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STANDARDIZATION POTENTIAL ACROSS NAVIGATION SYSTEMS (SPANS)

The Analytic Sciences Corporation
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Reading, Massachusetts 01867

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Wright-Patterson Air Force Base, Ohio 45433

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The objective of the SPANS effort is to assess the potential for standardization across avionic navigation systems by identifying standard hardware and software configurations that minimize life-cycle costs while satisfying Air Force operational requirements. The primary output of the effort is a computerized Standardization Evaluation Program (STEP) that quantifies the impact of standardization in those areas of avionics (such

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20. ABSTRACT (Continued)

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as navigation) defined by the program data base. The methodology uses a life-cycle cost model in an iterative manner over a number of aircraft and their associated mission profiles. The life cycle cost model is sensitive to the cost benefits, obtained by widespread use of standard equipment across several aircraft, through cost learning and reliability improvement functions. The SPANS data base consists of three files, including aircraft/mission data, navigation subsystem data and standard cost factors data, that provide the inputs necessary for operation of the STEP program. The major outputs of the STEP program are life-cycle cost/mission effectiveness "maps" for proposed avionic suites for each aircraft, and the total (global) life-cycle cost value resulting from selection of the lowest life-cycle cost, mission-responsive avionic suites for all aircraft considered. With these outputs, a System Analyst can explore the effects on Global life cycle cost of various standardization options.

FOREWORD

This report, AFAL-TR-77-188, was submitted on 15 July 1977 as TR-840-1 by The Analytic Sciences Corporation, Six Jacob Way, Reading, Massachusetts 01867 under Contract No. F33615-76-C-1121 with the Avionics Synthesis and Analysis Branch (AAA) of the Air Force Avionics Laboratory. This study was performed during the period April 1976 through April 1977. Capt. R.A. Wakefield was the Project Engineer during the early part of this period. Mr. J. Garcher assumed the role of Project Engineer during the later stages of the study period.

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INTRODUCTION

1.1 BACKGROUND

The concept of avionics standardization across different aircraft in the USAF inventory has attracted considerable attention in recent years as a potential method for reducing equipment life-cycle costs (LCC). Several equipment-related standardization programs have evolved in response to perceived areas of functional commonality across different types of aircraft. Notable among these are the AN/ARN-118 TACAN Receiver program, the Form, Fit and Function Standard Inertial Navigation System (F^3 INS) program, the Common Strategic Doppler program and various programs aimed at establishing standard configurations of electronic modules and subsystems with wide applicability.

In general, these programs were inaugurated on the basis of sound, but localized, analyses of applicability and cost which related specifically to the type of equipment under consideration and to its limited function as an autonomous element within established avionics suites. Little effort has been expended in attempting to solve the more general forecasting problems associated with defining new avionics suites for aircraft in the future USAF inventory and identifying subsystems within those avionics suites for which equipment standardization would yield maximum LCC benefits.

Recognizing the need for such a "top-down", quantitative analysis of future standardization opportunities and their cost-savings potential, the Air Force Avionics Laboratory (AFAL) has embarked on a program to identify areas of avionics for which standardization will yield the highest payoffs in reduced life-cycle costs. To establish a useable methodology, The Analytic Sciences Corporation (TASC) was awarded a contract by AFAL to assess the Standardization Potential Across Navigation Systems (SPANS) through accomplishment of the following tasks:

- Identification of navigation system performance requirements for the major USAF baseline mission areas
- Assessment of present and projected navigation subsystem and system capabilities and costs
- Establishment of a LCC model accounting for standardization considerations
- Quantitative tradeoff analyses using the LCC model to identify promising candidates for standardization.

This report documents the methods developed and the results obtained during the contracted study.

1.2 TECHNICAL APPROACH

Figure 1.2-1 presents an overview of the technical approach used in the SPANS study. The core element of this approach was the development of a computerized Standardization Evaluation Program (STEP) for conducting the tradeoff analyses. This program is a generalized adaptation of the Design to System Performance/Cost (DSPC) methodology developed by the Directorate of Aerospace Studies, Kirtland AFB and described in Ref. 1. The principal generalization involves the computation and use of global system life-cycle costs over multiple aircraft programs. A life-cycle cost model, which is sensitive to the cost benefits obtained by widespread use

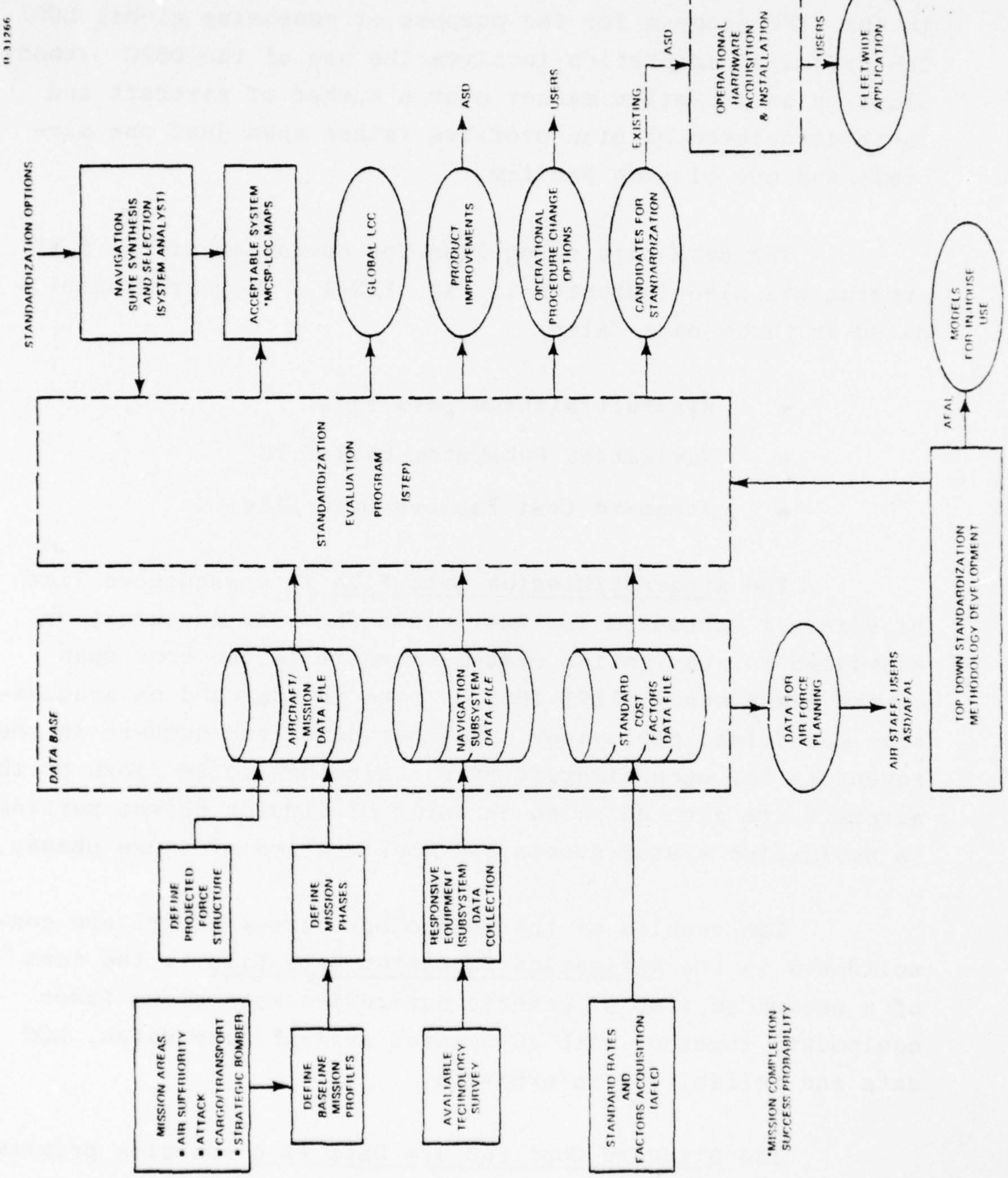


Figure 1.2-1 Overview of Technical Approach

of standard equipment across several aircraft, is embedded in the STEP program for the purpose of assessing global LCC. The principal adaptation involves the use of the DSPC methodology in an iterative manner over a number of aircraft and their associated mission profiles rather than just one aircraft and one mission profile.

The data inputs required for operation of the STEP program are also indicated in Fig. 1.2-1. They are consolidated in three data files:

- Aircraft/Mission Data File
- Navigation Subsystem Data File
- Standard Cost Factors Data File.

The Aircraft/Mission Data File is a sequenced list of aircraft scheduled for entry into the USAF inventory or scheduled for navigation system retrofit in the time span of the SPANS study (1977-1991). Data is included on acquisition schedules, deployment, phaseout dates and numbers in the inventory for each aircraft type. Missions to be flown by the aircraft are also detailed in terms of mission phases pertinent to navigation system events and the duration of those phases.

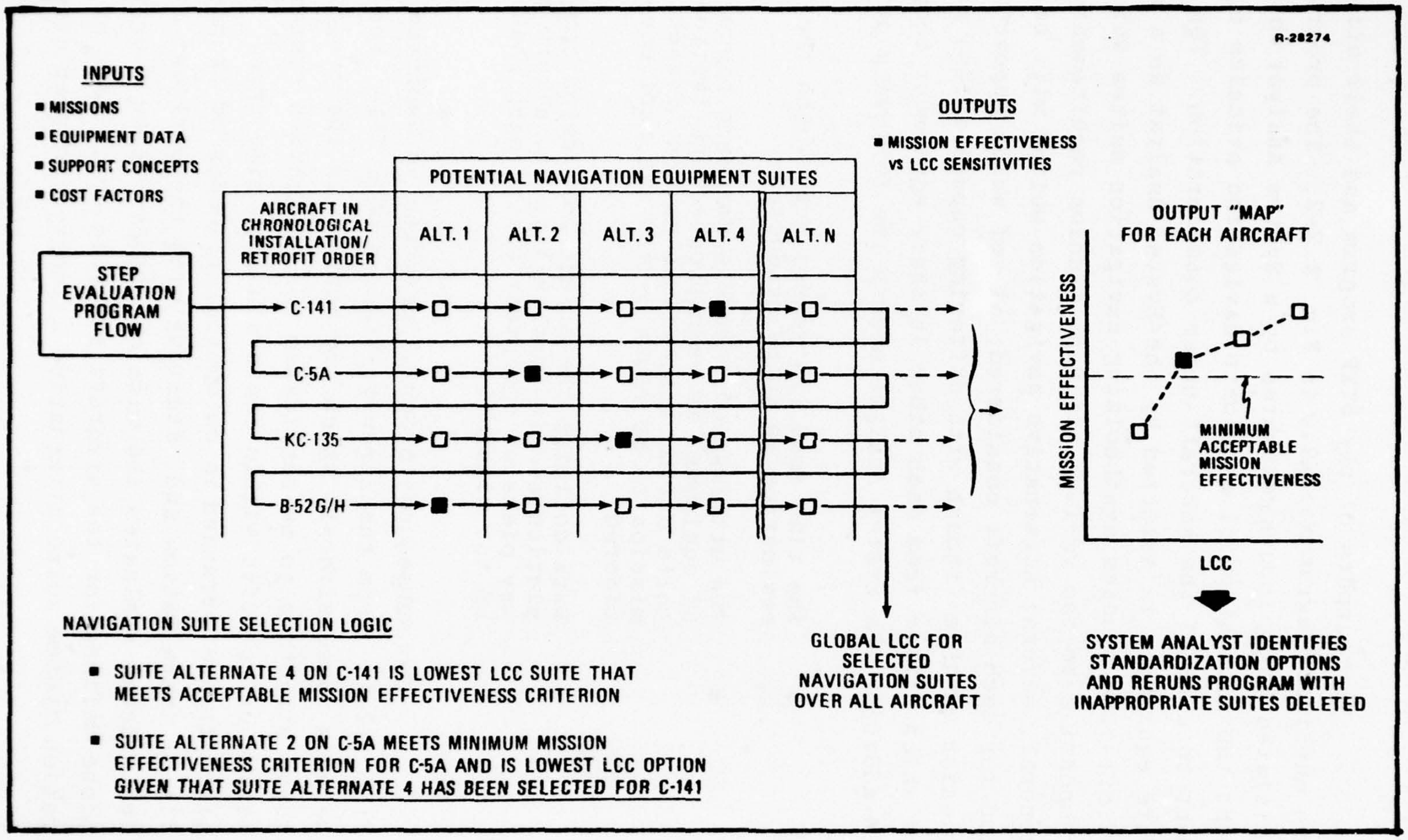
The results of the Technology Survey effort are consolidated in the Navigation Subsystem Data File in the form of a sequenced list of generic navigation subsystems (user equipment) together with associated availability dates, LCC data and reliability information.

The Standard Cost Factors Data File contains program constants and LCC parameters that are relatively independent of aircraft and navigation technology (e.g., maintenance labor rates, shipping cost standards).

The outputs of the STEP program and their utilization are outlined diagrammatically in Fig. 1.2-2. The program is initiated using inputs generated by a System Analyst which represent the allocation of candidate navigation avionics equipment to each of the aircraft under consideration. The candidate equipment is selected by the System Analyst as a result of off-line studies synthesizing navigation suites which are responsive to the various aircraft mission requirements. In general, several alternative navigation suites will be selected for each aircraft considered, all of which appear to be mission capable (though with differing capabilities) and all of which differ from each other in their equipment complement. In addition the System Analyst enters the following data:

- The time span (in years) over which the evaluation is to be conducted
- The utilization schedule for each piece of equipment in each proposed navigation suite during the various phases of each mission to be flown by the aircraft considered
- Data defining the effect on mission completion success probability of failure of any piece of equipment during each phase of the mission.

The subsequent program operation is depicted in Fig. 1.2-2. From the Aircraft/Mission Data File, the program selects those aircraft which are defined in the projected force structure to be candidates for navigation system installation or retrofit within the evaluation time span. These aircraft are arranged in chronological order of proposed retrofit or installation and, starting with the earliest aircraft, the program evaluates the mission effectiveness over the missions defined for the aircraft and life-cycle cost of each navigation system suite alternative allocated to that aircraft.



NAVIGATION SUITE SELECTION LOGIC

- SUITE ALTERNATE 4 ON C-141 IS LOWEST LCC SUITE THAT MEETS ACCEPTABLE MISSION EFFECTIVENESS CRITERION
- SUITE ALTERNATE 2 ON C-5A MEETS MINIMUM MISSION EFFECTIVENESS CRITERION FOR C-5A AND IS LOWEST LCC OPTION GIVEN THAT SUITE ALTERNATE 4 HAS BEEN SELECTED FOR C-141

Figure 1.2-2 Standardization Evaluation Program (STEP) Operation

Cost and reliability data for the subsystems comprising each navigation system suite are extracted from the Navigation Subsystem and Standard Cost Factors Data Files during this process. Mission phase data and the anticipated employment of the aircraft on each type of defined mission are extracted from the Aircraft/Mission Data File during program operation.

The program then steps into the second aircraft in the chronological list and repeats the mission effectiveness - LCC evaluation process for the equipment suites proposed for that aircraft. However this evaluation is characterized by one important difference in the nature of the equipment cost and reliability data used. If an item of equipment proposed for use on the second aircraft forms a part of the lowest LCC navigation suite meeting the mission effectiveness criterion for the first aircraft, the program adjusts the cost and reliability figures associated with that piece of equipment in its second application to reflect the fact that it already has a development and production history. In cases in which the two aircraft carrying the common piece of equipment are expected to be colocated at common bases, this expectation is also registered in the Aircraft/Mission Data File so that allowance will be made by the program for the use of common support equipment and spares.

