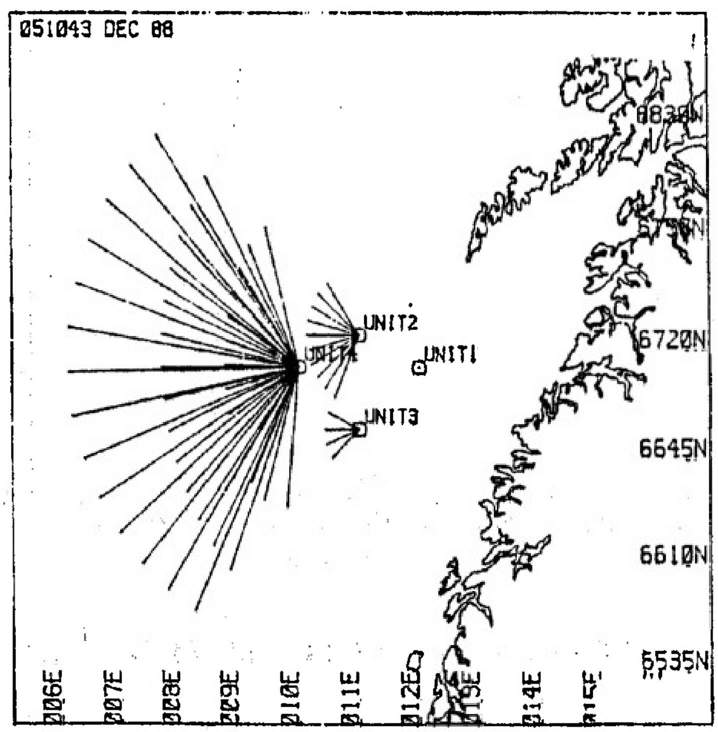


FIGURE IV-29. JOTS/ITDA/SATVUL--EFOV PLOT

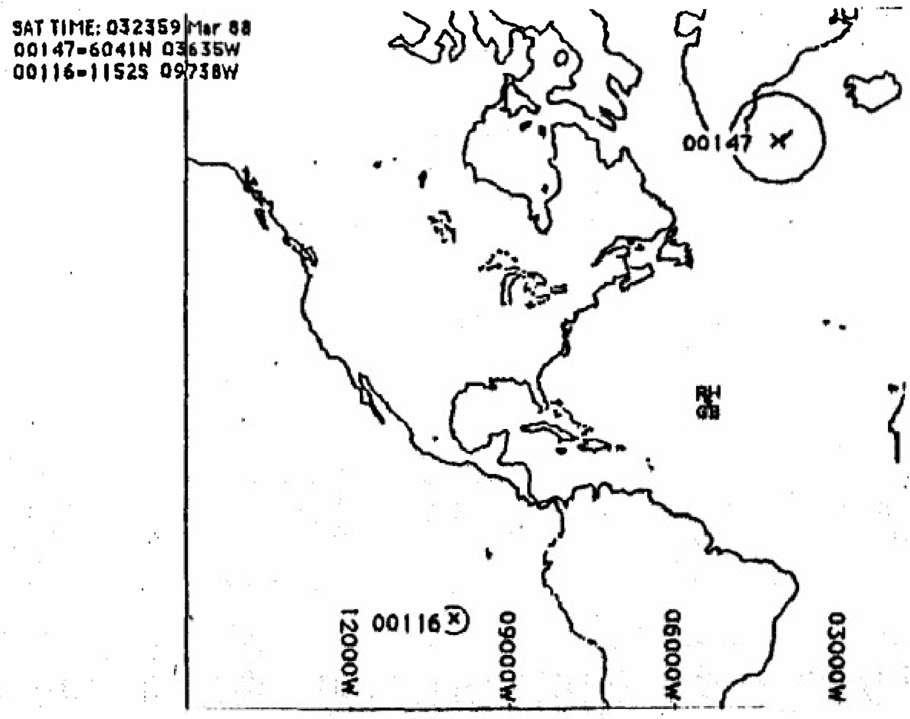


FIGURE IV-30. JOTS/ITDA/SATVUL--VULNERABILITY PLOT

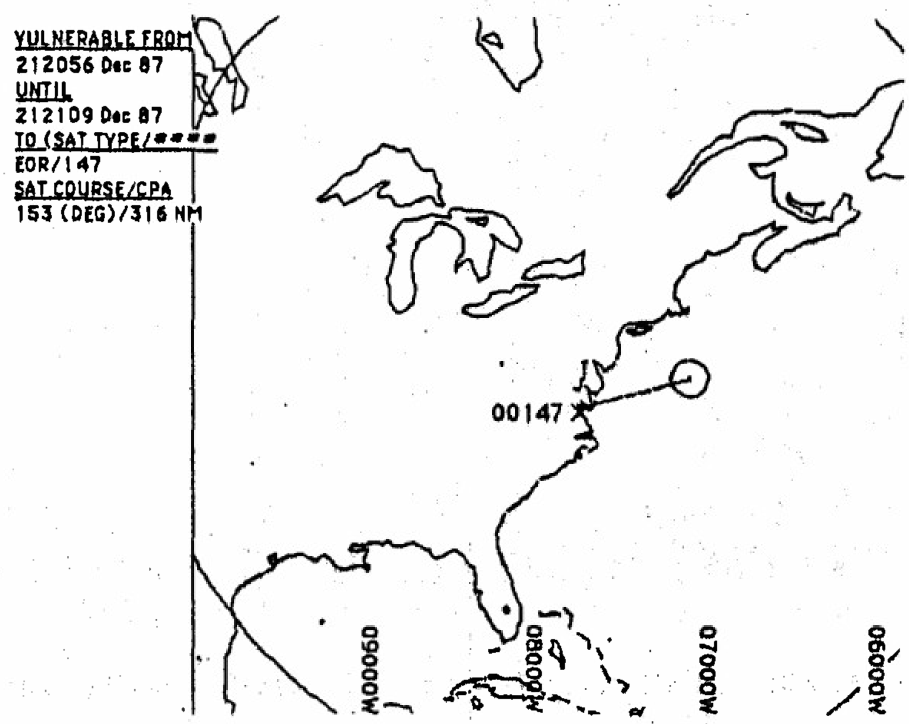
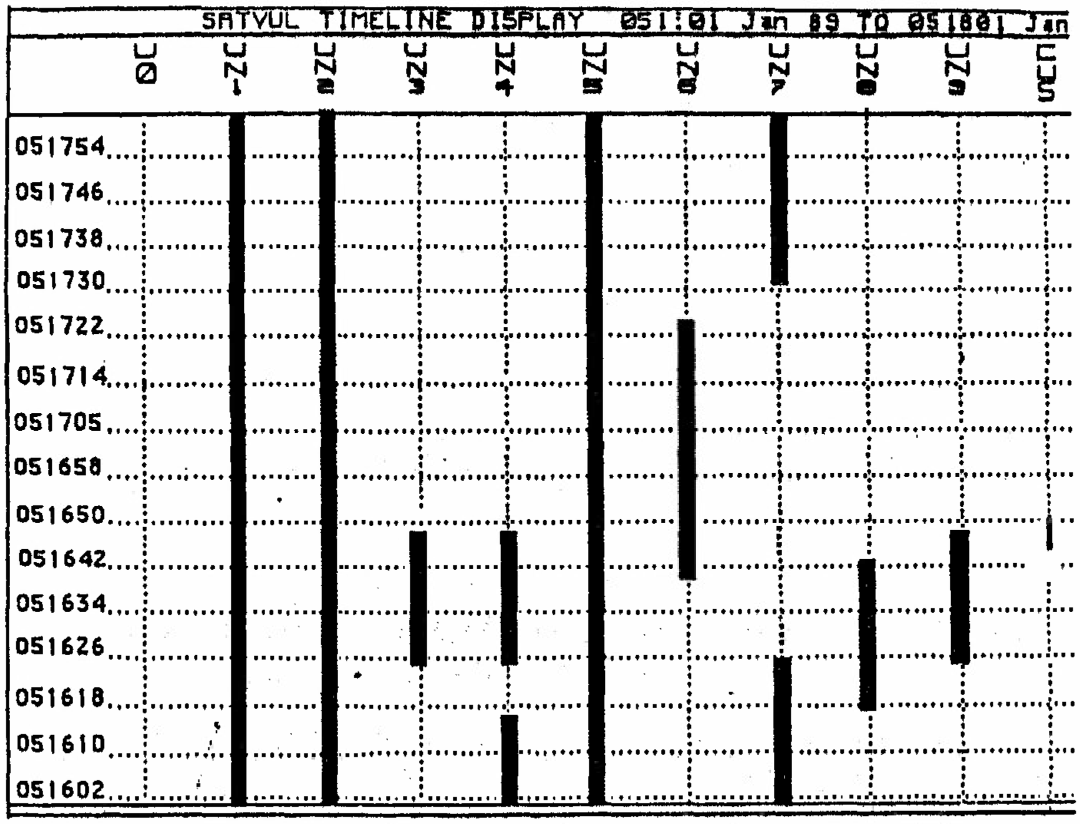


FIGURE IV-31. JOTS/ITDA/SATVUL--VULNERABILITY TIME LINE



4.5.2. ITDA/RADAR SHADOWING and JOTS/SHADOW. These programs output displays which show the aircraft positions relative to a ship from which there is line of sight between the two without terrain intervention and without atmospheric refraction. (In developing this program in the MED, CNA found that accuracy would not be improved by trying to account for refraction.) Ship height is ignored. This information is useful in determining ship detectability by aircraft approaching from land, the ship's ability to detect such aircraft, and detectability of carrier strike aircraft en route to land targets.

Crucial to the terrain shadowing programs is the world-wide data base, Digital Terrain Elevation Data (DTED), from the Defense Mapping Agency. Unfortunately, this data base takes up considerable storage space. In ITDA, for example, inclusion of DTED may require exclusion of some others of various optional data bases, depending on disc capacity available. Optional data bases may be switched in and out, but each insertion requires a two hour tape run. However, one may store DTED for relevant parts of the earth's terrain without covering all of it.

Outputs are illustrated in Figures IV-32 to IV-34, taken from reference [d]. Figure IV-32 shows a static shadowing situation in vertical cross-section. The shadowed portion of an overland aircraft track is shown in Figure IV-33. Blind zones for aircraft over land at a given altitude against an off-shore ship are shown in Figure IV-34.

FIGURE IV-32. ITDA/JOTS/RADAR SHADOW--STATIC AIRCRAFT

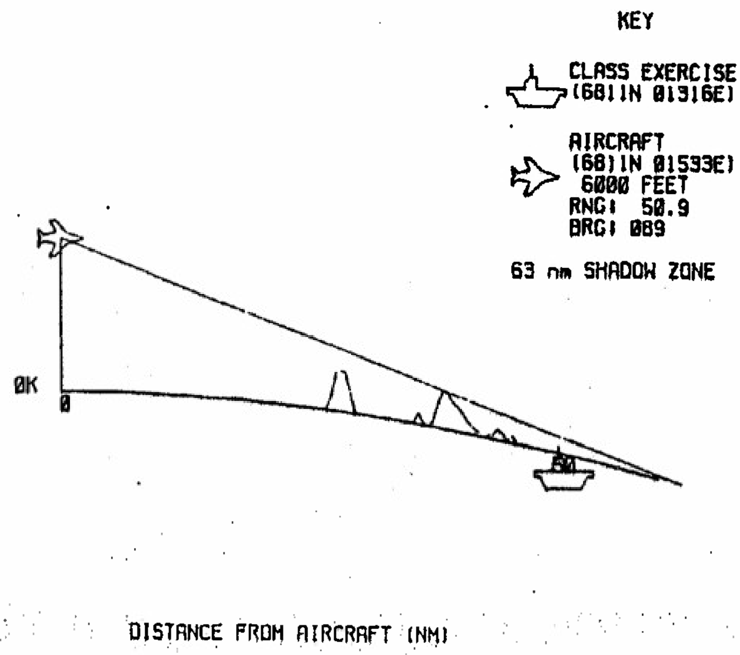


FIGURE IV-33. ITDA/JOTS/RADAR SHADOW--MOVING AIRCRAFT

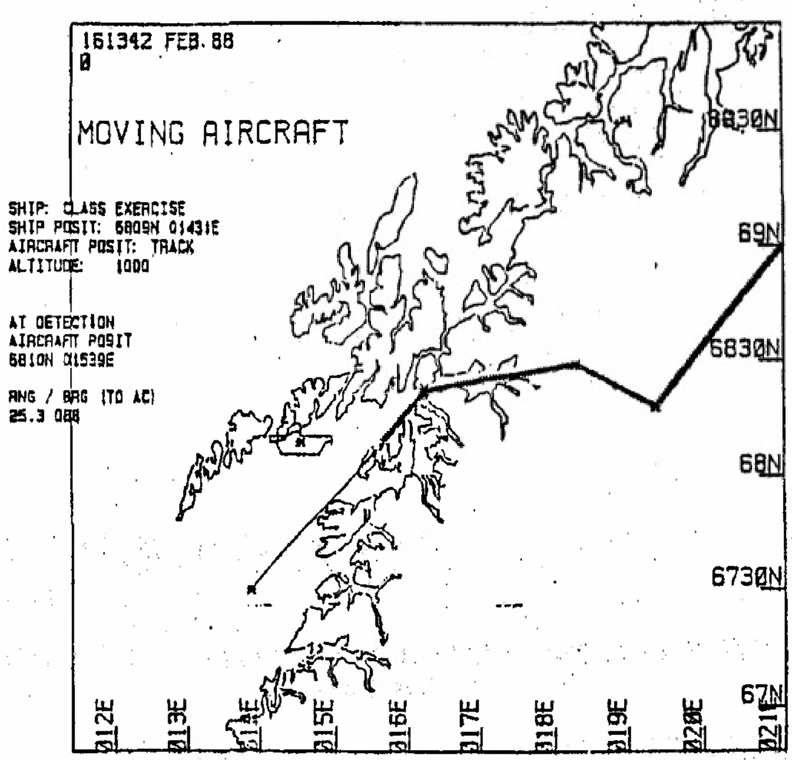
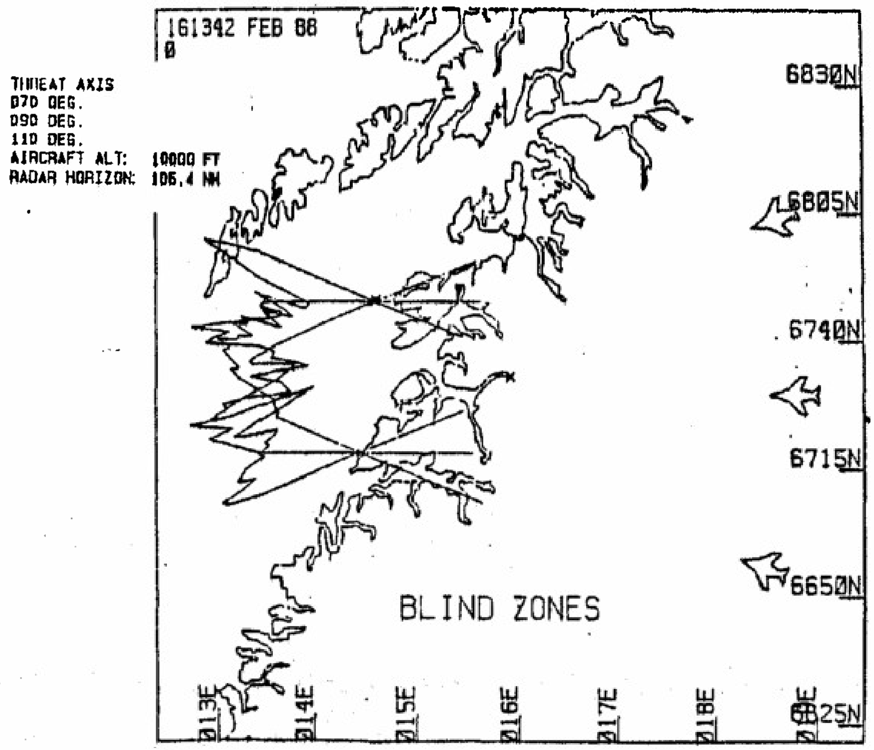


FIGURE IV-34. ITDA/JOTS/RADAR SHADOW--BLIND ZONES



4.5.3. ITDA/SATCAT. This deals with a communications relay (SATCAT) aircraft. If the region of required communications is known, the program computes the lat/long position and minimum altitude of the aircraft. If the aircraft station, including altitude, is known, the program computes the communications coverage. In both cases, the blind zone of the relay pod is determined, and the coverage and blind zone are displayed as in Figure IV-35.

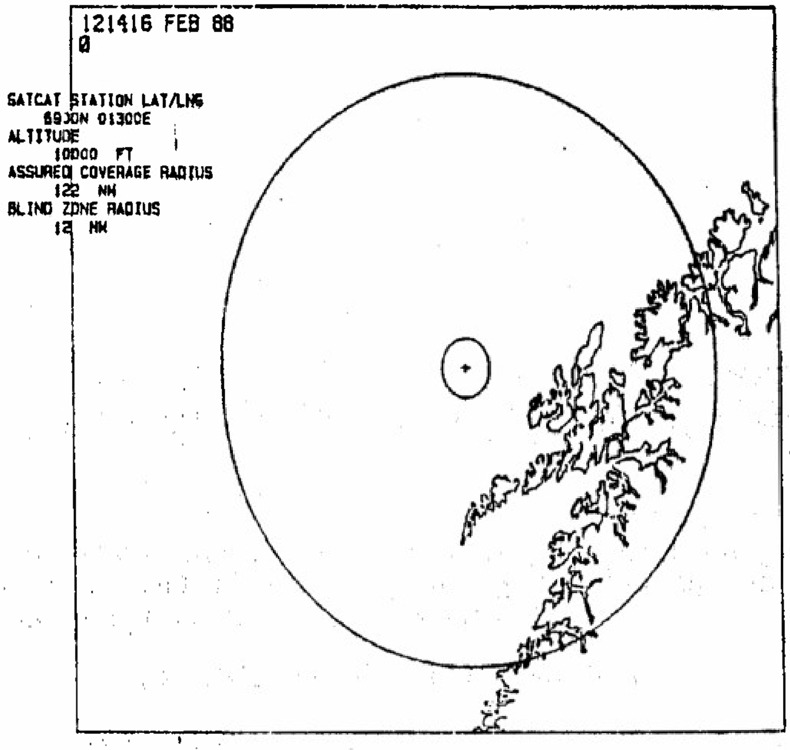
A recently developed communications relay TDA, pertaining to Chainsaw (see 4.4.4), is reported in reference [u], the NPGS thesis of LT C. W. Steffen under LCDR W. J. Walsh.

4.6. Tactical Aircraft Mission Planning System (TAMPS)

TAMPS is the Navy's principal air strike planning TDA. It is operational in carrier CVIC spaces and other air strike planning centers. It was developed by McDonnell Douglas in 1986, in major part by adapting previous software for planning Tomahawk strikes and using off-the-shelf hardware. The CPU is a MicroVAX II or III. Air crews are trained in TAMPS mainly at the Naval Strike Warfare Center ("Strike University"), NAS Fallon, Nevada.

Use of TAMPS is by individual strike pilots and NFOs, especially strike leaders. It is a very convenient software library which automates and substantially enhances information retrieval from a considerable array of manual sources of information such as in NATOPS, etc. Thus TAMPS enables naval aircraft strike planning to be done much more expeditiously and in a much more orderly fashion than was possible without software assistance. TAMPS presents to the user tactical options and consequences of user choices, without making recommendations to the user. Its evaluations are basically by table look-up rather than by internal modeling. It appears to be a very useful TDA.

FIGURE IV-35. ITDA/SATCAT



The organization of TAMPS is divided between data base maintenance and mission planning. The separate user's guides for these two functions are references [v] and [w].

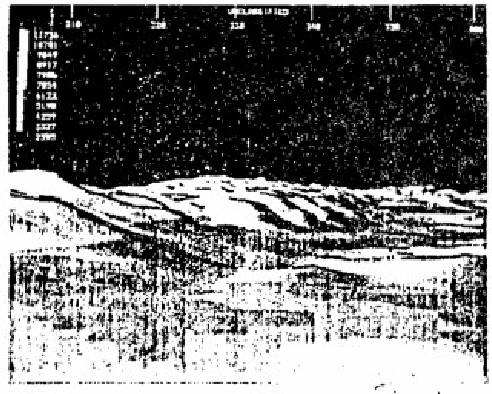
The principal outputs of TAMPS are weight and drag of weapon loadings, fuel consumption (reflecting weapons weight and drag), displays of enemy order of battle information (partly user-entered and partly from intelligence data bases), route information including radar terrain masking (RTM), anticipated attrition, and imagery showing pilot visual and radar views en route. It does not provide recommended weapon loadings, for which the planner uses other sources such as tactical manuals for particular aircraft and the Joint Munitions Effectiveness Manuals (JMEMS). A considerable part of the software is devoted to data base management. Figure IV-36 illustrates various output graphics (losing much from color originals).

A planned follow-on system which will include TAMPS is the Integrated Strike Planning System (ISPS). Specifications for development are in preparation. Among other enhancements, it will reflect influences of the planning and execution of separate strikes on each other. TAMPS permits simultaneous consideration of separate strikes, but not their interdependence. TAMPS will in the future be integrated with TESS (3) (see Chapter V), as will presumably ISPS.

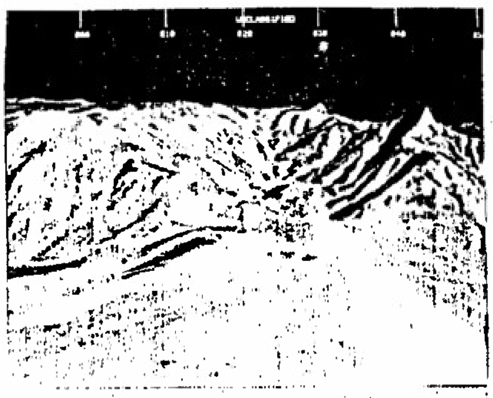
Let us review a typical planning session using TAMPS.

FIGURE IV-36. ILLUSTRATIVE TAMPS GRAPHICS

Planned mission



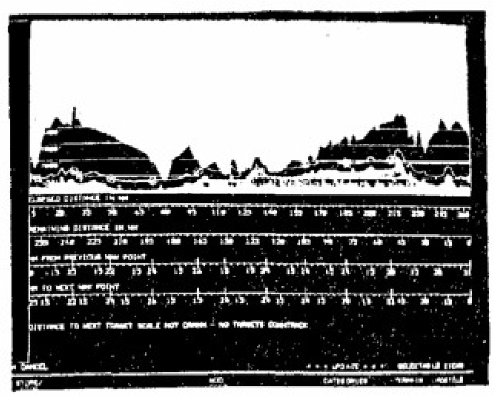
Perspective view of shaded terrain



Perspective view mountain image

Satellite Imagery

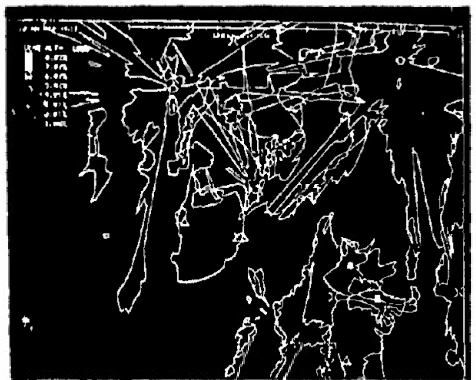
Joint Operational Graphics Scale chart
1:250,000 scale



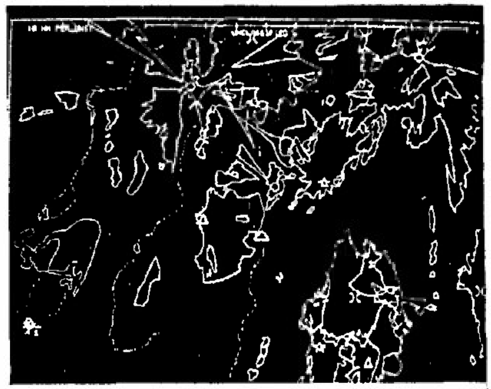
Vertical Mission Profile

(Continued)

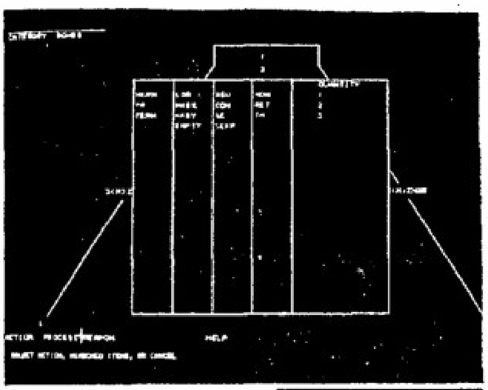
FIGURE IV-36 (Continued)



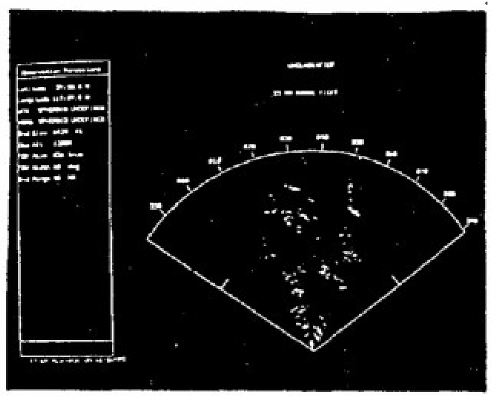
[illegible] Radar Terrain Masking and Threat Density display



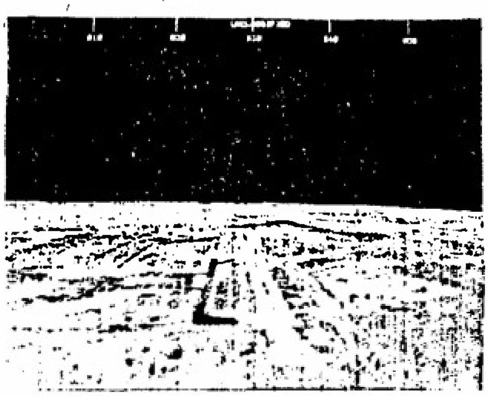
200' Radar Terrain Masking of enemy defenses



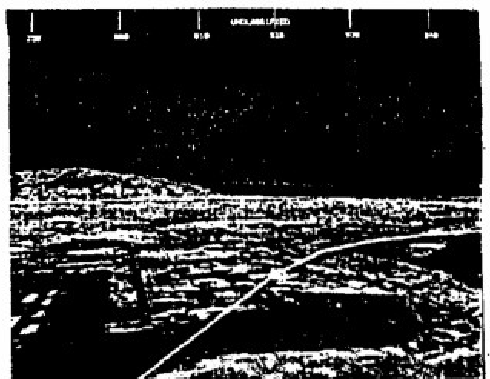
Weapon Load data [redacted]



Radar Prediction



Perspective view airfield



Perspective view harbor with route overlay [redacted]

Preliminaries include designation of aircraft type and strike origin, listing accessible airbases, designation of recovery/divert airbases, and expected fuel consumption increase over straight and level flight reflecting terrain elevation variability. Bank angles expected at relevant altitudes are entered. These affect radii of turns and accordingly consumption of fuel and time.

A diagram of the aircraft weapon stations is presented, and is used by the planner to assign a weapon loading. The weapons have been previously chosen by the user as noted above. Weight and drag of the loading are output.

These weight and drag outputs are the starting point for fuel analysis. The planner is now told in knee-pad format (hard copy available) the fuel remaining at various stages of the strike.

On a map of the strike route region, enemy EW and GCI radar, SAM sites, and AAA sites and their respective radii of effectiveness are displayed as are terrain elevation features. Regions of RTM at user-chosen altitudes are shown, based on computations made with the Defense Mapping Agency's Digital Terrain Elevation Data (DTED (see 4.5.2)). The masking is unrefracted.

The planner now has good bases for tentative choices of ingress and egress routes and check points, which are done by cursor entry. Contours are shown of attrition density, expressed in kill probability per mile. These are indicative to the planner of the relative unattractiveness of various route segment candidates, but they are not used for survival analysis. Attrition probability estimates are based on hostile single-shot kill probabilities, effectiveness regions of weapons and radars, etc. If ECM aircraft are used, attrition probabilities are multiplied by a fixed percentage to allow for ECM.

Weapon delivery tactics and their effectiveness are shown, for user choice of tactics. Detailed RTM displays in the target area can be usefully employed.

The plan is further reviewed on a terrain relief map constructed from DTED (computer response is several seconds).

Visual and radar views are displayed as seen by the pilot and NFO at various ingress and egress points. These afford excellent rehearsal for the flight. A flight/terrain vertical profile of the route is given, with and without a profile of RTM.

In summary, TAMPS aids in strike route planning by providing reasonably good estimates of fuel consumption for various flight profiles and weapons loadouts and of comparative exposure to defenses given assumed and/or known defense locations and actual terrain. In speed and orderliness of planning it is an important improvement on previous methods.

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CHAPTER V

ENVIRONMENT-DOMINATED TDAS

Most naval operations are significantly affected by the environment, accordingly so are most naval operational decisions and most naval TDAs. In this chapter we address TDAs where environmental considerations tend to play a *dominant* role.

The centerpiece for naval environment-dominated TDAs is TESS, the Tactical Environmental Support System. TESS is a comprehensive modular aggregate of TDAs and other programs, based on predominantly environmental inputs, which are oceanographic, atmospheric, and, for strike planning, terrestrial. It is sponsored by the Oceanographer of the Navy, OP-96. The versions in operation, TESS 2.0 and previously 1.0, have been developed and maintained by his subordinate activities, primarily CNOC and NAVOCEANO in Bay St. Louis, and by NEPRF in Monterey which is the ONR structure. Development of TESS (3) has been assigned by OP-96 to SPAWAR.

TESS 1.0 and 2.0 reside on the HP 9020A, the Navy's Standard DTC. TESS (3) will have a new hardware configuration and will interface with many other systems aboard major combatants. At sea TESS is intended for use by meteorology personnel in their spaces. The user's guide for TESS 2.0, the version currently in use, is reference [a].

For most of the programs in TESS, the outputs as well as the inputs are predominantly environmental. These are important to tactical decision-makers, directly or indirectly, in part through other programs which are TDAs. Our interest here is primarily with TDAs in TESS whose outputs are *directly* tactical recommendations and involve significant tactical analysis. Exposition on programs whose outputs as well as inputs are essentially environmental, without substantial tactical analysis, is better left to other expertise.

Pursuant to our interest, we have selected for review in this chapter four TDAs from TESS: NAVSAR, a CAS program for search and rescue (SAR) at sea; ESPA, the Environmental Strike Planning Aid; TESR, the Tactical Environmental Ship Routing System; and CHAPPS, the Chaff Planning and Prediction System. CHAPPS and NAVSAR include yet additional applications of the IOU process that has played a prominent role in TMA and search TDAs.

TESS 1.0 was released in 1984, TESS 2.0 was released in 1987, and TESS (3) is scheduled to be in the Fleet by 1992.

Figures V-1, V-2, and V-3 list the main programs and data bases in these three versions of TESS. Note that in addition to the listings for 2.0 and (3), 2.0 contains everything in 1.0, and (3) contains 2.0.

The TESS 2.0 main menu is shown in Figure V-4 as it is displayed by the program. Figure V-5 shows the submenus for the five application areas in the main menu.

FIGURE V-1. TESS 1.0 PROGRAM MENU

APPLICATIONS SOFTWARE	PERMANENT DATA BASE ELEMENTS
RADIOSONDE INITIAL ANALYSIS (RIA)	TEMPERATURE-SALINITY PROFILES
D-VALUES	BOTTOM DEPTH
SOUND FOCUS	BOTTOM LOSS
ELECTROMAGNETIC PROPAGATION CONDITIONS SUMMARY	AMBIENT NOISE
PATH LOSS VS. RANGE	LAYER/VOLUME SCATTERING COEFFICIENTS
EM COVERAGE DIAGRAM	SHIPPING DENSITY
ESM RANGE TABLES	WEAPON/SENSOR CHARACTERISTICS (EMITTERS, BALLISTIC ZONES)
SURFACE SEARCH RANGE TABLES	GEOGRAPHIC DATA
HISTORICAL PROPAGATION CONDITIONS	TIDAL CONSTITUENTS
ECM EFFECTIVENESS	HISTORICAL DUCT STATISTICS
NEAR-SURFACE OCEAN THERMAL STRUCTURE	
SOUND SPEED PROFILE (PROFGEN)	
ACOUSTIC PROPAGATION LOSS	
GENERAL RAYTRACING (GENRAYT)	
LATERAL RANGE PREDICTION (LATRAN)	
OCEAN DATA ANALYSIS (ODA)	
TIDAL PREDICTION (TIDES)	
BALLISTIC WINDS AND DENSITIES	
RADFO	
SATELLITE EPHEMERIS (RECSAT)	
AMBIENT NOISE	
DATA QUALITY BRIEFING SUPPORT	

Let us note some specific TESS interfaces. The outputs of TESS 2.0 are transmitted to tactical users by hand-carry and by closed circuit TV (CCTV). It interfaces with the SMQ-6 satellite receiver and a radio teletype, by which it receives formatted raw weather observations. TESS (3) at IOC will additionally interface with the Flag Data Display System (FDDS) in the Tactical Flag Control Center (TFCC) and with ITDA (see Chapter IV) for both input and output. Later it may interface with the Naval Message Automated Communications System (NAVMACS). It may have a new satellite receiver, the SMQ-11. For current in situ data it will use the Shipboard Meteorological and Oceanographic Observation System (SMOOS) for surface weather conditions and sea water temperatures and the Mini RAWINSONDE System (MRS) for conditions above the surface. It will interface ashore with the Defense Data Network (DDN) and at sea with the Direct Access Multiple Address (DAMA) system. It will support the ASWOCs.

We remark that the naval environmental community has shown very laudable initiatives in at least the past decade in making its products more operationally useful. TESS is the principal TDA embodiment of these initiatives. Environmental influence on TDAs has also been important in various other ways, notably in suites of environmental programs, such as IREPS, ICAPS, and the Geophysical Fleet Mission Program Library (GFMPL), that are used in integrated TDAs for battle group command (Chapter IV). The SPARS data base is crucial to COSP use of PACSEARCH (see 2.6). Also, ICAPS was the principal vehicle by which VPCAS (Chapter II) acquired NAVSEA sponsorship in the ASWOCs.

FIGURE V-2. TESS 2.0 PROGRAM MENU

NEW APPLICATIONS SOFTWARE

TELETYPE MESSAGE MANAGEMENT (INCLUDES ENCODE/DECODE, ACCEPTANCE/REJECTION, SORTING, CONTINGENCY FILING, DATA QUALITY, SPECIAL DATA TEST, PRIORITY ALERT, STORAGE/RETRIEVAL, SELECTIVE PURGING, AND MESSAGE CONSTRUCTION FUNCTIONS)
LOCAL OBSERVATION ENTRY AND ARCHIVAL
MAP SELECTION (AREA, SCALE, PROJECTION)
OBSERVATIONS PLOT ON MAP
CONTOUR DIGITIZATION (RESOLVING CONTOURS INTO GRID POINTS)
GRAPHIC PRODUCT STORAGE/RETRIEVAL
WARNINGS PLOT ON MAP (HIGH WINDS, SEAS, TROPICAL CYCLONE)
CVIC/CCTV BACKGROUND DISPLAY (WITH AUTOMATED TIMED PAGING)
CVIC/CCTV LIVE BRIEF (WITH POINTER)
INTERACTIVE MULTIVARIABLE ENVIRONMENTAL ANALYSIS (USING LAST ANALYSIS AS FIRST-GUESS FIELD)
SEARCH AND RESCUE (NAVSAR)
CHAFF PLANNING AND PREDICTION SYSTEM (CHAPPS)
TROPICAL CYCLONE WARNING DISPLAY (TCASS)
DETECTION/VULNERABILITY MIXED EMITTERS
MIXED PLATFORM DETECTION/VULNERABILITY
FLIR RANGE FORECAST
SINGLE STATION ANALYSIS (TIME SERIES AND CROSS-SECTIONS: RADS, BT, SFC WX)
SATELLITE IMAGE OVERLAY
SATELLITE SEA SURFACE TEMPERATURE ANALYSIS
SATELLITE CLOUD ANALYSIS
CONTRAIL/ICING PROBABILITY
OPARS

NEW PERMANENT DATA BASE ELEMENTS

WEATHER STATION INDEX
OCEAN FRONTAL STATISTICS
CURRENT LOCATION AND CHARACTERISTICS
SATELLITE DATA CONVERSION CONSTANTS

In 5.1, we give a brief history of TESS. The TDAs NAVSAR, ESPA, TESR, and CHAPPS are reviewed in 5.2, 5.3, 5.4, and 5.5.

5.1. History of TESS

The origins of TESS have been attributed to the development of IREPS on the HP 9845 DTC by NOSC and CNOC around 1977. This development provided motivation for more environmental aids on computers. NEPRF exerted considerable initiative in this direction and with the support of CNOC and NAVAIR developed into the early 1980's stand-alone environmental programs such as Ballistic Winds, Heavy Weather, NAVSAR, CHAPPS, Tropical Cyclones, Radiation Fallout (RADFO), etc., with S. Brand of NEPRF playing a lead role.

FIGURE V-3. TESS (3) INITIAL MENU OF PROGRAMS

NOTE: These are the programs in being to be adapted by the TESS(3) Engineering Development contractor. More will be added.

METEOROLOGICAL APPLICATIONS

RADIOSONDE INITIAL ANALYSIS
DA-VALUES
SOUND FOCUS
BALLISTIC WINDS AND DENSITIES CORRECTIONS
RADIOLOGICAL FALLOUT
SEARCH AND RESCUE

ELECTROMAGNETIC APPLICATIONS

ELECTROMAGNETIC PROPAGATION CONDITIONS SUMMARY
ELECTROMAGNETIC PATH LOSS VERSUS RANGE
ELECTROMAGNETIC COVERAGE DIAGRAM
ELECTROMAGNETIC SUPPORT MEASURES RANGE TABLES
SURFACE-SEARCH RADAR RANGE TABLES
HISTORICAL ELECTROMAGNETIC PROPAGATION CONDITIONS
ELECTROMAGNETIC COUNTERMEASURES EFFECTIVENESS
PLATFORM VULNERABILITY
BATTLE GROUP VULNERABILITY
FLIR RANGE DISPLAY
ELECTROMAGNETIC DEVICE EDITOR
ATMOSPHERIC REFRACTIVE PROFILE GENERATOR
CHAFF PLANNING AND PREDICTION

OCEANOGRAPHIC APPLICATIONS

NEAR-SURFACE OCEAN THERMAL STRUCTURE
SOUND SPEED PROFILE
TIDAL PREDICTION
RAYTRACE

ACOUSTIC APPLICATIONS

PASSIVE ACOUSTICS PROPAGATION
AMBIENT NOISE
SENSOR PERFORMANCE PREDICTION

SATELLITE EPHEMERIS

The lead developer of NAVSAR (references [b] and [c]) and CHAPPS (references [d] and [e]) was R. J. Lipshutz of DHWA, assisted by K. E. Trummel on both and by J. R. Weisinger and R. P. Pember on CHAPPS. NEPRF direction was by Brand and T. K. Brown on NAVSAR and by Brand, P. A. Harr, and L. D. Phegley on CHAPPS. Both programs were on the HP 9845 and were later converted to the HP 9020.

These early TDA and other environmental programs at NEPRF became the beginnings of the Shipboard Numerical Aid Program, SNAP. After 13 or so programs, SNAP outgrew NEPRF, and this activity started to come under the GFMPL project at NAVOCEANO under the direction of L. J. Bernard. There were also in the early 1980's environmental programs on the Zenith 120 and on hand-held programmable calculators. All of this activity led to impetus from NAVAIR and CNOC for the TESS program. The Oceanographer of the Navy made it happen.

FIGURE V-4. TESS 2.0 MAIN MENU

```
0   Return to previous level
1    - ANALYSIS UTILITIES
2    - ATMOSPHERIC ANALYSIS
3    - METEOROLOGY
4    - EM PROPAGATION
5    - OCEANOGRAPHY
6    - ACOUSTICS
7    - MESSAGE COMPOSING
8    - SATELLITE TRACKING
9    - BRIEFING SUPPORT
10    - ADVANCE PAPER
```

NAVOCEANO has had the lead on TESS 1.0 and 2.0. It coordinates development activity, notably at NEPRF and NOSC, and disseminates software and documentation to the Fleet.

TESS 1.0 was formed by aggregating various separately developed programs, mostly pre-TESS developments. TESS 2.0 was a successor in kind in an expanded role. In July 1988, SPAWAR awarded Lockheed at Austin, Texas the Full Scale Engineering Development contract for TESS (3), including hardware and adaptation of existing software programs. Provisions for additional environmental TDAs and other programs in TESS (3) are anticipated.

In early 1986, NEPRF awarded a contract to the Monterey office of Systems and Applied Sciences Corporation (now ST Systems) with DHWA as subcontractor for general development of TESS programs. Among the ensuing programs was TESR (reference [f] and 5.3 below), developed primarily by Lipshutz, Weisinger, and D. S. Schaffer, under Phegley of NEPRF and scheduled for TESS (3).

Another TDA intended for TESS (3) and possibly for the strike planning TDA TAMPS (see 4.6), is the Environmental Strike Planning Aid (ESPA). The ASM weapon launch portion of ESPA is reviewed in 5.3. This is being derived by J. M. Sierchio and B. J. Cook of NEPRF from a USAF TDA known as the Operational Tactical Decision Aids (OTDA--obviously this name needs more adjectives), which has been developed for the Air Force Geophysical Laboratory from 1983 to the present by G. J. Higgins, P. J. Hilton, and various others of ST Systems (see references [g] and [h]). This evolution has been paralleled by related "research grade" TDAs, produced by the Air Force Wright Aeronautical Laboratories. The Mk II version of OTDA is operational in the USAF on a PC-compatible. Development of the Mk III version is ongoing by these organizations. Some of its advances over the Mk II are noted in 5.3. The preliminary design of ESPA is being based on OTDA Mk II, and the first operational version of ESPA will be based on the Mk III.

We now review NAVSAR, ESPA, TESR, and CHAPPS in turn.

5.2. Navy Search and Rescue (NAVSAR)

NAVSAR is intended to provide at-sea support to search and rescue (SAR), in contrast to the shore-based support provided by CASP (see 2.8). It is a CAS program as defined and discussed in Chapter II. It uses knowledge and assumptions of target position and motion, search asset capabilities, and unsuccessful search to produce probability maps of target position and recommended search plans. The environment intervenes through oceanographic and wind effects on drift of floating targets, cloud cover and white-capping effects on visual detection range, and wind effects on parachute drift.

FIGURE V-5. TESS 2.0 PRINCIPAL APPLICATIONS SUBMENUS

ATMOSPHERIC ANALYSIS MENU

```
0  Return to previous level
1   - OBSERVATION PLOT
2   - WEATHER ANALYSIS
3   - WARNINGS PLOT
4   - LOCAL OBSERVATION ENTRY / ARCHIVAL
```

METEOROLOGY MENU

```
0  Return to previous level
1   - VIEW ATMOSPHERIC ENVIRONMENTAL FILE
2   - RIA
3   - D-VALUES
4   - SOUND FOCUS
5   - BALLISTICS
6   - RADFO
7   - AIRCRAFT ICING
8   - TOMAHAWK
```

EM PROPAGATION MENU

```
0  Return to previous level
1   - ENVIRONMENTAL STATUS
2   - FILE MAINTENANCE
3   - PROPAGATION CONDITIONS
4   - SYSTEMS APPLICATIONS
```

EM SYSTEMS APPLICATIONS MENU

```
0  Return to previous level
1   - COVER
2   - LOSS
3   - SURFACE SEARCH RADAR RANGES
4   - ESM INTERCEPT RANGES
5   - PLATFORM VULNERABILITY
6   - BATTLE GROUP VULNERABILITY
7   - ECM
8   - FLIR
9   - CHAFF
```

(Continued)

FIGURE V-5. (Continued)

OCEANOGRAPHY MENU

```
0  Return to previous level
1   - VIEW OCEANOGRAPHIC ENVIRONMENTAL DATA FILE
2   - SOUND SPEED PROFILE
3   - OCEAN DATA ANALYSIS
4   - RAYTRACE
5   - NEAR-SURFACE OCEAN THERMAL STRUCTURE
6   - TIOAL PREDICTION
7   - SEARCH AND RESCUE
```

ACOUSTICS MENU

```
0  Return to previous level
1   - PASSIVE PROPAGATION LOSS
2   - SENSOR PERFORMANCE PREDICTION
3   - AMBIENT NOISE
```

SATELLITE TRACKING MENU

```
0  Return to previous level
1   - EOIT ORBITAL ELEMENT SET
2   - ORBITAL SATELLITE PREDICTION
3   - GEOSTATIONARY SATELLITE PREDICTION
```

5.2.1. NAVSAR overview and preliminaries. NAVSAR contains two levels of modeling, Level I which is analytic and Level II which is Monte Carlo. The reason for the two-level approach is that the original hardware host was slow. Speed is not a problem for the HP 9020 to which it has been converted. If NAVSAR had been originally designed for an HP 9020, Level I would not have been included. However, the ways in which Level I differs from Level II contain some interesting modeling ideas, so we will review both levels.

The choice between the two levels is made by the program, transparent to the user. The only difference visible to the user is the form of the search plan recommendation: A Level I recommendation is a placement of a rectangle within which search is uniform, and a Level II recommendation is an allocation of effort over the search region which permits fine division of effort among the cells of the region.*

* An allocation which assumes that the effort is infinitely divisible is sometimes called a "peanut butter" plan. In the stanza by R. J. Lipshutz and D. P. Kierstead entitled "How Mathematicians Do It," this has given rise to the line "Search theorists do it with peanut butter."

In Level I, all of the random variables are normal, so each is characterized by its mean and covariance matrix (in a 1-dimensional case, variance). Of course, the mean and covariance of a sum of random variables are the sums of their means and, if the variables are independent, their covariances.

The inputs utilized by NAVSAR are as follows:

(1) Target description. This can vary from a person adrift to a ship of over 10,000 tons.

(2) Target location (last known). This can be POSITION (distress position is bivariate normal), TRACKLINE (distress position is on a transit track of up to four legs each between circular normal endpoints, and distress time has a triangular distribution), or AREA (distress position is uniformly distributed over a rectangle). Multiple scenarios with weights are permitted, although usually only one scenario will be used. Position uncertainties are related to type of navigation system used.

(3) Currents. These are typically from FNOC monthly reports on sea currents supplemented by in situ surface wind data to provide wind-driven currents.

(4) Weather. These are primarily wind versus altitude, cloud cover, and visibility data.

(5) Search assets. Needed are name of asset, search speed, and sweep width. For visual or electronic search, the program computes sweep width as an automation of procedures in reference [i]. Electronic detection range is limited by the unrefracted horizon.

(6) Search plans. This refers to previous effort on the current problem, for negative information updating.

A status board maintains information on target location, sea current, wind current, wind, visibility, cloud cover, depth of mixed layer, and search assets available. The Executive Level Options Table is the main menu and offers mainly the options to revise the status board, compute a probability map, or recommend a search plan.

A wind at some altitude or a current at some time is entered as mean speed s, mean direction b, and standard deviations σ_s and σ_b. It is assumed that this vector random variable is normal in a rectangular coordinate system with mean (s sin b, s cos b), 1-sigma semiaxes σ_s and $s\sigma_b$, and orientation b. Plausibility of normality in rectangular coordinates has been confirmed with meteorologists. Reservations may be expressed as to how well (s sin b, s cos b) approximates the mean of the random variable

(speed x sin direction, speed x cos direction)

or the mean of some other plausible transform of (speed, direction), whether or not (speed, direction) is normal; as reference [c] notes, best accuracy is obtained when σ_b is small.

Wind and current vector statistics are treated as constant over suitably chosen altitude or time intervals and independent from one interval to another, so covariances as well as means may be summed over intervals to obtain the covariance and mean of the vector variable sum.

5.2.2. Modeling of target initial position and motion. If the initial target location is a (bivariate normal) POSITION in a *single* scenario, Level I is used; otherwise Level II is used. We describe Level I modeling of target initial position and motion first. Much will apply to Level II.

Suppose the scenario involves a pilot ejection. It is assumed that the ejection imparts displacement .8 nm in the direction of the aircraft heading (entered without variability), to be augmented by drift during descent. Within an altitude layer in which wind is deemed constant, downwind displacement in nm, d, is modeled by

$$d = .000013 \times \text{layer height in feet} \times \text{wind speed in knots}, \qquad \text{(V-1)}$$

as a fit to data in reference [i]. The standard deviations of wind speed and direction are taken to be .1 knots and 5 degrees; together with the mean wind speed and direction observed in a given layer, these are transformed as above to mean and covariance of the wind vector in rectangular coordinates. From these and formula (V-1), mean and covariance of displacement in the layer follow. Adding these means and covariances over the layers to those of the aircraft position at ejection and to the deterministic displacement at ejection yields the mean and covariance of the (normal) initial position.

If ejection is not involved, the mean and covariance of position are obtained directly from the inputs.

Target motion is the sum of sea current, wind-driven current, and leeway (displacement from wind blowing on exposed surface). While it is a problem to separate data on the first two, it is assumed that data on sea currents from oceanography centers are devoid of wind effects, and the latter are contributed by winds locally observed in the last 48 hours.

To model motion further, time intervals, which we'll call "model intervals," are taken from a mid-point between two data report times to the next such mid-point, typically 12 hours. In a model interval, *statistics* of sea current, wind current, and leeway are taken to be constant, and each is modeled as an IOU process with velocity drift (see Appendix B). Among distinct model intervals, these statistics are taken to be independent, so single-interval covariances may be added. One may prefer a better basis for choosing model intervals. Short intervals tend to make the independence suspect, and long intervals tend to make the constancy of statistics suspect.

The IOU assumption implies that if a model interval duration is δt, V and C are the sea current mean and covariance (transformed from speed and direction data), then the *displacement* due to sea current during the interval has

$$\begin{aligned} \text{mean} &= V\delta t, \\ \text{covariance} &= 2\,(\beta)^{-2}(\beta\delta t + \exp(-\beta\delta t) - 1)C. \end{aligned} \qquad \text{(V-2)}$$

The parameter β is roughly the average rate of change in sea current per hour. It is taken to be .2 per hour. Since reference [a] and the TESS 2.0 input prompts have no provision for uncertainty in sea current speed and direction, we infer that in the implemented program C is fixed internally, perhaps in percentage terms, although that did not appear to be the intent of reference [c].

Wind current is related to wind by the following differential equation suggested by R. W. Garwood of NPGS:

$$c'(t) = Ac(t) + a(t),$$

where c(t) is the wind current at time t, a(t) is the resulting acceleration of the water, and A is a 2 x 2 skew-symmetric matrix dependent on coriolis coefficient, latitude, and a time decay constant; also, letting w(t) be the wind vector and |w(t)| its length,

$$a(t) = k|w(t)|w(t),$$

where k depends on density of water, density of air, drag coefficient, and depth of mixed layer. Now w is approximated as piecewise linear (by Taylor expansion about the mean of w), and over a linear interval of length δt the differential equation can be solved in closed form. From this the mean of c(t) can be given in closed form in terms of $\exp(A\delta t)$, which itself can be given in closed form even though A is a matrix. Covariance of wind current is deemed small compared to other covariances and is hence taken as the zero matrix.

Leeway speed mean and standard deviation are a fixed percentage of wind speed mean and standard deviation. The percentage depends on target type, ranging from 2% for a person in water to 7% for a rubber raft without drogue. Leeway direction standard deviation is wind direction standard deviation plus divergence. Divergence, which depends on target type, is defined as the difference between wind direction and the direction imparted by the wind to a floating object, e.g., the tacking effect on a sailboat. (One would think variances would be added here.) These statistics lead to mean and covariance of leeway velocity in rectangular coordinates for the interval.

To convert velocity statistics to displacement statistics for wind current and leeway in a model interval, formulas (V-2) are again applied, however with $\beta = 5$ per hour.

Now suppose we want to update target position from time 0 to time T. To the mean and covariance of the initial position, including effects of ejection if any, we add the mean and covariance of the total displacement from time 0 to time T, computed as the sum of the means and covariances of displacements due to sea current, wind current, and leeway over all the model intervals. The normal distribution with the resulting mean and covariance is the target position distribution updated for motion.

In Level II, the initial target position distribution is not normal, so we cannot confine attention to mean and covariance as in Level I. Instead Monte Carlo with 500 repetitions is used, with each repetition corresponding to an initial position of the target. The 500 points are divided over the scenarios (up to five are permitted) in proportion to the scenario weights.

For a POSITION or AREA scenario, the points are drawn from a normal or uniform distribution respectively and a track starts at time 0 from each point. For TRACKLINE, for each point an activation time is first drawn from a triangular distribution. This lies on a leg, a draw is made from each of its normal end-points, and spherical interpolation between them gives the position at activation.

If a scenario includes ejection, the point is displaced by an amount computed as in Level I for the *mean* displacement, except that here for each altitude layer the wind vector is taken as a Monte Carlo draw from its normal distribution for that layer.

All points in all scenarios are given the same initial weight.

To update a point for target motion, i.e., the composite effect of sea current, wind current, and leeway, the means and covariances are developed for all the distributions and all model intervals treated in Level I, the intervals are divided into two-hour subintervals, and in each two-hour interval an independent draw is made from each of the bivariate normal distributions of sea current and leeway determined by their means and covariances. For wind current the mean is used rather than a draw because covariance is zero. From activation time to map time, these velocity vectors are multiplied by interval duration to yield displacements and these are added to the initial position to update that point for target motion. If the point has not been activated at map time, it is unchanged under the update.

There is some resemblance between this Monte Carlo treatment of target motion and the bundle of 500 tracks used in VPCAS (see 2.4). The principal difference is that in NAVSAR model intervals have more complicated modeling (of environmental impact) than the building block modeling of submarine motion in VPCAS. Initiation of a motion stochastic process at an uncertain time as in TRACKLINE occurs, e.g., in CASP (see 2.9) and JOTS/TRANSIT SEARCH (adapted from MEDSEARCH--see 4.2.5).

5.2.3. Update for unsuccessful search. We have described how NAVSAR models target initial position and target motion in Levels I and II. We now describe how updating for negative information is handled for both.

For both Levels I and II, the only type of search plan recognized in negative information updating is uniform placement of effort in a rectangle. For Level I that is also the only type of plan recommendation output by the program. Level II outputs more general (peanut butter) recommendations, with the intent that each such plan be approximated by the user by one or more uniform rectangular placements.

Effectiveness of search effort is treated via sensor sweep width, the same in Levels I and II. The user may input sweep width. If not, for electronic search the program uses a quadratic fit of range versus search altitude to data in reference [i]. Visual sweep width is also based on data from reference [i], and is taken as the product of (1) an "uncorrected" sweep width depending on target type, sensor altitude, and meteorological visibility, (2) a whitecap correction factor depending on target type and surface wind speed, and (3) a lighting correction factor depending on cloud cover. A later model of visual detection capability is given in reference [j].

Sweep width is converted to swept area by multiplication by search speed and search time. Swept area is converted to detection probability by the classic inverse cube law (see references [k] or [l]):

$$\begin{aligned}\text{detection probability} &= f(\text{swept area, rectangle}) \\ &\equiv \operatorname{erf}(\tfrac{1}{2}\sqrt{\pi}\ \text{swept area/rectangle area}),\end{aligned} \qquad \text{(V-3)}$$

where

$$\operatorname{erf}(z) \equiv (2\sqrt{\pi}) \int_0^z \exp(-x^2)dx.$$

This is an estimate of detection probability which is intermediate between the optimistic definite range law and the generally pessimistic "random" search law.

For a negative information update, Level I begins with the motion update of the map *from time 0* to the map time, *unaffected by any prior searches*. Thus it does *not* update from the preceding map, if any. Then it updates each search rectangle for target motion from the time the rectangle was placed to the map time. (This procedure was suggested during development by L. D. Stone.) To do this, it takes the ellipse inscribed in the rectangle as the 1-sigma ellipse of a normal distribution, updates the mean and covariance as was done for the motion update for position, finds the 1-sigma ellipse of the update, and uses as the updated rectangle that which circumscribes that ellipse. One can now regard the relationship of the updated search rectangle to the updated position distribution as the same as existed at the time the rectangle was placed. The program ignores the effect of target motion *during the life* of the rectangle. It is the area of the updated rectangle that is entered in formula (V-3).

To apply Bayes' theorem, let P_{ij} be the probability that the target is detected in the ith map cell by the jth search rectangle, computed by formula (V-3) (if the jth rectangle does not contain the center of the ith cell, then $P_{ij} = 0$). Let p_i be the probability that the target is in the ith cell according to the distribution updated for motion and let

$$q_i = p_i \prod_j (1-p_{ij}),$$

$$Q = \sum_j q_j.$$

Then the posterior probability that the ith cell contains the target is q_i/Q. An array of these probabilities is output as the probability map updated for motion and unsuccessful search, using a scaled single digit per cell as in VPCAS (see 2.4). Moreover $1-Q$ is the cumulative detection probability (cdp) to date, which is an output of separate interest.

In Level II, negative information updating is done by updating the weights of the 500 points in the Monte Carlo representation. If a given point is active and in a given search rectangle at the time the latter is active, w and w' are the respective weights of the point before and after the search, and P is the detection probability computed on the condition that the target is in the rectangle, then

$$w' = w(1-P).$$

Each point weight is updated in this way for each search in turn. The updated point weights are normalized to probabilities. Again, cdp is a by-product. If there are N active points at map time and Q is the sum of their probabilities, then

$$cdp = N/500 - Q.$$

The Level II update for motion and unsuccessful search is converted to a probability map by preliminarily taking as each cell probability the sum of the updated probabilities of the points active at map time that lie in that cell. Each cell is then smoothed with its neighbors: An interior cell is weighted 12 times as much as each corner neighbor and six times as much as each other neighbor. When this has been done to all cells, it is repeated five more times to obtain the cell probabilities. (This is an FNOC smoothing algorithm.) This is displayed as an array of scaled single digits as in Level I.

5.2.4. Search plan recommendations. It remains to describe how NAVSAR develops search plan recommendations. The differences between Levels I and II resemble those of 5.2.3.

Ordinarily a CAS system alternates between updating for motion and negative and positive information and generating a search plan which if executed leads to a new update, etc. In Level I, if this alternation were followed, after the first search execution we would depart from the normality which is crucial to the analytic methods employed in Level I. SALT (see 2.8) has a similar problem in that its search plan analysis always begins with a normal distribution. SALT solves this problem by approximating the updated map by a normal distribution. Level I takes a different approach which relates to that of 5.2.3.

In Level I analysis, we are given a normal distribution of position, cdp from previous search computed as in 5.2.3 and not reflected in the position distribution, and available asset expenditure which translates into a swept area, A. The problem is to place the swept area uniformly in some rectangle to maximize the post-search cumulative detection probability, cdp*. It is shown in reference [m] that for some k, the optimal rectangle is inscribed in the k-sigma ellipse of the normal distribution. What k maximizes cdp*? Reference [m] also shows that

$$cdp^* = f(k^2\sigma_1\sigma_2, A)\,[\Phi(-k/2)]^2 + [1 - f(k^2\sigma_1\sigma_2, A)]cdp,$$

where f is as in formula (V-3), Φ is the cumulative unit normal distribution function, and σ_1 and σ_2 are the standard deviations of the position distribution. The derivative of cdp* with respect to k can be found analytically, and its root is found by binary search to yield the optimal k, i.e., the optimal rectangle.

This optimization procedure depends on the previous search having been conducted within (after motion update) the recommended search rectangle. That will be true if the previous sequence of search increments was non-decreasing and was planned by this same method.

Level I, and not Level II, offers an additional basis for a search plan recommendation. The user may specify cdp* and search asset sweep width, and the program will output the search time required and the rectangle to be searched to achieve the specified cdp*. It does so by a binary search of search times and for each time tried finds the best k as above, until cdp* close to the required value is found.

Level II, not being restricted to normality, does search plan analysis on the smoothed position distribution updated for motion *and* negative information, as achieved in 5.2.3. It uses the classic Lagrange multiplier method given, e.g., in reference [n] as a generalization of a method in reference [k]. Search effectiveness in a map cell is given by formula (V-3). The desired multiplier is found by binary search. As noted earlier, the output is an allocation in infinitely divisible, i.e., "peanut butter," form and is to be approximated by uniform rectangles.