Navigation suite alternatives for subsequent aircraft in the force structure selection for the defined time span are evaluated for life-cycle cost and mission effectiveness in a similar manner. In each case the cost and reliability characteristics of the equipment used are updated to reflect prior selection on the earlier aircraft programs. Two principal types of output result from the program operation:

- LCC-Mission Effectiveness "maps" for the navigation suites proposed for each aircraft. For the purposes of subsequent discussion these LCC values will be termed local life-cycle costs (L-LCC) since they apply to one aircraft only.
- The total life-cycle cost value resulting from the selection of the lowest L-LCC, mission-responsive navigation suites on all the aircraft considered using the program procedures described above. This value is termed global life-cycle cost (G-LCC) in the subsequent discussion.

At this point no deliberate attempt at standardization (the use of a common piece of equipment across large numbers of aircraft) has been made. However, armed with the initial L-LCC vs System Effectiveness maps, the System Analyst is now in a position to explore the effects on G-LCC of standardization options identifiable in the overall systems synthesis process. To this end he may inhibit the selection of any particular navigation system suite on any aircraft (or, alternatively, specify the selection of a particular navigation system suite on any aircraft) in the interests of making wider use of common equipment across many aircraft. Subsequent STEP program runs are conducted under these externally-imposed constraints. They yield the G-LCC impacts associated with the adoption of standardization applied to any selections of equipment the System Analyst chooses.

1.3 SUMMARY OF RESULTS

The STEP methodology described in Section 1.2 of this report was designed and developed into a working computer program during the course of the contract study. The methodology developed is pragmatic in its approach. Considerable System Analyst participation in the synthesis of navigation system suites and in the evaluation of the impact on mission effectiveness of equipment performance and reliability is required. The program is well-suited to the use of mission effectiveness weighting factors resulting from off-line performance and mission reliability impact studies conducted using other programs such as AFAL's Avionics Evaluation Program (Ref. 2). The possibility of on-line incorporation of such evaluation programs into STEP remains to be fully explored.

Realistic force structure profiles for the period 1978-1991 were acquired and employed as inputs to the STEP program. These profiles included deployment projections for the aircraft enumerated (together with probable colocation identifiers) and factors defining projected multi-mission aircraft allocation to each of the possible mission types. Required navigation avionics installation or retrofit programs associated with each of the aircraft types in the force structure were identified from USAF planning documents and incorporated (together with projected schedules) into the STEP input data base.

A study of available literature on mission doctrines in the defined mission areas was conducted and resulted in the definition of twelve (12) representative missions to cover the spectrum of possible aircraft utilization. These twelve missions were fully detailed in terms of:

- Phases encompassing different navigation system events
- Phase duration
- Natural, induced and tactical environments experienced by the aircraft
- Geographic locations and availability of external navigation aids.

The mission phase tables were used both in setting up mission data file inputs to the STEP program and in the selection of mission-responsive navigation suites.

The technology survey resulted in definition of the major navigation technologies currently in operational use or expected to reach operational status in the period of interest. These were included in the general categories of Radio Navigation, Radar Navigation, and Non-Radiating, Autonomous Navigation. User equipment data, including cost and reliability figures, were acquired on representative equipment for each type of navigation technology. Particular emphasis was placed on the refinement of cost and reliability estimates associated with the higher cost items such as inertial navigation sets, Doppler radars, Loran C/D receivers, and airborne computers. In each case the field and depot support equipment required to maintain the user equipment was identified and its cost estimated.

Alternative navigation equipment suites were synthesized for ten major aircraft programs (new aircraft or scheduled for navigation system retrofit) in the period of interest. The suites were comprised of equipments identified in the technology survey which, as integrated navigation systems, would satisfy the navigational requirements in each of the missions flown by the aircraft. These suite alternatives served as a basis for identifying potential areas for standardization.

The STEP program was used to analyze a number of topical standardization issues in the present technology era (1978-84). The cost tradeoffs associated with the following options were evaluated:

- Use of a standard, moderate accuracy INS for Attack, Fighter, Tanker and Cargo/Transport aircraft vs a unique INS on each aircraft type
- Use of a standard OMEGA navigation set on Tanker and Cargo/Transport aircraft vs a unique OMEGA on each aircraft type.
- Use of a standard airborne computer on Attack, Fighter, Tanker and Cargo/Transport aircraft vs a unique airborne computer on each aircraft type
- Use of a standard Doppler radar for all strategic aircraft vs use of a unique Doppler radar on each aircraft type.

A synopsis of the salient results is presented in Table 1.3-1. A more detailed breakdown of the contributing factors to G-LCC difference for the Standard vs Non-Standard inertial systems is shown in Table 1.3-2.

TABLE 1.3-1

GLOBAL LCC BENEFITS OF ALTERNATIVE STANDARDIZATION CONCEPTS

R 29406

ASSUMPTIONS

- CASE 1: STANDARD SUBSYSTEM APPLIED IN EACH AIRCRAFT
- CASE 2: NEW SUBSYSTEM DEVELOPED FOR EACH AIRCRAFT
- COST CHARACTERISTICS OF EACH NEW SUBSYSTEM AND STANDARD SUBSYSTEM ARE INITIALLY IDENTICAL

NAVIGATION SUBSYSTEM	APPLICABLE AIRCRAFT	CASE 1 GLOBAL LCC	CASE 2 GLOBAL LCC	BENEFITS (CASE 2 - CASE 1)
INERTIAL NAVIGATION SYSTEM	F-16, A-10A, A-10B, FOI, AMST ATCA, KC-135	$402 M	$718 M	$316 M
OMEGA	AMST, ATCA, KC-135	$ 14 M	$ 20 M	$ 6 M
DIGITAL COMPUTER	F-16, A-10A, A-10B, FOI, AMST, ATCA, KC-135	$210 M	$357 M	$147 M
DOPPLER RADAR	B-52, B-1, KC-135	$ 28 M	$ 42 M	$ 14 M

TABLE 1.3-2

BREAKDOWN OF GLOBAL LCC BENEFITS FOR INS STANDARDIZATION

R-29407

ASSUMPTIONS

- GLOBAL LIFE-CYCLE COSTS CONSIDERED OVER F-16, A-10A, A-10B FOI, AMST, ATCA, KC-135
- CASE 1: STD INS USED IN EACH PROGRAM
  CASE 2: NEW INS DEVELOPED FOR EACH PROGRAM
- COST CHARACTERISTICS OF EACH NEW INS AND STD INS ARE INITIALLY IDENTICAL

LCC ELEMENT	CASE 1 STANDARD INS	CASE 2 NON-STANDARD INS
ONE-TIME COSTS	$ 13 M	$ 91 M
HARDWARE ACQUISITION	$160 M	$210 M
SUPPORT EQUIPMENT	$ 12 M	$ 25 M
SPARES	$ 44 M	$ 77 M
RECURRING MAINTENANCE	$173 M	$315 M
TOTAL	$402 M	$718 M

1.4 OVERVIEW OF REPORT

The SPANS study is described in further detail in the remainder of this report. The projected USAF force structure driving future navigation requirements, and its relationship to basic areas of avionics technology development, is described in Chapter 2. The baseline missions considered in the study are discussed in Chapter 3, which includes detailed profiles of several missions and associated navigation requirements. Existing and forecasted navigation system technologies are described in Chapter 4. Chapter 5 describes the standardization tradeoff methodology and how equipment commonality considerations are incorporated in the global LCC evaluation. Representative standardization concept evaluation studies are presented in Chapter 6. The detailed equations comprising STEP are documented in Appendix A.

SECTION II

FORCE STRUCTURE CONSIDERATIONS

2.1 INTRODUCTION

The overall objective of the Avionics Laboratory standardization evaluation program is to provide a quantitative method for identifying those areas of avionics in which standardization will yield the highest payoff in reduced life-cycle costs. Avionics navigation systems were singled out for attention, in initial studies, as being representative of avionics equipment in general for purposes of developing a standardization evaluation methodology.

The objective of the SPANS program, therefore, is to assess the potential for standardization across avionic navigation systems by identifying candidate standard hardware and software configurations that minimize system life-cycle costs while satisfying Air Force operational requirements. Implicit in this statement of objective is the requirement that the life-cycle costs to be minimized are those pertaining to the entire USAF inventory of navigation avionics equipment, and not those associated with any one aircraft navigation suite or any one type of navigation equipment. It is evident from this point of view that the complement of the total force structure must be considered in the evaluation since the proportions of different types of aircraft in the inventory will affect the results.

The essential difficulty in standardization studies lies in the time-varying, interdependent nature of the force structure, the technology available for solution of mission navigation problems and the missions themselves. At any point in time the Air Force must be equipped with sufficient aircraft of all types to meet anticipated tactical and strategic objectives in the face of developing adversary capabilities. This objective must be attained in the face of aircraft obsolescence and replacement in active service, and in the face of navigation avionics obsolescence which may precede the retirement of the aircraft from active service. Thus the force structure used for SPANS evaluations must include time-related, quantitative data for all aircraft on which installation or retrofit of new navigation equipment is anticipated.

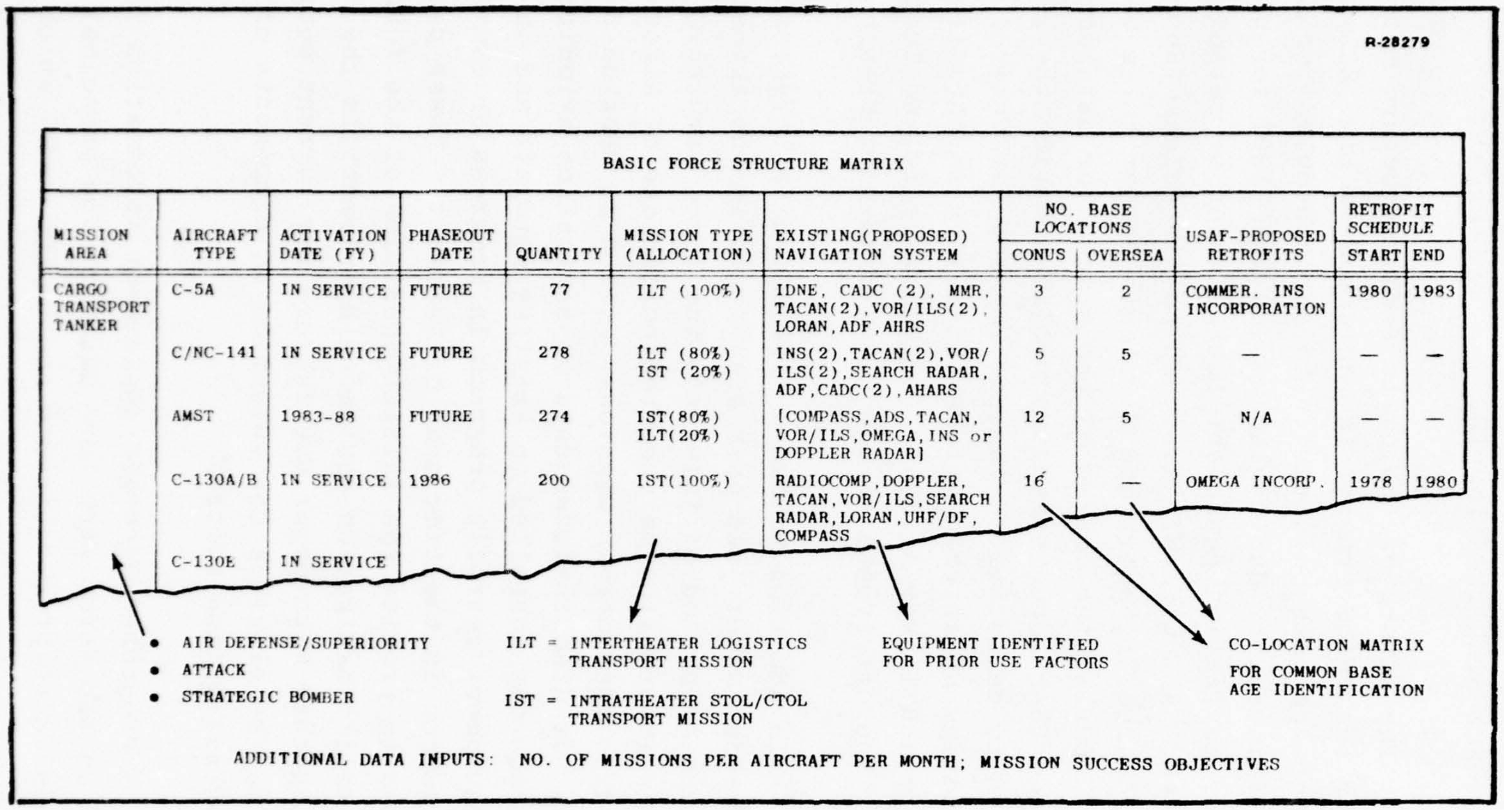
In addition, the projected introduction into service of new technology must also be recognized in the SPANS methodology through a parallel, time-related schedule of available technology. The interaction between available navigation technology and mission doctrine is strong. To keep the SPANS evaluation methodology reasonably compact, one of these variables has to be treated as a fixed, or parametric, input. The approach taken in the reported study was to define fixed missions and mission requirements (which are described in Section 3) and to devise responsive navigation avionics suites based on available technology. Even under these circumstances the capability potential of some projected navigation technologies (notably the Global Positioning System (GPS) and the Joint Tactical Information Distribution System (JTIDS)), together with the need to attain the required mission capabilities prior to their introduction, has led to the definition of specific time frames (technological eras) over which SPANS evaluations are conducted. These technological eras are discussed further in Section 2.3 of this report.

2.2 FORCE STRUCTURE INPUTS

The nature of the basic force structure matrix developed for the SPANS program is indicated in Fig. 2.2-1. This matrix contains data on aircraft in (or scheduled for entry into) the USAF inventory during the period 1978-1991 for which a need for navigation equipment installation or retrofit was predicted. All aircraft assigned to Air Defense/Superiority, Attack, Cargo/Transport and Strategic Bomber roles were included. During the course of the study, the data collected on projected USAF force structure profiles during the period 1978-1991 led to decisions to include Forward Air Control (FAC) aircraft having an interim attack capability in the Attack Mission category and Tanker Aircraft (both Strategic and Tactical/ Airlift Support types) in the Cargo/Transport Mission category.

In addition to basic aircraft data (type, activation and phaseout dates, and peak quantities in the inventory during the time period of interest) the force structure matrix contains information on expected percentage of aircraft allocated to the various missions defined in Section 3 of this report. It also includes data on navigation avionics equipment presently installed on existing aircraft and on navigation equipment retrofit programs in progress or committed for installation in the time span of interest. These data were included to provide the initial condition of the force structure and its navigation equipment complement to the SPANS program together with prior use factors for current equipment which may be eligible for selection as components of newly-defined navigation suites.