5.2.5. Examples. We illustrate use of NAVSAR with a Level I example and a Level II example.

In the Level I example, the location distribution at distress time of a small craft adrift is shown in Figure V-6. This, of course, is a single-scenario POSITION distribution. Sea current is 3 knots in direction 030. Wind is 20 knots from 180. Four hours later, the distribution is as shown in Figure V-7. The center has shifted a few miles to the northeast. The recommended search rectangle to start a 2-hour helo radar search at that time at 1000 feet altitude is shown in Figure V-8. The posterior map after this search, presumed unsuccessful even though it had a success probability of 82%, is shown in Figure V-9. Note the hole about the size of the rectangle that results from the negative information from this high probability search. Because of the depth of this hole one should next switch to Level II, since a new rectangle concentric with the previous one is obviously not optimal.

The Level II example is a single-scenario TRACKLINE distribution with legs as in Figure V-10, distress time probability map as in Figure V-11, and the map 24 hours later as in Figure V-12. Sea current and wind inputs are also shown in Figure V-10. The recommended allocation of effort for 4 hours of aircraft visual search at 250 knots and 1000 feet is as in Figure V-13. A user-entered rectangle approximating this allocation is in Figure V-14, and the posterior map from applying this rectangle unsuccessfully is in Figure V-15.

5.3 Environmental Strike Planning Aid (ESPA)

ESPA is intended eventually to cover the full scope of assistance to pre-flight strike planning, to the extent that such is provided by TESS. It will include IREPS for radar coverage, an aerodynamics data base from JMEMS or NATOPS, a meteorological data base from the TESS data base, and an aid to ASM launch derived from the USAF OTDA. Our interest here is in the latter, which will provide guidance to environmentally-constrained weapon launch in the target area. Three types of ASM guidance are treated: infrared (IR), TV, and laser. All are affected by the atmosphere in target detection and lock-on capabilities, and IR and TV are affected by terrestrial background. The atmosphere also affects the detection capabilities of radars and other electronics which help to defend the target.

Although our objective is to describe the USN version of this TDA in ESPA, we will primarily review the USAF OTDA from which it is derived.

FIGURE V-6. LEVEL I EXAMPLE PRIOR MAP

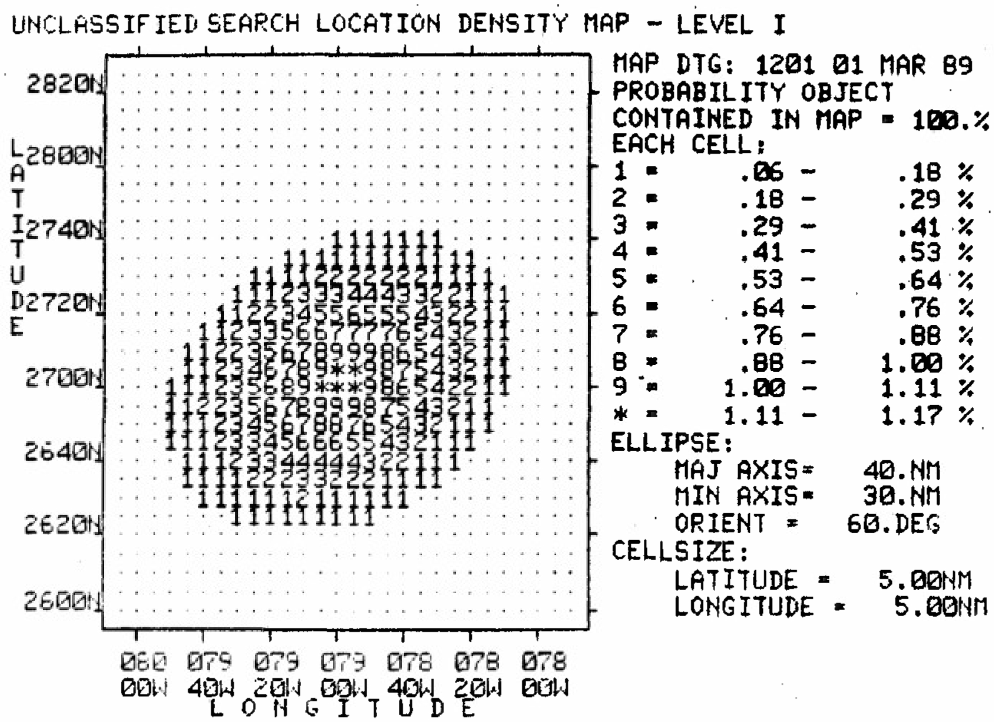


FIGURE V-7. LEVEL I MAP AFTER FOUR HOURS

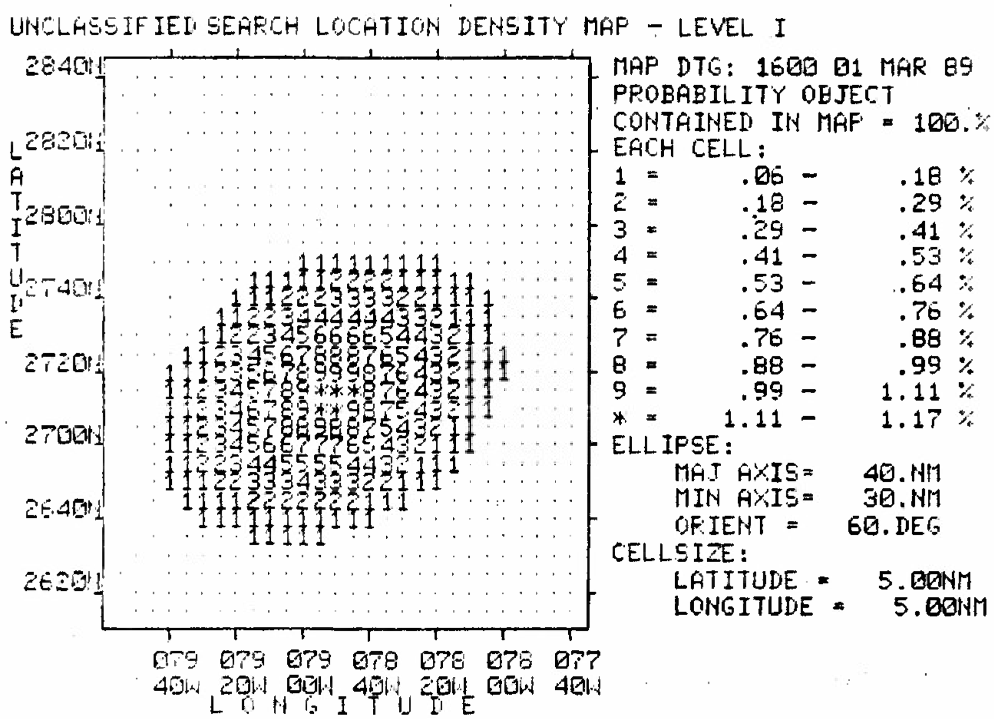


FIGURE V-8. LEVEL I EXAMPLE SEARCH RECOMMENDATION

SEARCH RECOMMENDATION - LEVEL I

SEARCH TIME: 0100891600

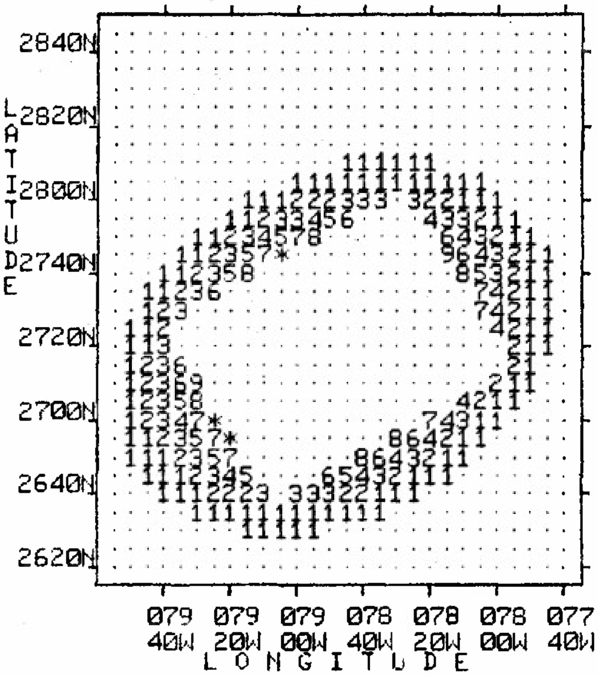
PROB OF SUCCESS: 82.%
CUM DETECTION PROB: 82.%
SEARCH AREA RECTANGLE:
CENTER LATITUDE: 2714N CENTER LONGITUDE: 07852W
LENGTH: 74.NM WIDTH: 55.NM
ORIENTATION: 60.DEG TOTAL AREA: 4083.SQ-NM

SEARCH ASSET INFORMATION AND RECOMMENDATION

ASSET NAME	SPEED (KTS)	ALTITUDE (FEET)	SENSOR	ON STA (HHMM)	AREA COVERED (%)	(SQ-NM)
HELO	100.	1000.	E	0200	100.	4083.

FIGURE V-9. LEVEL I EXAMPLE POSTERIOR MAP

UNCLASSIFIED SEARCH LOCATION DENSITY MAP - LEVEL I



MAP DTG: 1800 01 MAR 89
PROBABILITY OBJECT
CONTAINED IN MAP = 99.%
EACH CELL:

1 =	.08 -	.23 %
2 =	.23 -	.39 %
3 =	.39 -	.55 %
4 =	.55 -	.70 %
5 =	.70 -	.86 %
6 =	.86 -	1.02 %
7 =	1.02 -	1.17 %
8 =	1.17 -	1.33 %
9 =	1.33 -	1.49 %
* =	1.49 -	1.57 %

CELLSIZE:
LATITUDE = 5.00NM
LONGITUDE = 5.00NM
PROB OF SUCCESS = 28.%
CUM DETECT PROB = 86.%

FIGURE V-10. LEVEL II EXAMPLE INPUTS

TRACKLINE OF SEARCH OBJECT INPUT FORM

LOCATION SCENARIO 1

OTG OF DISTRESS (DDMMYY)(hhmm) Z [310389] [1600]
CONFIDENCE IN DISTRESS TIME (0,100) [50] PERCENT
COURSE TYPE (G=GREAT CIRCLE, R=RHUMB LINE) [R]

AIRCRAFT EJECTION (Y/N) [N]

ENTER UP TO FOUR TRACK LEGS
STARTING POINT AND TRACK LEG LOCATION

		DTG		LAT		LONG		POS. ERROR (0,500)
		(DDMMYY)	(hhmm)	(ddmm)	(h)	(dddmm)	(h)	(nm)
START	1	[310389]	[1200]	[2530]	[N]	[16900]	[W]	[10]
LEG 1	2	[310389]	[1530]	[2510]	[N]	[16830]	[W]	[10]
LEG 2	3	[310389]	[2000]	[2510]	[N]	[16750]	[W]	[10]
LEG 3	4	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
LEG 4	5	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

ENVIRONMENTAL CONDITIONS INPUT FORM

	DAY/TIME		SEA CURRENT DIR	SEA CURRENT SPEED	*SC INCL. WC?	WIND DIR	WIND SPEED	CLOUD COVER	VIS	MIXED LAYER DEP
	(DDMMYY)	(hhmm)		(KT)	(Y/N)		(KT)	(%)	(NM)	(FEET)
1	[310389]	[1600]	[060]	[2]	[N]	[270]	[20]	[50]	[10]	[200]
2	[310389]	[2200]	[060]	[2]	[N]	[270]	[20]	[50]	[10]	[200]
3	[10489]	[400]	[060]	[2]	[N]	[270]	[20]	[50]	[10]	[200]
4	[10489]	[1000]	[060]	[2]	[N]	[270]	[20]	[50]	[10]	[200]
5	[10489]	[1600]	[060]	[2]	[N]	[270]	[20]	[50]	[10]	[200]
6	[310389]	[1000]	[060]	[2]	[N]	[270]	[20]	[50]	[10]	[200]
7	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]
8	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]	[ ]

If the sea current includes the wind current enter "Y" otherwise enter "N".

FIGURE V-11. LEVEL II EXAMPLE PRIOR MAP

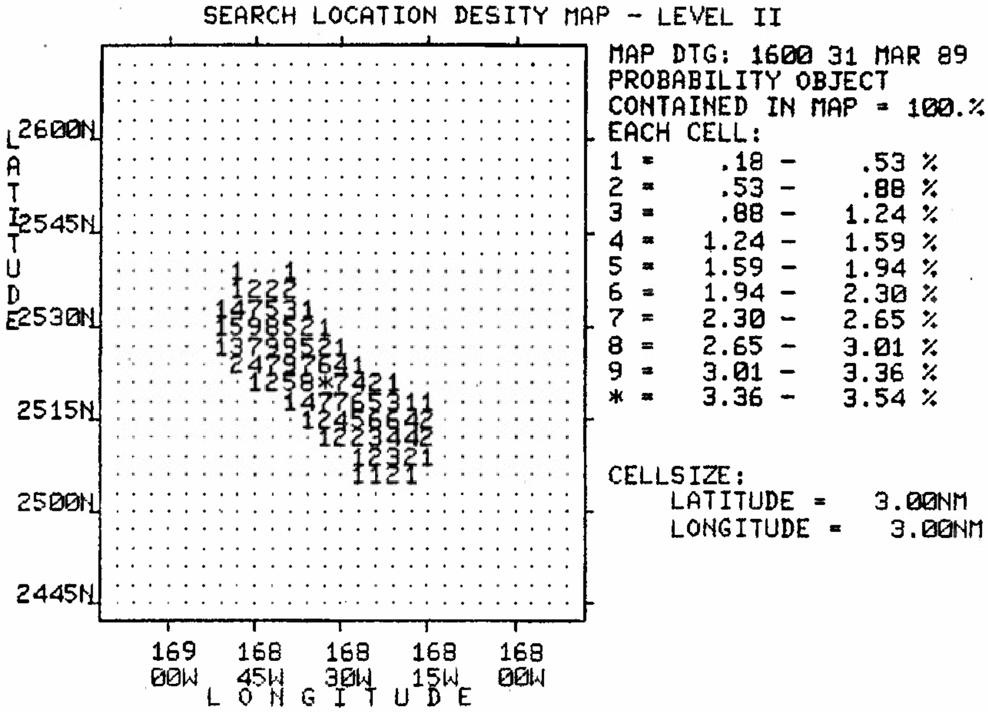


FIGURE V-12. LEVEL II MAP 24 HOURS LATER

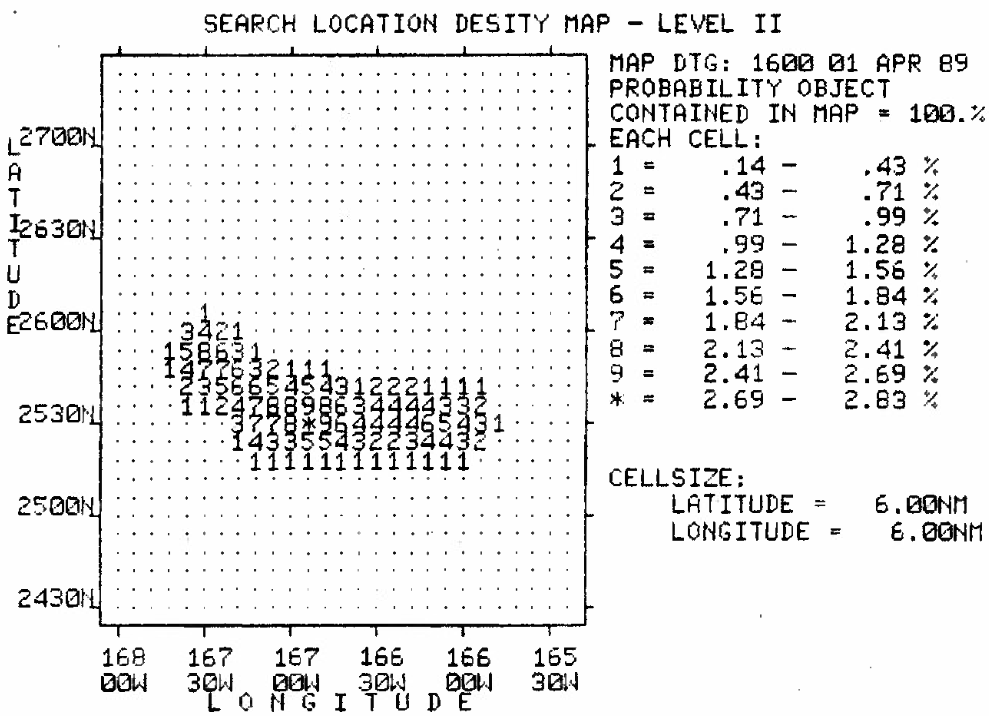
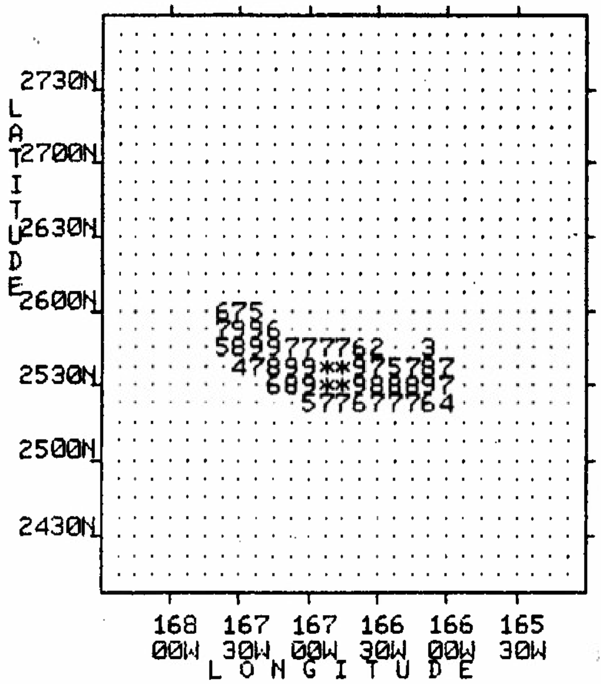


FIGURE V-13. LEVEL II EXAMPLE SEARCH RECOMMENDATION

SEARCH EFFORT DENSITY MAP - LEVEL II



DTG OF MAP:
1600 01 APR 89

TOTAL SWEPT AREA
IN SEARCH = 3957.SQ NM

EACH CELL:

1 =	5.4	-	16.1 SQ-NM
2 =	16.1	-	26.9 SQ-NM
3 =	26.9	-	37.6 SQ-NM
4 =	37.6	-	48.4 SQ-NM
5 =	48.4	-	59.1 SQ-NM
6 =	59.1	-	69.9 SQ-NM
7 =	69.9	-	80.6 SQ-NM
8 =	80.6	-	91.4 SQ-NM
9 =	91.4	-	102.1 SQ-NM
* =	102.1	-	107.5 SQ-NM

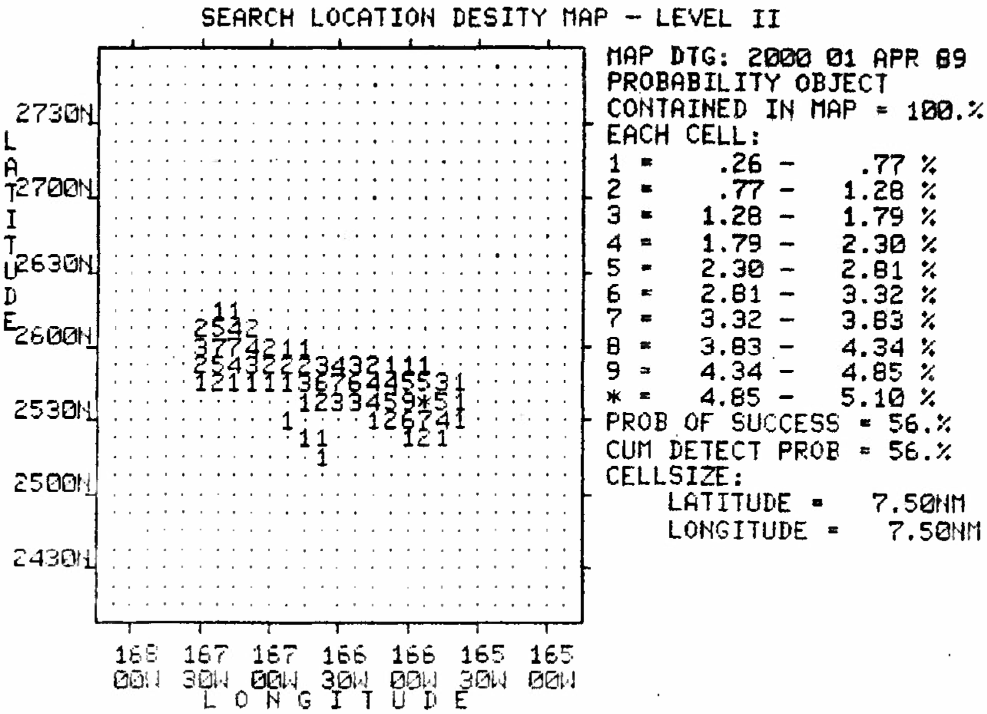
PROB OF SUCCESS = 87.%
CUM DETECT PROB = 87.%
CELLSIZE:
LATITUDE = 7.50NM
LONGITUDE = 7.50NM

FIGURE V-14. LEVEL II EXAMPLE SEARCH PLAN

NOTE: This is a user-chosen rectangle plan approximating the recommendation in Figure IV-13.

```
                SEARCH PLAN DATA INPUT FORM


SEARCH PLAN DATA # 1

DTG OF SEARCH EFFORT (DDMMYY)(hhmm) Z  [ 10489] [1600]
CENTER OF SEARCH RECTANGLE (LAT LON) (ddmm)(h)(dddmm)(h) [2530][N] [16650][W]
LENGTH OF SEARCH AREA RECTANGLE (0,500) [ 80] NM
WIDTH OF SEARCH AREA RECTANGLE (0,500) [ 18] NM
ORIENTATION OF LENGTH FROM NORTH (0,360) [110] DEG.

ENTER UP TO FIVE SEARCH ASSETS
   ASSET      SEARCH  ALTITUDE
   NAME       DUR     (0,50000)
              (hhmm)  (FEET)
S-3 VIKING    [ 400]  [1000 ]
              [    ]  [     ]
              [    ]  [     ]
              [    ]  [     ]
              [    ]  [     ]
```

FIGURE V-15. LEVEL II EXAMPLE POSTERIOR MAP



An objective of ESPA development is to provide graphical output such as Figure V-16. This, by illustration, shows envelopes of positions from which the attack aircraft can make IR detection and lock-on, and the target's defensive radar range, all atmospherically affected; also shown are aerodynamic limits on weapon launch which are not much affected by atmospherics. The size of the shaded region which meets these criteria from the aircraft point of view, indicates the desirability of conducting the attack, in addition to providing guidance for attack tactics indicated by the envelope. Figure V-17 shows an additional form of useful graphics: SAM radar detection envelopes at three probability levels and IR detection ranges against three types of targets. At the present stage of development of ESPA and OTDA Mk II, outputs are tabular without graphics. OTDA does not address target defensive radars; ESPA is doing so based on IREPS from the GFMPL.

The operational version of ESPA, and the OTDA Mk III on which it will be based, will have graphics, presumably providing output such as Figures V-16 and V-17. Other advances of these prospective systems over their predecessors include a large menu of IR types, compared to five in OTDA Mk II, and physical models of the IR emission of IR targets, compared to empirical "inherent" signals assumed at present.

Our illustrations of input/output are taken from the OTDA Mk II user's guide, reference [h].

FIGURE V-16. ILLUSTRATIVE ASM LAUNCH CONSTRAINTS

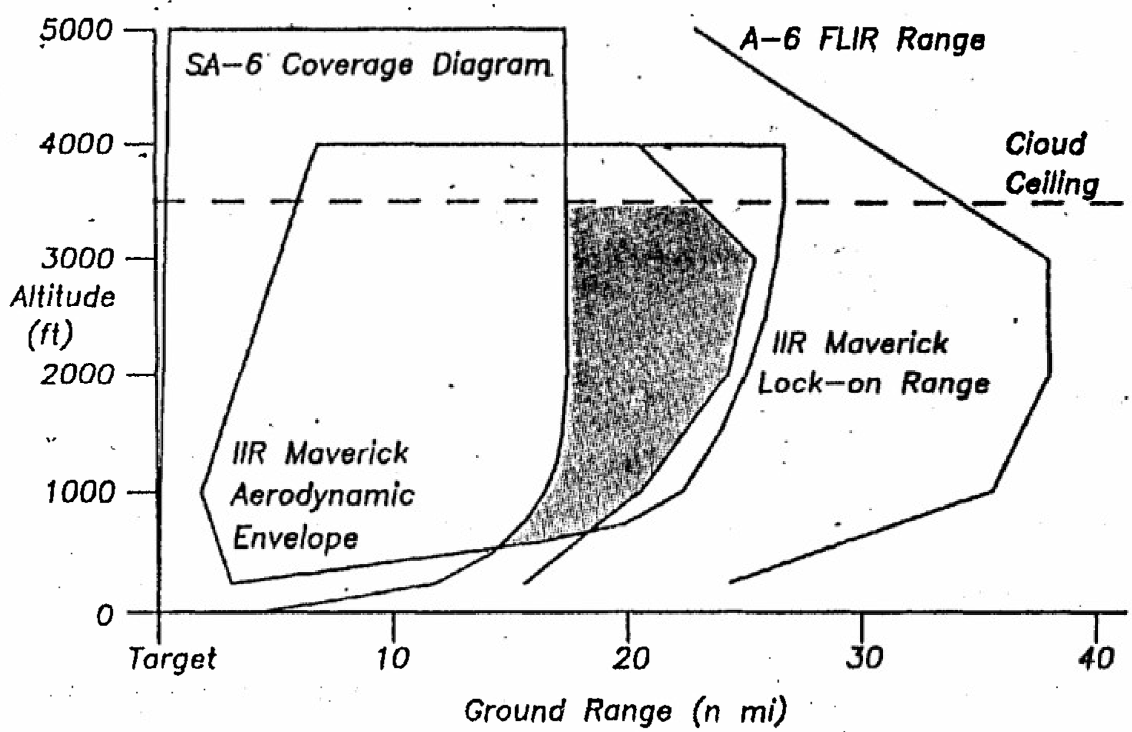
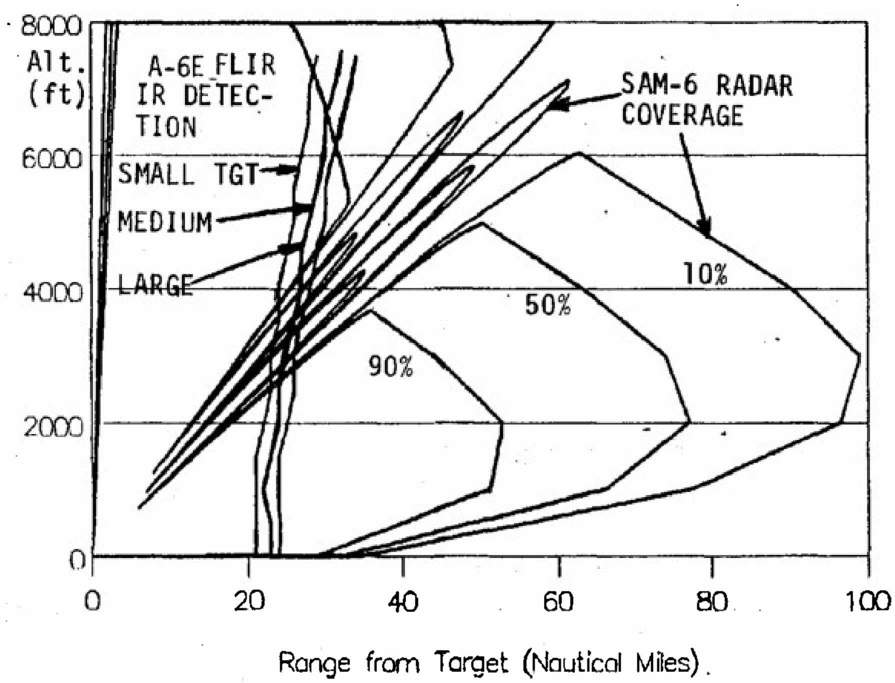


FIGURE V-17. IR DETECTION RANGES VS SAM RADAR RANGES



In effect, ESPA and OTDA contain three TDAs in one; for IR, TV and laser guidance respectively. The meteorological and site (Met/Site) table of inputs is the same for all three, as in Figure V-18, even though not all three use all of the inputs in this table. These inputs may be entered in any one of the three TDAs and be stored for use in the other two as needed. The solar and lunar elevation and azimuth are displayed on request in the lower portion of Figure V-18, there occupied by a menu of options.

FIGURE V-18. MET/SITE SAMPLE DATA AND OPTIONS

```
---------------------------------- MET/SITE DATA ------------------------------------
|          SURFACE              |                               |      UPPER LAYER        |
|                               |(10) VIS          15.0 mi      |                         |
| (1) LAT            38.00 N    |(11) PRECIP         NONE       |(18) DEFAULT ?     YES   |
| (2) LONG           90.00 W    |(12) RAIN RATE                 |(19) TEMP           *    |
| (3) DATE         07/10/87     |(13) WIND SPD         8 kts    |     DEWPT          *    |
| (4) TOT             1800 Z    |(14) INV HT        60.0 hft    |(20) AER            *    |
| (5) GEN BKG ID        50      |                               |(21) VIS            *    |
| (6) TMAX/TMIN      63/ 42 F   |  CLOUDS       TYP/ HT/AMT     |                         |
| (7) TOT-3 TEMP        55 F    |                               |                         |
| (8) TEMP              60 F    |(15) LOW         0/000/0       |   * DEFAULT USED        |
|     DEWPT             48 F    |(16) MID         3/160/3       |                         |
| (9) AER              URB      |(17) HIGH        0/000/0       |                         |
-----------------------------------------------------------------------------------------
|              From the form above enter the index to be changed    OR                  |
|                  Select one of the following options:                                 |
|                    (C) Continue to next process.                                      |
|                    (R) Re-enter entire MET/SITE data set.                             |
|                    (Q) Quit MET/SITE EDITOR, without data update.                     |
|                    (S) Display SOLAR INFORMATION.                                     |
|              ENTER:                                                                   |
-----------------------------------------------------------------------------------------
```

While the environmental data are entered in the common Met/Site table, each of IR, TV, and laser has its own table of operational inputs, which are not environmental.

The IR operational input display is shown in the upper part of Figure V-19(a). This gives data on the IR sensor type, including user's choice (when available) of field of view (FOV) as narrow or wide, and on type, size and aspect of target, all of which impact detection and lock-on. The lower part of the display is alternatively those parts of the Met/Site data that are relevant to IR (as shown) or the menu of options for the user's next choice. The environmental inputs list three chosen backgrounds (of 29 in the menu) and factors affecting thermal contrast between target and background, which is central to detection. Absolute thermal emission is measured by the equivalent blackbody temperature (EBBT), normalized to 300K. Thermal contrast between an object and its background is measured by difference between their EBBT's, and is denoted Delta-T. If the sign of Delta-T is reversed, strength of contact remains the same, hence so does detectability.

In addition to the five menu targets, the user may specify a box target of arbitrary dimensions and Delta-T.

The main outputs are in Figure V-19(b). This shows for an M60 tank target and each of three backgrounds and for both normal and wide FOV, the detection range and maximum lock-on range (MLOR), along with other data that lead to these tactical outputs. These types of outputs may be displayed in various other arrangements, e.g., Delta-T's between backgrounds, ranges versus Delta-T's, ranges versus aspects, etc.

The TV TDA supports three lock-on/detection sensors, six detection sensors, and four night vision goggle (detection) sensors. The latter is affected by a clutter input, i.e., the "busyness" of the target scene. Two sensors offer narrow and wide FOV's. There are 29 menu combinations of target length, height, and width; the user may also choose his own dimensions. From a menu of 158 target materials, the user may choose two and percentages for each for both the top and the sides of the target. Figure V-20 illustrates target description by dimensions, aspect, and, as a reference, heading. Up to three menu backgrounds may be used. From solar or lunar data and slope and downslope of background, the program determines whether the target is directly illuminated.

TV operations input data are illustrated in the upper part of Figure V-21(a). The user may choose a single viewing (compass) direction or eight compass points from 0 to 315.

The main TV outputs are detection and, if applicable, lock-on ranges, as illustrated in Figure V-21(b). Alternatively, detection ranges only may be displayed for both narrow and wide FOV's. "DIR" and "CLD" mean that the target is respectively in direct illumination and in a cloud shadow. Additional outputs are illumination data, as illustrated in Figure V-21(c). The probability of the target being in direct illumination pertains to the degree of cloud cover. Both the range and illumination outputs may be displayed in other ways against the inputs.

The laser TDA is simpler to the user than IR or TV. It supports several laser ASMs operating at 1.06 micrometers. Laser operation is illustrated in Figure V-22. A designator must "lase," i.e., be trained on, the target, guided by IR or some other optical device. A receiver on the launch aircraft receives the omnidirectional laser echo and thereby perceives accurate direction to the target. The designator may be on the launch aircraft (colocation), a separate aircraft, or on the ground. The TDA finds a receiver range for a specified designator range, and designator range for a specified receiver range or a colocated range.

A target is specified by choosing up to three items from a menu of 187 vehicles, materials, and vegetations, and percent of composition for each. Background is not used.

Laser operations inputs are illustrated in Figure V-23(a). In this case, designator range is entered, so receiver range is to be output, as chosen in input (1). Outputs are shown in Figure V-23(b). In addition to maximum receiver range, transmissivities are shown. These are attenuations of 1.06 micrometer radiation along 4 km paths. Total attenuation and no attenuation are transmissivity 0 and 1 respectively.

FIGURE V-19. IR INPUT/OUTPUT

(a) Inputs

```
+------------------------- IR OPERATIONS DATA ------------------------------+
|                                                                            |
| (1) SENSOR ID          1        (8)  TARGET ID          M60 TANK     3     |
| (2) SENSOR HT       14.0 hft    (9)  OPERATING STATE        EXERCISED      |
| (3) RANGE OPT       BOTH        (10) ASPECT ANGLE                200 deg   |
| (4) DET MTH         MRT         (11) TARGET LENGTH              22.80 ft   |
| (5) FOV OPT         BOTH             TARGET WIDTH               11.91 ft   |
| (6) CLUTTER LVL     LOW              TARGET HEIGHT              10.76 ft   |
|                                 (12) TARGET ELEVATION             125 ft   |
| (7) BACKGROUNDS:                (13) BIC                            0      |
|        TALL GRASS - GROWING      1                                         |
|        PLOWED FIELD - WET       11                                         |
|        DIRT ROAD - WET          19                                         |
+----------------------MET/SITE INPUT DATA-----------------------------------+
|                                                                            |
|        LOCATION:       38.00 N    90.00 W   07/10/87   1800 Z     50       |
|        TEMPS:          65 F/ 42 F     55 F     60 F/ 48 F                  |
|        CONDITIONS:     URB      15.0 mi  0-0      8 kts      60.0 hft     |
|        CLOUDS:         0/000/0      3/160/3      0/000/0                  |
|        UPPER LAYER:    DEFAULT                                             |
|                                                                            |
+----------------------------------------------------------------------------+
```

(b) Ranges outputs

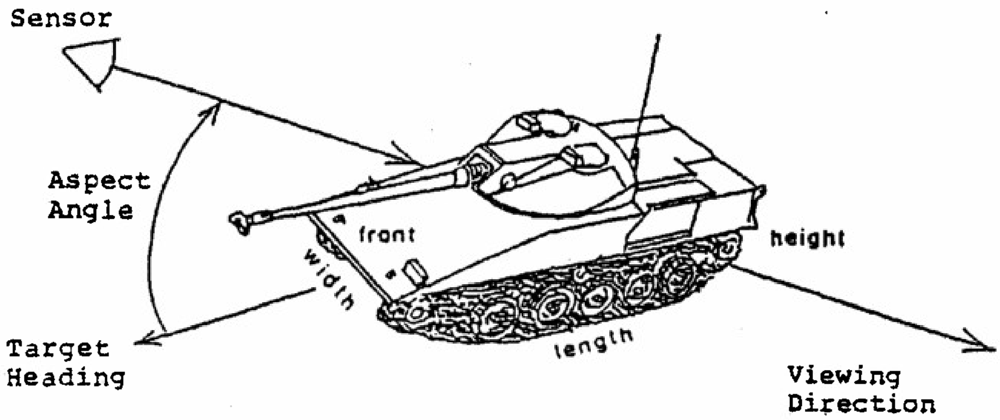
```
                          RANGES VS. BACKGROUNDS
              ------------------------------------------------------

TARGET:           M60 TANK   SENSOR ID:            1    BACKGROUND: SEE BELOW
OP STATE:         EXERCISED  SENSOR HT (HFT):     14    TEMP (K):   SEE BELOW
ASPECT (DEG):     200        DET. METHOD:         MRT
TEMPERATURE:      305.5      CLUTTER LEVEL:       LOW
LENGTH:            22.8 ft   4 KM TRANS:          0.53
WIDTH:             11.9 ft
HEIGHT:            10.7 ft
                                                            RANGES (KFT)
                                                       --------------------
                                                           DET        MLOR
                                                       ----------    ------
    BACKGROUND               TEMP (K)       DELTA-T    NFOV  WFOV
TALL GRASS - GROWING         290.4           13.8      46.0  26.9      44.8
PLOWED FIELD - WET           291.7           12.8      44.8  26.9      44.2
DIRT ROAD - WET              283.4           14.7      46.6  27.5      46.0
```

The electro-optical models underlying OTDA Mk II and the preliminary design of ESPA are described in detail in reference [g]. For each of IR, TV, and laser guidance, a target model (radiation or reflection), a transmission model, and a sensor model are given. In general these models involve considerable physical technology, and we will not attempt to summarize them here. An extensive bibliography in reference [g] indicates considerable prior research leading to these models, evidently mostly by ST Systems under sponsorship of the Air Force Geophysical Laboratory.

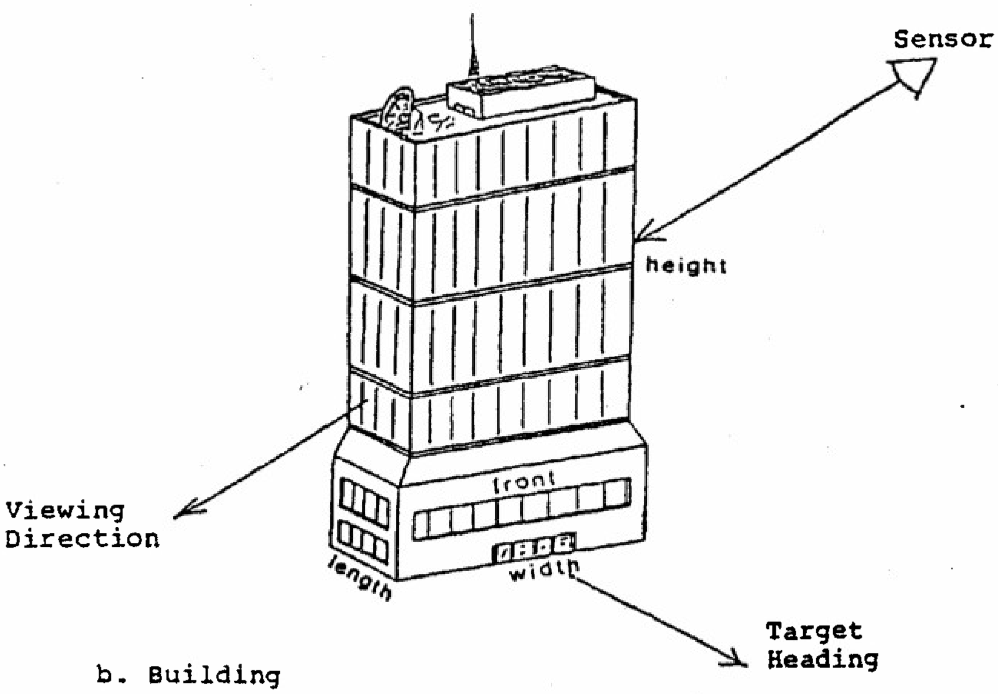
5.4 Tactical Environmental Ship Routing (TESR)

TESR is a generalization of what has become a classical (e.g., see reference [k]) dynamic programming approach to least-time ship routing in the presence of variable currents. In TESR a more complicated penalty function is formed as a weighted sum of individual penalties, called costs, each dependent on the environment, position, and time.

FIGURE V-20. TV TARGETS--SIZING AND ASPECT



a. Tank



b. Building

FIGURE V-21. TV INPUT/OUTPUT

(a) Inputs

```
+------------------------------- TV OPERATIONS DATA -------------------------------+
!                                                                                  !
! (1) SENSOR ID          31      (10) TARGET        T62 TANK-OLIVE GREEN    1      !
! (2) SENSOR HT         14.8 hft (11) TARGET TOP                                   !
! (3) RANGE OPT          3                                                         !
! (4) FOV OPT                    (12) TARGET SIDE                                  !
! (5) CLUTTER LVL                                                                  !
! (6) BKG SLOPE          5 deg   (13) TARGET HT      7.87 ft                       !
! (7) DOWNSLOPE DIR     85 deg        TARGET LEN    22.04 ft                       !
! (8) VIEWING DIR      350 deg        TARGET WD     10.99 ft                       !
! (9) TARGET HDG       200 deg   (14) BACKGROUNDS   LIVE GRASS              50     !
!                                                   SANDY-LOAM              88     !
!                                                   LIVE CROP FOLIAGE       73     !
+------------------------------MET/SITE INPUT DATA---------------------------------+
!                                                                                  !
!       LOCATION:      38.00 N    90.00 W   07/10/87    1800 Z     50              !
!       TEMPS:         65 F/ 42 F     55 F      60 F/ 48 F                         !
!       CONDITIONS:    URB      15.0 mi   0-0       8 kts        60.0 hft          !
!       CLOUDS:        0/000/0      3/160/3      0/000/0                           !
!       UPPER LAYER:   DEFAULT                                                     !
!                                                                                  !
+----------------------------------------------------------------------------------+
```

(b) Range outputs

TV TDA DETECTION RANGE (kft)

TARGET: T62 TANK-OLIVE GREEN

	LIVE GRASS		SANDY-LOAM		LIVE CROP FOLIAGE	
VIEW DIR	DIR	CLD	DIR	CLD	DIR	CLD
350	6.7	6.4	6.7	6.1	6.7	5.5

TV TDA LOCK-ON RANGE (kft)

	LIVE GRASS		SANDY-LOAM		LIVE CROP FOLIAGE	
VIEW DIR	DIR	CLD	DIR	CLD	DIR	CLD
350	6.7	6.4	6.7	6.1	6.7	5.5

(c) Illumination outputs

TV TDA MARK II OUTPUT
NORMALIZED BRIGHTNESS (4 KM)

TARGET: T62 TANK-OLIVE GREEN

VIEW DIRECTION: 350

TARGET IN DIRECT ILLUMINATION

	SIDE 1	SIDE 2	TARGET TOP	SHADOW	BACKGROUND
LIVE GRASS	0.3	0.5	0.5	0.4	1.0
SANDY-LOAM	0.4	0.7	0.7	0.4	1.0
LIVE CROP FOLIAGE	0.4	0.7	0.8	0.4	1.0

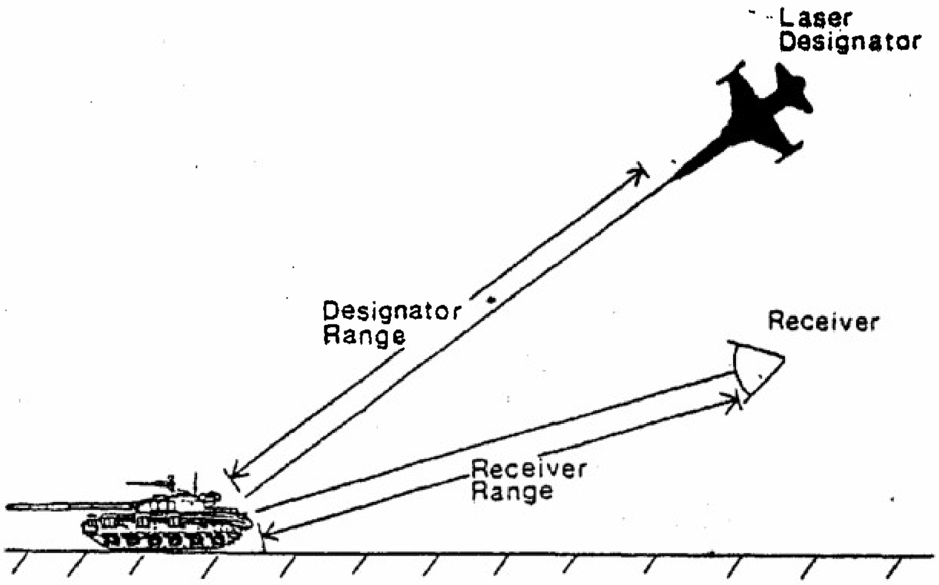
TARGET IN CLOUD SHADOW

	SIDE 1	SIDE 2	TARGET TOP	SHADOW	BACKGROUND
LIVE GRASS	0.5	0.5	0.6	N/A	1.0
SANDY-LOAM	0.6	0.6	0.8	N/A	1.0
LIVE CROP FOLIAGE	0.7	0.7	0.9	N/A	1.0

PROBABILITY OF TARGET BEING IN DIRECT ILLUMINATION: 74 %

SOLAR: ELEV	AZIMUTH	LUNAR: ELEV	AZIMUTH	PHASE	GNDILL (MLUX - FC)	
46 deg	184 deg	-42 deg	355 deg	100 %	.7304E+08	.6786E+04

FIGURE V-22. LASER SCHEMATIC



Specifically a ship's origin and destination are specified and costs are assigned to a discrete set of (lat, long, time)'s as follows:

Tropical cyclone wind (at various levels) probability

Ocean wave height

Pitch, roll, heave

Surface wind speed

Ocean current

Ice accretion

Acoustic propagation

EM propagation

Water depth

Cloud cover

Each of these attributes is assigned a "cost" rating of 0 for good, 1 for fair, 2 for poor, or unacceptable. These ratings are determined by whether various numerical desciptors of these attributes fall between user-entered bounds. For example, wave height for a given (lat, long, time) triple, is rated according to the following, where H is the predicted height for the triple:

0 = good	if $H \leq h_1$,
1 = fair	if $h_1 < H \leq h_2$,
2 = poor	if $h_2 < H \leq h_3$,

unacceptable if $h_3 < H$,

where $h_1 < h_2 < h_3$ and these thresholds are user-entered. Here a low value of H is desirable as is usually the case with each of the above attributes except water depth and cloud cover, which are usually desired to be high. Where large values are desirable, the inequalities in the above rating scheme are reversed. In fact for acoustic and EM propagation, the user may choose to reverse the order of preference (and set the thresholds accordingly). Also, wave height has a one-dimensional descriptor. Some attributes have two or more descriptors, and their corresponding inequalities define regions in higher-dimensional space.

FIGURE V-23. LASER INPUT/OUTPUT

(a) Inputs

```
+--------------------------- LASER OPERATIONS DATA ---------------------------+
|                                                                             |
| (1) MODE             RECEIVER         (4) RECEIVER HEIGHT        70.0 hft   |
| (2) RECEIVER ID         11            (5) DESIGNATOR HEIGHT      15.0 hft   |
| (3) DESIGNATOR ID        1            (6) COLOCATED HEIGHT        --  hft   |
|                                                                             |
|                   (7) RECEIVER RANGE        --  kft                          |
|                   (8) DESIGNATOR RANGE    10.0 kft                          |
|                                                                             |
|                   (9) TARGET                  ID      %                      |
|                       CEMENT BUILDING         183     60                     |
|                       AGD ASPHLT SHGL ROOF    169     30                     |
|                       GLASS                   182     10                     |
+--------------------------MET/SITE INPUT DATA--------------------------------+
|                                                                             |
|      LOCATION:       38.00 N   90.00 W  07/10/87   1800 Z    50             |
|      TEMPS:          65 F/ 42 F     55 F    60 F/ 48 F                      |
|      CONDITIONS:     URB     15.0 mi  0-0     8 kts     60.0 hft            |
|      CLOUDS:         0/000/0      3/160/3     0/000/0                        |
|      UPPER LAYER:    DEFAULT                                                |
|                                                                             |
+-----------------------------------------------------------------------------+
```

(b) Outputs

```
                         LASER OUTPUT
                         ------------

TARGET TO RECEIVER 4-KM TRANSMISSIVITY     0.71
TARGET TO DESIGNATOR 4-KM TRANSMISSIVITY   0.75

MAXIMUM RECEIVER RANGE          20.23 KFT
```

The user also assigns an importance weight to each attribute, and the weighted sum of these costs is called the tactical cost. Presumably in a given problem, most of these weights are zero, so one is dealing with only a few of these attributes.

- Land, exclusion zones, and sea ice are yes/no constraints.

Fuel cost is computed for each triple based on ocean current, surface wind direction, and wave direction (as relative directions).

The user further assigns weights to tactical cost and fuel cost, and the weighted sum of these two is total cost. Hence, to find a least-fuel route, one weights the tactical cost zero.

By dynamic programming, TESR now computes a track incrementally to minimize total cost subject to constraints, e.g., if a candidate track segment has a cost of unacceptable or violates a yes/no constraint, this is given such a high cost number that the program will choose it over alternatives only in extraordinary cases. The program will also evaluate a user-entered track in light of total cost defined as above.

A simple example of the dynamic programming analysis is shown in Figure V-24. The ship is constrained to proceed from the single stage 0 point to the single stage 3 point via one of the three stage 1 points and then one of the three stage 2 points. The branches in Figure V-24(a) are labeled with the cost assigned to each permitted leg.

To attain a given stage 1 point, there is only one choice, the leg from the origin to that point; that point is labeled with the cost of that leg as shown in Figure V-24(b). To attain a given stage 2 point there are three stage 1 points from which to proceed. For cost evaluation we need not look earlier than stage 1, since we have already recorded the cost of attaining each point in that stage. The given stage 2 point is labeled with the *least* cost of the three routes by which it is reached and the least-cost route itself is recorded with that point; this is shown in Figure V-24(c) by darkening the route. Finally, the least-cost route to destination, stage 3, is found in Figure V-24(d) by comparing the costs of arriving from each of the three stage 2 points.

By confining the choice among alternatives at each stage to one-stage look-back, we have obviated evaluation of several routes that would have been included if we looked back to the origin. This is the essence of dynamic programming. In this simple example, the computation savings are negligible, but in a ship routing problem of realistic complexity they can be very large. Note that in standard texts in industrial OR, this problem is usually called finding a shortest path through a network.

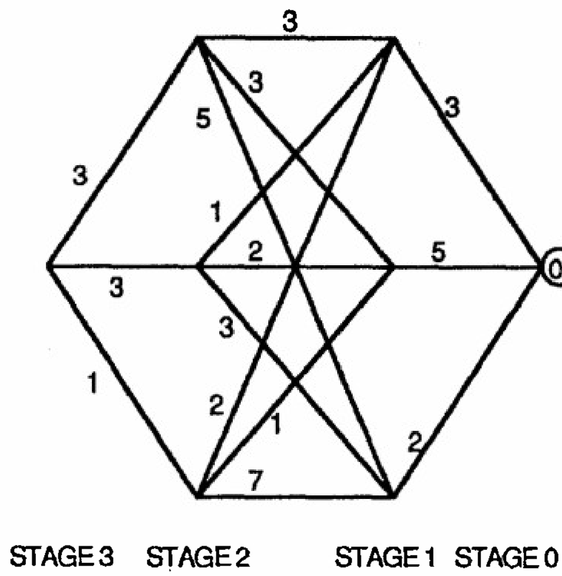
5.5 Chaff Prediction and Planning System (CHAPPS)

Chaff consists of a man-made cloud of small strips of radar-reflecting material called dipoles, and is intended to make aircraft within the cloud undetectable by radar. The characteristics of the dipoles are keyed to the frequencies of the opposing radar(s). CHAPPS provides a basis for a chaff user to decide on assets to employ, to create chaff density sufficient for the desired protection, and to decide on where to place the chaff. It further provides predictions of the chaff cloud behavior. Choice of chaff tactics to defend a ship against cruise missiles is a separate CHAPPS module.

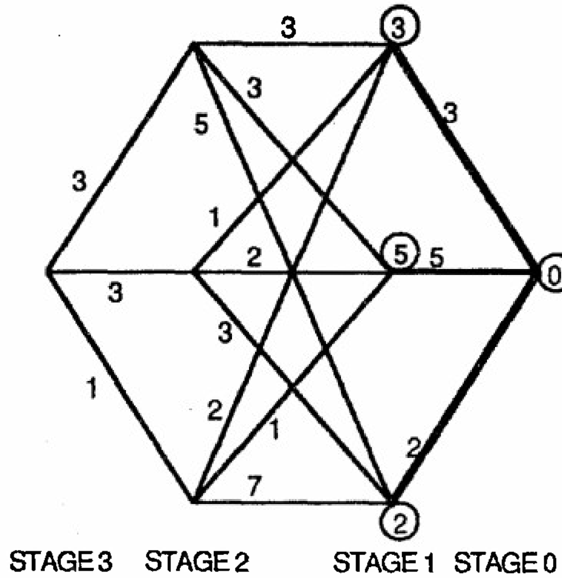
CHAPPS is also intended to help to avoid fouling civilian activities during exercises which use chaff. It was problems in this area that provided the original impetus for CHAPPS.

FIGURE V-24. SIMPLIFIED ILLUSTRATION OF DYNAMIC PROGRAMMING IN TESR

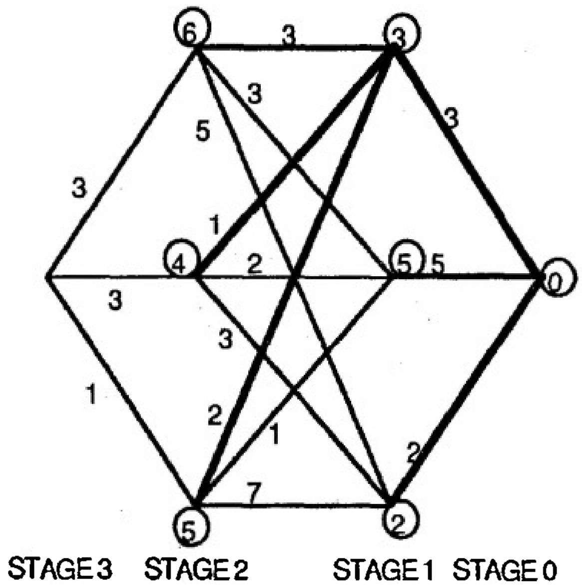
(a) Grid/Cost of track segments



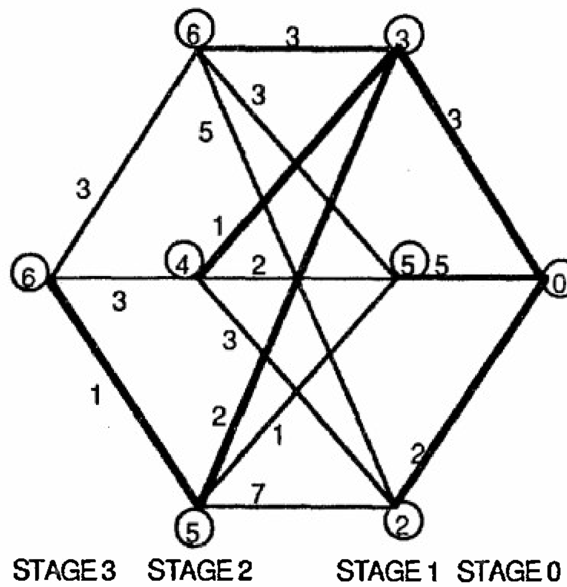
(b) Stage 1 cost computed



(c) Stage 2 cost computed



(d) Stage 3 cost computed



The main menu offers the user the following options:

(1) Display chaff response, i.e., radar cross section (RCS) in square meters per inch of chaff material at various radar frequencies.

(2) Calculate the required dispensing choices to yield the density of the chaff cloud to provide an RCS twice that of the protected aircraft against the threat radar. The length of the corridor provided by this dispensing is also calculated.

(3) Calculate where the chaff corridor should be placed.

(4) Predict the displacement of the chaff cloud centroid after deployment.

(5) Predict dispersion of the chaff cloud about its centroid after deployment.

(6) Predict the RCS of the deployed chaff.

(7) Recommend a tactic for Super Rapid Bloom Offboard Chaff (SRBOC) against anti-ship cruise missiles.

To perform these functions, CHAPPS draws on the TESS data bases for data on threat radars, friendly radars, chaff characteristics, chaff dispenser characteristics, dispensing aircraft, protected aircraft RCS, and winds aloft. Most of these data files are user-maintained. We note that the tactic of using a lengthy chaff corridor to protect strike aircraft, which underlies (2) through (6), does not appear to be much in vogue.

SRBOC tactical choices are classified, are by table lookup from reference [o], and do not relate directly to the other options. We say nothing more about SRBOC.

5.5.1. Chaff response. Chaff response is taken directly from the data base and is displayed as curves of RCS per inch of strip versus frequency. Figure V-25 is an example. Quadratic interpolation is used between the discretely stored values.

5.5.2. Chaff density. The purpose of chaff density calculation is to obtain choices of dispensers, dispenser settings, and dispensing aircraft which will provide chaff RCS twice that of the protected aircraft against the threat radar. This RCS requirement is stated per radar resolution cell (RRC). An RRC is approximately a 3-dimensional rectangular prism, within which the radar cannot distinguish two points. Chaff corridor length is also calculated.

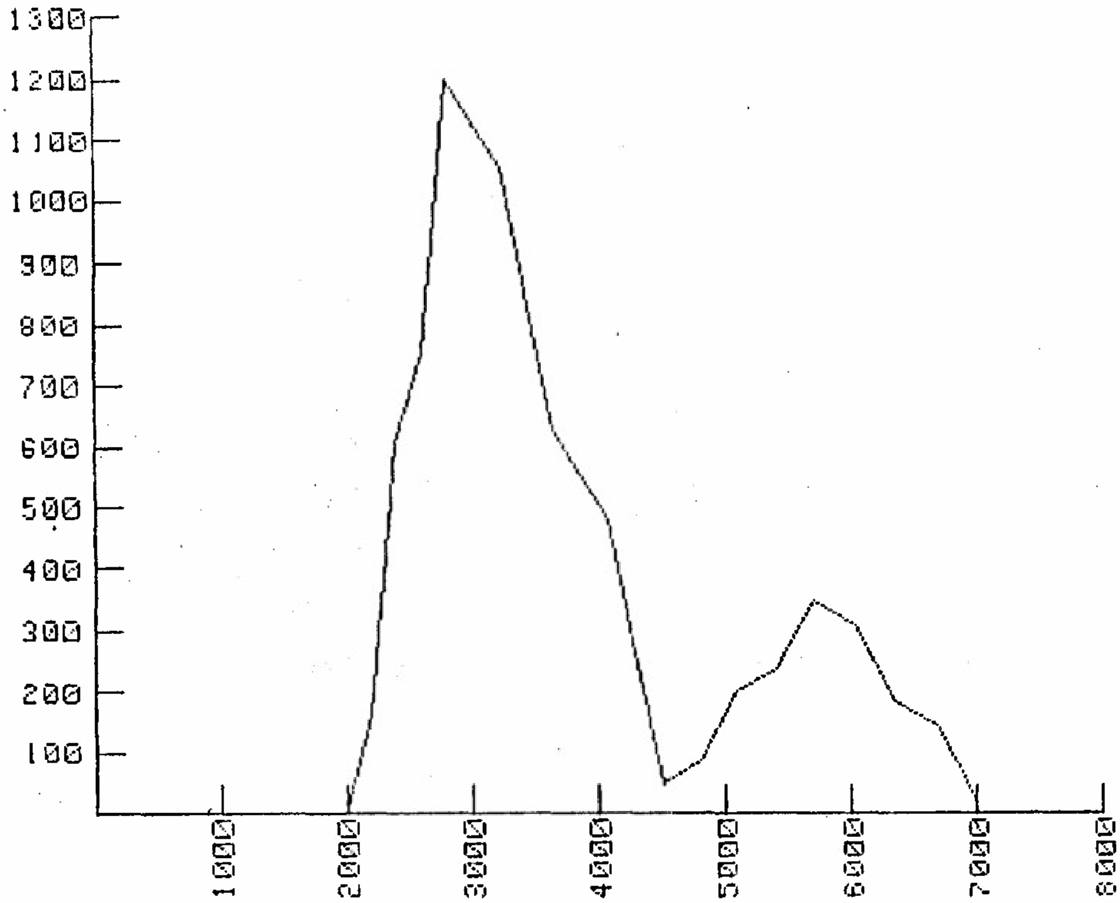
An example of the output of this module is in Figure V-26. The pulse interval and length pertain to pulsed dispensing, which is an alternative to continuous dispensing. The spread between the upper and lower bounds on RCS is due to the spread in dispensing efficiency.