Projected aircraft deployment information is also included in the force structure matrix. The principal reason for this is to provide inputs to the LCC model which assigns



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BASIC FORCE STRUCTURE MATRIX

MISSION AREA	AIRCRAFT TYPE	ACTIVATION DATE (FY)	PHASEOUT DATE	QUANTITY	MISSION TYPE (ALLOCATION)	EXISTING(PROPOSED) NAVIGATION SYSTEM	NO. BASE LOCATIONS		USAF-PROPOSED RETROFITS	RETROFIT SCHEDULE	
							CONUS	OVERSEA		START	END
CARGO TRANSPORT TANKER	C-5A	IN SERVICE	FUTURE	77	ILT (100%)	IDNE, CADC (2), MMR, TACAN(2), VOR/ILS(2), LORAN, ADF, AHRS	3	2	COMMER. INS INCORPORATION	1980	1983
	C/NC-141	IN SERVICE	FUTURE	278	ILT (80%) IST (20%)	INS(2), TACAN(2), VOR/ILS(2), SEARCH RADAR, ADF, CADC(2), AHARS	5	5	—	—	—
	AMST	1983-88	FUTURE	274	IST(80%) ILT(20%)	[COMPASS, ADS, TACAN, VOR/ILS, OMEGA, INS or DOPPLER RADAR]	12	5	N/A	—	—
	C-130A/B	IN SERVICE	1986	200	IST(100%)	RADIOCOMP, DOPPLER, TACAN, VOR/ILS, SEARCH RADAR, LORAN, UHF/DF, COMPASS	16	—	OMEGA INCORP.	1978	1980
	C-130E	IN SERVICE									

- AIR DEFENSE/SUPERIORITY
- ATTACK
- STRATEGIC BOMBER

ILT = INTERTHEATER LOGISTICS TRANSPORT MISSION

IST = INTRATHEATER STOL/CTOL TRANSPORT MISSION

EQUIPMENT IDENTIFIED FOR PRIOR USE FACTORS

CO-LOCATION MATRIX FOR COMMON BASE AGE IDENTIFICATION

ADDITIONAL DATA INPUTS: NO. OF MISSIONS PER AIRCRAFT PER MONTH; MISSION SUCCESS OBJECTIVES

Figure 2.2-1 Basic Force Structure Matrix different transportation costs and resupply times to bases located inside and outside the continental U.S. For any given run of the evaluation program, corresponding to a defined analysis time frame, probable colocation of different types of aircraft at a common base is recognized by program interrogation of the deployment data. Cost reductions due to the use of common field level AGE on common items of equipment in the different aircraft types are recognized accordingly.

Two force structure associated inputs are identified in Fig. 2.2-1. The first is an aircraft utilization factor, the number of missions flown per month by each aircraft type. The second is the mission success objective for each aircraft type. These are treated outside the basic force structure matrix as parameters which are likely to be subject to variation during parametric studies.

In conducting standardization tradeoff studies, a selection of aircraft from the basic force structure is used that corresponds to the aircraft subject to navigation system installation or retrofit in the time frame under analysis. This selection forms the force structure data input for the tradeoff study. In the case of new aircraft requiring installation of navigation suites, the corresponding equipment production schedule is assumed by the program to be compatible with the aircraft service entry schedule. In retrofit programs the retrofit schedule has to be separately defined in the force structure matrix. Chronological ordering of the installation and retrofit programs is accomplished during selection of the specific force structure data from the basic force structure matrix.

2.3 TECHNOLOGICAL ERAS

The impact of new technology on USAF acquisition policies for future navigation avionics equipment is complex and, in many cases, profound. If the new technology is evolutionary, in the sense that it creates improved (lower cost, higher reliability, more accurate) equipment for performing traditional functions, then the evaluation of that impact in terms of life-cycle cost and mission effectiveness during equipment introduction into service is, in general, a manageable exercise. Usually the performance improvements are not of such magnitude that mission concepts or navigation avionics suite compositions are radically changed. If, on the other hand, the new technology is revolutionary, in the sense that it performs new functions or provides a capability in the performance of established functions which is dramatically superior to traditional technology, then the evaluation of its impact is a more complex matter.

To start with, the potential arrival of a revolutionary new technology must not detract from efforts to achieve satisfactory system capability before its arrival. This is particularly true in cases where the new technology is characterized by areas of high technical risk which have not been fully resolved by DT&E and IOT&E programs at the time of impact evaluation. Secondly, when the new technology has been proved to live up to its promise and does become available for widespread use, it has to be considered for retrofit into aircraft comprising the force structure at the time of its availability, as well as into new aircraft subsequently scheduled to enter the inventory. By definition, the existing aircraft will be capable of performing their assigned missions satisfactorily without the incorporation of the new technology. Furthermore, the avionics suites on these aircraft will probably have been designed around a balanced blend of older technologies, each of which provides contributions to the navigation and weapon delivery error budget that are consonant with overall system capability. The incorporation of a higher capability technology will not necessarily improve mission capability on the established missions of the affected aircraft. On the other hand, it may well extend the range of missions covered by the aircraft. (For example, the incorporation of a JTIDS terminal in a navigation avionics suite in place of existing Doppler radar, UHF-DF and TACAN equipment may provide a blind bombing capability which was not originally planned into the required mission roles of the affected aircraft).

The desirability of revolutionary new technology retrofits for existing aircraft allocated to defined mission roles is heavily conditioned by force mix, economics and adversary capability considerations under the circumstances described above. While the STEP methodology is well suited to incorporation of these considerations and quantitative evaluation of the desirability of retrofits in such a transition period, the major thrust of work conducted in the reported study was concentrated on development and validation of the methodology itself. The acquisition of detailed, authoritative information correlating future mission roles with aircraft in the inventory and with projected available technology proved to be a time-consuming effort. To avoid delay in proving the methodology, a structure was established for evaluation in which the introduction of radically new technologies were treated as discontinuities creating "technological eras". SPANS tradeoff studies were restricted to the time frames determined by single technological eras.

Three technological eras were defined:

- The Current Technology Era (1978-1984). This era is characterized by the use of proven, existing technology for attainment of a defined, interim, mission capability.

- The JTIDS/GPS/DAIS Era (1984-1988). This era is characterized by the introduction into service of JTIDS and GPS navigation equipment and by the design of avionics suites around the Digital Avionics Information System (DAIS) concept which allows "missionizing" of aircraft by substitution of different navigation equipment in the field.

- The Advanced Aircraft/MIRA Era (1986-19XX). This era is characterized by the introduction into service of VSTOL and composite structure aircraft and the revision of mission doctrines to exploit the capabilities of these aircraft. It also encompasses a potential revolution in inertial system technology in which the traditional INS or IMU configurations are replaced by Multifunction Inertial Reference Assemblies (MIRA). The MIRA sensors will perform the functions of the flight control rate gyros and accelerometers, vertical gyros, heading and attitude reference system, central air data computer and lead computing gyros in addition to providing the usual angular rate and specific force inputs to the inertial navigation computations.

The initial STEP tradeoff studies were restricted to the Current Technology Era. This fact should not be interpreted as implying any limitations on the capabilities of the methodology to handle other technological eras or transitional periods covering two or more technological eras. SPANS program follow-on studies have been initiated by AFAL to identify standardization opportunities offered by the introduction of new technologies (specifically JTIDS and MIRA) through application of the STEP methodology to future eras and transitional periods.

SECTION III

MISSIONS AND MISSION REQUIREMENTS

3.1 INTRODUCTION

The development of mission profile and mission requirements data was initiated through a search of government literature (Refs. 3 through 15) describing future aircraft operational capability requirements and navigation system/subsystem demands. These were found to provide insufficient definition in a number of areas relating to typical mission profiles. Sample profiles were generated as part of the SPANS contract effort and subsequently refined through discussions with USAF specialists in mission analysis. The resulting mission data, which is discussed in Section 3.2, was developed specifically for SPANS studies and does not represent an official USAF position on the nature of present or projected aircraft missions.

3.2 MISSION PROFILES

Four mission areas were designated for consideration in the reported study:

- Air Defense/Superiority
- Attack
- Cargo/Transport
- Strategic Bomber

Within these mission areas, twelve distinct mission profiles were synthesized as indicated in Table 3.2-1. The

TABLE 3.2-1
MISSION PROFILES FOR EVALUATION

T-1314

MISSION AREA	MISSION PROFILES
Air Defense/Superiority	Air Defense Point Intercept (ADPI) Escort Intercept (EI)
Attack	Close Air Support (CAS) Forward Air Control-Interim CAS (FAC) Defensive Strike, Volatile Target (DS) Preplanned Deep Strike (PPS)
Cargo/Transport	Intertheater Logistics (ILT) Intratheater STOL/CTOL (IST) Tanker, Tactical/Airlift (TTA) Tanker, Strategic (TS)
Strategic Bomber	Strategic Bomber, Penetration (SBP) Strategic Bomber, Standoff (SBS)

inclusion of the forward air control and tanker mission profiles resulted from recognition of the large number of aircraft in these categories which are subject to navigation system installation or retrofit within the period of interest. The mission profiles were chosen and developed to encompass the anticipated extremes of normal demand on the performance capabilities of navigation systems selected for use on aircraft flying these missions. An Advanced Penetration profile was also identified in the Air Defense/Superiority area and several significant mission variations were recognized in association with the use of tactical VTOL aircraft. These were not included in the reported phase of SPANS studies since they relate to aircraft projected for service in the Advanced Aircraft/MIRA technological era. The conventional Support Bombardment mission role of certain strategic bombers was also omitted since it did not appear to exercise the applicable navigation systems in any way that was not laready encompasses in the derived penetration and standoff mission profiles.

The extent to which individual mission characteristics were detailed for generation of inputs to the STEP program is indicated in Fig. 3.2-1 and Table 3.2-2 and Fig. 3.2-2 and Table 3.2-3. A mission profile diagram was created for each of the twelve mission types identifed and was used in each case to identify mission phases associated with different modes of operation of the navigation system complex. The profiles were supplemented in each case with mission phase tables identifying the duration of each phase, the events occurring in each phase which relate to navigation system operation, aircraft velocity, natural and induced environmental influences, geographic factors, and tactical environment encountered by the aircraft, the nuclear radiation environment (where applicable), and the availability of external aids. In general, while the mission profiles and phase tables were developed to represent realistic missions, the environmental influences were deliberately scaled towards the harsh end of the anticipated spectrum to force full consideration of subsystem limitations in the navigation suite synthesis process.

The data contained in the mission phase tables was used in three distinct ways in setting up inputs to STEP for tradeoff studies:

- As direct inputs to the data files
- As factors in determining in-flight reliability of navigation equipment
- As equipment selection factors

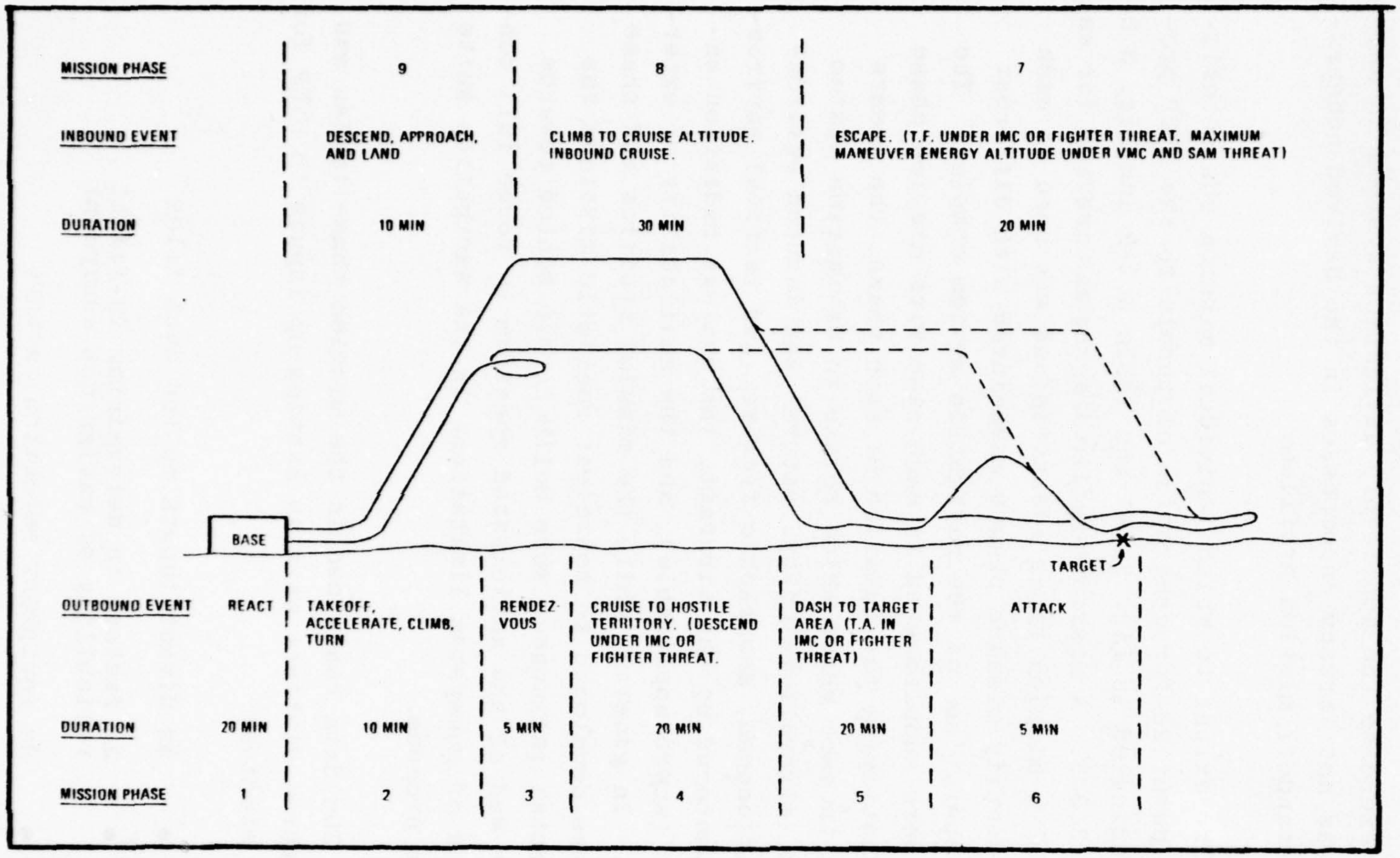


Figure 3.2-1 Preplanned Attack Mission Profile - Fixed Defended Targets (and Defense Suppression)

TABLE 3.2-2

PREPLANNED ATTACK MISSION PHASE TABLE

MISSION PHASE / CHARACTERISTIC	1.PREFLIGHT	TAKEOFF, TURN, 2.CLIMB	3.RENDEZVOUS	CRUISE TO HOSTILE 4.TERRITORY	DASH TO TARGET 5.AREA	6.ATTACK	7.ESCAPE	INBOUND 8.CRUISE	DESCEND, APPROACH, 9.LAND
Duration	20min	10min	5min	20min	20min	5min	20min	30min	10min
Events	Startup,Power On, Funct. Checks, Nav. System Align/ Calib., Taxi	Flight Functional Checks	Tactical Nav. formation closing maneuvers	Tactical Nav. with position updates.Descend	Low Alt.T.A. or max. maneuver energy altitude. Tactical Nav.	(Pop-Up) Target Ident. Target designate weapon delivery	Random Navigate at low level (T.A.)or at max maneuver energy altitude	Tactical Nav. to base area	Possibility of letdown and landing without radiating ground aids
Aircraft Velocity	--	250-300kt	300-400kt	350-450kt	400-450kt	350-400kt	400-450kt	400-500kt	400-150kt
Meteorological Environment	IMC	IMC-VMC	VMC	Mixed IMC/VMC	IMC or VMC	3-10,000ft overcast	IMC or VMC	VMC-IMC	IMC
Induced Environment: Altitude	Base at sea level 5,000ft	to 20,000ft	20-25,000ft	25-30,000ft	SAM threat 15-20,000ft IMC or fighter threat 300-500ft	Down to laydown alt. Down to laydown alt.	SAM threat 15-20,000ft IMC or fighter threat 300-500ft	25-35,000ft	Base at sea level to 5,000ft
Attitude	Level	±60°roll ±30°p	±40°roll ±20°p	±40°roll ±20°p	±60°roll ±30°p	±90°roll ±45°p	±60°roll ±30°p	±40°roll ±20°p	±60°roll -20°p
RMS Vibration	Negligible	3g	2g	2g	3g	3g	3g	2g	2g
Normal Accel. (Max)	1g	2g	1.5g	1.5g	3g	4g	3g	1.5g	1.5g
Geographic	Base Lat: 70°N to 70°S Base Long: Any	ALL FLIGHT OVERLAND WITHIN 350nm RADIUS OF BASE							Base Lat: 70°N to 70°S Base Long: Any
Tactical Environment	Cooperative	Cooperative	Cooperative	Coop ¦ Disputed	Hostile (fighter/SAM)	Hostile (Fighter/SAM)	Hostile (Fighter/SAM)	Cooperative	Cooperative
Availability of External Aids									
Invulnerable	--	GPS/TDS	GPS/TDS	GPS/TDS	TDS(Radar)	TDS(Radar)	TDS(Radar)	GPS(TDS)	GPS/TDS
Limited or Vulnerable	--	VOR/TAC, Ground Control Comm. LORAN	VOR/TAC, Ground Control Comm. LORAN	VOR/TAC, LORAN	LORAN,GPS	LORAN,GPS	LORAN,GPS	VOR/TAC, LORAN	VOR/TAC, LORAN, GCA, ILS, ADF

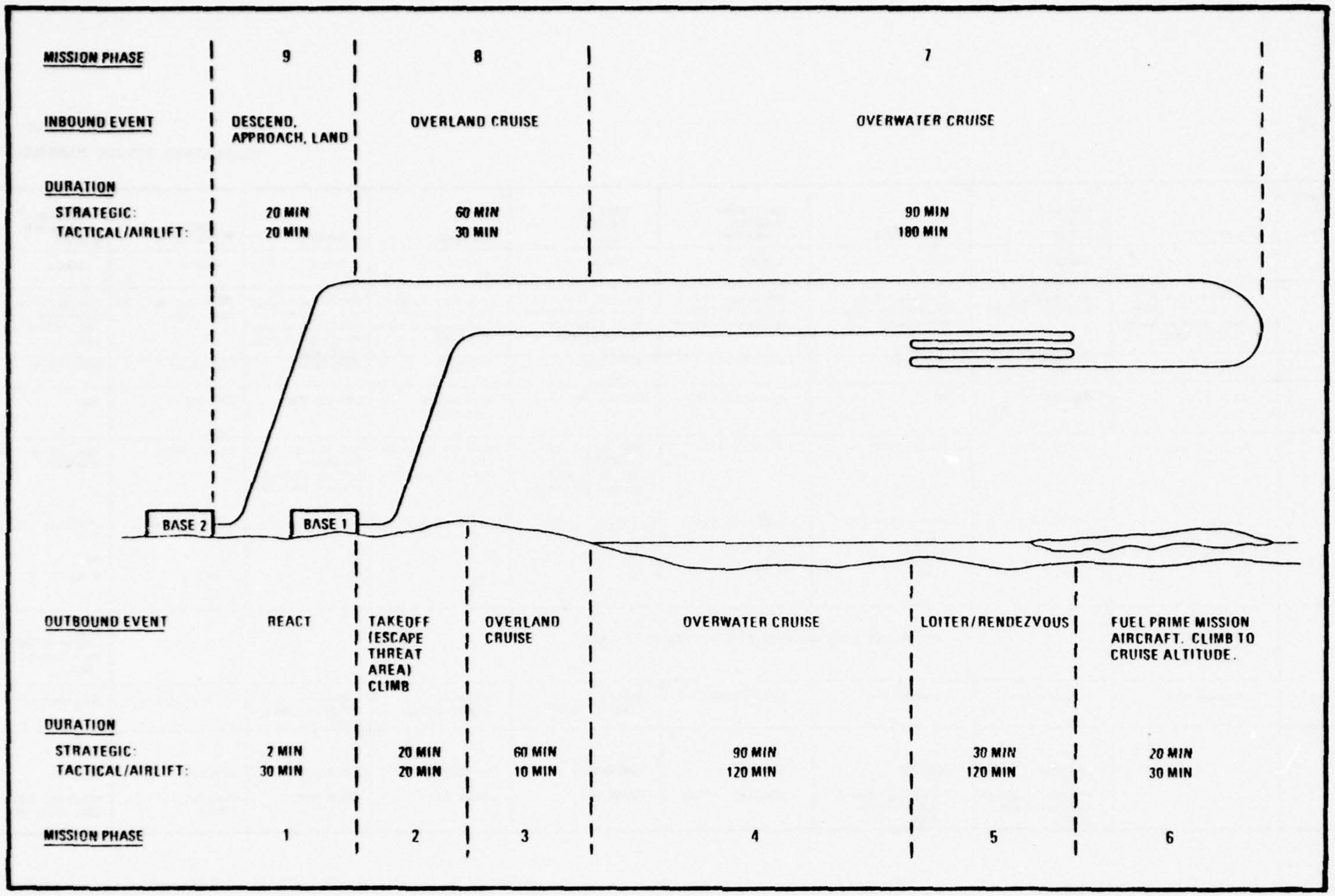


Figure 3.2-2 Tanker Mission Profiles

TABLE 3.2-3

TANKER MISSION PHASE TABLE

MISSION PHASE / CHARACTERISTIC	1. PREFLIGHT	TAKEOFF, (ESCAPE), 2. CLIMB	OVERLAND 3. CRUISE	OVERWATER 4. CRUISE	LOITER/ 5. RENDEZVOUS	AIR 6. FUEL	OVERWATER 7. CRUISE	OVERLAND 8. CRUISE	DESCEND, APPROACH, 9. AND LAND
Duration: Strategic:	2min	20min	60min	90min	30min	20min	90min	60min	20min
Tactical/ Airlift	30min	20min	10min	120min	120min	30min	180min	30min	20min
Events: Strategic	Power On, Startup funct. checks, Taxi	Flight Funct. Checks Nav. system partial align	Fix updates to Nav. system (align/calibrate)	Tactical Nav. to Rendezvous area	On-station nav. Prime mission A/C contact	Formation flight with prime mission A/C	Tactical Navigation to landfall	Fix updating, Corridor navigation	Unaided letdown, Passive aided landing
Tactical/ Airlift	As above with Nav. Align.	Standard (RNAV) departure	Fix updates	Corridor Nav. (ICAO Lanes) to rendezvous area	On-station nav. Prime mission A/C contact	Formation flight with prime mission A/C	Corridor Navigation (ICAO lanes) to rendezvous area	RNAV to terminal area	Conventional ILS approach landing
Aircraft Velocity	Taxi Speed	150-450kt	480kt	480kt	480kt	400kt	500kt	500kt	450-130kt
Meteorological Environment:	IMC/WX	IMC	IMC	VMC	VMC	VMC	VMC/IMC	IMC	IMC(CatII)
Induced Environment:									
Altitude	Sea level to 5,000ft	To 35,000ft	35-40,000ft	35-40,000ft	35,000ft	30,000ft	35-40,000ft	35-40,000ft	0-5,000ft
Attitude	Level	±40°r +15°p	±30°r ±10°p	±30°r ±10°p	±30°r±10°p	±30°r±10°p	±30°r±10°p	±30°r±10°p	±45°r -15°p
RMS Vibration	Negligible	0.5g	0.3g	0.3g	0.3g	0.3g	0.3g	0.3g	0.5g
Normal Acceleration(Max)	1g	2g	1.5g	1.5g	1.5g	1.5g	1.5g	1.5g	2g
Geographic: Strategic:	Base lat. 40°N to 70°N Base Long. 55W to 180°W				Near Polar Flight				
Tactical/ Airlift:	Base lat. 70°N to 70°S Base Long. Any	← USING, OR IN VICINITY OF ICAO AIRLANES →							
Tactical Environment:	Cooperative	Cooperative	Cooperative	Neutral	Neutral	Neutral	Neutral	Cooperative	Cooperative
Nuclear Environment: (EWO Only)	← DELAYED IONIZATION AND EMP →								
Availability of External Aids									
Invulnerable	--	Runway heading	Radar checkpoints	None	(X-band beacon)	None	None	Radar checkpoints	K_A band reflectors, visual ident.
Limited or unreliable in EWO	--	VOR/TAC GPS, OMEGA, LORAN	VOR/TAC, LORAN, GPS, OMEGA	LORAN ¦ GPS, OMEGA	GPS, OMEGA	GPS, OMEGA	GPS, OMEGA ¦ LORAN	GPS, OMEGA, LORAN VOR/TAC	ADF/ILS, VOR/TAC ground radar/comm.

Direct inputs to the data files consist of the number of mission phases in each mission, the duration of each phase and, after equipment selection has been accomplished, the equipment utilization schedules.

The induced environment data is used in establishing reliability degradation factors for electronic and electromechanical equipment which typify its use in the mission under consideration. For the purposes of the SPANS study all reliability (MTBF) figures associated with selected subsystems were initially scaled to conform to cargo/transport aircraft environment. Degradation of MTBFs from these values that result from use of the equipment in harsher operational environments were handled by associating k-factors with the aircraft. The evaluation of these k-factors was based on previously documented studies on operational influences on reliability (Refs. 16,17,18).

The principal equipment selection factors derived from the mission phase tables were concerned with establishing the constraints under which navigation system suites are required to perform during each mission while achieving acceptable mission effectiveness standards. Salient among these factors are:

- Reaction time
- Meteorological conditions which prohibit the use of visual navigation or weapon delivery aids
- Aircraft environmental conditions (attitude; altitude) which limit the useability of certain navigation sensors (doppler radar, radar altimeters and line-of-sight radio aids)
- Geographic factors (overwater flight, overice flight) which cause performance degradation of certain navigation sensors (doppler radar, mapping radar)

- Nuclear environment which leads to a requirement for equipment hardening
- Limitations in coverage from a radio navigation system attributable to either aircraft geographic location or hostile electronic countermeasures.

The equipment selection factors derived from the mission phase tables are not used in a direct, quantitative manner as inputs to the STEP program. Instead they are used, in conjunction with the mission performance requirements, discussed in Section 3.3 below, to synthesize mission-responsive navigation system suites from available equipment selections, as described in Section 5.2 of this report.

3.3 MISSION REQUIREMENTS

In parallel with the development of mission profiles and mission phase tables described in Section 3.2 above, data was acquired and analyzed on performance requirements for the navigation systems used in each mission. This resulted in a compilation of distilled mission requirements, one set for each mission defined, representing projected USAF navigation performance objectives in the time frames covered by the study. Two samples are shown in Tables 3.3-1 and 3.3-2.

The sources of data used in these compilations were numerous. In addition to Required Operational Capability (ROC) documents (Refs. 3 through 7) and navigation subsystem specifications (for example, Ref. 10), FAA publications were used in establishing several Cargo/Transport/Tanker aircraft requirements (Refs. 13,14,15) and extensive use was made of prior mission performance analyses (Refs. 11,19,20,21).

TABLE 3.3-1

MISSION REQUIREMENTS FOR ATTACK AIRCRAFT -- PREPLANNED ATTACK/DEFENSE SUPPRESSION

1. MISSION TYPE: Preplanned Attack Profile

2. REACTION TIME: $\leq$ 20 minutes

3. NAVIGATION SYSTEM, GENERAL: Single Primary Nav. System with Mode Hierarchy

4. EXTERNAL AIDS: Mission-capable mode independent of external aids in VMC or high overcast (min. requirement). Blind bombing capability in IMC desirable.

5. ACCURACY: <u>Position</u>: Required $R_{50} \leq 1$nm for visual target acquisition (in VMC or high overcast). Required $R_{50} \leq 100$ft in Rel. Nav. coordinates for blind bombing. Navigation through mission: $R_{50} \leq 1$nm/hour of flight.
   <u>Velocity</u>: Per channel RMS velocity error $\leq$3ft/sec at time of attack.

6. WEAPON DELIVERY REQUIREMENT: Unrestricted attack profile in all primary modes (CCIP). 7 mils CEP conventional bomb delivery (computer release) in CCIP mode.

7. REDUNDANCY: To extent permitted by overlapping functions of mission-essential equipment only.

8. BACK-UP SYSTEMS/MODES: Degraded attack modes down to 20mils CEP, visual. Stand-alone, back-up Nav. System for safe return.

9. APPROACH/LANDING: Aided precision approach to CAT II ILS accuracy (Min. Req't.)
   Unaided approach to CAT I ILS landing at uninstrumented field (Min. Req't).
   Distant radio-aided precision approach to CAT II ILS accuracy (Rel. Nav. Coord) desirable.

10. HARDENING: Not required.

TABLE 3.3-2

MISSION REQUIREMENTS FOR INTRATHEATER STOL/CTOL TRANSPORT

1. MISSION TYPES: Employment: Intratheater STOL Transport
Deployment: Intertheater Logistics Transport

2. REACTION TIME: ≤ 25 minutes

3. NAV. SYSTEM, GENERAL: Deployment: Primary and Secondary Nav. Systems Required.

4. EXTERNAL AIDS: Deployment: One system (minimum) independent of external aids.
Employment: Forward site: Marker beacon or distantly located radio nav. system
Base areas: TACAN, VOR/ILS.

5. ACCURACY: Deployment: To FAR 121-89 Appendix G($R_{95} \leq 1$nm/hour up to 10 hrs). To FAA/AC25-4 over 10 hours.
Employment: Enroute: $R_{95} \leq 4$nm. Drop Zone: to CARP requirements (IMC).
Domestic Overflight: To FAA/AC90-45 enroute and terminal RNAV accuracies with existing VOR/TAC ground facilities.

6. REDUNDANCY: (No crew navigator option): Single fail operative with positive identification and isolation of failed system.

7. BACK-UP SYSTEMS: Stand-alone for safe return or routine mission completion.

8. APPROACH/LANDING: Deployment: Precision CTOL approach to present CAT II ILS accuracy (with back-up capability).
Employment: Forward site (bare base) IMC approach/STOL or CTOL landing capability.

9. HARDENING: Not required.

The DSPC methodology embodied in STEP is capable of drawing attention to the need for redundant equipment in navigation suites for cases in which the use of a single item of equipment results in unacceptable Mission Completion Success Probability (MCSP). If the need for redundant equipment is identified before running the program, the System Analyst can specify such redundancy and the program will operate with both cost and composite reliability figures adjusted to reflect the presence of two functionally identical subsystems in the navigation suite. If the need for a redundant subsystem is suspected (but not positively identified) by the System Analyst before running the program, he can specify the use of either one or two such subsystems by the program. Cost and MCSP outputs for both options will be evaluated and printed out by the program as though two distinct navigation suites were being evaluated. If redundancy of a piece of equipment is necessary for satisfactory MCSP, but is not recognized in advance by the System Analyst, the program will output an unacceptable MCSP value and, on demand, will indicate which piece of equipment is the dominant contributor to the low MCSP value. Several of the missions evaluated (particularly those involving large aircraft on transoceanic profiles) were characterized by mandates on equipment redundancy. Such mandates were also recorded in the mission requirements tables and were used extensively as ground rules in synthesizing mission-responsive navigation suites for the affected aircraft.

Navigation system performance requirements emanating from weapon delivery, terminal area approach and landing, deployment and employment missions, navigation within domestic and international civil-controlled air space, and Emergency Warfare Operation (EWO) conditions are synopsized in the mission requirements tables. Where possible, the mission requirements were condensed into "lowest common denominator" statements. A case in point concerns the projected requirement (for the foreseeable future) for all aircraft having an air-to-ground attack role to possess a basic, visual-attack-with-conventional-bombs capability which is not jeopardized by special mission tailoring of these aircraft and which is independent of external aids. This requirement places a basic and stringent requirement on the on-board, self-contained navigation capability of these aircraft which is registered as a mandate in the mission requirements tables. Extended capabilities for specific aircraft, such as blind bombing, are treated as add-ons to this basic requirement and are allowed for during navigation suite synthesis for the affected aircraft.