To obtain Figure V-26, CHAPPS first displays in turn, for user choice, types of threat radars, chaff, dispensers, and dispenser aircraft, each display being determined by the preceding choice. The types of chaff and types of dispenser available are few. The user also chooses the time by which the dispensing aircraft leads the protected aircraft.

Density computation is based on the dimensions and orientation of the RRC centered at a typical point in the chaff corridor, as illustrated in Figure V-27. The key computation is of d, the length of the section of the corridor contained in the

RRC, shown as a dashed line in Figure V-27. A further calculation is made of the area A_H of the area of the horizontal projection of the RRC. In Figure V-27, the radar beam height is finite; if it were infinite, the RRC would be infinite in a dimension close to the vertical. By dividing the required chaff RCS by both d and A_H, one obtains the required chaff RCS per unit length along the corridor and per unit of horizontal area.

FIGURE V-25. ILLUSTRATIVE CHAFF RESPONSE GRAPHIC



By multiplying number of dispensers, number of rolls per dispenser, rate of dispensing, RCS per inch for the chaff type, and dispensing efficiency, one obtains RCS per inch dispensed per unit time. By dividing this by required chaff RCS per inch (preceding paragraph), i.e., required density, the required aircraft speed is obtained. The calculations are modified if pulsed dispensing is used. It is observed that if the chaff RCS requirement is met by a given speed, then it is met by any smaller admissible speed. There are only finitely many choices of number of dispensers, rate of dispensing, and, if applicable, dispensing pulse interval and length. The program examines all of these and finds the maximum speed, if any, by which the chaff density requirement can be met in each case. The satisfactory cases are displayed as in Figure V-26. Also shown is the minimum, i.e., required, chaff RCS per unit area of the horizontal projection of an RRC, obtained by dividing twice the required protected aircraft RCS by A_H.

FIGURE V-26. ILLUSTRATIVE CHAFF DENSITY RECOMMENDATION

```
                         MINIMUM RCS REQUIREMENTS

        MINIMUM RCS PER RRC(SQ. METERS):                        40
        MINIMUM RCS AS PERCENTAGE OF HORIZONTAL
                 CROSS-SECTIONAL AREA OF AN RRC:
                                                                .025 %

             ****** LIST OF FEASIBLE SOLUTIONS ******

        LEGEND
                 ND   NUMBER OF DISPENSERS

                 DA   AVERAGE RCS (SQ. METERS) PER RRC

                 DL   LOWER BOUND FOR DA

                 DU   UPPER BOUND FOR DA

                 LC   CORRIDOR LENGTH IN NAUTICAL MILES


PULSE INTERVAL(SEC)=      .8
PULSE LENGTH(SEC)=        1.2
DISPENSER RATE(IN/SEC)=   1
```

SPEED (KNOTS)	ND	DL	DA	DU	LC
535	1	32	46	93	297
600	2	58	81	166	333

From the additional knowledge of the roll length it is straightforward to calculate the length of the corridor that can be laid with the required chaff density, also given in Figure V-26.

5.5.3. Corridor placement. The next issue is where to place the corridor whose density and length have just been calculated. The corridor placement module does this by working back from the desired strike flight path, *having constant course and altitude*, using the lead time of the dispensing aircraft and winds aloft and chaff fall rate data from the TESS data base. Fall rate is taken to be constant in each 1000 foot altitude layer. (The user may enter fall rate, the same at all altitudes, instead of using the data base.) The wind vector is linearly interpolated over each 1000 foot interval and is taken to be the same throughout the corridor even though it might be some 300 nm long.

The calculation begins at a generic point on the strike path. Given the fall rate at 1000 feet higher, the time is found to fall the 1000 feet. For that time increment, the horizontal back-drift is found by integrating the wind vector with respect to time over the 1000 foot altitude interval. These two steps are repeated until the lead time is exhausted. The result is the total horizontal and vertical displacements from the point in the strike path to the dispensing point, throughout the corridor. An output illustration is shown in Figure V-28.

FIGURE V-27. RADAR GEOMETRY

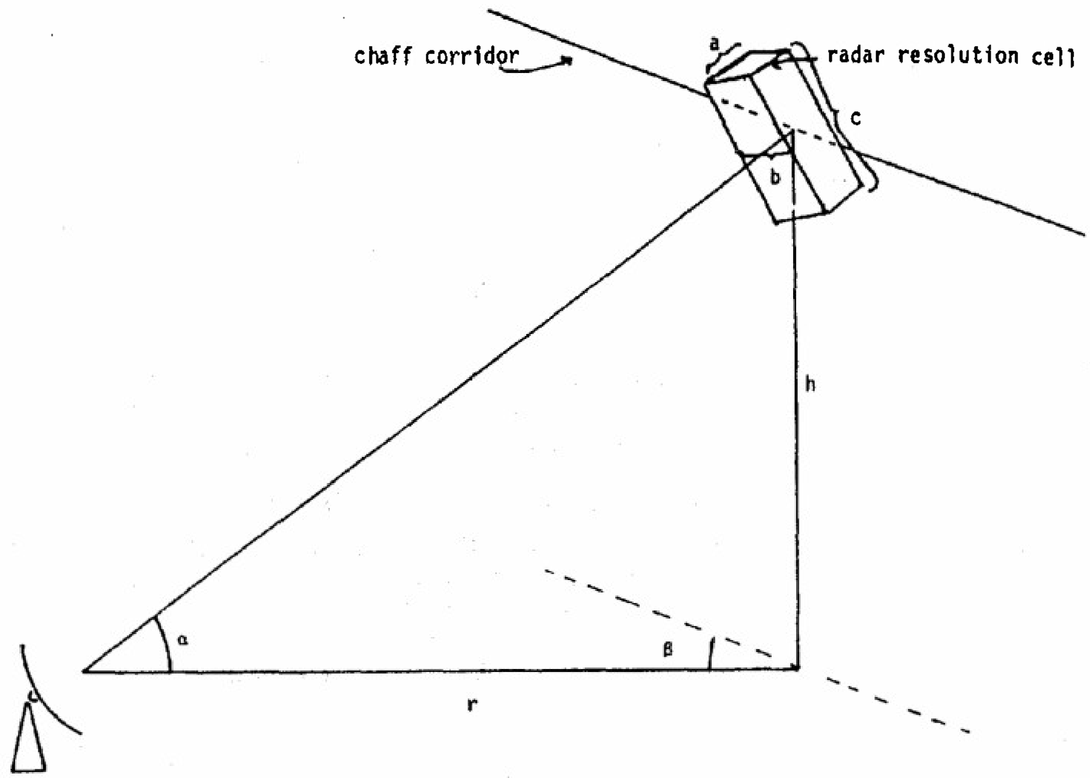


FIGURE V-28. ILLUSTRATIVE CORRIDOR PLACEMENT RECOMMENDATION

NOTE: Latitude and longitude correspond to the initial point on the corridor. Bearing of corridor is measured from this point.

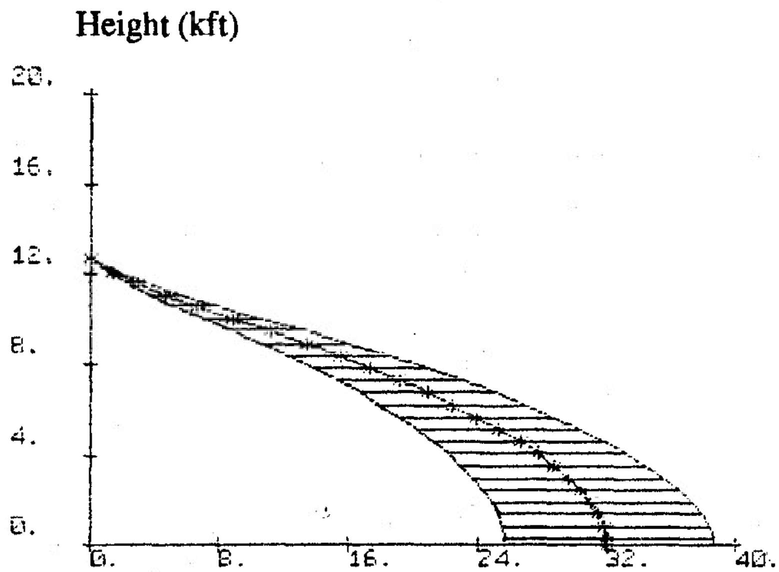
STARTING POSITION OF THE DISPENSING CORRIDOR:	4504N 04508E
LENGTH OF THE DISPENSING CORRIDOR:	15 NM
HEADING ALONG THE DISPENSING CORRIDOR:	180 DEG CW FROM NORTH
ALTITUDE OF THE DISPENSING CORRIDOR:	21.0 KFT

5.5.4. Chaff displacement. The next module produces a prediction of the displacement of the centroid of the chaff cloud, starting at a given dispensing point, at various times after dispensing. In the mean, this is essentially a reversal of the computation of corridor displacement; provision is made for time increments for computation purposes which are greater than fall times through some of the 1000 foot intervals.

Uncertainty limits in displacement of the centroid are attributed entirely to uncertainty in the horizontal wind vector, which is assumed to be circular normal. It is further assumed that (1) for each altitude increment, the standard deviation of the horizontal displacement during that increment is 1/10 of the mean displacement, and (2) these displacements are completely correlated, so their standard deviations may be summed (rather than sum the variances if they were independent), to obtain the standard deviation of the total displacement up to a given time.

The output of this module consists of graphs of, for a fixed fall time, altitude versus the mean horizontal displacement (vertical section) and horizontal displacement versus bearing (horizontal section), together with 2-sigma limits in both cases, as shown in Figures V-29 and V-30 from reference [a].

FIGURE V-29. TEMPORAL VERTICAL CHAFF DISPLACEMENT



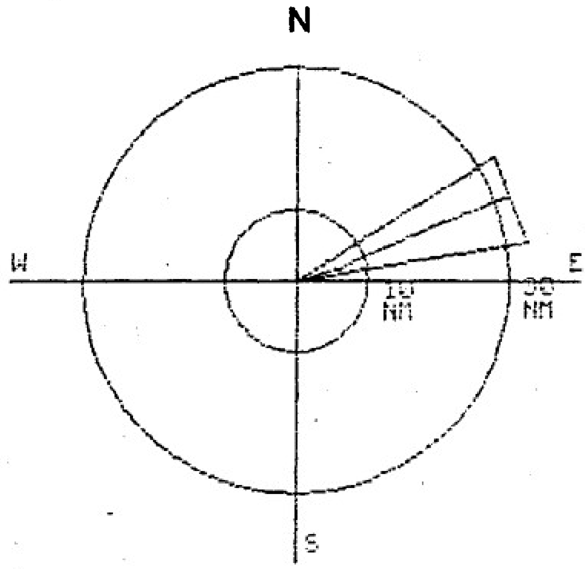
RANGE (nm)
Total fall time 70 minutes.
95% confidence envelope for chaff cloud centroid at specified times.
251800Z FEB88 2828N 08033W

5.5.5. Chaff dispersion. Having found the displacement versus time of the *mean* position of the chaff dispensed along a corridor, we also wish to portray the *dispersion about* the mean. Specifically we want to produce percentage containment limits as shown in Figure V-31, V-32, and V-33 for 10%, 50%, and 90% containment (from reference [a]).

These containment limits are also contours of probability density of the event that some dipole (i.e., chaff particle) is at a given point at the given instant. The origin of the portrayal coordinates is the mean position of the chaff cloud at some point along the corridor at that instant. The X coordinate is the horizontal projection of the line of sight to the radar. The vertical is Z, and Y is perpendicular to X and Z. In this example, evidently the dispensing is pulsed. Whether the dispensing is continuous or pulsed, what is shown is the bivariate projections on the reference planes of the trivariate distribution of chaff density centered at the chosen origin along the chaff corridor. If the corridor is in the X direction, it would appear that only the YZ projection would be of interest, since the distribution would be uniform in X over the corridor length.

FIGURE V-30. TEMPORAL HORIZONTAL CHAFF DISPLACEMENT

Horizontal distance (nm) and bearing from initial point of chaff drop



Total fall time 70.56 minutes
95% confidence envelope for chaff cloud at specified times.
251800Z FEB88 2829N 08033W

Note that the bivariate projections describe, but do not fully characterize the trivariate distribution from which they came, even under normality. I.e., in general there are many trivariate normal distributions for given three mutually orthogonal bivariate normal projections. However, the bivariate projections are ordinarily as much information as can usefully be considered in decision-making, so we don't mind losing the additional information.

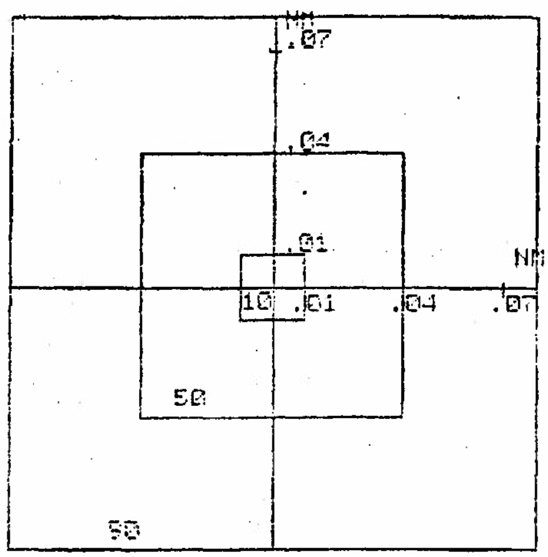
With the objective of this portrayal, we first describe the stochastic behavior of a single dipole. Since it is at an arbitrary position along the corridor, we use north/east/up coordinates, ignoring the radar position. For display, we convert to the above XYZ.

The single-dipole position distribution spreads about the mean due to atmospheric turbulence, and we will model it as a trivariate normal distribution with growing covariance. We need only its covariance since we already know its mean. Having found that, we find its bivariate normal projections on the north/east, north/up, and east/up reference planes.

To obtain the bivariate projection of the probability density that there is a dipole at a particular point in space at some instant, we must also consider the contributions of the corresponding bivariate normal projections of all the other dipoles dispensed in a line along the corridor. I.e., we must find the distribution of the sum of independent bivariate variables, one normal and the other uniform on a line segment. The line segment is the entire corridor axis at the mean position for the instant in the case of continuous dispensing, and is limited to the pulse length in case of pulsed dispensing. The sum distribution is the convolution of the normal with the uniform.

FIGURE V-31. CHAFF DISPERSION--XY PLANE

Location of center of mass of chaff cloud:
Bearing to center of corridor: 35.0 deg, Range: 67.1 nm, Altitude: 10.0 kf



Contours contain 10%, 50%, 90%, of the chaff.
The radar lies directly to the left.
251800Z FEB88 2828N 08033W

It then remains to find the contours of probability density at levels which contain the desired percentages and convert to XYZ, for display as in Figures V-31, V-32, and V-33.

We outline first how the trivariate distribution of a single dipole is found and then outline the remaining analysis.

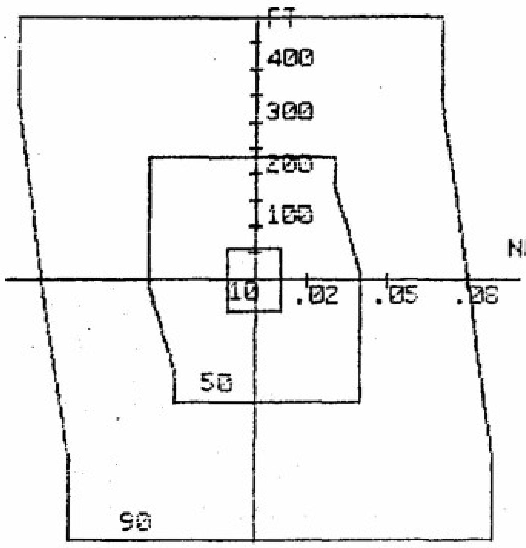
Let the state of the dipole at time t be given by (T means transpose)

$$S(t) = (x(t), y(t), z(t), u(t), v(t), z(t))^T,$$

where (x(t), y(t)) is horizontical position (in north/east coordinates, not XY), z(t) is vertical position, and u(t), v(t) and z(t) are the respective speeds in the same coordinates. As with displacement, we treat the S process by 1000 feet altitude layers. Fix a layer. Let a and b be the respective *changes* in the x and y components of wind speed from top to bottom of the layer, found from winds aloft data (a and b may change from one layer to another).

FIGURE V-32. CHAFF DISPERSION: XZ PLANE

Location of center of mass of chaff cloud:
Bearing to center of corridor: 35.0 deg, Range: 67.1 nm, Altitude: 10.0 kf



Contours contain 10%, 50%, 90% of the chaff.
The radar lies directly to the left.
251800Z FEB88 2828N 08033W

We postulate that for some positive constants β and σ, for small $h > 0$,

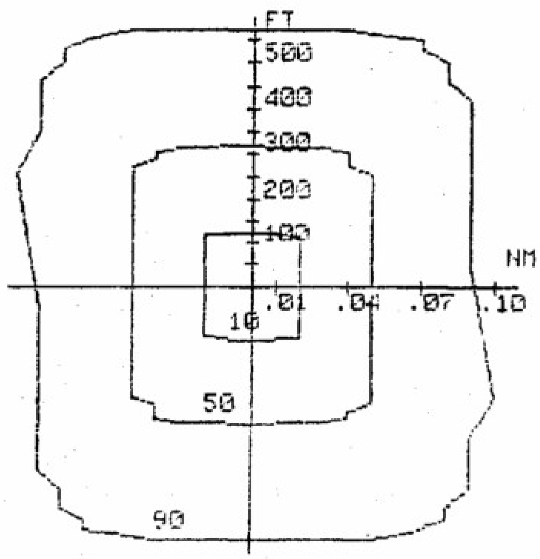
$$S(t+h) - S(t) \approx h \begin{bmatrix} u(t) \\ v(t) \\ w(t) \\ -\beta u(t) + aw(t) \\ -\beta v(t) + bw(t) \\ -\beta w(t) \end{bmatrix} + \sigma\sqrt{h} \begin{bmatrix} 0 \\ 0 \\ 0 \\ p \\ q \\ r \end{bmatrix}, \qquad \text{(V-4)}$$

where p, q, and r are independent normal variables with zero mean and unit variance. Let's compare (V-4) to (III-1) of 3.5. We have added a vertical dimension and have introduced drift in horizontal velocity via a and b. (In principal, β and σ for the vertical component could differ from the horizontal values, and that is how they are modeled in reference [d], but as estimated in reference [d] they turn out to be the same. Also, in reference [d], a, b, and β are called α, β, and λ respectively.) Under (V-4) we have that S is a 3-dimensional IOU process in position with drift in horizontal velocity--see Appendix B and for an interpretation in terms of velocity changes, see D.1 of Appendix D. (Our previous encounters with IOU with drift in velocity were in NAVSAR (see 5.2) and the motion model in VPCAS historical analysis (see 2.5).)

As in 3.5.2, we think of β as the average rate of course changes of the dipole per unit time and $\sigma/\sqrt{\beta}$ as the dipole's average instantaneous speed. From fitting solutions of (V-4) to chaff dispersion data in reference [p], reference [d] estimates $\beta = .1$ per second and $\sigma = .27$ meters per second$^{3/2}$ (reference [d], p. 68 says meters per second, which for dimensional consistency must be in error).

FIGURE V-33. CHAFF DISPERSION: XZ PLANE

Location of center of mass of chaff cloud:
Bearing to center of corridor: 35.0 deg, Range: 67.1 nm, Altitude: 10.0 kf



Contours contain 10%, 50%, 90% of the chaff.
The radar lies directly to the left.
251800Z FEB88 2828N 08033W

Let's look at some physical interpretation of (V-4). The first three components simply say that change in position (on the left) is current velocity times time increment. The last component, with vertical speed on the left, is 1-dimensional IOU, interpreted as in, e.g., 3.5.2 or D.1. However, each of the fourth and fifth components, with a horizontal speed on the left, has a term involving a or b, e.g., in the fourth component the term haw(t). This term is also a[z(t+h) - z(t)], by the equation for the third component. As pointed out in reference [d], a is the change in the north component of wind speed per meter change in altitude, so a[z(t+h) − z(t)] is the incremental change in the north component of wind speed, thus wind shear is thereby introduced into the model.

A solution to (V-4) must in the first three components be a trivariate gaussian process, as desired. As initial values for (V-4) we take S(0) as a 6-vector with zero mean whose covariance with (0, 0, 0, p, q, r) is zero. As noted before, we already know the mean position of the solution, so we merely need position covariance at each time. This can be found by generalizations on the method outlined in 3.5.2. That entails considerably more complication than in 3.5, partly by including the vertical dimension, but much more so from the drift in horizontal velocity. We refer to reference [d] for details.

After projecting the distribution thus determined on the reference planes, we next must convolve each of the bivariate normals with a uniform distribution on a line segment. To do this, reference [d] takes advantage of the fact that the uniform distribution, although stated as bivariate for compatibility, is concentrated on a 1-dimensional set. By a linear transformation of the variables in both distributions (a rotation, a stretch different in the two coordinates, and the reverse rotation), the problem is reduced to one of convolving a bivariate normal having *independent* coordinates, with a uniform distribution concentrated on one of the coordinate axes. The probability density function of that convolution can be computed in terms of the cumulative normal distribution.

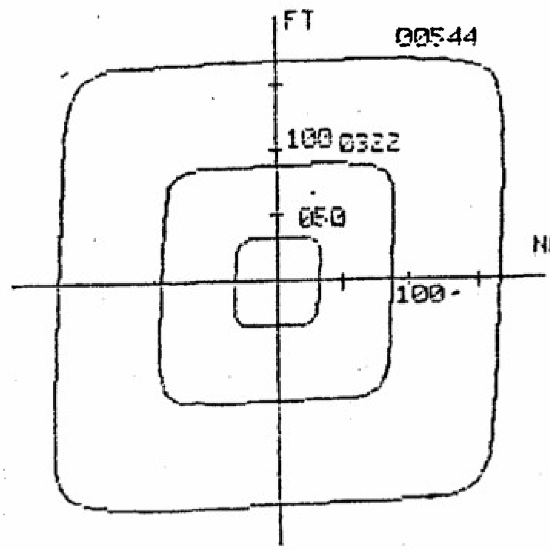
Remaining in the transformed coordinates, one can by binary search compute several points on a probability density contour at a chosen level. By further numerical methods, reference [d] shows how to find the level of the probability density contour corresponding to a desired containment level. Then the reverse linear transformation is applied to the correspondingly computed density contour points to obtain the desired containment limit points in the original coordinates. This completes the outline of the methods underlying the portrayal of chaff dispersion in Figures V-31, V-32, and V-33.

More recent models in reference [q] (prepared for FNOC), use IOU processes in a somewhat different way to find displacement and dispersion simultaneously.

5.5.6. RCS prediction. Here the object is use the dispersion prediction to predict the RCS of an RRC centered at the mean of the chaff cloud at a chosen moment. Inputs needed in addition to those of 3.5.5 are radar frequency, number of dispensers, and number of rolls per sensor. The dispersion analysis is followed to the point where probability densities of the convolved distribution are found. Instead of computing contours, this probability density, applied to points mapped by the inverse linear transformation, is converted to RCS and is integrated over the dimensions of the centered RRC. Only the YZ projection is output; this affords a boresight view from the radar. Output is illustrated in Figure V-34.

FIGURE V-34. RADAR CROSS SECTION PREDICTION

The RCS in a RRC centered at the mean if 38 sq. m.
Location of center of mass of chaff cloud:
Bearing to center of corridor: 35.0 deg, Range: 67.1 nm, Altitude: 10.0 kf



Contours represent RCS density in sq. m/cubic nm. Projection of the chaff cloud onto a plane perpendicular to the line of sight of the radar.
251800Z FEB88 2828N 08033W

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[j] J. R. Weisinger and D. D. Engel, *Estimating Visual Detection Performance at Sea*, Operations Research, Vol. 36, No. 5, September-October 1988.

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[p] R. Traci, *Chaff Dispersion Analysis: Preliminary Development and Scoping Studies*, Science Applications, Inc. Report to U. S. Army ERADCOM DRDELCCM, January 1981.

[q] M. G. Monticino, *Two Approaches to Incorporating a Vertical Wind Component into CHAPPS*, DHWA Memorandum to ST Systems, 1989.

GLOSSARY OF ACRONYMS

AAA: Anti-aircraft artillery
AAC: Atlantic Analysis Corporation
AAM: Air-to-air missile
AAW: Anti-air warfare
AE: Atmospheric Environment [in GFMPL]
AEW: Airborne early warning
AOP: Area of position
APAIR: Approved air ASW simulation model
APL/JHU: Applied Physics Laboratory, Johns Hopkins University
APP: Acoustic Performance Prediction
ASM: Air-to-surface missile
ASMD: Air-to-surface missile defense
ASUW: Anti-surface warfare
ASW: Anti-submarine warfare
ASWOC: ASW Operations Center
ASWTDA: ASW Tactical Decision Aid
ATTAC: Automated TMA Tactical Aid to Commanders
C^2: Command and Control
C^3: Command, Control, and Communications
CAP: Combat air patrol
CAS: Computer-assisted search
CASE: Composite Area Search Evaluation
CASP: Computer-Assisted Search Planning [USCG SAR]
CAST: Computer-Assisted Stationing Tool
CBK: Carrier-based tanker aircraft
CCS: Constant course and speed
CDP [or cdp]: cumulative detection probability
CGN: Nuclear-powered guided missile cruiser
CHAPPS: Chaff Planning and Prediction System
CIC: Combat Information Center
CINCLANTFLT: Commander-in-Chief, Atlantic Fleet
CIWS: Close In Weapon System
CNA: Center for Naval Analyses
CNO: Chief of Naval Operations
CNOC: Commander Naval Oceanographic Center
COMASWFORLANT: Commander ASW Forces, Atlantic Fleet [later COMSECONDFLT]
COMCARGRU: Commander Carrier Group
COMDESRON: Commander Destroyer Squadron
COMNAVAIRLANT: Commander Naval Air Forces, Atlantic Fleet
COMOCEANSYSLANT: Commander Oceanographic Systems, Atlantic Fleet
COMOCEANSYSPAC: Commander Oceanographic Systems, Pacific Fleet
COMPATWINGSLANT: Commander Patrol Wings, Atlantic Fleet
COMPATWINGSPAC: Commander Patrol Wings, Pacific Fleet

COMSECONDFLT: Commander Second Fleet
COMSIXTHFLT: Commander Sixth Fleet
COMSUBDEVGRU TWO: Commander Submarine Development Group Two [later COMSUBDEVRON TWELVE]
COMSUBDEVRON TWELVE: Commander Submarine Development Squadron Twelve [formerly COMSUBDEVGRU TWO]
COMSUBLANT: Commander Submarine Forces, Atlantic Fleet
COMSUBPAC: Commander Submarine Forces, Pacific Fleet
COSL: COMOCEANSYSLANT
COSP: COMOCEANSYSPAC
CPA: Closest point of approach
CPWL: COMPATWINGSLANT
CPWP: COMPATWINGSPAC
CSDG-2: COMSUBDEVGRU TWO [later CSDS-12]
CSDS-12: COMSUBDEVRON TWELVE [formerly CSDG-2]
CSE: Course
CV: Aircraft carrier
CWC: Composite Warfare Commander
CZ: Convergence zone
D/E: Depression/elevation
DDG: Guided missile destroyer
DCRT: Destination-Constrained Random Tour
DHWA: Daniel H. Wagner, Associates
DLI: Deck-launched interceptor
DP: Direct path
DTC: Desktop calculator or computer
DTED: Digital Terrain Elevation Data
DTG: Date-time group
EBBT: Equivalent black body temperature
ECM: Electronic countermeasures
EFOV: Effective field of view
EM: Electromagnetic
ESPA: Environmental Strike Planning Aid
EW: Electronic warfare [in some usages, not here, early warning]
FASTAD: Fleet ASW Tactical Decision Aid
FCS: Fire control system
FNOC: Fleet Numerical Oceanography Center
FOM: Figure of merit
FOTC: Fleet Over-the-Horizon Coordinator
GD/EB: Electric Boat Division, General Dynamics Corporation
GFMPL: Geophysical Fleet Mission Program Library
GST: Generic Statistical Tracker
HHPC: Hand-held programmable calculator
HS: Sea-based helicopter
INRI: Inter-National Research Institute
IOU: Integrated Ornstein-Uhlenbeck
IR: Infra-red
IREPS: Integrated Refractive Effects Prediction System
ISPS: Integrated Strike Planning System

ITDA: Integrated Tactical Decision Aids
ITO: Initially topped off
JCS: Joint Chiefs of Staff
JMEMS: Joint Munitions Effectiveness Manuals
JOTS: Joint Operational Tactical System
KAST: Kalman Automatic Sequential TMA Program
LANT: Atlantic
LBK: Land-based tanker aircraft
LOB: Line of bearing
LR: Long range [CAP]
LRT: Likelihood Ratio Tracker [in SALT]
LTT: Long-Term Tracker [in P-3C Update IV]
MATE: Manual Adaptive TMA Evaluator
MED: Mediterranean
MET: Meteorological
MEU: Mission essential unit
MLOR: Maximum lock-on range
MOE: Measure of effectiveness
MR: Medium range [CAP]
MTST: Maneuvering Target Statistical Tracker
NAS: Naval Air Station
NATOPS: Naval Air Training and Operating Standardization
NAVFAC: Naval Facility [under COSL or COSP]
NAVOCEANO: Naval Oceanographic Center
NAVSAR: Naval Search and Rescue
NAVSEA: Naval Sea Systems Command
NAVSPASUR: Naval Space Surveillance System
NEPRF: Naval Environmental Prediction Research Center
NFO: Naval Flight Officer
NOSC: Naval Ocean Systems Center
NOTS: Naval Ordnance Test Station
NPGS: Naval Postgraduate School [usually NPS]
NSRDC: Naval Ship Research and Development Center
NSWES: Naval Ship Weapons Engineering Station
NTSA: Navy Tactical Support Agency
NUSC: Naval Underwater Systems Center
NUWRES: Naval Underwater Weapons Research and Engineering Station [later NUSC/Newport]
NWP: Naval Warfare Publication
OASIS: Operational ASW Search Information System
OE: Ocean Environment [in GFMPL]
OEG: Operations Evaluation Group [later within CNA]
ONR: Office of Naval Research
OP-xxx: The office numbered xxx in the OPNAV hierarchy
OPNAV: Office of the Chief of Naval Operations
OR: Operations research
ORSA: Operations Research Society of America
OTCIXS: Officer in Tactical Command Information Exchange System
OTDA: Operational Tactical Decision Aid [USAF]

OTH-T: Over-the-Horizon Targeting
PAC: Pacific
PACQ: Probability of acquisition
PHIT: Probability of hit
RANGEX: Ranging exercise
RCC: Rescue Coordination Center [USCG]
RCS: Radar cross section
RRC: Radar resolution cell
RTM: Radar terrain masking
SAG: Surface action group
SALT: Search and Localization Tactical Decision Aid
SAM: Surface-to-air missile
SAR: Search and rescue
SASHEM: SAG-against-SAG Harpoon Engagement Model
SDE: Stochastic differential equation
SE: Signal excess
SEP: Search effectiveness probability
SFMPL: Submarine Fleet Mission Program Library
SMS: Search Management System
SOA: Speed of Advance
SPA: SOSUS Probability Area
SPAWAR: Naval Space Warfare Systems Command
SPD: Speed
SRBOC: Super Rapid Bloom Offboard Chaff
SSPO: Strategic Systems Project Office
STT: Short-Term Tracker [in P3-C Update IV]
SURTAC: Surveillance Tactical Aid for Commanders
SVP: Sound velocity profile
SWDG: Surface Warfare Development Group
TAC D&E: Tactical Development and Evaluation
TACCO: Tactical control officer
TACTRAGRULANT: Tactical Training Group, Atlantic Fleet
TAMPS: Tactical Aircraft Mission Planning System
TARS: Tanker AAW Refueling Schedules
TDA: Tactical decision aid
TDAU: Tactical Data Acquisition Unit
TESR: Tactical Environmental Ship Routing
TESS: Tactical Environmental Support System
TMA: Target motion analysis
TSS: Tactical Surface Surveillance
USNA: U.S. Naval Academy
USNUSL: U.S. Naval Underwater Sound laboratory [later NUSC/New London]
VP: Naval shore-based patrol aircraft
VPCAS: VP Computer-Assisted Search
VS: Sea-based fixed-wing ASW aircraft

APPENDIX A

USER FRIENDLINESS IN TDA DESIGN

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This appendix is addressed to Operations Analysis students who may become involved in the design of a tactical decision aid. It treats the basic principles of user interface design. These principles apply to the design of a wide variety of interfaces applicable to many different applications. The reader is encouraged to pursue references [a] and [b] for more detailed coverage of the topics discussed below.