SECTION IV

NAVIGATION SYSTEM TECHNOLOGY

A survey of the present and forecasted navigation system state-of-the-art through 1980 was conducted to identify equipment candidates for potential application in the baseline mission areas considered in SPANS. Major navigation technologies that have been successfully demonstrated, at least at the laboratory level, prior to the time of the SPANS study were included in the survey. The discussion in this chapter focuses primarily on the generic capabilities and limitations of major technologies as they relate to the syntheses of acceptable aircraft navigation suites for initial SPANS studies. Reliability and LCC data for generic equipments within each technology were developed for utilization in the STEP analyses.

4.1 LORAN

Loran-C is a low frequency, long range, all weather, pulsed hyperbolic radio navigation system which is capable of providing horizontal position fixes of very high repeatable accuracy but only moderate absolute accuracy. Loran-C evolved out of Loran-A which was originally developed during World War II as an aid to navigation. It is presently operational in several parts of the world and an extensive expansion program is currently underway. The military has been using Loran-C for the past 10 to 15 years, thus numerous Loran-C user equipments are available. Ref. 22 contains a discussion of the normal operation of Loran-C as a hyperbolic navigation system. Loran-C can also be used in a direct ranging mode at the expense of increased complexity of user equipment. This direct ranging mode is capable of providing increased accuracy through a reduction in user/loran transmitter geometry dependency errors (Ref. 23).

Loran-D is similar to and compatible with Loran-C, but designed for military tactical use. The transmitting stations are helicopter transportable and can be quickly erected.

Loran-C service in a region is provided by a chain of transmitting stations consisting of a master and three or more secondaries. Each chain can provide service to an area within 1500 nm from the chain baselines. The U.S. Coast Guard is currently responsible for the operation of seven Loran-C chains throughout the world. Fourteen additional stations are planned to complete the coverage of the U.S. Coastal Confluence Zone and a large portion of the northern hemisphere. The existing and proposed Loran-C coverages are shown in Fig. 4.1-1 (Ref. 22). There are presently three Loran-D chains in the U.S. and one in Europe.

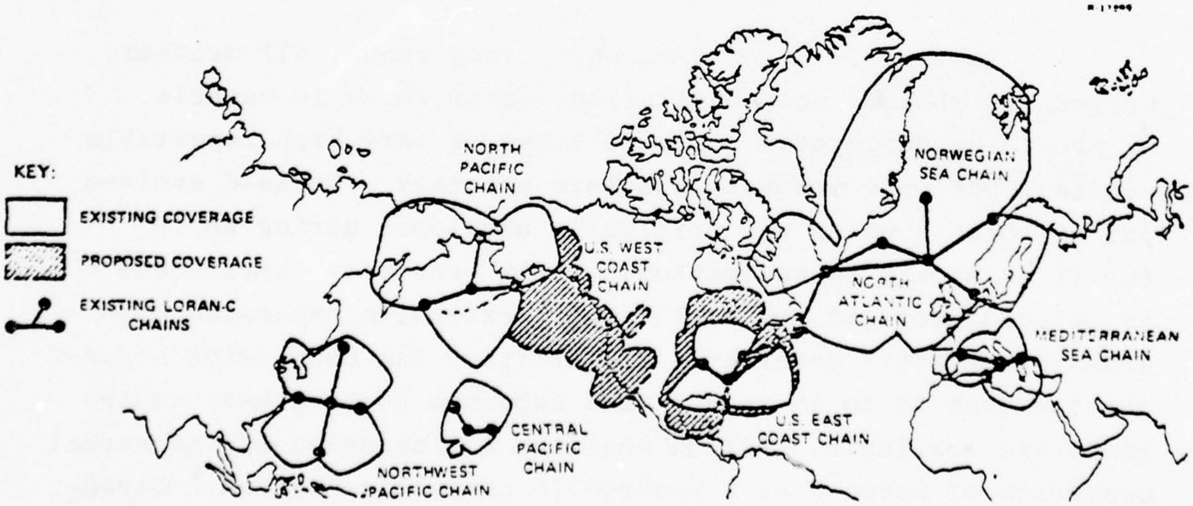


Figure 4.1-1 Existing and Proposed Loran-C Coverage

4.1.1 Performance Capabilities

The Loran-C navigation system is capable of providing absolute navigation (horizontal position) accuracies of 0.25 nautical mile rms or better and repeatable navigation accuracies of 50 - 300 ft rms (Refs. 24,25). The absolute accuracy can be improved by a factor of 2 or 3 using sophisticated user equipment and prior calibration of progagation abnormalities.

The Loran-C system does not inherently provide for velocity measurements. However, the Loran-C time difference (TD) measurements can be differentiated to provide velocity estimates, although the resultant accuracy will be poor. It is not known at this time whether existing Loran-C receivers provide velocity estimates. Research on this issue is continuing.

The Loran-C user equipment can be integrated with an inertial navigation system (INS) to provide velocity estimates with an accuracy set by the INS (typically 1 kt to 2 kt rms) (Ref. 26). This capability is provided with the Lear Siegler, Inc. AN/ARN-101 Loran/Inertial System.

4.1.2 Performance Limitations

The Loran-C navigation system is useable only within the designated coverage areas outlined in Fig. 4.1-1. However, the Air Force can deploy a Loran-D system in a tactical theater in a relatively short time.

As with all radio navigation systems, Loran-C/D is susceptible to jamming by an adversary. Anti-jamming capabilities can be built into the receivers to reduce their vulnerability to jamming. Reference 27 indicates that the jamming radius of a jammer with power equal to that of the Loran-D transmitters is about 4 km at a distance of 400 km from the Loran-D transmitters (assuming maximum anti-jam capability in the Loran receiver). The analysis in this reference indicates that it is only practical for an adversary to jam a small area in the vicinity of the jammer.

Nevertheless the possibility of jamming over target or established hostile areas (particularly of the difficult-to-detect meaconing variety which corrupts the navigation data without causing loss of receiver lock-in to the transmitter frequency) limits the utility of Loran as an autonomous tactical navigation system. In attack, reconnaissance, and close tactical transport applications it is ultimately useful only in a symbiotic role with other onboard, non-corruptible navigation subsystems. Currently the most potent such combination is the Loran-Inertial complex with a Kalman filtering algorithm for data integration. This combination provides, not only the maximum immunity of the Loran receivers from the blanketing type of jamming through inertial velocity aiding of the tracking loops, but also a mechanism for detecting meaconing attempts by an adversary and for preventing their effects from corrupting the navigation system outputs.

4.1.3 User Equipment

A list of military Loran receivers is presented in Table 4.1-1. Although some receivers in the table are no longer operational, it is believed that the list contains all of the Loran systems of current interest (Ref. 28).

TABLE 4.1-1

U.S. MILITARY LORAN RECEIVERS

DESIGNATION	CONTRACTOR	AGENCY	COMMENTS
AN/BRN-5	Magnavox	Navy	Direct Ranging/Hyperbolic receiver, marine use
AN/ARN-78	Sperry	USAF	Loran C receiver
AN/ARN-85	Sperry	USAF	Loran C/D receiver, modification of -78, prototype for -92
AN/ARN-92	ITT/LSI	USAF	Loran C/D receiver, with lat/long, UTM converter
AN/ARN-94	EPSCO	Military Aircraft	Loran C with Loran D compatability, receiver only
AN/ARN-98	DECCA	Military Aircraft	Loran C receiver (uses ADL-21)
AN/ARN-101	ITT or LSI	USAF	Loran C/D receiver integrated with inertial, UTM, lat/long converter
AN/ARN-109	DECCA	Military Aircraft	Loran C receiver, uses ADL-21
AN/ARN-110	Litton	Army Aircraft	"HELNAVS" program, Helicopter Navigation System, Loran C/D, UTM conversion
AN/ARN-114	Tracor or Teledyne	Army Aircraft	Follow up of HELNAVS; airborne Manpack; Loran C/D, UTM conversion
AN/ARN-181	ITT	USAF	AN/ARN-92 receiver (Version -2), different controller
AN/APN-9a		USAF	Loran A, C-130
AN/APN-70a	RCA	Military Aircraft	Loran A receiver
AN/APN-70b	Dare Inc.	Military Aircraft	Loran A/C receiver
AN/APN-81	EDO	Presidential Fleet	Loran receiver only
AN/APN-145	ITT	USAF	C-141, Loran C receiver
AN/APN-151	ITT	USAF	Loran C receiver, RC-135B
AN/APN-175	ITT	USAF	Loran C receiver, C-130, C-141A
AN/APN-180	EDD	Military Aircraft	C-9A, Loran receiver only
AN/APN-199	Collins	USAF	Loran receiver, LRN-104 in C-5A
AN/PSN-2	EPSCO	Military Vehicle	Loran C receiver, may be man carried
AN/PSN-4	Teledyne	U.S. Army	Manpack prototype, Loran C receiver
AN/PSN-6	AMECOM	U.S. Army	Manpack, Loran C/D with UTM converter (*AMECOM formerly LITCOM*)
AN/TRN-21a	Sperry	Coast Guard	Loran D transmitter
AN/TRN-32	Sperry	Coast Guard	Loran D receiver group
AN/TRN-35	Sperry	Coast Guard	Loran C/D transmitter includes mini computer
AN/TRN-35	LITCOM	Coast Guard	Loran monitor receiver
AN/WPN-3	Sperry	Navy	Loran A/C marine receiver
AN/WPN-4	Sperry	Navy	Loran C receiver
AN/SPN-32	Sperry	Navy	Loran C receiver

NOTE: Some are no longer in the inventory.

The military receivers currently of most importance are the Air Force AN/ARN-92 and AN/ARN-101. The latter is an integrated navigation and weapon delivery/reconnaissance system for the RF-4C and F-4E aircraft and is built by Lear Siegler, Inc. The overall system features long-range and tactical navigation in three coordinate systems (Latitude/Longitude, UTM, and Loran T.D.) and provides for all-weather blind bombing, unconstrained weapon delivery profile and reconnaissance steering data inputs. A central computer processes both inertial platform and Loran data via a Kalman filter to provide precise position and velocity information. An interactive control-display is utilized for data input and output.

The physical characteristics of the AN/ARN-101 are summarized in Table 4.1-2 (Ref. 29). A Singer/Kearfott IMU (SKI-2300) has been selected for use in the AN/ARN-101 System by the USAF.

4.2 OMEGA

OMEGA is a terrestrial based radio navigation system with global all weather coverage that is capable of providing moderately accurate position fixes (Ref. 30). The system operates with eight very low frequency (VLF) transmitter stations located around the world. Currently, the transmitter network consists of seven of the eight planned permanent stations and one temporary transmitter. The eighth permanent transmitter, to be located in Australia, is scheduled to become operative in late 1979 (Ref. 31). However, the present operational system provides coverage for most of the globe. The Air Force recently completed a program to develop an OMEGA navigation equipment set for use on transport type aircraft.

TABLE 4.1-2

PHYSICAL CHARACTERISTICS OF DIGITAL MODULAR AVIONICS SYSTEM AN/ARN-101

T-0396

SYSTEM/UNIT NOMENCLATURE			SIZE (INCHES)			VOLUME	WEIGHT
NAME	USAF TYPE NO.	PART NO.	L	W	H	(CU IN)	(LBS)
Antenna Coupler	CU-2150/A	156189-01-01	7.53	2.91	2.54	75	2.5
Loran Receiver	R-1960/A	156368-01-01	12.86	3.76	7.63	370	13.0
Navigational Computer (1)	CP-1157/A	153512-01-01	11.66	11.06	7.6	970	36.0
Signal Data Converter	CV-3270/A	153613-02-01	9.02	7.61	9.25	625	19.5
Power Supply	PP-6994/A	153545-01-01	7.53	7.52	6.76	380	11.75
Inertial Measurement Unit (2)	MX-9482/A	153542-01-01	14.96	11.0	9.0	1481	34.5
Inertial Measurement Unit (3)	MX-9483/A	153640-01-01	13.18	8.44	7.25	806	22.0
Inertial Meas. Unit Buffer	MX-9697/A	153536-02-01	6.25	9.25	6.02	363	11.0
Keyer Control	C-9474/A	153524-01-01	6.6	5.75	7.87	299	8.5
Digital Display Indicator	ID-1942/A	153527-01-01	6.6	5.75	3.0	114	2.8
Nav. Computer Set Control	C-9472/A	153533-01-01	4.82	5.75	3.0	83	3.0
Digital Display Ind. (Aux.)	ID-1943/A	153530-01-01	6.63	2.38	2.38	38	1.5

NOTES:
(1) This unit contains 2 memories. For each additional memory add 1.6 inch.
(2) A TALONS System LRU purchased from Litton. Model number is LSI 2054A.
(3) A TALONS System LRU purchased from Singer/Kearfott. Model Number is LSI 2054B.
(4) One or the other TALONS System Inertial Measurement Unit (Notes 2 and 3) is to be used at any one time.

This equipment is scheduled for delivery and installation on C-130 aircraft starting in mid-1977. This will be followed by phase out of DoD support for the Loran-A radio navigation network in December 1977.

4.2.1 Performance Capabilities

The Air Force OMEGA navigation equipment specification requires accuracies of 2nm or better, 50 percentile and 4nm or better, 95 percentile. Such performance was indeed demonstrated on Air Force conducted performance tests (Ref. 32). While the OMEGA system does not inherently provide for velocity measurements, the airborne equipment should internally implement dead reckoning for velocity aiding of signal tracking and for minimizing of lane-jump probabilities during temporary loss of the OMEGA signal. The dead reckoning capability is enhanced by automatic compass heading and true airspeed inputs. System velocity errors commensurate with dead reckoning navigation from these devices are to be expected if they are installed in the aircraft. Maneuvering susceptibility of current system designs is restricted to sustained high bank angle conditions and is not expected to be an operational problem.

To increase the airborne navigation accuracy available with OMEGA (especially in high performance aircraft) an inertial navigation system (INS) can be integrated with the OMEGA navigation equipment. According to previous TASC studies of OMEGA navigation equipment integrated with a 1 nm/hr (CEP rate) inertial navigation system, position estimates can be obtained with an accuracy of 1 nm CEP (Refs. 33 and 34). Also, since an INS is employed, velocity estimates are available with an rms accuracy of 1-2 kts.

4.2.2 Performance Limitations

Although OMEGA is a long-range, moderate accuracy global navigation system, it cannot be considered for use as a primary, autonomous navigation system in either strategic or close tactical operations. Its absolute accuracy is limited by sudden phase distortions due to ionospheric disturbances and by polar cap absorption effects (Ref. 35), both of which though infrequent, can lead to temporary errors as large as 8 nm without special mechanizations. The transmissions are conceptually subject to wide-area deceptive jamming in certain theaters of operation (e.g. Eastern Europe). The transmitters are vulnerable to attack and their operability is subject to political agreements which could easily be voided in times of international stress. Thus the OMEGA system should, at best, be regarded as a system for tactical or logistics transport enroute navigation to an objective area with transition required to Loran C/D, ground-based tactical transponders or routine terminal aids (TACAN, VOR or PAR) in the objective area.

4.2.3 User Equipment

The OMEGA navigation set currently being procured for installation in the C-130 transport aircraft is representative of the present state-of-the-art in OMEGA technology. This system (AN/ARN-131) is being manufactured by Dynell Electronics and consists of the following three Line Replaceable Units (LRUs).