A.1. The Importance of Good User Interfaces

A user interface is the part of a software/hardware system that *touches* the user, and through which the user interacts with the system. An integration of software and hardware, the user interface may be as simple as a prompt for textual information or as complex as a graphics based window management system with mouse, overlapping windows, color, icons, pull-down menus and keyboard function keys. The skill with which the designer selects and integrates interface technology to suit a particular application has a tremendous impact on a number of important factors affecting users, including:

- Confidence
- Productivity
- Training costs
- Morale

To underscore the importance of these and other factors, the reader should note that in most successful interactive systems of any complexity, the cost of design and development of the user interface is a sizeable proportion of the total system cost. This is as true for hardware as for software.

A.2. Design Goals for User Interfaces

The first and foremost rule governing the design of anything used by a person is know the user. With this rule in mind, the following is a representative list of design goals:

- **Use the user's conceptual model.**

  A conceptual model is the knowledge base a person builds up over time to rationalize the behavior of a system (any system). Violating this model leads to confusion, frustration, long learning times and poor retention.

  An example of this is the standard operating system user interfaces for UNIX, VMS or MS-DOS. They are text based, formed from large and loosely coupled sets of complex commands with many different options and parameters, and run on top of a file system which, though organized hierarchically, is hard to understand. Users on these systems are forced to alter their conceptual model to match that of the system. These interfaces are not user friendly, and applications designers must extend the capabilities of these operating system interfaces to provide more effective interface capabilities. Typically this involves a display/window manager.

- **Provide immediate feedback.**

  The amount of delay the typical user will tolerate varies for the type of action being performed, but rarely exceeds 2 seconds. An interface must provide feedback to maintain user confidence, even if only to tell the user to wait while processing is being performed. The interface should also permit a graceful interruption of the current task to correct/modify the user's inputs.

  All successful interactive interfaces provide virtually instantaneous feedback on every user action. Part of this must be provided by powerful hardware (a high performance graphics-capable workstation), but use of clever techniques can reassure the user when certain functions require several seconds/minutes to complete. A good example of this is the small clock or hourglass which replaces the standard cursor on the screen while time-consuming processing is being performed. The user knows the system is responding and is not left guessing about the result of some operation on the screen.

- **Don't force the user to do things which are hard.**

  Things which fall into the category of hard are abstract concepts, creating things from scratch, understanding invisible operations, programming, and so forth. An interface should bridge the gap between the user and complex tasks by offering views of those tasks which seem intuitive and appropriate and by providing facilities for translating difficult tasks into a sequence of simple operations for the user.

  The iconic interfaces used on most commercial window-based products (such as the Macintosh, GEM, MS Windows, Sun Windows, "desktop" with "objects" on it), which preserves the user's conceptual model, but also provide very simple and intuitive ways for creating, deleting and changing the properties of objects. All functions, controls and programs are oriented around sets of operations on windows and other familiar looking objects.

On systems which require the entry of large amounts of textual data (positions, times, dates, bounds, etc.) some method should be provided to ease the user's burden by providing default values and by facilitating the rapid recall and editing of previously entered information.

- **Preserve the impression that the user is in control.**

  Without exception, a complex and/or inconsistent interface violates this design goal. Complexity adds to uncertainty and confusion (especially in inexperienced/casual users). Inconsistency violates the user's intuition and expectations. Together, these two characteristics shatter a user's confidence in the system.

  We should note here that it is not an unreasonable design assumption for TDAs to assume that the average user is a novice. A TDA is only one of many systems the user will be using. When needed most it can be assumed stress and time will be constraints against the effective use of this and other systems. A TDA must provide a confidence-preserving user interface to be effective in this environment.

- **Be effective in the hands of all types of user.**

  An interface which caters to a particular user experience level will likely provide less than optimum performance for users at other levels. Most often, a successful interface will provide either several conceptual models, or a single model of sufficient generality to fit the needs of a wide range of users.

  A typical design decision aimed at this goal is to provide several ways of accessing the same functions, one for the novice/casual user, and one for more experienced users who require less assistance from the interface.

A.3. Types of Users

We have already asserted that knowing the user is a key principle in the design of user interfaces. The skill and experience level of a user is a determining factor in the kinds of things a user interface must provide to be successful. As it happens, the necessary characteristics that cater to a particular class of users often conflict with those designed for another. Consider the following types of user:

- **Novice.**

  The novice understands the basic idea behind the system being used and has enough experience to comprehend and use low level commands. This type of user needs examples and almost continuous feedback from the interface. What is sometimes referred to as the casual or occasional user is best put in this category. Novices do not have a global concept of the system which would enable them to utilize all its features in an optimum way.

  Interfaces designed for the novice must be highly visual and graphical, must provide tutorial and context sensitive help and should have some mechanism for aiding the user in navigating through the system.

  It is likely that a large proportion of TDA users will always be novices.

- **Experienced.**

  The experienced user understands how most of the low level functions of the system fit together and can confidently navigate without assistance. This type of user is able to understand (or find out without assistance) complex tasks.

  Experienced users need some feedback and online help but are more tolerant of inconsistency because of their understanding of the value of certain "features" the system offers. Immediate access to functions (usually through keyboard function keys) is very important. Traversing several levels of menus (valuable for the novice) will frustrate the experienced user.

- **Expert.**

  The expert differs from the experienced user in his understanding of how to extend or modify the behavior of the system to increase its effectiveness. Experts are frustrated when a system does not offer facilities for extending functionality and customizing the user interface.

  Experienced users need almost no feedback since they are usually ahead of the system. The most important characteristic for an interface which will be used frequently/primarily by experts is invisibility. To the expert user, anything which does not actually contribute to performing the intended function is in the way.

A.4. Characteristics of User Friendly Interfaces

- **Simple.**

  Avoid forcing the user to do "hard" things (few commands, no memorization, no programming).

  Represent functions and operations in intuitive ways (things which ought to be easy are easy, things which ought to be quick are quick).

  Leads the user through complex operations by decomposing in simpler, logically related operations.

- **Consistent.**

  Preserves a single conceptual model throughout the system.

  Similar names, functions, commands, symbols, colors, locations, messages, formats, input/output formats for similar things.

  A single command language/metaphor throughout the system.

- **Robust.**

  Will not fail or act unpredictably on erroneous/invalid input.

- **Responsive.**

  Immediate feedback.

  Meaningful warnings and help messages when the user is likely to do something dangerous/irreversible.

- **Permissive.**

  Things which ought to be possible (in the conceptual model offered by the interface) are possible.

  The user should feel in control of the system (not the other way around).

A successful harmony of the above characteristics is difficult to achieve. It is made more difficult when the user's conceptual model is not well understood or well defined or when technological constraints are imposed by other, conflicting system requirements. For example, it is almost impossible to design a text-based user interface for a complex system which exhibits all the above characteristics to an acceptable degree. It is vital that the designer understand the importance of the interface to the success of the whole design and allocate sufficient resources to provide the necessary performance.

A.5 Some Practical Guidelines

The guidelines listed below should give the reader an understanding of how some of the principles discussed above apply to specific situations in actual systems.

- **Hierarchical menus.**

  Most small computer users are familiar with this type of interface. Pressing a key (or selecting a symbol/object on the screen with a pointing device, such as a mouse or cursor keys) causes a small window to open on the display showing a list of possible selections. The user may select one of these (using the same procedure as before, which may perform some operation or which may cause another menu to appear, on which further selections are displayed.

  Such a system provides a simple mechanism (especially for non-graphical displays) for partitioning the functions of a system into a hierarchy. The user then navigates up and down a "tree" of menus until the desired function is reached. The following observations pertain:

  Many functional models do not map easily (or consistently) into a strict hierarchical decomposition. As a result, there may not only be many different "paths" to the same menu, but many functions will end up being displayed on different menus in different parts of the tree. Both occurrences violate the principle of consistency.

  Hierarchical menus for complex systems tend to be deep, and often require the user to traverse back "up" through several menus and "down" another path to reach a needed function. This works only for novices (as a teaching method), and frustrates more experienced users. The answer to this problem is to provide facilities for direct selection of often used commands (using special key strokes, for example) regardless of the user's location in the menu tree. User friendly interfaces usually display the mappings of function/control keys to menu selections next to the selection to which they pertain on the appropriate menu. The user's memory is then reinforced with continuous reminders that these functions may be immediately accessed.

- **Avoid modes.**

  A *mode* is a condition of a system or interface in which certain functions or selections are not available or whose meanings have changed. An example of this would be a word processor or text editor which had an "input" mode and a "command" mode. In the input mode, all keystrokes result in characters being inserted in the document being edited. These same keys would have different functions in the command mode, such as delete to end of line, delete character, move the cursor, etc.

Modes are very dangerous, since the user is usually expected to remember what condition the system is in, which can lead to unintended errors, loss of confidence and destruction of the user's impression that he is in control. Since modes often cannot be avoided (usually due to a limited set of commands, keys, space on the display, etc.) the usual way of dealing with the problem is to ensure some unobtrusive but recognizable change is made to the display. For example:

> Change the shape of the cursor.
>
> Alter the texture/color of icons, symbols, borders, etc. On a menu system, for example, display the usual set of commands on each menu, but display those which are not available in the currently selected mode in a different typestyle, texture or brightness.

- **Operations should be visible.**

Nothing of any consequence should be performed by the system without some indication of what is happening being displayed to the user.

- **Messages should be unobtrusive.**

A beeping, flashing, verbose interface violates this guideline. The designer must be clever in providing feedback which is informative, polite, recognizable and subtle.

- **Be consistent.**

A good interface preserves regularity and uniformity throughout the system, thereby reinforcing the user's memory and building confidence. Examples:

> Menus, symbols, windows and so forth should all have standard places on the screen.
>
> An interface which uses pull-down menus should present them in a consistent order and locate them in familiar places, without exception.
>
> Those selections not valid in the current mode should still be displayed (to preserve the consistent view for the user) but in a way which makes it clear to the user they may not be selected.

A symbol used to represent something in one mode/place/window should not represent something else in another.

If the user is asked to input a date, time, distance or other textual data, the way this is done should be consistent throughout the system. For example, if the user must enter a date in one format for some function but in a different format for another, this violates the consistency guideline.

Color used to represent a certain type of information in one part of the system should not be used to indicate a different thing somewhere else.

- **Use reasonable defaults.**

  Whenever input is expected, some reasonable default value should be presented. This not only saves time, but gives the user a template to edit (easy) so that information does not have to be created from scratch (hard).

References in Appendix A

[a] R. M. Baecher, W. A. S. Buxton, *Readings in Human-Computer Interaction: A Multidisciplinary Approach*, Morgan Kaufmann, 1987.

This book is a comprehensive survey of the seminal literature on human factors (including user interfaces) in software/hardware system design. It includes reprints of over 60 important papers and essays on the subject.

[b] B. Shneiderman, *Software Psychology*, Winthrop, 1980.

A detailed treatment of how humans react to software. It includes a discussion of design goals and rationales for user interface designers.

APPENDIX B

STOCHASTIC PROCESSES IN TDAs

This appendix discusses, in hopefully elementary terms, some concepts of stochastic processes in time, and some particular stochastic processes, which are prominent in TDAs. The most usual use of stochastic processes in TDAs is to model target motion, notably in CAS (Chapter II) and TMA (Chapter III). Another important application area is cumulative detection probability (Appendix C). They are further applied in Chapter V to model oceanic and atmospheric movements.

Some basic knowledge of random variables and probability distributions is assumed.

One may think of a stochastic process as a *dynamic* quantitative representation of uncertainty. This will be clarified below. By contrast, one may think of a random variable as an *instantaneous* or *static* quantitative representation of uncertainty.

Throughout, we consider processes defined on a time interval from 0 to T, or defined on a sequence of discrete times denoted 1, 2, ..., m.

B.1. Definitions of a Stochastic Process

There are three ways of defining a particular stochastic process (any one would determine the other two):

(I) Define a random variable X(t) for each time t between 0 and T. This is how one most often thinks of a stochastic process: a function of time, each of whose values is a random variable. However, this is not enough. We must also specify the *bi*variate distribution of $[X(t_1), X(t_2)]$ for *every* t_1 and t_2 between 0 and T, the *tri*variate distribution of $[X(t_1), X(t_2), X(t_3)]$ for every t_1, t_2, t_3 between 0 and T, etc. These multivariate distributions are needed to convey the interdependence, if any, among the instantaneous random variables.

(II) Specify a mechanism which generates the random variable X(t) for each t. The mechanism must be enough to *determine* the multivariate distributions in (I), but the latter need not be shown explicitly.

(III) Specify a family of (deterministic) functions all defined for time from 0 to T, and specify a probability distribution over this family. Each function in this family is called a "sample path" of the process. This specification determines the random variables X(t) and the multivariate distributions as in (I).

In (I), (II), and (III), with X(t) defined or determined for all t between 0 and T, we say that X is a *continuous*-parameter process. When we are dealing with discrete time, we write $X_1, X_2, ..., X_m$ instead of $X(1), ..., X(m)$, and we say X is a *discrete*-parameter process. We say that X is a discrete-*state* process if the number of values that the X(t)'s or X_n's may take is finite. Computer implementation of a stochastic process is always as a discrete-parameter discrete-state process. This is often an approximation to a continuous-parameter continuous-state process.

B.2. Stochastic Process Motion Models in Monte Carlo CAS

The three types of definitions of stochastic processes in B.1 all arise in the Monte Carlo CAS methods of Chapter II.

In VPCAS, PACSEARCH, and their airborne successor in the P-3C Update IV, the bundle of 500 target tracks *each with probability attached* is a stochastic process as in (III). The same holds for the simpler 16-track illustration we have used. A similar statement holds for all prior Monte Carlo CAS systems, going back to CASP and LANT-72 in 1972.

We also use the type (II) definition when we generate this bundle by first generating a prior distribution of target position and then generate legs and intervals of legs using as building blocks the simple 2-point distributions in the 16-track illustration or the more general building blocks actually used in VPCAS.

We also use the type (I) definition of this process when we construct a probability map of target position, which is an instantaneous random variable; however the multivariate distributions in (I) do not come into play at that point.

B.3. Poisson Processes in TDAS

We encounter Poisson processes in TDAs primarily as a basis for the (λ,σ) process (see B.4) used to find cumulative detection probability and for the random tour and generalized random tour (see B.5) models of motion that are approximated by other motion models in several TDAs. Poisson processes are very useful generally in tactical modeling; they model occurrences of events at *random* times, i.e., at times unrelated to each other.

At a given time in a Poisson process, the main entity of interest is the random variable time-to-next-event. This random variable has a cumulative distribution function $1-\exp(-\lambda t)$, where λ is a positive number, called the "event occurrence rate," which characterizes the process; λ is measured in events per unit time. The mean time-to-next-event is $1/\lambda$. Also, time-to-next-event is unrelated to time-since-last-event. This definition of a Poisson process may be regarded as a definition of type (II) as in B.1.

While we may not need it in TDAs, the *number* of events occurring during a time interval of length t, is a random variable with a "Poisson *distribution*." This distribution is related to, but is not to be confused with, the Poisson *process*. The mean of this distribution is λt and the probability that the number of events is exactly n, for n=0, 1, 2, ..., is

$$\frac{(\lambda t)^n}{n!}\exp(-\lambda t).$$

B.4. (λ,σ) Processes

A (λ,σ) process (see Appendix C) is often used to compute cumulative detection probability (cdp), e.g., in VPCAS, PACSEARCH, and ITDA/SCREEN EVAL. (*Any* Bayesian update of a probability map of target position for negative information requires *some* model of cdp.)

The use of a (λ,σ) process to compute cdp is to represent the difference between *deterministically predicted* values of signal excess or signal-to-noise ratio (which governs detection) and the *actual* values of these quantities. (Note that the (λ,σ) process does *not* represent noise as such.) In so doing, we also incorporate inter-glimpse dependence, thus avoiding the usually spurious assumption of independence.

To define a (λ,σ) process, we begin with a Poisson process having rate λ. We also fix a normal distribution with mean 0 and standard deviation σ. We generate a sample path of the (λ,σ) process by choosing its initial value from the normal distribution and holding it constant until occurrence of the first event of the Poisson process. Then we choose a new value from the normal distribution, *independent* of what has already happened. That value is held constant until the next event and the procedure repeats.

If X is a (λ,σ) process, one can show that the correlation between $X(t_1)$ and $X(t_2)$ is

$$\exp(-\lambda\,|t_2-t_1|),$$

which decreases as separation between t_1 and t_2 increases.

One may replace the normal distribution by some other distribution, e.g., if signal/noise were expressed in power (rather than db), we would use a log-normal distribution (z is lognormally distributed if ln z is normally distributed). Usually in TDA cdp's we will stick to db and normality.

B.5. Generalized Random Tour

A generalized random tour is a motion process used in several TDAs as an "ideal" model of target motion. It is approximated by other processes more amenable to analysis i.e., a Markov chain, an IOU process, or an IOU process with drift. These approximating processes are discussed in the next two sections.

A generalized random tour is most simply described as follows (given knowledge of (λ,σ) processes): In a (λ,σ) process, replace the normal distribution by an arbitrarily chosen two-dimensional distribution. Let the resulting process model target velocity as a function of time. The resulting target motion is a generalized random tour. It is physically realizable, which an IOU process is not.

This model generalizes the random tour model studied by Washburn in 1969 (reference [e] of Chapter II), wherein speed was deterministic and course was uniformly distributed over all directions.

We generalize this further to the concept of destination-constrained random tour (DCRT). This is defined in simulation terms, but it can apply to an analytic model: Choose in advance distributions of start position, destination position, base speed, speed variation, and course variation. The start distribution may be the outcome of an earlier simulation. Draw a base speed, a start position, and a destination position; these are fixed during the repetition of the simulation. Now generate a generalized random tour beginning at the start point and drawing the new course and speed on each leg from the course and speed *variation* distributions respectively. To each leg speed thus drawn add the base speed. To each leg course thus drawn add the course from the leg start point to the originally drawn destination point. Thus there is always a tendency to proceed toward destination, but with probabilistic variations. Having modeled start position and velocity at each instant, we have specified a complete motion model, which we define as DCRT.

If the base speed distribution is specified to be deterministically zero, DCRT reduces to a generalized random tour. If the destination distribution is, for example, uniform on a circle of very large radius, it is negligible as a constraint.

The VPCAS/PACSEARCH motion model (see 2.4.3) is DCRT and except for specialization of the fixed distributions offers the user the full generalization just described. The motion models used as "ideals," and approximated by Markov chains, in SALT (see 2.8.3), ITDA/SCREEN EVAL (see 4.2.8), and CASE/ASWTDA (see 2.13 and the introduction to Chapter IV) are all within the more special generalized random tour.

B.6. Markov Chain Motion Models

Target motion in SALT in 2.8 (except in search planning) and in ITDA/ASW SCREEN EVAL in 4.2.9 is modeled as a "Markov chain." This is a type (II) definition: the process generation is governed by transition matrices, after specifying the initial state or distribution of states. PACSAI and OASIS were CAS systems in the latter 1970's which modeled target motion by Markov chains (see 2.13).

If there were only three states, the transition mechanism could be illustrated as follows: denote the states by a, b, c. Each sample value of each of the random variables X_1, X_2, ... would be one of a, b, or c. At time i let

$$p_i(d) = \Pr\{\text{state is } d \text{ at time } i\},$$

where d is one of a, b, c.

Let's illustrate by saying that at time 1, $p_1(a) = .2$, $p_1(b) = .5$, and $p_1(c) = .3$. Thus p_1 is the probability distribution for the random variable X_1. We illustrate how to find p_2:

State at time 2

State at time 1

$$
\begin{array}{ccc}
p_1(a) & p_1(b) & p_1(c) \\
[.2 & .5 & .3]
\end{array}
\quad
\begin{array}{c}
\\ a \\ b \\ c
\end{array}
\begin{array}{c}
\begin{array}{ccc} a & b & c \end{array} \\
\left[\begin{array}{ccc}
.1 & .6 & .3 \\
.2 & .5 & .3 \\
.2 & .4 & .4
\end{array}\right]
\end{array}
=
\begin{array}{ccc}
p_2(a) & p_2(b) & p_2(c) \\
[.18 & .49 & .33]
\end{array}
$$

The 3 x 3 matrix is the transition matrix at time 1, e.g., .2 in the b row and a column means that if the state is b at time 1, then the probability is .2 that the state will be a at time 2. Note that each row of a transition matrix adds to 1. We compute, e.g.,

$$p_2(a) = .2 \times .1 + .5 \times 2 + .3 \times .2 = .18.$$

The transition matrix at time 2 (to convert $[p_2(a), p_2(b), p_2(c)]$) to $[p_3(a), p_3(b), p_3(c)]$) may differ from that at time 1. In SALT such changes in matrix are in accord with changes in velocity state distributions and other updates. Also in SALT a typical number of states is 56448 rather than three. However, most entries in the transition matrices are zero, which makes the computation feasible.

There is available well-developed methodology for further analysis of Markov chains.

B.7. Motion Models by IOU Processes

Integrated Ornstein-Uhlenbeck (IOU) processes have been used rather extensively in TDAs and other applications, to model motion of slowly maneuvering vehicles, notably submarines. In VPCAS and successors, they are used (with an added velocity drift term) to model target motion in historical analysis. In SALT they are used in search planning analysis to model motion of a patroller or transitor target. In TMA they underlie the MTST method (see 3.5) which is much used in embedded weapons control software and in the TDA Generic Statistical Tracker. In NAVSAR (see 5.2), they are used with drift to model sea current, wind-driven current, and leeway. In CHAPPS (see 5.5) they are used with drift to model atmospheric turbulence. We give here a description of an IOU process with drift; somewhat simpler descriptions (without drift) are given in 3.5.2 and Appendix D.

A basic representation of a two-dimensional IOU position process without drift is

$$X(t) = \int_0^t V(s)ds,$$

where V(s) is the random variable target velocity at time s. The integration must be done over each sample path of V and for each coordinate (chosen to make the coordinate components independent of each other). Here V must be modeled as a stationary Ornstein-Uhlenbeck, i.e., Gauss-Markov, process (see below).

A more computable IOU representation, and this time with drift, is to discretize time and require that (X_1, X_2, ...) obey the following recursive relation (Δt is the time from i to i+1):

$$\dot{X}_{i+1} = (1-\beta\Delta t)\,\dot{X}_i + U\Delta t + \sigma\sqrt{\Delta t}\begin{bmatrix} p_i \\ q_i \end{bmatrix}$$

where the p_i's and q_i's are independent normal variables with zero mean and unit variance, and U(two components), $\beta > 0$, and $\sigma > 0$ are parameters. We may estimate these parameters from empirical data, as is done in VPCAS historical analysis, as follows: Let $\bar{V}$ be the motion's stationary (steady state average) velocity (two components) and σ^* be the standard deviation of velocity about $\bar{V}$ (the same in both components). Then

β = rate at which sample velocity approaches $\bar{V}$,

$U = \beta\bar{V}$ = drift velocity per unit time,

$\sigma = \sqrt{2\beta}\,\sigma^*$.

IOU without drift has $\bar{V} = 0$. However, this can be used to model transitor behavior, e.g., see Appendix D, Model 3, by choosing a low value of β so the target velocity approaches its zero limiting velocity only slowly. Nevertheless, in the applications where there is an *identified* velocity, such as velocity estimation in historical analysis or mean ocean current, it can be more convenient to include velocity drift, i.e., the U term above.

To implement the above recursion on a computer, sample p_i and q_i independently from a unit normal distribution, transform the recursion to a (deterministic) differential equation and solve that equation analytically for computation. The results must be averaged with respect to the (normal) distribution of p_i and q_i.

To complete the "basic" definition of IOU above (not needed for computation), we define the Gauss-Markov (OU) process, which models target *velocity*. This is given by requiring that (1) each X(t) have a normal distribution (for present purposes, having the same mean and standard deviation for all t), each ($X(t_1)$, ..., $X(t_k)$) have a multivariate Gaussian distribution and (3) for some λ the correlation between any $X(t_1)$ and $X(t_2)$ be $\exp(-\lambda\,|t_2 - t_1|)$.

Note that a (λ,σ) process and a Gauss-Markov process with the same λ and σ have the same instantaneous random variables and the same correlation behavior. However, they are *different* processes, because the multivariate distributions of a (λ,σ) process are *not* normal in contrast to the Gauss-Markov process.

APPENDIX C

CUMULATIVE DETECTION PROBABILITY USING (λ,σ) METHODS

If a sensor searches for a target over a time interval [0,T], what is the probability that detection occurs *at least* once? This is called *cumulative detection probability* (cdp). It is assumed to begin with that at each instant between 0 and T, detection capability is known. To this much knowledge must be added knowledge of interdependence of the separate glimpses in order to obtain cdp.

To a tactical decision maker, and consequently to a tactical analyst, cdp is generally of *much* greater importance than instantaneous detection probability. This appendix discusses (λ,σ) methods of computing cdp and compares them to some alternative methods.

C.1. Solution Under Sequential Independence

Suppose that the search method is a discrete sequence of n glimpses. Let p_i be the probability that the ith glimpse will succeed. Suppose that the glimpses are statistically independent of one another. Then the probability of *no* detection in [0,T], 1–cdp, is the probability that *all* glimpses *fail* to detect, i.e.,

$$1 - \text{cdp} = \prod_{i=1}^{n}(1-p_i),$$

$$\text{cdp} = 1 - \prod_{i=1}^{n}(1-p_i). \qquad \text{(C-1)}$$

Unfortunately, in practice this independence is seldom realized, i.e., in general wide separation between glimpses would be required.

To avoid the usually spurious assumption of sequential independence necessitates some mathematical complication, but for reasonably realistic tactical analysis something better than the independence assumption *must* be adopted. What follows appears to be the best available compromise, under present empirical knowledge, between reality and simplicity.

C.2. A Model Which Incorporates Sequential Dependence

In order to incorporate sequential dependence, we put more structure into our model of the detection process. Initially we proceed in terms of n discrete glimpses as before, and then we generalize to continuous looking.

We postulate a "signal excess" process $(S_1, S_2, ..., S_n)$ and assume that the sensor "sees" the target on the ith glimpse if and only if $S_i > 0$. We express S_i as the sum of a deterministic component m_i and a random component d_i:

$$S_i = m_i + d_i, \quad \text{for} \quad i = 1, ..., n.$$

Here m_i is the signal excess on glimpse i resulting from the known *causal* relationships that bear on the sensor's ability to see the target, e.g., range from sensor to target, target "visibility," sensor operator efficiency, etc. While these quantities which are inputs to the causal estimation of S_i are in general random, we regard m_i as the *mean* of this estimation. Also, the random deviations of S_i from its mean m_i are given by d_i, which is a random variable with mean zero.

To illustrate, suppose each glimpse is an active sonar ping. Then m_i is the value of signal excess on ping i predicted from the values of the terms of the active sonar equation, each term being predicted separately from known conditions and relations.

It is in a model for the sequence of random variables, i.e., stochastic process, $(d_1, d_2, ..., d_n)$ that we incorporate sequential dependence. Specifically, a useful model of this sequence is formed as follows: Suppose events occur in a Poisson process at rate λ per unit time. Each time an event occurs, we draw a sample value from a normal distribution which has mean zero and standard deviation σ. Let this sample value be the value of the d-process until the time of the next event in the Poisson process. Upon that next event a sample value is drawn from the (fixed) normal distribution, *independent* of previous values. This model of the d-process is called a "(λ,σ) process"; it is characterized, of course, by the two parameters λ and σ.

It is important *not* to confuse the d-process (modeled as a (λ,σ) process) with *noise*. In effect, prediction of noise is included in the prediction of signal excess, i.e., in m_i. What d_i represents is the *deviation* between *predicted* signal excess (noise included) and *actual* signal excess (noise included).

If t_i is the time of the ith glimpse, then d_i is the value of d-process, modeled as a (λ,σ) process, at time t_i. A particular sampling of the d-process, called a "sample path" in stochastic process terminology, is a "step function," illustrated in Figure C-1. The deviation values could be taken from this sample path at discrete times as shown or they could be taken continuously.

Figure C-2 illustrates how the (λ,σ) example in Figure C-1 would apply to detection. Mean signal excess is shown as a continuous curve. The result of adding the step function sample path to the continuous curve is also shown; this represents *actual* signal excess and must exceed the zero threshold (shown) for detection to occur. Now nobody believes that the actual signal excess behaves in this discontinuous way in reality, but by averaging the effects of the population of such discontinuous curves, it is plausible to obtain realistic cdp's.

If it were known that, as in Figure C-1, t_i and t_j are separated by one or more jump times, then d_i and d_j would be independent of each other. However, *absent* that knowledge there *is* a dependence between d_i and d_j which derives from the uncertainty that a jump occurs between them. From the elementary properties of Poisson processes we know that the probability of no jump event between t_i and t_j is $\exp(-\lambda|t_j-t_i|)$, and it is easy to show that the correlation coefficient between the random variables d_i and d_j is that same quantity. Note that if t_i and t_j are close to each other, then this correlation is close to 1, i.e., d_i and d_j are highly correlated with each other. Also if t_i and t_j become increasingly farther apart, then this correlation decreases toward zero, i.e., toward independence. These observations agree with one's intuition as to appropriate correlation behavior.

FIGURE C-1. ILLUSTRATIVE SAMPLE PATH FROM (λ,σ) PROCESS

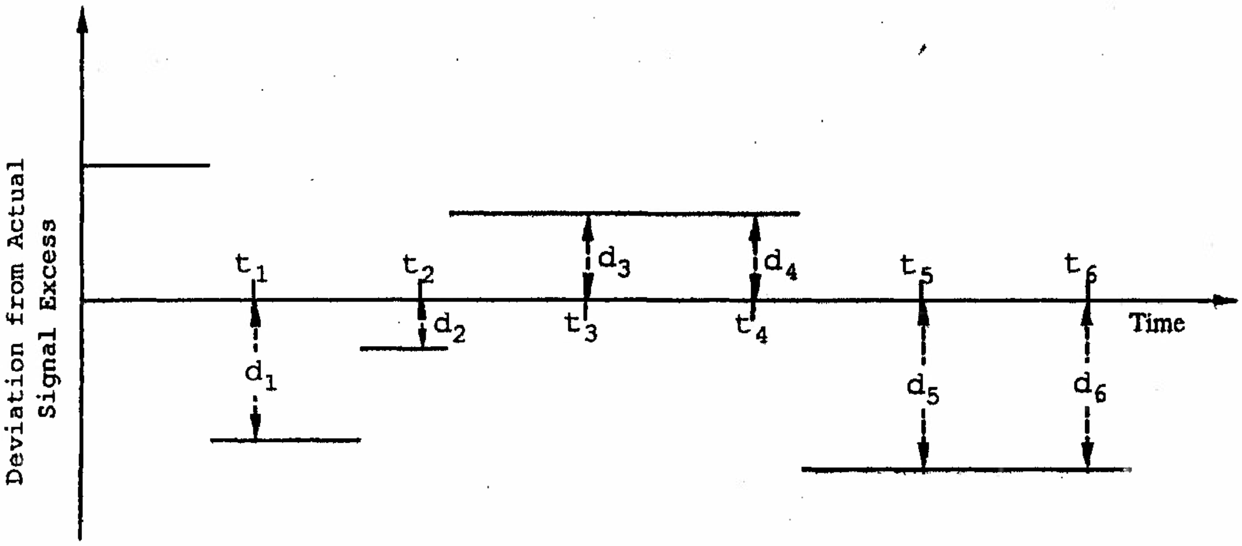
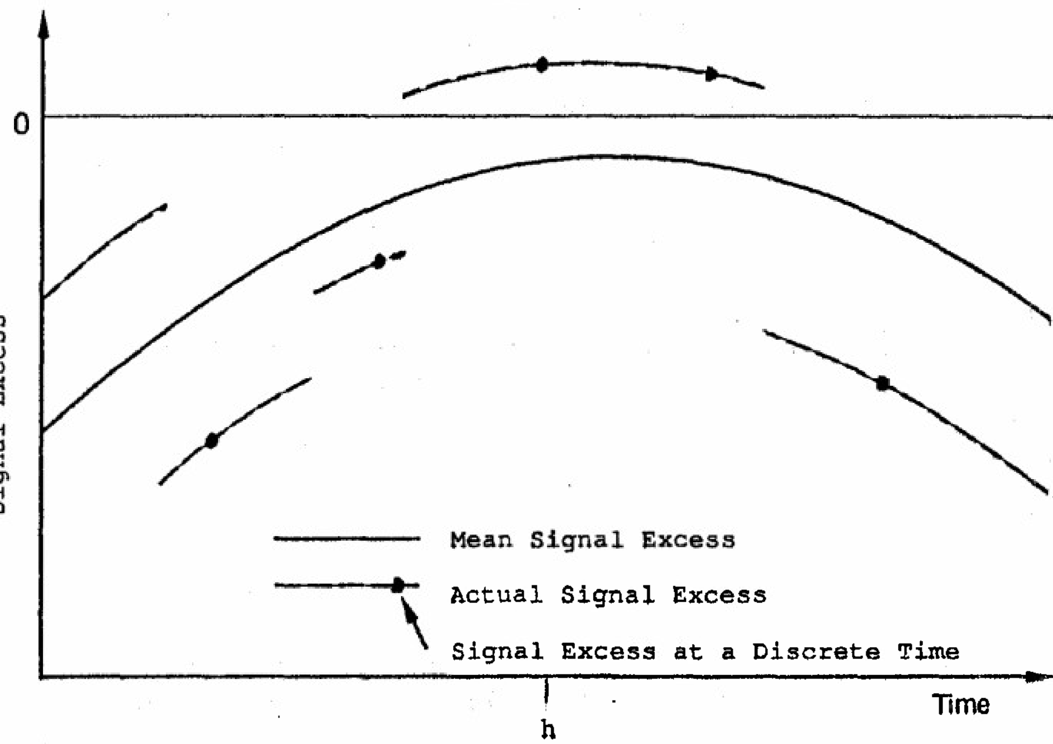


FIGURE C-2. ILLUSTRATIVE MEAN AND ACTUAL SIGNAL EXCESS



Note further that $\lambda = \infty$ corresponds to zero correlation, i.e., sequential independence, and $\lambda = 0$ corresponds to complete correlation among the glimpses, i.e., the deviation in one glimpse would be repeated in all of them.

The same correlation remarks apply to signal excess.

It is important to realize that the statistical fluctuations that are modeled above are quite different from the kinds of statistical fluctuations that are treated in signal processing methods which are used to separate "signals" from "noise." The latter fluctuations occur typically much more frequently, e.g., multiply per second, and they impact on instantaneous detection probability. The rate of fluctuations, i.e., jumps, in a (λ,σ) process, is typically a few per hour when applied to acoustic sensors, somewhat faster for electromagnetic sensors. By the same token, use of correlation behavior in signal processing is quite different from use of correlation in cdp analysis.

We now turn to applying the above modeling to compute cdp.

C.3. Unimodal Formula for cdp (Discrete Glimpses)

We give below a formula for cdp under the above modeling for a case which has rather wide applicability in tactical analysis.

Recall that our criterion for the sensor being able to "see" the target on glimpse i is that

$$m_i + d_i = S_i > 0.$$

This is equivalent to

$$d_i > -m_i.$$

Thus for detection to occur, the random deviation d_i, modeled as a (λ,σ) process, must exceed a threshold $-m_i$ which is deterministic and which varies with i. We denote the probability of this event by p_i, i.e.,

$$p_i = \Pr\{d_i > -m_i\} \quad \text{for} \quad i = 1, \ldots, n.$$

We now suppose that as i increases, p_i rises to a maximum and once it starts decreasing it never increases thereafter. Precisely we assume that there is a glimpse index h such that $1 \le h \le n$,

$$p_i \le p_j, \quad \text{equivalently } m_i \le m_j, \text{ whenever } 1 \le i \le j \le h,$$

and

$$p_i \ge p_j, \quad \text{equivalently } m_i \ge m_j, \text{ whenever } h \le i \le j \le n.$$

This is illustrated as in Figure C-2. In this circumstance we say that p_i versus i is "unimodal" (equivalently, m_i versus i is unimodal).

If instantaneous detection probability is non-decreasing as range increases (not true of sonar search using convergence zones), this unimodal assumption is realized in cases of passing targets, i.e., when a target is on constant course passing a fixed sensor, a moving sensor on constant course is passing a fixed target, or, simply when *relative* course is constant with moving sensor and target. These cases occur frequently in tactical analyses.

Suppose p_i versus i is unimodal, p_h is a maximum (not necessarily unique as shown above) over $\{p_1, ..., p_n\}$, the deviation process $(d_1, d_2, ..., d_n)$ is modeled as a (λ,σ) process, and the glimpses are uniformly Δt apart in time. Then it can be shown that

$$\text{cdp} = 1 - (1-p_h)\prod_{\substack{i=1 \\ i\neq h}}^{n}(1-ap_i), \tag{C-2}$$

where

$$a = 1 - \exp(-\lambda\Delta t). \tag{C-3}$$

Formulas (C-2) and C-3) constitute the (very useful) unimodal formula for cdp under discrete glimpses and a (λ,σ) model.

C.4. Unimodal Formula for cdp (Continuous Looking)

Continuous looking is typified by passive sonar search for submarines and passive ECM search for radar stations or radar-bearing vehicles. To extend the previous (λ,σ) approach to continuous looking, we define at time t with $0 \le t \le T$, s(t) to be signal excess, m(t) to be the mean of s(t), and d(t) to be s(t) - m(t). Thus

$$\begin{aligned} \text{cdp} &= \Pr\{s(t) > 0 \text{ for } \textit{some } t,\ 0 \le t \le T\} \\ &= 1 - \Pr\{s(t) \le 0 \text{ for } \textit{all } t,\ 0 \le t \le T\} \\ &= 1 - \Pr\{d(t) \le -m(t) \text{ for all } t,\ 0 \le t \le T\}. \end{aligned}$$

Let

$$p(t) = \Pr\{d(t) > -m(t)\} \text{ for all } t,\ 0 \le t \le T.$$

Now suppose p is unimodal, $0 \le h \le T$, p(h) is the maximum value of p over [0,T], and d is a (λ,σ) process. Then it can be shown that

$$\text{cdp} = 1 - (1-p(h))\exp[-\lambda \int_0^T p(t)dt]. \tag{C-4}$$

This is the (also very useful) unimodal formula for cdp under continuous looking and a (λ,σ) model.

C.5. Non-Unimodal p

For cases where p is not unimodal, recursive formulas are given in reference [d] to compute cdp. These formulas are beyond the scope of these notes and would ordinarily require a computer for use.

It is also the case that in VPCAS and PACSEARCH (see Chapter II), for example, when convergence zones are present, cdp's for negative information updates are computed by the unimodal formula, (C-4), even though the unimodality assumption is not satisfied. Analysis has shown that this is usually not a bad approximation.

C.6. Illustrative Computations by a Unimodal Formula

We now illustrate the discrete-glimpse unimodal formula by some computed examples. For this purpose, we first develop illustrative instantaneous detection probabilities in Figure C-3.

In this example we suppose that the target is an SSN whose motion relative to the sensor is at 30 knots on a constant course, with 20 nm range at closest approach (CPA). Glimpses occur every .1 hours and begin when the target is 21 nm from CPA (29.0 nm from the sensor). The relation between range and mean signal excess, m_i, is one of direct path spherical spreading. Note that *mean* signal excess is negative throughout, so that if there were *no* deviation, the target would never be detected. We assume $\sigma = 6$ db.

Single-glimpse detection probabilities are given in the last column and are obtained by entering a table of the normal distribution with the next to last column.

Under the independence assumption of (C-1), the cdp for the first five glimpses is

$$\begin{aligned} cdp_5 &= 1 - (1-.15)(1-.18)(1-.23)(1-.28)(1-.33) \\ &= 1 -.26 = .74, \end{aligned}$$

which is unrealistically high. For all 15 glimpses this becomes $cdp_{15} = .94$, which is quite unrealistic.

Now suppose deviations from mean signal excess are modeled as a (λ,σ) process with $\lambda=1$ per hour. We note that m_i versus i is unimodal, so we apply the discrete unimodal formula, (C-2) and (C-3). Since $\Delta = .1$ hr, by (C-3)

$$a = 1 - \exp(-\lambda\Delta) = 1 - \exp(-.1) = .095.$$

Hence the cdp for the first five glimpses is, by (C-2),

$$\begin{aligned} cdp_5 &= 1 - (1-.33)(1-.095x.15)(1-.095x.18)(1-.095x.23)(1- .095x.28) \\ &= 1 - .62 = .38 \end{aligned} \qquad \text{(C-5)}$$

Note that the p_h in (C-2) is .33. A similar computation for all 15 glimpses (where $p_h = .4$) yields $cdp_{15} = .59$.

Note that in (C-5) glimpse 5 (maximum p_i) dominates the computation. The influence of the other factors is reduced through the .095 factor. This does *not* mean that these other glimpses, *taken individually*, have abnormally reduced effectiveness. It merely means that when *all* five glimpses are considered *in aggregate*, glimpse 5 has the main influence and the other glimpses augment glimpse 5, but the interdependence makes this augmentation substantially less than it would be if the glimpses were independent of each other.

FIGURE C-3. EXAMPLE SINGLE-GLIMPSE DETECTION PROBABILITIES

Target speed relative to sensor = 30 kts.

Range at closest point of approach (CPA) = 20 nm.

Glimpses are every .1 hr, i.e., every 6 min.

σ = 6 db.

Time	Glimpse #, i	Distance to CPA	Range	Mean Signal Excess, (m_i)	(m_i/σ)	$Pr\{SE_i>0\}$
0 hrs	1	21 nm	29.0 nm	–6.3 db	–1.05	.15
.1	2	18	26.9	–5.4	–.90	.18
.2	3	15	25.0	–4.4	–.73	.23
.3	4	12	23.3	–3.5	–.58	.28
.4	5	9	21.9	–2.7	–.45	.33
.5	6	6	20.4	–1.8	–.80	.38
.6	7	3	20.2	–1.6	–.27	.39
.7	8	0	20.0	–1.5	–.25	.40
.8	9	3	20.2	–1.6	–.27	.39
.9	10	6	20.4	–1.8	–.30	.38
1.0	11	9	21.9	–2.7	–.45	.33
1.1	12	12	23.3	–3.5	–.58	.28
1.2	13	15	25.0	–4.4	–.73	.23
1.3	14	18	26.9	–5.4	–.90	.18
1.4	15	21	29.0	–6.3	–1.05	.15

FIGURE C-4. ILLUSTRATIVE COMPARISON OF ALTERNATIVE CDP METHODS

Data of Figure C-3 apply

cdp Method	cdp_5	cdp_{15}
(λ,σ) method, λ = 1/hr	.38	.59
(λ,σ) method, λ = 2/hr	.43	.71
Independence method	.74	.94
Adjustment factor method, A = .39	.38	.83
Adjustment factor method, A = .45	.43	.87
Relaxation time method, relaxation time = .6 hr		.60
Relaxation time method, relaxation time = .4 hr		.69

If we repeat the above computations with $\lambda = 2$ per hour, then $a = 1 - \exp(-.2) = .18$, and we obtain $cdp_5 = .43$ and $cdp_{15} = .71$ versus .38 and .59 respectively when $\lambda = 1$ per hour.

C.7. Some Alternative cdp Methods

Let us consider some alternative methods for finding cdp. We will also make some comparisons by numerical examples.

One approach to cdp is to introduce an adjustment factor A, $0 < A < 1$, into the independence formula:

$$cdp = 1 - \prod_{i=1}^{n}(1-Ap_i). \tag{C-6}$$

The factor A reduces cdp below the value obtained under independence and is intended to adjust for sequential correlation. In the absence of an established name for this method let us refer to it as the "adjustment factor" method. The blip-scan method of finding radar cdp, as given in references [f] and [g], can be reduced to this method.

Formula (C-6), which does *not* require unimodality, bears striking resemblance in *form* to formula (C-2). The distinction is that (C-2) contains a factor $(1-p_h)$ in place of $(1-ap_h)$ in (C-6). However, the distinction in substance is much greater than the apparent difference in form as we will see below.

Another cdp method in use is to apply the independence formula, but confine attention to glimpses which are so widely separated that they are deemed to be approximately independent. This time separation is usually called "relaxation time." This is probably the most frequently used cdp method, at least in ASW modeling. However, it begs the question as to what glimpse separation achieves independence, and it ignores intermediate glimpses. Incidentally the term "relaxation time" is sometimes used for $1/\lambda$ in a (λ,σ) process, which is an unfortunate confusion of terms since at separation $1/\lambda$ the inter-glimpse correlation is $\exp(-1) \approx .36$, which is too high for approximate independence to be considered present.

A cdp model with substantial merit in simulation applications is reference [1]'s buoy field model RADS taken from APAIR. RADS treats the effects of integration time and multiple detection criteria, but we will ignore these two features for simplicity. The user specifies a sampling time interval d and the variance of each of three independent zero-mean normal distributions, P_1, P_2, and P_3. Take a single repetition of a target's history of mean signal excess at a given buoy, generated by a causal acoustic model. Add to the entire history a single draw from P_1 (long term variability). At time 0, d, 2d, ..., add a draw from P_2, independent of other draws, which applies until time d later. Now add a draw from P_3 to the entire history. Repeat the procedure for each buoy, each having its own history of mean signal excess and its own independent draw from P_3. The draws from P_1 and P_2 affect all buoys in the same way. This constitutes one repetition. From detection outcomes in multiple repetitions, one constructs a curve of estimated cdp versus time for the field or, if one wishes, for a single buoy.

This model of deviation from mean signal excess incorporates temporal and inter-buoy correlation and variability from one encounter to another. The shapes of these correlation behaviors are governed by the ratios of the chosen variances of P_1, P_2, and P_3. The inter-buoy correlation does not depend on distance separation between buoys, and temporal correlation versus time is a one-step step function, both of which are counter-intuitive. If the draws from P_2 were made as events in a Poisson process, then the temporal correlation would damp exponentially to a limit which is positive because of the time-independent effects of P_1 and P_3. These time-independent effects are plausibly real, are attractive features of the model, and are not found in the (λ,σ) model by itself. LT C. W. Goodman is conducting a numerical investigating of issues of this sort in NPGS thesis work under R. N. Forrest. Allowing for distance effects on inter-buoy correlation is more complicated: reference [k] contains a way of handling this (but see C.8).

To summarize this method, with the suggested Poisson modification, it has the attraction of enhancing the (λ,σ) method with stochastic contributions or detriments to detection which affect all buoys alike and others which affect everything in an encounter alike, and such effects are plausibly real. It appears to be well suited to simulation. A semi-analytic method would be to use a (λ,σ) unimodal formula for single-buoy temporal effects, while adjusting the detection threshold for the P_1 and P_3 draws, and averaging numerically with respect to these draws; that does not sound advantageous over simulation of all three of P_1, P_2, and P_3.

Still another cdp method is to compute cdp separately under assumptions of independence, i.e., formula (C-1), and complete dependence, i.e., cdp=max $\{p_1, ..., p_n\}$, and use a weighted average of these two as an estimate of cdp. This approximation appears to be too crude to inspire confidence. Actually, its main use has been to estimate the probability that at least one out k sonobuoys detects (a spatial rather than a temporal cdp), with weight .45 on independence and .55 on dependence, and in that context this approach apparently has done not badly. This is often called the "45-55 rule."

Finally we note a discrete-glimpse cdp method given in reference [g]: for i = 1, ..., n let g_i be the probability that the ith glimpse succeeds *given* that the prior glimpses fail. Then as shown in reference [g],

$$\text{cdp} = 1 - \prod_{i=1}^{n}(1-g_i).$$

This looks like (C-1), the independence formula, but of course it combines *conditional* probabilities, conditioned on events with commonality among them. The difficulty with this approach is that estimation of *each* g_i thus defined involves a sequential dependence which is itself akin to a cdp estimation.

Some numerical comparisons of the (λ,σ), independence, adjustment factor, and relaxation time methods are shown in Figure C-4. Note that we can use the adjustment factor method with A = .39 to match the cdp_5 = .38 obtained by the (λ,σ) method for λ=1 per hour; however the resulting comparison of cdp_{15}'s is a bad mismatch, .83 versus .59. Similarly with A = .45 we can match

cdp_5 with that of (λ,σ) for $\lambda=2$ per hour, i.e., .43; however, this again produces a mismatch in cdp_{15}, .87 versus .71.

We can use a relaxation time of .6 hours to obtain cdp_{15} = .60, approximately that of (λ,σ) with $\lambda=1$ per hour; the rule here is to apply (C-1) to the best glimpse (#8) and those removed from it by integral multiples of .6 hours (#2 and #14). We can similarly approximate the cdp_{15} = .71 using λ = 2 per hour by a relaxation time of .4 hours, using glimpses 8, 4, and 12, to obtain cdp_{15} = .69. However, this choice of relaxation time suggests that we should extrapolate to include times −.1 and 1.5 (which would be glimpses 0 and 16). That calculation would tell us that relaxation time .4 hours is too short to achieve the approximation. However a longer relaxation time would lead us to extrapolate uncomfortably far into time regions where no search is being conducted. This illustrates some difficulties in using the relaxation time method.

Consider the method of combining the independence estimate, cdp_{ind}, and complete dependence estimate, cdp_{dep}, as a weighted sum:

$$k\, cdp_{dep} + (1-k) cdp_{ind} \approx cdp.$$

Now cdp_{dep} is just the maximum single-glimpse probability among those considered, and cdp_{ind} is given by (C-1). To approximate the results of λ=1 per hour, we would need k=.15 for cdp_5 and k=.33 for cdp_{15}; for the result of λ=2 per hours, we would need k=.29 for cdp_5 and for cdp_{15}. We won't try to illustrate the conditional probability method of reference [g], because we would have to make additional assumptions as to conditional probabilities, or the RADS/APAIR method which involves simulation.

The above comparisons of alternative methods appear to assume implicitly that the (λ,σ) method is "ground truth," given knowledge also fo the values of λ and σ. that has by no means been proved. What we have shown is that a choice among these alternative methods does make a material difference in cdp estimation, apart from the problem of estimating the key parameters, i.e., i.e., a single choice of A, relaxation time, or k will not produce a consistent approximation to the (λ,σ) results for a given λ.

Because of the modest empirical basis for the (λ,σ) model and its basic plausibility, it is recommended as the soundest approach to cdp that has yet been found for general tactical analysis. It has been frequently used, e.g., in models employed in OPNAV studies and games and Fleet TDAs. It has reasonable motivation insofar as aberrations from causal predictions in environmental impacts, humans, and equipments behave in toto as being fairly constant between random fades and surges. Of course such effects are never precisely step functions. It is worth considering to add time-independent stochastic variability to the (λ,σ) process, as in the RADS/APAIR method. Applicability to radar as well as sonar appears quite plausible. The limiting factor in applying the (λ,σ) method to either sonar or radar is the empirical basis for estimating λ and σ, discussed next.

C.8. Empirical Basis and History

It is important to provide one's cdp model with empirical links to reality. *Good* empirical bases are not at hand, but more has been done with (λ,σ) methods than with other methods, at least in ASW applications. Let us review some history of (λ,σ) cdp methods, both empirical and theoretical contributions.

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The (λ,σ) process was first used as a tool to find cdp in ASW by J. D. Kettelle in 1960 (see reference [a]). Kettelle was motivated by reviewing data on propagation loss versus time at convergence zone range as found by E.A. Anderson of NEL (now NOSC). He observed fairly constant levels between random fades and surges.

In 1962, R. F. DelSanto and T. G. Bell of USNUSL (now NUSC) reported in reference [b] a good basis for assuming that deviations of actual signal excess from predicted signal excess have a normal distribution and for estimating its mean to be zero and its standard deviation to be 9 db. They did not address temporal behavior. Their method is worthy of revisitation with contemporary sonars and exercises. They examined substantial exercise data on detection of submarines by passive submarine sonars. For each detection, they predicted detection ranges from data known in advance and they estimated the db adjustment needed to make predicted range agree with actual range. (A similar method is used in 2.12.) A histogram of these deviations was approximately normal with mean zero and standard deviation 9 db.

The 9 db standard deviation had been further supported in the 1960 era by USNUSL estimates synthesized from estimates of variability of the separate terms in the sonar equation.

The theory of cdp was investigated extensively by DHWA in the 1960s, under sponsorship of USNUSL (C. S. Walker) and then NADC (M. L. Metersky), reported primarily in references [c], [d], and [e]. This work was largely on (λ,σ) themes and variations thereon. Chapter I of reference [c] reviews earlier approaches to cdp by OEG and others, notably a Markov chain approach by B. O. Koopman, also explored in Chapter II of reference [c]. As a WWII method which compensates for lack of independence, we cite the blip-scan method for radar cdp given in references [f] and [g]. As noted in C.2, this is an example of the "adjustment factor" method.

The unimodal formulas, (C-2), (C-3), and (C-4) above, were found by E. P. Loane in reference [c]. For the case of continuous looking with p monotone (i.e., $h = 0$ or $h = T$) and differentiable, (C-3) was given by Kettelle in reference [a]. The recursive algorithms for cdp under (λ,σ) assumptions without unimodality were obtained by Loane and L. K. Arnold during the DHWA investigations. A recommended exposition of these and other (λ,σ) results is given by B. J. McCabe and B. Belkin in a 1973 theoretical investigation, reference [b]. They explored use of a mixture of a (λ,σ) process and a Gauss-Markov process as a model for d, including each process separately. Analytic computation of cdp under Gauss-Markov can be done only in special cases.

The most extensive empirical investigation ever made of cdp, and of (λ,σ) methods in particular, was undertaken by CSDG-2 with support by NSRDC in 1969-71. CAPT C. E. Woods was CSDG-2 and CDR L. A. Stoehr was his Director, Tactical Analysis Group, both NPGS alumni. Dr. J. Pulos headed the NSRDC work, and G. D. Elmer was their main participant. The OR and statistical work was largely by D. C. Bossard and B. J. McCabe of DHWA, M. M. Fox of Analysis and Technology, and C. E. Gasteyer of GD/EB. The methods and results are reported in reference [i] and the Elmer article in Volume II of reference [j].

This investigation analyzed data from numerous CSDG-2 submarine ASW exercises in an effort to validate (λ,σ) cdp methods and to estimate λ and σ. Interesting inferential tools were developed, principally by Bossard, notably a truncated Kolmogorov-Smirnov test, to deal with the problem of censored data, i.e., observation efforts interrupted by occurrence of the desired event, a detection. The estimation of λ and σ was done jointly with estimation of an additive db adjustment to figure of merit, which improved the fit but weakened the conclusions. The estimates were made in varied environments; the values which were most generally consistent with the data were $\lambda = 2$ per hour and $\sigma = 9$ db (the latter as in reference [b]). Experienced analysts advise that for contemporary passive sonars, lower values of λ and σ are more appropriate. This CSDG-2/NSRDC investigation appeared to confirm the adequacy of (λ,σ) cdp methods for the environments considered, but it cannot be considered a general validation, which indeed would be difficult to achieve.

Various articles relevant to cdp are in reference [j], which reports a 1975 workshop on the subject at NSRDC.

Using a weighted sum of cdp's under independence and complete dependence assumptions has been primarily used to combine single-buoy detection probabilities (each being a temporal cdp) into a *field* cdp, accounting for *spatial* buoy-to-buoy dependence. This method originated in CNA, apparently at CPWP in the early 1970's as part of the SPAM model for evaluation of sonobuoy fields. In 1977, McCabe (reference [k]) developed for CDR P. M. Harvey of CPWP a more elaborate model, CSPAM, for spatial correlation. He found that the CSPAM results were well approximated by the simpler SPAM, so he recommended continued use of the latter.

A more recent exposition of various cdp models, including (λ,σ), is given by W. J. Hurley of CNA in reference [m].

A more recent empirical investigation of (λ,σ) methods, and sensitivity to λ and σ of cdp computed by (λ,σ) methods is given in the 1985 NPGS master's thesis of LT C. D. Lipscombe, reference [n]. As to sensitivity, he confirmed earlier findings that an increase in λ generally increases cdp when signal excess is small and generally decreases cdp when signal excess is high. His estimation of σ^2 was by adding estimated variances of the components of SE; his conclusion agreed with Naval Weather Service guidance (reference [o]) to use

(1) $\sigma = 6$ db when ambient noise measurements have been made and target type and speed are known;

(2) $\sigma = 8$ db if ambient noise is estimated from forecasts, speed is known within 8 knots, and type is known;

(3) $\sigma = 10$ db when ambient noise is estimated and target type and speed are unknown.

He further estimated λ to be 3.5 to 4 per hour, by analysis of holding and gap time data. We remark that while this investigation appears to be useful, particularly under the paucity of empirical results, estimation of λ and σ is best done, or at least best confirmed, in the context of measurements of cdp itself from operational data.

done, or at least best confirmed, in the context of measurements of cdp itself from operational data.

A workshop sponsored by the surface ASW desk in OP-71 at SWDG in Little Creek, 19 January 1989, under the leadership of LCDR J. R. Oakes of SWDG (NPGS alumnus) and W. Richter of SPAWAR, was devoted almost half to cdp methods (with emphasis on (λ,σ)) and the balance to automated reconstruction methods. Presentation slides are available as reference [p].

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[k] B. J. McCabe, *Comparison of SPAM and CSPAM*, DHWA Memorandum Report to COMPATWINGSPAC, 30 August 1977.