- Antenna - coupler
- Receiver - processor

- Control - display

Each LRU will be maintained by the manufacturer under a Reliability Improvement Warranty (RIW) for five years. However, the system is designed to permit USAF in-house maintenance at both the intermediate and depot levels. The required support equipment has been defined.

Several manufacturers have developed commercial OMEGA sets for airline application that are similar in performance capabilities to the USAF system. These manufacturers include Bendix, Tracor, and Canadian-Marconi.

4.3 GLOBAL POSITIONING SYSTEM (GPS)

GPS is a satellite based radio navigation system designed to provide highly accurate navigation fixes to properly equipped users. This system is presently in the development stage, but limited operation is scheduled to commence in the early 1980's with full operation in the mid 1980's. Three types of GPS user equipment are being designed to satisfy the various Air Force mission requirements. Preliminary designs are to emphasize commonality of equipments as much as possible in order to reduce costs.

4.3.1 Performance Capabilities

The accuracy with which a GPS user can determine his position and velocity depends upon the measurement accuracy of his user equipment, the mission scenario and the errors in the satellites ephemeris and clock data received from the satellites. The measurement accuracy of the user equipment depends upon the equipment type. The Air Force has identified three types of user equipment for the various Air Force aircraft and missions. The Type X user equipment is designed for the tactical high dynamics mission, Type Y for the strategic mission, and Type Z for the benign transport mission. The user equipment makes pseudo-range and pseudo-range rate measurements to the GPS satellites. These are not true range and range rate measurements since the time the signals were initiated by the satellite is unknown. However, with four sets of these measurements, the user is able to estimate his position and velocity as well as the GPS system time. The pseudo-range and pseudo-range rate measurement accuracies of the three types of user equipment as specified by the Air Force (Ref. 36) are summarized in Table 4.3-1.

TABLE 4.3-1

GPS USER EQUIPMENT MEASUREMENT ACCURACIES

Type	Pseudo-Range (m)	Pseudo-Range Rate (mps)	Smoothing Times (sec)	Remarks
X	1.5	0.006	>0.1	High Performance
Y	1.5	0.006	>0.1	Medium Performance
Z	15.0	0.006	>0.1	Low Cost

The other major influence on the accuracy of position and velocity estimates are the errors in the satellite ephemeris and clock data. This data is required by the user in the solution of the GPS navigation equations (see Ch. 4 of Ref. 37 for details of these equations and their solution). These errors tend to be the dominant source of errors and thus determine the accuracy limits.

The navigation accuracies expected with the three user equipment types are summarized in Table 4.3-2. These accuracies are for airborne type users and were obtained from previous TASC studies (Ref. 38, 39). These performance numbers are generally confirmed by other reported studies (Ref. 40).

TABLE 4.3-2
GPS NAVIGATION ACCURACIES

User Equipment Type	Position (m)	Velocity (mps)
X	10 - 15	0.1 - 0.2
Y	10 - 15	0.1 - 0.2
Z	20 - 30	0.5 - 1.0

4.3.2 Performance Limitations

The GPS user is highly vulnerable to intentional jamming since the satellites are over three earth radii from the user and the GPS navigation signals are very weak. The GPS signal structure provides some inherent immunity to jamming, but this is often not enough to prevent intentional jamming by the adversary which can destroy the useability of unaugmented GPS receiving equipment for position determination at appreciable distances from a target area (Ref. 38). The user equipment can be augmented with special antennas (e.g., directional phased array antennas) as well as inertial navigation systems (INS) to improve its vulnerability to jamming. One method of reducing vulnerability to jamming is to increase the smoothing time or reduce the receiver bandwidth. However, this will reduce the acceptable dynamic environment of the user. If the user equipment is augmented with a directional antenna and employs an INS, the effective jamming range of an adversary is reduced to about 10 km (with a 1 kW jammer). Increasing or decreasing the jammer power correspondingly changes the potential jamming ranges.

4.3.3 User Equipment

Presently, the user equipment is in the design stage, thus the size, weight, etc., of actual deployable user equipment is not available. However, the Air Force user equipment specification (Ref. 36) contains the restrictions on size, weight, and power shown in Table 4.3-3

TABLE 4.3-3

PHYSICAL CHARACTERISTICS OF GPS USER EQUIPMENT

Type	Size (m^3)	Weight (kg)	Power (W)
X	0.2	56.1	632
Y	0.2	52.1	552
Z	0.11	11.5	151

The user equipment can be conveniently divided into the following functional modules:

- Antenna Preamp (optional)
- Receiver Front End (RF/IF)
- Signal Processors (tracking loops and code generator)
- Receiver Master Clock (crystal oscillator and timing circuits)
- Data Processor
- Power Supply

- Control and Display Unit

A given user equipment type should be useable in similar types of aircraft (i.e., strategic, tactical or transport). In addition, it should be possible to have commonality of modules (specified above) among the receiver types and thus across all classes of aircraft.

4.4 DOPPLER RADARS

A doppler radar is an aircraft velocity sensor which is based on the doppler effect and provides velocity measurements in aircraft coordinates relative to the earth. It consists of a radar transmitter which radiates multiple beams toward the earth's surface and a radar receiver which receives energy backscattered by the earth. The doppler frequency shift with respect to any beam provides a measure of the aircraft velocity component with respect to the earth along the beam. It is a self-contained, all-weather system which can provide velocity information anywhere on earth. The technology has been in existence for several years and several systems are currently in the USAF inventory. Current military efforts are directed at equipment size and cost reduction.

An aircraft navigation capability is achieved by integrating doppler velocity measurements with some form of directional sensor such as a compass or attitude-heading reference system. A doppler radar can also be combined with inertial and/or radio navigation sensors in integrated navigation systems.

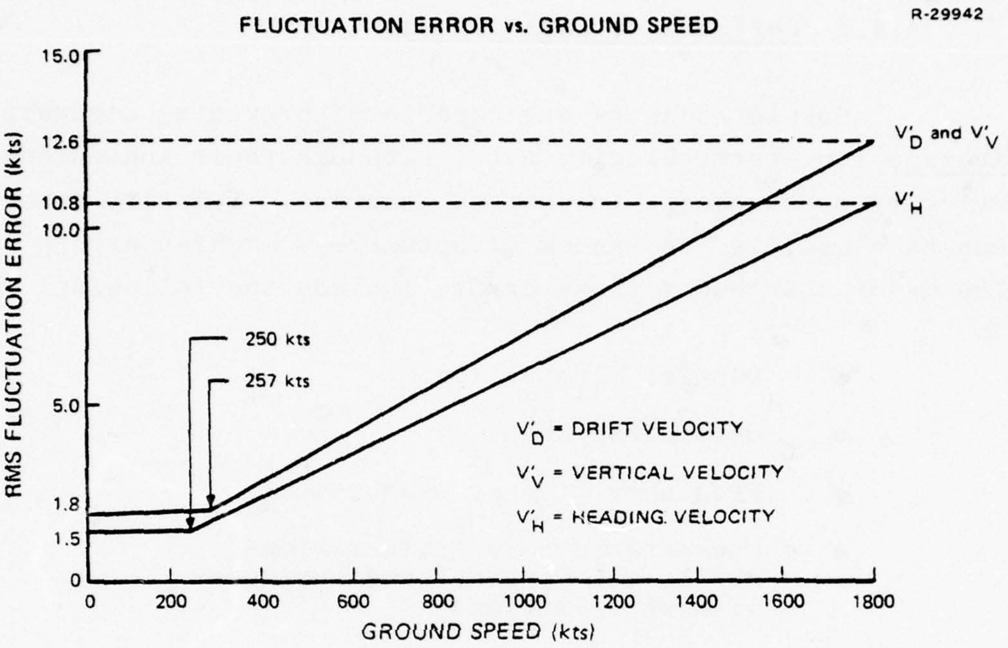
4.4.1 Performance Capabilities

Doppler sensors are capable of providing accurate average long-term velocity data; although their instantaneous velocity measurements are not as accurate. Velocity errors can be classified as random (fluctuation) or bias errors. The major sources of these errors include the following:

- Doppler fluctuation
- Beam direction
- Frequency-tracker measurement
- Overwater errors (calibration-shift, sea current, and surface-wind water-motion)
- Maneuver-induced errors
- Attitude stabilization
- Installation and calibration

Representative performance for state-of-the-art doppler sensors is illustrated in Fig. 4.4-1. These are performance specifications for a doppler velocity sensor to be procured by the Aeronautical Systems Division for strategic aircraft applications. In the figure, heading velocity is the component measured along the aircraft heading, and drift velocity is the cross-heading component. Vertical velocity is the component along the aircraft vertical coordinate axis.

The position error in a doppler navigation system is determined by the errors of the doppler radar and the aircraft heading reference. For state-of-the-art components, this error is estimated in Ref. 41 to be less than 0.25 percent of distance traveled.


FLUCTUATION ERROR vs. GROUND SPEED

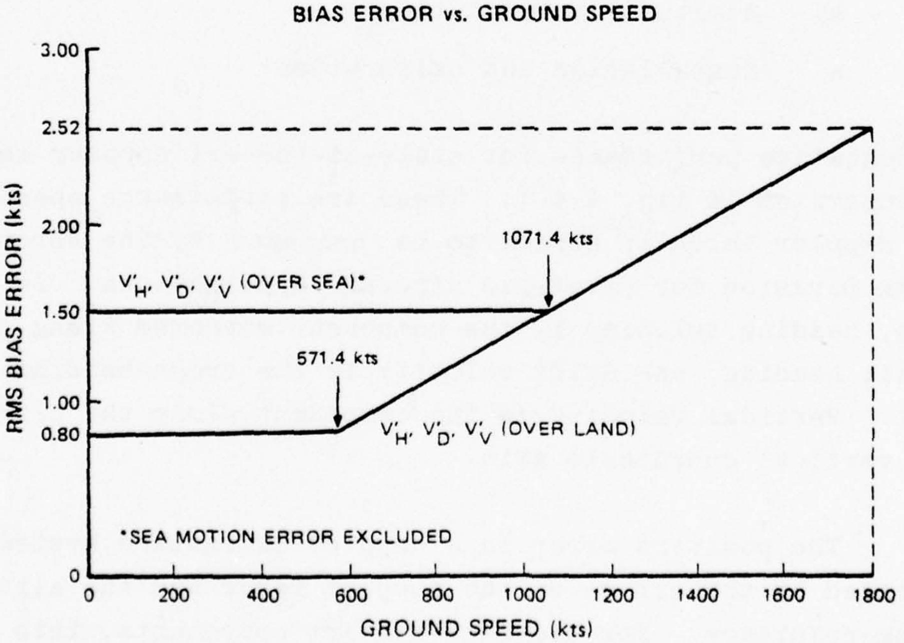

BIAS ERROR vs. GROUND SPEED

Figure 4.4-1 Performance Requirements for the Common Strategic Doppler (Ref. 42)

4.4.2 Performance Limitations

A doppler navigation system requires an external reference for heading information and an internal or external vertical reference in order to convert its sensed velocity data into earth coordinates. Its position estimates degrade with distance traveled and thus some form of position update capability is generally required for long missions. There are also velocity and altitude limits outside of which performance is significantly degraded. For example, Table 4.4-1 identifies the specification limits for the Common Strategic Doppler. Limits are also specified in Ref. 42 for aircraft roll and roll rate limits (±40° and 20°/sec respectively) and aircraft pitch and pitch rate (±25° and 0.2°/sec respectively).

TABLE 4.4-1

PERFORMANCE LIMITS FOR THE
COMMON STRATEGIC DOPPLER (REF. 43)

	HEADING VELOCITY	DRIFT VELOCITY	VERTICAL VELOCITY	ALTITUDE
Minimum Limit	96kts	0	0	40ft
Maximum Limit	1800kts	±200kts	±40kts	70,000ft

Doppler performance is also limited by overflown terrain conditions. While advances have been made, overwater operation continues to be the most severe operational problem in this area. The doppler bias shifts between overwater and overland operation (sea bias error), and over water the doppler return includes water surface motion in the measured aircraft velocity. Compensation of the sea bias error is limited by predictability of sea state conditions and for some design approaches must be considered for doppler applications in aircraft performing overwater missions.

In situations where the strength of the doppler return signals drop sufficiently so as to prevent an accurate velocity measurement, a "memory" mode is mechanized during which the system outputs its last valid velocity indication. Entry into the memory mode can be precipitated by operation over certain surfaces such as smooth water, or by aircraft attitudes which exceed the doppler system's operational limits. Memory mode operation is particularly significant in tactical air operations where the attitude limitations can be exceeded frequently. Under these conditions, the doppler velocity indication is unreliable and an alternative velocity measurement system (e.g. inertial navigation system) is required if the aircraft systems need accurate instantaneous velocity data.

4.4.3 User Equipment

A doppler radar generally consists of an antenna, a transmitter-receiver, and a frequency tracker. A computer may also be included to convert doppler signals into velocity data or to integrate doppler data with other aircraft avionics sensors to derive positional information. Several doppler systems currently exist in the USAF inventory including the following:

- AN/APN-199 (A-7)
- AN/APN-185 (FB-111,B-1)
- AN/APN-108 (B-52)
- AN/APN-147 (C-130, C-141)
- AN/APN-81/82/99 (KC-135)

As mentioned earlier, there is an ongoing program in ASD to acquire a standard doppler velocity sensor for strategic aircraft. The specifications for this equipment are representative of the current state-of-the-art. Two manufacturers, Teledyne-Ryan and Singer-Kearfott Division, are producing prototypes and one will be selected for the production contract. The system consists of two LRU's, a Doppler Velocity Sensor and a Ground Speed Drift Indicator. The total weight is specified to be less than 73 lbs. and the equipment is designed for three-level USAF maintenance. A nuclear hardening requirement exists due to the nature of the proposed application.

4.5 INERTIAL NAVIGATION SYSTEMS

There are a number of different equipment configurations which are employed for inertial navigation. Common to them all is the inertial measurement unit (IMU) which is the assembly of inertial instruments used for sensing aircraft motion and for measurement of attitudes. The basic instruments consist of accelerometers for motion sensors and gyros for attitude determination.

The IMU is configured in either of two ways: gimballed or strapdown. The gimballed configuration is the most commonly employed arrangement in aircraft systems. In this configuration, the accelerometers and gyros are mounted on a common structure which is supported by a set of gimbals. The gimbals are arranged to permit the IMU case to rotate freely about the instrument assembly. In strapdown systems, no gimbals are used. As the name implies, the inertial instrument assembly is rigidly mounted to the IMU case, which in turn is mounted to the vehicle. As in gimballed systems, accelerometer and gyro triads are formed to provide motion data in a three-dimensional coordinate frame. Because the inertial instruments are not stabilized in attitude relative to the earth navigation frame, it is necessary in strapdown systems to create a stable frame of reference analytically in the system computer.

The conceptual difference between gimballed and strapdown IMU's results in fundamental equipment differences. The gyros in strapdown systems are subjected to a much wider attitude rate dynamic range than in gimballed systems. Accordingly, the types of gyros used in gimballed systems are not generally suitable for strapdown system applications. In addition to the differences in gyro technology, strapdown and gimballed systems impose different requirements on the navigation system computer. In strapdown systems, the need to analytically form a stable frame of reference for navigation requires additional computer resources relative to gimballed system mechanization requirements. However, the advances made in computer technology have considerably reduced the significance of this difference.

4.5.1 Performance Capabilities

Inertial navigation equipment (INE) has a number of unique characteristics which make it well suited for aircraft applications. These include the capability for determination of vehicle attitude (roll, pitch and yaw), acceleration, velocity and position. It is self-contained, providing an autonomous navigation capability for use anywhere in the world. Inertial equipment is virtually invulnerable to electronic countermeasures, greatly enhancing its applicability in strategic and tactical missions. It is also able to be integrated with other navigation systems such as Loran, Doppler, GPS, and OMEGA.