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[n] C. D. Lipscombe, III, *The Lambda-Sigma Jump Detection Model, VP Search Parameters*, Naval Postgraduate School Thesis, March 1985.

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APPENDIX D†

MOTION MODEL IN THE GENERIC STATISTICAL TRACKER (GST)

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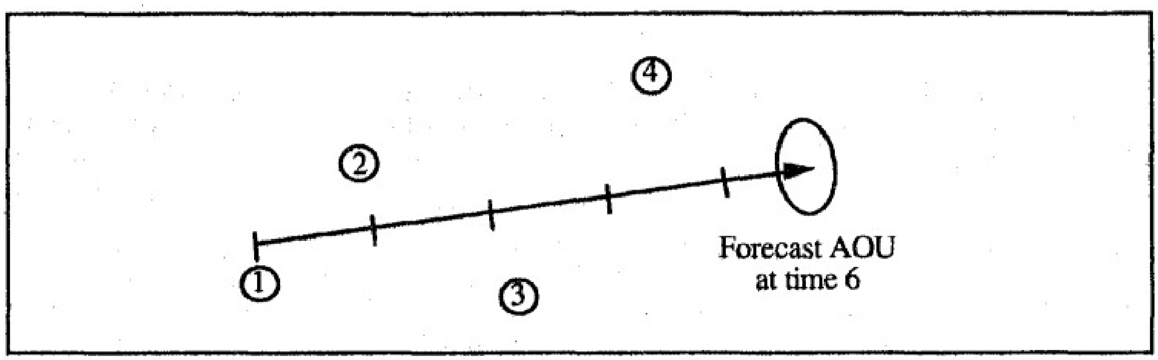
Every tracker needs a motion model. A target is observed only at certain specific times, and it is the job of a tracker to draw inferences about the target's location at other times. For this purpose some assumption about target motion is necessary.

The simplest motion model is the "constant course and speed" model. The tracker assumes that the target has a constant velocity, and hence a straight-line track; and among all such tracks, it selects the one which best fits the observations. The same assumption underlies the common practice of "dead reckoning" in order to forecast a target's future location. This assumption is fine for short intervals under the right conditions.

But sometimes, this assumption is plainly at variance with the data. Suppose, for example, we are given observations like those in Figure D-1, small datum circles at one-hour intervals. A constant-course-and-speed tracker will do its job, and forecast a track such as the one shown in Figure D-1; but this is often not what the operator wants. In this case, a more sophisticated motion model is required.

FIGURE D-1. CONSTANT COURSE AND SPEED (MODEL 1)



What is wanted is a track which is consistent both with the observations and with reasonable assumptions about target motion. The model must be flexible enough that when the observations are known to be accurate, the tracker will be able to fit a track through them; but it must also contain enough information to allow the tracker to fit a sensible track when the observations are sparse.

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†This appendix is adapted from a DHWA document. It explains the motion model used in a six-state version of MTST (see Chapter III). An IOU process (see Appendix B) is obtained by setting the long-term velocity at zero as is done in D.2.2, or the short-term velocity at zero as is done in D.2.3.

Ultimately the job of a motion model is to tell us which tracks are possible, which tracks are likely, and which tracks are unlikely. The tracker then calculates the track which is most likely, given the observations. If the observations are dense and accurate, the tracker will (if possible) find a track consistent with them regardless of the motion model; but if the observations are sparse or have large uncertainties, the motion model will largely determine which track is most likely.

This appendix briefly discusses the motion model in the GST tracker. Because the tracker must run almost instantaneously on a small machine, the model represents a compromise between mathematical tractability and what ships actually do. Still, the model has proven effective in a variety of tracking situations. This appendix is kept at a non-technical level, and is intended to help an operator to decide when to use the default parameters in the model, and when to experiment with other choices of the parameters.

D.1. Theory of the GST Motion Model

The tracker keeps track of both target position (in two dimensions) and target velocity. Target velocity is assumed to be composed of two parts, "short-term velocity" and "long-term velocity." Of course, there is no physical difference between the two parts, and only their sum ("total velocity") affects target position. In fact, changes in target position are fully determined by target velocity, so the motion model is concerned mainly with changes in target velocity.

Long-term velocity represents the target's "base velocity" or "base track." Changes are moderate and infrequent. Short-term velocity represents the random tactical or miscellaneous maneuvers about the base track. Military vessels are prone to frequent random maneuvers, especially in the critical moments of an engagement, so it is best to use a motion model that takes such maneuvers into account, even if the result does not perfectly describe target motion during routine transits.

The GST long-term model depends on two parameters: the "long-term course change rate," CCHRL, and the "long-term root-mean-square speed," SPDL. The first is measured in units-per-hour, and the second in knots. The short term model uses similar parameters, called CCHRS and SPDS. All four of these parameters are ultimately set by the GST operator, although he may be unaware of the choice because of the GST program's default values. The default values are chosen to be acceptable in almost all situations, but sometimes the performance of the model can be improved by a different choice of the parameters.

To see the models work, let us focus on the short-term velocity. We need to assume a short interval of time, dt (say 0.01 hour). (The actual model represents a limit as dt approaches zero.) The model assumes that during each interval of length dt, a fraction of short-term velocity disappears, and is replaced by a random increment of velocity. In effect, a fraction of a random velocity change occurs. The amount of velocity that disappears is equal to (dt) times (CCHRS) times the current short-term velocity. The random increment is drawn from a circular bivariate normal distribution with variance (in each dimension) equal to (SPDS squared) times (CCHRS) times (dt/2). The long-term process is exactly the same, but since the long-term course change rate CCHRL is likely to be much smaller than CCHRS, a small fraction of long-term velocity is being replaced in each time interval.

Since we never know a target's velocity (short-term or long-term) exactly, we cannot actually carry out the above calculations. But the above assumptions tell us how to convert a probability distribution for each velocity component at time t into a probability distribution for each velocity component at time (t+dt). That is exactly what we need for tracking: it tells us how to forecast future velocity and how to calculate the uncertainty of the forecast. When an observation conflicts with the forecast (as all observations do, to some extent) the model tells us how to compromise between them (by weighing the uncertainty of the forecast against the uncertainty of the observation).

D.2. Some Special Cases

The behavior of the model depends on the choice of the four parameters CCHRS, CCHRL, SPDS, and SPDL. Some special cases illustrate the significance of the parameters.

The GST operator can elect to use any of these special cases by selecting a "motion model" other than the default model. The user is invited to choose model 1, 2, 3, or 4. (Choosing "model 5" allows the user to set all four parameters directly, which is normally a job for specialists.)

D.2.1. Constant Course and Speed (Model 1). By setting CCHRS and CCHRL both to zero, the user creates a constant-velocity model. That is, the fraction of each velocity component that disappears in each interval is zero, and the random increments are also zero. Given the observations in Figure D-1, the tracker will now select the track in Figure D-1, because no better-fitting track is possible.

D.2.2. On-Station Target (Model 2). By setting SPDL to zero, the operator effectively eliminates the long-term component of velocity, leaving only the random maneuvers. This is appropriate for a target that seems to be loitering on station. Since short-term velocity can change quickly, the target regards very curvy tracks to be likely, and also assumes that any estimates it makes of velocity become worthless after an hour or two (the default value of CCHRS is one per hour). Given the observations in Figure D-1, the on-station-target model will fit a track such as that in Figure D-2. If asked to make a forecast two hours after the last data point, it will project the track forward only a short distance and attach a very large uncertainty ellipse, representing its essential ignorance of the target's motion since the last observation.

D.2.3. Transitor (Model 3). By setting SPDS equal to zero, the operator effectively eliminates the short-term part of velocity, leaving only the base track. This is appropriate for transitors (especially merchants) but is completely inappropriate for rapidly-maneuvering targets. The model assumes that moderately wavey tracks are possible, but that frequent sharp turns are extremely unlikely. Given the same data as before, it will fit a track like that in Figure D-3. Asked to forecast motion two hours after the last data point, it will continue to advance the target's position along the fitted track, with moderate uncertainty regions: it has correctly identified the target's west-to-east long-term motion, but failed to accommodate the rapid north-to-south variations.

FIGURE D-2. ON-STATION TARGET (MODEL 2)

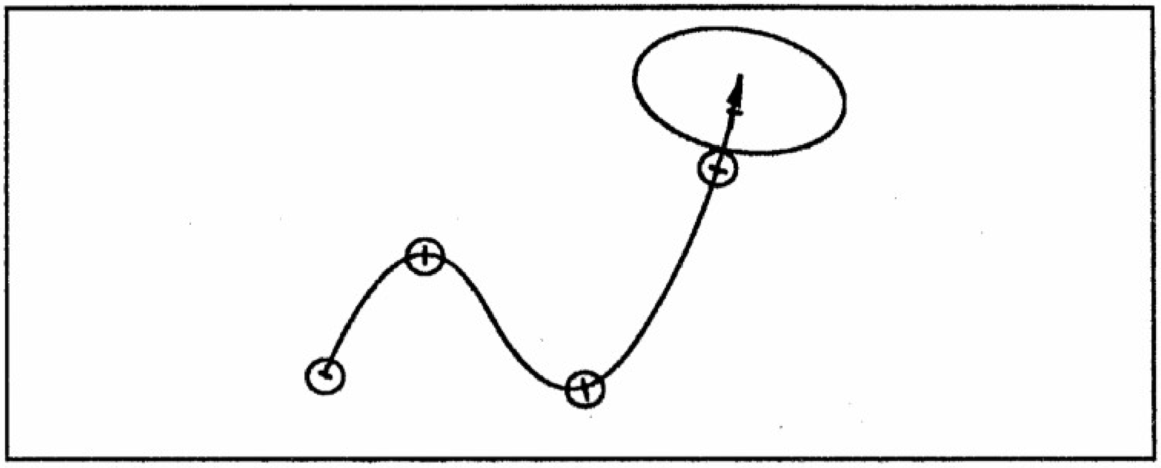
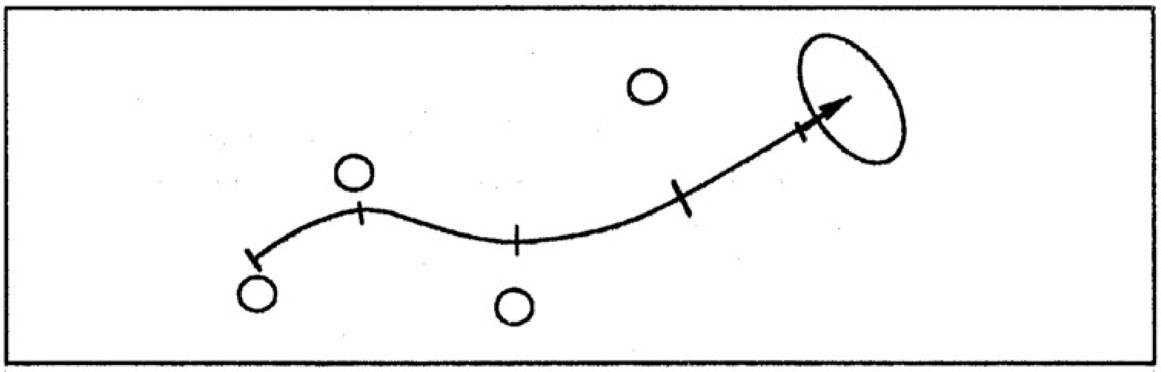


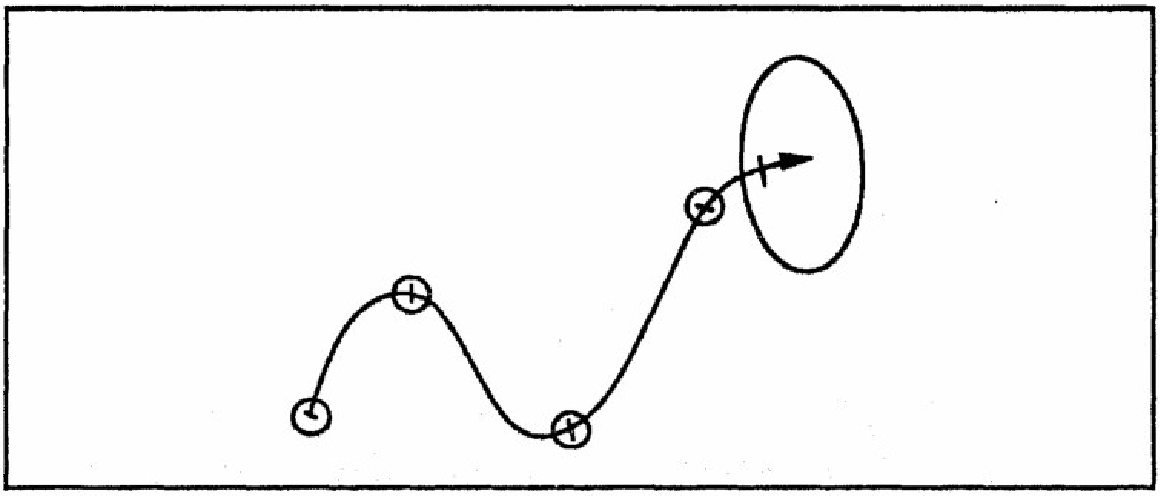
FIGURE D-3. TRANSITOR (MODEL 3)



D.2.4. Meandering Transitor (Model 4). This is the default model. In this model CCHRS is 1 per hour, CCHRL is .10 per hour, and the rms speeds are such that the two components of velocity are weighted about equally. Given the observations from the previous figures, this model yields the fitted track in Figure D-4. Asked to forecast the target's position two hours ahead, the tracker will forecast a moderate turn to the right, as shown in the figure, together with reasonably large uncertainty areas.

The forecast of a right turn is characteristic of this model, and warrants some attention. What is happening is that the best-fitting track accounts for the north-south motions of the target in terms of short-term velocity, since it is clearly changing quickly; but it accounts for the west-east motions in terms of long-term velocity. The former decays quickly, but the latter persists, creating the appearance of a right turn in the forecast track. Some thought will verify that the forecast is reasonable--but that the large uncertainty areas, reflecting the possibility of additional short-term maneuvers, are also reasonable. It would be a mistake to assume that the target is actually turning right; that is the most likely track, but the large uncertainty suggests that many other random maneuvers are nearly as likely.

FIGURE D-4. MEANDERING TRANSITOR (MODEL 4)



This default model is appropriate under a wide range of conditions. If a target does not engage in short-term maneuvers during a period of observation, then the tracker will find a best-fit track with little or no short-term velocity. But its forecast uncertainty areas will nevertheless reflect the possibility that the target will begin to exhibit short-term velocity changes in the future.

D.3. Choice of Models

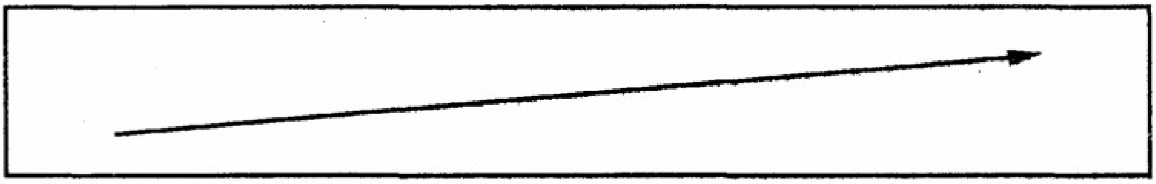
Selecting a motion model for a particular tracking evolution is as much an art as a science. There is no substitute for experience.

Ultimately the selection must be based on the operator's judgment as to what types of target tracks are most likely. In cases in which the observations are not frequent enough to dictate the fitted track, the choice of motion model will largely determine the shape of the tracker's output.

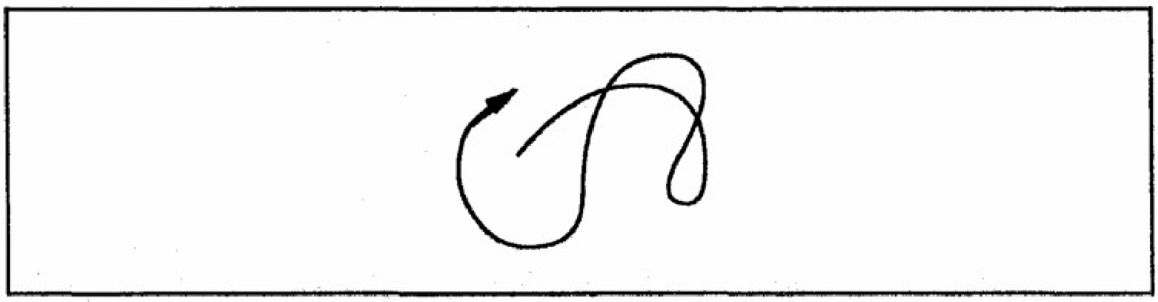
Figure D-5 summarizes the types of tracks that are thought to be highly probable, according to each of the four models described above.

FIGURE D-5. TYPICAL TRACKS FOR THE STANDARD GST MOTION MODELS

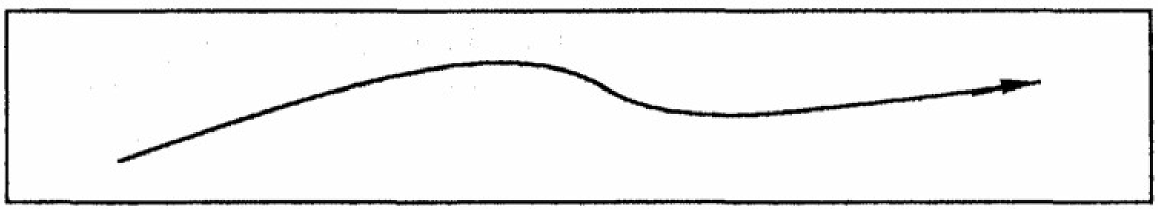
Constant Course and Speed (Model 1):



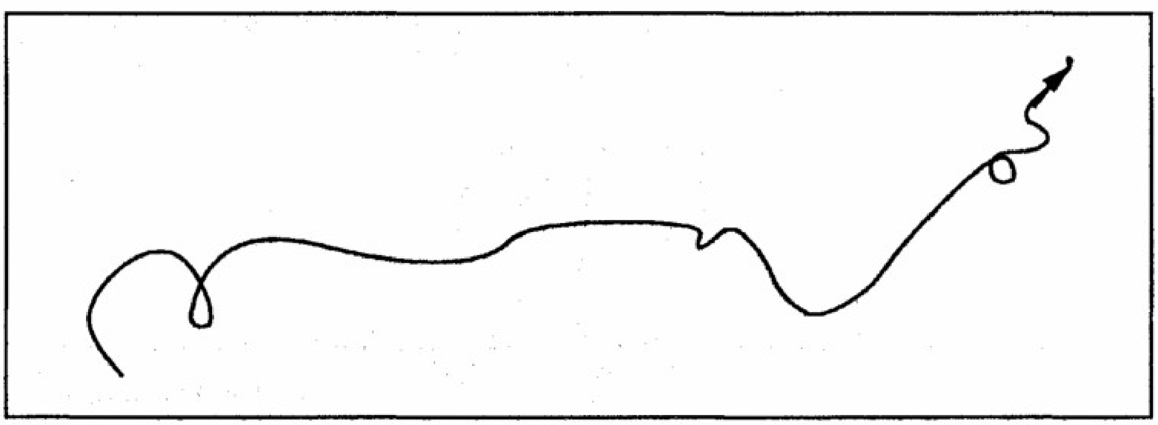
On-Station Target (Model 2):



Transitor (Model 3):



Meandering Transitor (Model 4; Default):



APPENDIX E

TDA TRAINING AND USER'S GUIDES

In this appendix we make some comments on TDA training and on some requisites for user-friendliness in TDA user's guides. Without question, both of these areas are vitally important to successful use of TDAs, and they are both expensive. Similar observations about user-friendliness in *design* of TDA software and hardware are made in Appendix A and Chapter I. That these topics come at the end of this text is in no way indicative of their importance. W. P. Hughes makes the cogent points that good training is needed to impart *confidence* as well as competence, and that a good indicator of success of a naval TDA is that it is taught in the Training Command.

Our belief is that the Navy's investment in TDA training, with some exceptions such as submarine TMA (Chapter III) and the Strike Planning TDA TAMPS (4.6), has not been commensurate with its investment in TDA development. Investment in user's guides and quality produced have been mixed, sometimes excellent and sometimes rather inadequate.

Both training and user's guide preparation are harder for *integrated* TDAs, such as JOTS, ITDA, and TESS, than they are for an individual TDA. This is because an integrated TDA entails multiple individual TDAs, and this entails multiple training courses and user's guides. While there is great merit in integration of data bases and screen accessibility for diverse users, there is also a case for separate user's guides and separate training for separate major categories within an integrated system, such as ASW, AAW, etc., within ITDA and JOTS. For various *support* functions in an integrated TDA, training and guides will be common to all users.

The first section is on training and the second is on user's guides.

E.1. Training in TDAs

To maintain a good TDA training program is expensive in both instructors' time and trainees' time, generally more so than the cost of providing a good user's guide. The fact is that investment in good training has often come up short in the introduction of a new TDA, in comparison to investment in development.

It is also held by some that a TDA should be sufficiently user-friendly that the user can be self-trained with help of a user's guide. That view appears to overlook the fact that TDA functionality generally conflicts with user-friendliness, and that a high degree of functionality often provides important enhancement in combat effectiveness, *given* successful training in the TDA. The conclusion of reference [a], an excellent tutorial on CAS, puts it very well in paraphrasing Euclid: "There is no royal road to ASW," and it could just as well have said "generally speaking, to good use of TDAs."

We cite some cases of successful TDA training and some cases where excellent TDA potential has not been realized apparently because of inadequate training.

The most striking example of successful TDA training where the training problem has been difficult is in SSN TMA. If one looks at reference [b], one sees as much complication in mathematics and methods to be learned as may be found in the *use* of any TDA reviewed in this text. Now the complication we refer to is more in methods without use of electronic computers than in operation of the computer TDAs; facility with the former is taught for understanding of the latter. The notation in reference [b] is cumbersome, not suggestive as to meaning, and must be regarded as user-hostile. (In contrast the notation in reference [c] *is* suggestive as to meaning, although also cumbersome, e.g., S_tI means *s*peed of *t*arget *i*n line of sight.) It is believed that these remarks carry over from the doctrinal reference [b] to the training manuals used in Submarine School instruction.

Why is TMA instruction successful in spite of these problems? The answer is that the management of the SSN community, the instructors, and the trainees attach *importance* to TMA training, as manifested in the fact that qualification in TMA is a requirement for qualification as a submariner. The reason for this emphasis is that SSN ASW *cannot live without good passive TMA*, as observed at the beginning of Chapter III.

The lesson here is that leadership, instructors, and trainees must all recognize the importance of a TDA and accordingly the importance of good training in its use. It is dubious to introduce a TDA to Fleet operations if it cannot be done on the basis of sufficient importance in contribution to mission success to warrant a good training program.

Another example of successful TMA training is the USCG SAR program CASP (see 2.9 and 2.13). Here the key to success was that a knowledgeable officer *inside the user community* (LCDR J. H. Discenza) established good training at the initial introduction of the TDA. Once good training was established, the impetus for its continuation and updating when needed was from the continuing use of the TDA.

Here the lesson is that training can be greatly enhanced by knowledgeable initiative inside the user community.

A related point is that non-use of a TDA make it difficult to maintain well-trained readiness. It is likely that the NAVSAR program for SAR at sea (see 5.2) suffers from this problem. Needs for NAVSAR are infrequent, but when a need occurs it can make the difference in saving lives, *if* a user is at hand who understands the system.

The lesson is that practice in use of a TDA must be kept up in the absence of real needs for the TDA, to maintain readiness for needs when they arise. This is not different from most forms of combat readiness.

An important example of inadequate training is VPCAS. The principal training in the system appears to have been by developers during two or three days of initial on-site installation in late 1983 and early 1984. The durability of this training depended on how well it was passed from a trained operator to his relief. It takes only one weak link to break the chain at a given location. Training videotapes were prepared and distributed but do not appear to have been made part of a management mandated training program. As of early 1989, the ASWOC training program at Dam Neck included nothing about VPCAS and the facility did not possess a Navy Standard DTC to which VPCAS had been converted.

Since VPCAS had excellent sponsorship by senior people during its development, in the Fleet and in Washington, it seems surprising that better training provisions have not been made. One explanation may be inadequate understanding by management of the need for training, in that search planning TDAs on computers is relatively new to naval operations, compared to most forms of readiness needs. It is also likely that the required amount of instruction and learning of concepts and of complexities in the input process may have discouraged prospective users, and this was reflected in management attitudes. Again, these complexities and depth of concepts are not as great as in SSN TMA, but computer assistance to search planning does not appear to have the same essentiality in the eyes of users as it does in SSN TMA. I.e., a search planner may feel that he can do about as well by intuitive means as with TDA assistance. The comparative analysis of OASIS use (see 2.12), for example, strongly indicates otherwise.

The VPCAS example reinforces the above lessons and adds the point that training which is confined to TDA operators training their reliefs has inadequate durability.

Finally, we reiterate that training in an integrated TDA, such as ITDA, JOTS, or TESS has the problem that in each of them several TDAs are combined in one. The constraining effect of this is seen in ITDA training of Fleet personnel. That has been typically two days of briefings by NADC experts, covering the full gamut of support functions and TDAs. It is too much for a trainee to learn the full scope of these TDAs or to learn those in his own application area, such as ASW or AAW, in the time allotted to that specialty, within two days.

This further lesson is that an integrated TDA deserves separate training activities for the separate major categories of the TDAs it contains.

E.2. TDA User's Guides

Good user's guides are obviously indispensable to TDA training and use. In this section we outline qualities that are needed in TDA user's guides. These qualities are categorized as physical attributes, guideposts, and technical content, the latter being most important.

For four major TDAs we have reviewed at length, ITDA, JOTS, PACSEARCH, and TESS, the user's guides are references [d], [e], [f], and [g]. Reference [h] is a supplement, in the form of training notes, to the ITDA user's guide.

Of the various qualities called for below, each is found in good measure in some of these references and found lacking in others. We find the PACSEARCH guide, reference [f] (not referring to the overly condensed version in reference [d]), to be the best in technical content, the weakest in physical attributes, and fair in guideposts. The technical content in reference [f] is highlighted by a detailed example in its Chapter IV, which is helped by having been typed through the keyboard of the hardware host of the TDA, i.e., an HP 9020, which facilitated incorporating hard copy of CRT screens into the running text; however, this typing vehicle also adversely affected print clarity of the text.

As with training in general, an integrated TDA, being several TDAs in one, has the special problem in user's guide preparation that several TDAs must be described, generally involving users in a multiplicity of application areas.

E.2.1. Physical attributes needed in user's guides. Effective use of user's guides is enhanced, first of all, by attention and investment addressed to physical attributes. The main desired features are the following:

(1) The book should lie flat when open, for ease of reading. This can be achieved, e.g., by spine or ring binders, which also make it easier to insert revisions.

(2) Print should be on both sides of a page. This takes advantage of (1) and also reduces bulk.

(3) Excessive bulk should be broken into separate volumes.

(4) Print should be clear. Perhaps the biggest problem in print clarity is in hard copy of CRT screens, which are generally much needed in user's guides; for ITDA (references [d] and [h]), this is solved very well by redrawing the graphics and retyping the tableaus taken from the screens. Also, the JOTS 5.1 guide, reference [e], is an improvement over its 5.0 predecessor in that respect.

E.2.2 Guideposts. It is important to provide users with aids to finding quickly those parts of a user's guide that are needed at the moment. Such aids include the following:

(1) Table of Contents

(2) Glossary of Acronyms

(3) Tabs and/or dividers for major components of the guide

(4) Index

(5) Bibliography

The ITDA and JOTS guides have a key word index--that is difficult to compile but valuable. User's guides are intended to be self-sufficient and hence do not usually have bibliographies but references to modeling and developmental intents can be very helpful to the more inquisitive users.

E.2.3 Technical content. The guide should first motivate the overall use of the TDA. It should identify which decision-makers it is intended to serve, the types of decisions served, what its outputs contribute to the mission, and the types of inputs and data bases required.

Program initiation and termination must be described, and the menu organization must be made clear. Hopefully the program provides time-savers in keyboard entry and exits to avoid being trapped in a subprogram, and these should be described. Appendix A makes the point that exits should be uniform in appearance to the user, but if they are not it is all the more important that they be described.

The user should be told *why* various steps are taken. Model description in any depth is generally out of place in a user's guide but should be accessible to the user. The guide should tell the user what the program is accomplishing at various stages.

Important applications should be illustrated by examples described in a logical sequence. These should include screen displays, either copied or redrawn. It is helpful for the guide to display menus, prompts with user responses, and outputs.

Commercial software will generally not be popular nor accepted without the minimum standards described above for user's manuals. That Navy user's guides have seldom matched the quality of commercial users is an indication of under attention to the user relative to attention paid to software development.

References in Appendix E

[a] S. J. Benkoski, *Introduction to ASW and Computer-Assisted Search*, Commander Patrol Wings, Pacific Tactical Study SZ033-z-83, 26 September 1983.

[b] Office of the Chief of Naval Operations, *Target Motion Analysis (TMA) Techniques*, a 71-1-1, April 1985.

[c] Commander, Submarine Development Group Two, *Passive Ranging Manual*, CSDG-2 Report 2-69, December 1969.

[d] Naval Air Development Center, *Integrated Tactical Decision Aids User's Guide*, ITDA 2.02, 1 October 1988.

[e] Inter-National Research Institute, *JOTS User's Guide*, March1989.

[f] W. R. Monach, *PACSEARCH User's Guide*, DHWA Report to Commander Oceanographic Systems, Pacific Fleet, September 1987.

[g] Naval Oceanographic Office, *Tactical Environmental Support System, TESS 2.0 User's Guide*, July 1988.

[h] Naval Air Development Center, *Integrated Tactical Decision Aids Training Notes, ITDA 2.02*, November 1988.

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Various naval tactical decision aids (TDAs) are reviewed as to nature of inputs, outputs, and, in most cases, underlying models. The primary purpose is graduate instruction in operations research applied to development of TDAs. The principal categories of TDAs reviewed are search TDAs, target motion analysis TDAs, integrated TDAs for battle group command (ITDA and JOTS), and environmentally dominated TDAs (TESS). A history of each category is included. Appendices address user-friendliness in TDA design, TDA training and user's guides, and various stochastic process topics that are useful in TDAs.

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