A distinctive INE characteristic is the manner in which it is classified by its performance capabilities. Typically, the error in indicated position from an inertial navigator increases with time from equipment turn-on. The average rate of error build-up corresponding to a specific equipment design is used as an index in categorizing its performance. Equipment capable of providing navigation performance with an error build-up in the range of 0.1 to 0.5 nm/hr is typically classified in the high-accuracy category. The term "moderate accuracy" is applied to equipment in the 1.0 to 2.0 nm/hr range. Each of these classifications pertain to navigation with the equipment in its stand-alone configuration. When integrated with a position or velocity reference, the form of the error characteristic is changed and is dependent on the performance characteristics of the external reference.

4.5.2 Performance Limitations

Besides its life-cycle costs, which are relatively high, inertial equipment has the following disadvantages with respect to performance:

- Position and velocity measurement error increases with time
- Initial alignment is required

The former consideration is generally not too critical in fighter and attack missions which are of relatively short duration. However in the longer transport mission it can imply the need for an external position fix capability and for strategic bombers the need for a high-precision inertial navigator.

Initial alignment is required to initialize the differential equations that are solved to determine position in an inertial navigator. The performance impact of the alignment requirement is on aircraft reaction time. For air defense missions, which are characterized by a short (2.5 to 4 minute) reaction time and a short (1 hour) mission duration, the dominant inertial instrument errors are those attributable to the lack of adequate time for complete alignment.

4.5.3 User Equipment

With regard to implementing inertial equipment in a navigation system, there are primarily two alternate configurations which are used. These are:

- Inertial measurement set (IMS) configuration
- Inertial navigation unit (INU) configuration

The relationship between the two configurations is outlined in Fig. 4.5-1.

The IMS configuration consists of an inertial measurement unit, power supply, and signal interface electronics. It constitutes the minimum inertial equipment complement used in integrated avionics systems and is employed in applications where the bulk of the data processing, including the navigation equations, is mechanized in the system's central computer.

In the INU configuration, an IMS is interfaced with its own dedicated processor unit (DPU) and generally packaged as a single unit. The INU is mechanized to perform all of the

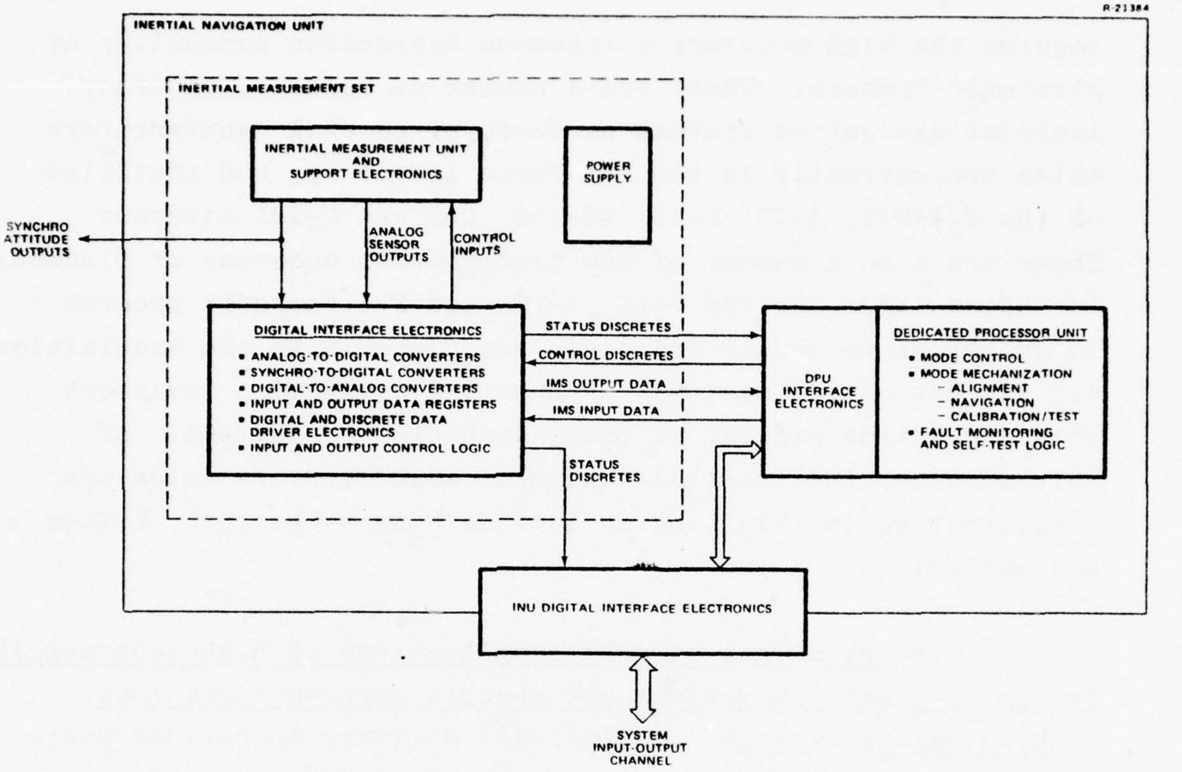


Figure 4.5-1 Alternate Inertial Equipment Configurations

inertial navigation functions which include initial alignment (ground-based), navigation, and self-test. It relies upon external inputs only for mode control, initialization data and reference altitude data for units which include a vertical accelerometer channel mechanization. The INU can also be mechanized to accept attitude, velocity and position updates for in-flight alignment and aided-inertial navigation.

Moderate accuracy INE is employed in virtually all nonstrategic aircraft applications. These include tactical attack, air defense/superiority, and cargo/transport/tanker missions. Strategic tanker aircraft are also scheduled to be outfitted with moderate accuracy INE because they don't require the high-accuracy autonomous navigation capability of strategic bombers. There are a number of moderate accuracy inertial navigation systems produced by several manufacturers which are currently in the Air Force inventory, and installed on the F-4/D/E, A-7D, F-15, AC-130, C-5 and C-141 aircraft. There are also a number of new procurements underway or planned, including those for the F-16, A-10, and F-4 retrofit program. In an effort to reduce the costs associated with the acquisition and support of new systems, an inertial navigation equipment standardization program is being conducted by ASD/AEA. At this writing, the inertial equipment manufacturers which are participating in this program include Singer-Kearfott, Litton, and Autonetics.

The principal aircraft applications of high-accuracy INE are in strategic operations and special purpose operations such as reconnaissance. In strategic military operations particularly, contingency situations are addressed in mission planning which assume that all navigation systems which employ ground-based transmitters (e.g., Loran, OMEGA) or satellites (GPS) are unavailable in the mission. Accordingly, high-accuracy INE is included in the strategic aircraft avionics suite to provide the necessary autonomous and accurate navigation capability. For the B-52 G/H strategic bombers, the inertial system currently in use employs the Litton LN-15S inertial measurement unit. A prime candidate for future use in the B-1 bomber and B-52 retrofits is the Honeywell SPN/GEANS (Standard Precision Navigator/Gimballed Electrostic Gyro Aircraft Navigation System).

Much of the recent work performed in the field of strapdown navigation has been developmental in nature. Increased activity in the field has paralleled the development of new gyro technologies, and specifically the development of the electrostatic gyro (ESG) and the ring laser gyro (RLG). The ESG is used in the Autonetics MICRON strapdown inertial navigation system, which is one of the candidate designs for the USAF Standard Moderate Accuracy Inertial Navigator program. The RLG is being used in strapdown systems under development by several manufacturers. Notable among these is the system being developed by Honeywell. Currently, the Honeywell program is in the advanced development phase. A prototype version of Honeywell's design has been flight tested at Holloman AFB.

4.6 NAVIGATION COMPUTERS

A digital computer is included in nearly all aircraft avionics suites. The computer performs the "dedicated" data processing specifically related to individual sensors (such as those discussed in preceding sections) and, in multisensor configurations, the processing of algorithms required to make the individual sensors "play together", i.e. the sensor integration computations. Other aircraft functions, such as weapon delivery, may be performed within the navigation computer and the computer may also be utilized for equipment maintenance functions, e.g. Built-In-Test (BIT).

4.6.1 Computer Performance and Categories

Navigation computer performance is measured differently than sensor performance. The most common measures are:

- Throughput capability
- Memory capacity

Throughput is typically expressed as the number of operations that can be performed per second. Memory capacity is expressed in terms of word size (usually 16 or 32 bits) and number of words. Most specific navigation problems can be translated into requirements with respect to these two factors, depending on the algorithm(s) mechanizing the solution to the problem.

Performance limits for state-of-the-art computers cannot be meaningfully stated due to the extremely volatile nature of the technology. At the time of this report most new navigation computer applications could be classified in one of the following categories:

- Large centralized computers
- Small dedicated computers

Centralized computers (for example, the B-1 avionics computer unit) are typically used in complex navigation/weapon delivery or integrated navigation management functions. Dedicated computers (for example, the F-16 INS computer) are typically used for simpler navigation computations such as the processing of individual sensor data into velocity, attitude, or position estimates. Dedicated computers are frequently physically integrated within the subsystem itself.

4.6.2 User Equipment

There are numerous manufacturers within both the centralized and dedicated computer classes. These include most of the major sensor contractors (e.g., DELCO, Singer-Kearfott, Autonetics) and microcomputer specialists (e.g., INTEL, Monolithic Memories Inc., Advanced Micro Devices, Texas Instruments, etc.).

Table 4.6-1 presents order-of-magnitude performance and size characteristics for current equipments within the identified computer categories.

TABLE 4.6-1

ORDER-OF-MAGNITUDE COMPUTER CHARACTERISTICS

T-1321

	THROUGHPUT (OPERATIONS/SECOND)	MEMORY (WORDSxBITS)	VOLUME (CUBIC IN.)	WEIGHT (POUNDS)
CENTRALIZED COMPUTER	500k	100k x 32	1000	50
DEDICATED COMPUTER	100k	8k x 16	10	0.5

In general, a centralized computer requires packaging as a medium-sized (2 ft × 2 ft × 8 inch) line-replaceable unit (LRU) with its own environmental control and power-conditioning provisions built into the LRU. The dedicated computer, on the other hand, usually consists of a group of electronic circuit cards that are incorporated into an LRU which also includes a major sensor subsystem; the computer relies, in this case, on power conditioning and environmental control provisions which are shared with the sensor subsystem. Certain other factors bear on the relative applicability of these two classes of computers. Centralized computers usually contain a more extensive instruction set, are programmable in higher-order languages, and operate in both fixed and floating-point arithmetic. Dedicated computers are generally hardwired and operate in fixed-point arithmetic only.* Thus truncation errors, initial programming, and program modifications are less of a problem with centralized computers.

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*Recent microcomputer advances indicate a trend away from these two limitations.

4.6.3 Future Trends and Standardization

A disadvantage of standardization is technology obsolescence. This is a particularly important consideration in the navigation computer area. Not only is the price (in dollars and size) of attaining specified levels of computer performance continually decreasing, but there are also trends in system architecture which have significant implications with respect to standardization.

Existing integrated navigation systems are centralized with a single computer processing raw data from several sensors simultaneously. The advent of microprocessors have made modular architectures, as illustrated in Fig. 4.6-1, possible. In this architecture data preprocessors operate on the sensor data and provide information to a data coordinator for integration. Since computations are performed in parallel, the throughput and memory requirements of any one computer are much less than that required for the computer in the centralized estimation architecture. This implies a standardization potential at the sensor/preprocessor level. The feasibility of such architectures utilizing state-of-the-art components is demonstrated in Refs. 43 and 44 .

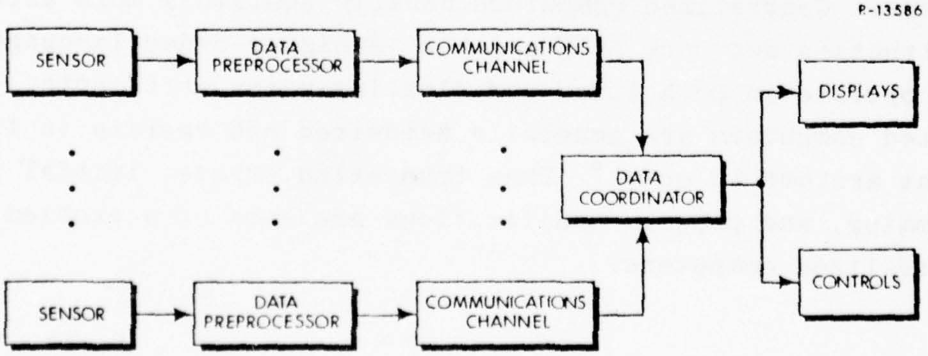

Figure 4.6-1 Modular Estimation Architecture

SECTION V

STANDARDIZATION TRADEOFF METHODOLOGY

5.1 OVERVIEW

The methodology for identifying and evaluating alternative standardization concepts consists of four phases:

Phase 1:	Formulation of alternative navigation equipment suites for the aircraft under consideration that satisfy mission requirements
Phase 2:	Design-to-System Performance/Cost (DSPC) analyses of the suite alternatives for each aircraft
Phase 3:	Identification of potential applications of common navigation equipments across different aircraft
Phase 4:	Global life-cycle cost tradeoff analyses of the standardization alternatives

This is not an entirely automated process. A System Analyst must perform the suite synthesis function in Phase 1, interpret the results of the DSPC analyses in Phase 2, and identify potential standardization concepts in Phase 3. The Standardization Evaluation Program (STEP) performs the analytic functions in Phases 2 and 4 and presents the results to the analyst in a format conducive to interpretation.

5.2 NAVIGATION SUITE SYNTHESIS

Alternative navigation suites for each aircraft under consideration are synthesized based on aircraft mission requirements (Chapter 3) and navigation equipment capabilities (Chapter 4). Each suite must be acceptable from the standpoint of navigation performance. While suite synthesis is primarily a function of the System Analyst, analytic models exist which can be utilized to verify that a defined suite satisfies the navigation requirements of each mission flown by the aircraft. In particular, the format of the SPANS mission profiles and suite definitions is compatible with the Avionics Evaluation Program (AEP) in use at AFAL (Ref. 2). The AEP was in fact applied to a sample of the SPANS navigation suites during the course of the study.

Alternative navigation equipment suites were synthesized for the aircraft considered in the SPANS study. For example, Table 5.2-1 presents a set of alternative suites for the KC-135 aircraft. The purpose of the syntheses was not to define an exhaustive set of alternative configurations, but rather to provide a basis for identifying potential areas for equipment standardization across some or all of these aircraft. Towards this objective, alternative suite architectures, as well as alternative subsystem types within a given architecture, were postulated.

The suite syntheses were driven by the mission requirements discussed in Chapter 3. The synthesis process was initiated by identifying the existing, or proposed, navigation suites for the applicable aircraft where this information was available. Otherwise a baseline suite was formulated

TABLE 5.2-1

ALTERNATE KC-135 NAVIGATION SUITES

T-1315

NAVIGATION AVIONICS TYPE	EXISTING AVIONICS	ALTERNATE 1	ALTERNATE 2	ALTERNATE 3
TACAN	AN/ARN-118	Same	Same	Same
VOR	AN/ARN-14D	Same	Same	Same
UHF-DF	AN/ARA-82	Same	Same	Same
OMEGA	--	-	AN/ARN-131*	AN/ARN-131*
LORAN	AN/APN-70	-	-	-
SEARCH RADAR	AN/APN-59	Improved AN/APN-59	Same	Same
DOPPLER RADAR	AN/APN-81,82	Common Strategic Doppler (CSD)	CSD	Dual CSD
RADAR ALTIMETER	AN/APN-133	Same	Same	Same
INS	--	Dual C-IV*	C-IV*	-
AHRS	--	AHARS (ALA 249-46)	Instrumentation (Standby)	Dual AHARS
COMPASS SYSTEM	N-1	Same	Same	Same
ADS	Instrumentation	Same	Same	DADC
COMPUTER	AN/ASN-7	Navigation Management Computer (Rudimentary)	Navigation Management Computer (Complex)	Navigation Management Computer (Rudimentary)

*Electromagnetic Pulse Hardening Required.

based on the existing/proposed suites of similar aircraft and accounting for unique navigation performance requirements of the aircraft under consideration. Modifications of the baseline suites which satisfied mission requirements were identified to formulate additional alternatives. The postulated suites are comprised of specific equipments which either currently exist or are in development, but are limited to the current technological era as defined in Chapter 2.

5.3 DSPC ANALYSES OF SUITE ALTERNATIVES

DSPC analyses are conducted over each navigation suite for each aircraft. Their purpose is to provide feedback to the system analyst concerning the relative cost-effectiveness and acceptabilities of the suites. The measure of effectiveness is the Mission Completion Success Probability (MCSP) and the measure of cost is life-cycle cost as defined in Section 5.5. While MCSP is generally defined in the total weapon system context, for purposes of SPANS it can be regarded as the probability that successful accomplishment of the defined mission is not precluded by an equipment failure, or combination of failures, in the navigation suite.

STEP input data relating to the DSPC analyses includes definition of equipment duty cycles and failure impact probabilities in the context of the mission profile for each mission flown by the aircraft. The equipment duty cycle is specified by

TO_{ikm} = Operating time of suite equipment i in phase k of the m'th aircraft mission (hours)

The failure impact probabilities are specified by

PA_{ikm} = Probability of mission failure given that suite equipment i fails in phase k of the m'th aircraft mission

A typical duty cycle/failure impact probability specification matrix developed for SPANS is shown in Table 5.3-1. The mission profile for this example was presented in Table 3.2-2. The MCSP determination, as documented in Ref. 1, is based on this matrix, equipment MTBFs, and equipment redundancy inherent in the defined suite.

TABLE 5.3-1

DUTY CYCLE/FAILURE IMPACT MATRIX FOR TANKER MISSION

T-1316

		MISSION PHASE																	
	EQUIPMENT	1		2		3		4		5		6		7		8		9	
1	TACAN	0.5	0	0.33	0	0.17	0	0	0	0	0	0	0	0	0	0.5	0	0.33	0
2	OMEGA	0.5	0.2	0.33	0.2	0.17	0.2	2.0	0.2	2.0	0.2	0.5	0	3.0	0	0.5	0	0.33	0
3	RADAR	0	0.5	0.33	0.5	0.17	0.5	0	0.5	0.5	0.5	0	0	0	0	0.5	0	0.33	0
4	ALTIMETER	0	0	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33	0
5	INS	0.5	0.5	0.33	0.3	0.17	0.3	2.0	0.3	2.0	0.1	0.5	0	3.0	0	0.5	0	0.33	0
6	AHRS(Stdby)	0.5	0.2	0.33	0.1	0.17	0.1	2.0	0	2.0	0	0.5	0	3.0	0	0.5	0	0.33	0
7	ADS	0.5	0.2	0.33	0.1	0.17	0.1	2.0	0	2.0	0	0.5	0	3.0	0	0.5	0	0.33	0
8	COMPUTER	0.5	0.1	0.33	0.1	0.17	0.1	2.0	0	2.0	0	0.5	0	3.0	0	0.5	0	0.33	0

Note: First tabular entry is operating time of equipment i in mission phase k. Second entry is probability of mission failure if equipment i is lost in mission phase k.

The nature of the DSPC output generated by STEP for each aircraft is illustrated in Fig. 5.3-1. From among the alternatives specified, a sequence of improved suites is identified which are optimal in the sense of achieving different levels of MCSP for the lowest LCC. The lowest LCC suite meeting the MCSP objective is identified and "selected" for the aircraft. If the aircraft flies multiple missions, then the lowest LCC suite meeting all MCSP objectives is selected. The standardization factors associated with each equipment in the selected suite are updated (see Section 5.5) prior to consideration in subsequent aircraft programs.

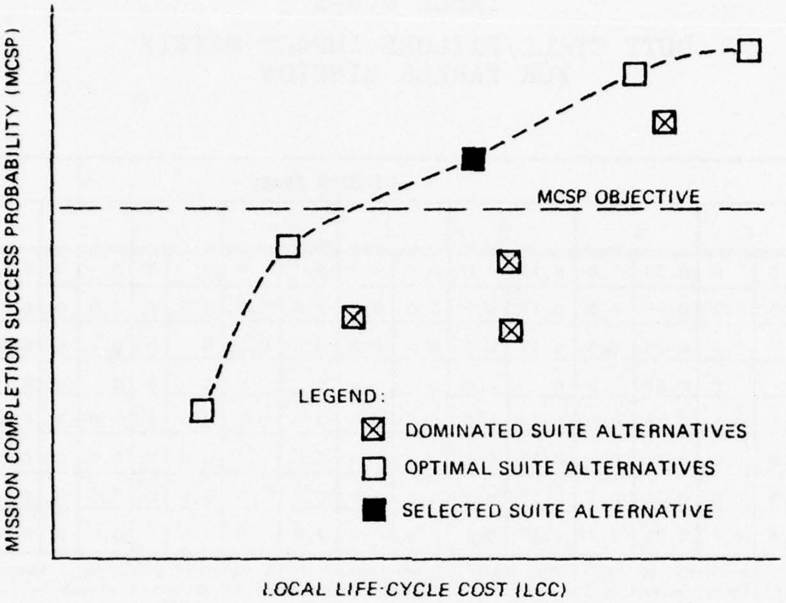

Figure 5.3-1 MCSP vs LCC for Navigation Suite Alternatives

5.4 IDENTIFICATION OF STANDARDIZATION CONCEPTS

A standardization concept is defined for purposes of SPANS by identifying both the equipment which is to be standardized and the specific aircraft on which it is to be applied. Standardization concepts are identified through examination of the equipment suite alternatives which are acceptable based on the DSPC analyses. As a first step, a rudimentary matrix of equipments and aircraft, such as displayed in Fig. 5.4-1, is developed. This matrix directs the System Analyst to specific equipments and aircraft that are candidates for standardization.

The identified candidates are then examined in greater detail as to the feasibility of standardization. For example, R-29404

	DOPPLER RADAR	OMEGA	INS	RADAR ALTIMETER	MAP RADAR	DIGITAL COMPUTER	GPS
F-16			✓		✓	✓	
FOI			✓		✓	✓	
A-10A			✓				
A-10B			✓				
ATF			✓				
AMST		✓	✓	✓			
ATCA		✓	✓				
KC-135	✓	✓					
B-1	✓						
B-52	✓						

Figure 5.4-1 Standardization Candidate Identification Matrix

Inertial Navigation System (INS) options are classified in accordance with the INS accuracy requirements associated the the candidate aircraft. Similarly, standard digital computer options are classified in accordance with memory size and processing time requirements associated with the corresponding navigation suites as well as any nonnavigational functions (e.g. weapon delivery) that the computer must perform. Through this process specific standardization concepts are identified for subsequent global LCC tradeoff analyses.

5.5 GLOBAL LIFE-CYCLE COST ANALYSIS

A life-cycle cost model is incorporated in STEP for the purposes of comparing alternative standardization concepts identified. This model is unique in that system life-cycle costs are computed on a global basis, that is over multiple aircraft programs as opposed to just one, with equipment commonality between different aircraft factored into the LCC computation.

5.5.1 Overview of STEP LCC Model

The manner in which G-LCC considerations are addressed in STEP is illustrated in Fig. 5.5-1. Crucial to the concept is that aircraft are analyzed in chronological order of their scheduled activation/retrofit programs. A table of "standardization factors" is maintained for each equipment that in effect reflect the degree to which that equipment has been applied on aircraft analyzed to date in the evaluation. These factors are parameters of the LCC computation for the aircraft under current evaluation. When this evaluation is complete, the standardization factors associated with each equipment are updated, reflecting their application on the aircraft. The updated factors are then utilized in any LCC computations for subsequent aircraft programs that utilize this equipment.

5.5.2 Elements of LCC Considered in STEP

It was not an objective of SPANS to estimate system life-cycle costs on an absolute basis. It was an objective to consider all major elements of LCC which are potentially influenced by standardization considerations and for which sufficient data exists to evaluate the relative differences between navigation technologies. The following LCC elements are included:

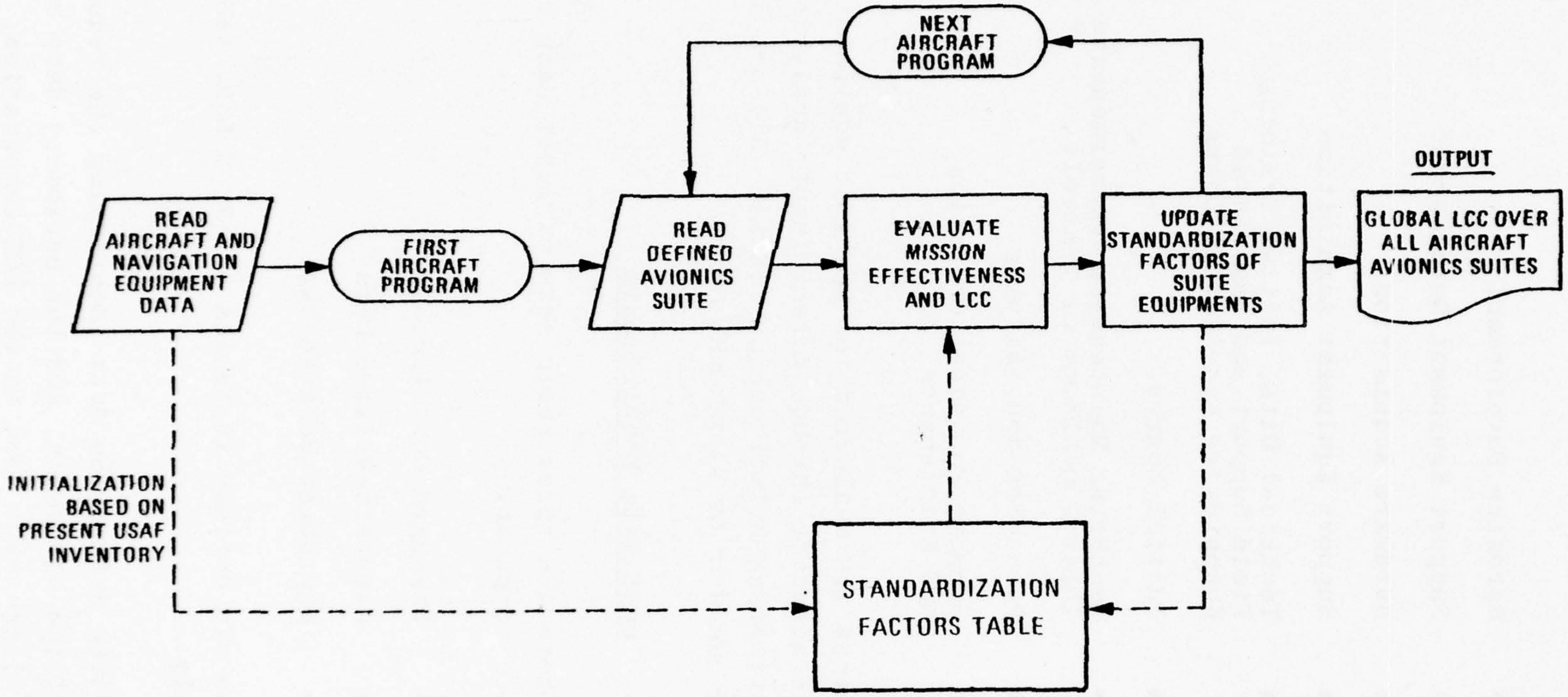

Figure 5.5-1 Overview of Global LCC Evaluation Model for STEP

- Hardware Development
- Support Equipment Development
- Hardware Acquisition
- Support Equipment Acquisition
- Technical Data, Initial Training, Field Support and Associated Nonhardware Acquisition Costs
- Initial Spares
- Recurring Maintenance (Intermediate or I-Level and Depot or D-Level)
- Packaging and Shipping
- Support Equipment Operation and Maintenance

These elements are evaluated for specific equipments utilized on specific aircraft through direct input, analytic expressions, or Cost Estimating Relationships (CERs). All are impacted in one way or another by standardization.

5.5.3 Input Data Requirements

There are three basic sets of input data required for the STEP LCC computation:

- Standard Cost Factors
- Aircraft-Related Data
- Equipment-Related Data

These items are defined in Tables 5.5-1, 5.5-2, and 5.5-3 respectively.

Suite definition data identifying the redundancy level (if any) of the equipment, and the equipment duty cycle (see Table 5.3-1) are also used in the LCC computation.

TABLE 5.5-1

STANDARD COST FACTORS DATA REQUIREMENTS

T-1317

FACTOR DEFINITION	STEP SYMBOL
Exponent of Production Learning Curve for Navigation Equipment	LC
Exponent of Production Learning Curve for Support Equipment	LCSE
Ratio of Nonhardware Acquisition Costs to First-Unit Cost	ROH
Depot Working Hours/Month	DHM
Support Equipment Utilization Factor (Utilizable Hours/Hour)	UTIL
I-Level Repair Turnaround Time (Months)	TAT
Resupply Time to CONUS Located Bases (Months)	RSTC
Resupply Time to Overseas Located Bases (Months)	RSTO
Shipping Time to Depot from CONUS Bases (Months)	BDSC
Shipping Time to Depot from Overseas Bases (Months)	BDSO
D-Level Repair Turnaround Time (Months)	DTAT
Depot Stock Safety Factor (Standard Deviations)	DSF
Reliability Growth Factor (Slope of Duane Curve)	α
I-Level Labor Rate (Dollars/Hour)	SBR
I-Level Materials Consumption Rate (Dollars/Hour)	SBMC
D-Level Labor Rate (Dollars/Hour)	SDR
D-Level Materials Consumption Rate (Dollars/Hour)	SDMC
Annual Support Equipment Operation and Maintenance Cost (% of SE Acquisition Cost)	CSEM
Packaging and Shipping Cost-CONUS (Dollars/Pound)	SPSC
Packaging and Shipping Cost-Overseas (Dollars/Pound)	SPSO

TABLE 5.5-2
AIRCRAFT DATA REQUIREMENTS

T-1318

DEFINITION	STEP SYMBOL
Initial Year of Activation/Retrofit Program	IBY
Final Year of Activation/Retrofit Program	IFY
Activation/Retrofit Rate (Aircraft/Month)	RP
Total Number of Aircraft	NA
Projected Aircraft Life	LIFE
Number of Base Locations	NB
Base Location Index; (Code No. for each USAF base)	IB_ℓ
Number of Aircraft (for each Base Location)	NBA_ℓ
Number of Missions Performed	NM
Mission Identifier Index (for each Mission)	IM_m
Missions Flown Per Month (for each Mission)	$NMPM_m$
Mission Success Probability Objective (for each Mission)	SPO_m
Availability Objective (Aircraft Availability for Mission)	AO
Reliability K-Factor (Operational MTBF/Baseline MTBF)	K

TABLE 5.5-3
EQUIPMENT DATA REQUIREMENTS

T-1319

DEFINITION	STEP SYMBOL
Projected Availability Date (Year)	IYA
Development Cost ($)	DC
First-Unit Acquisition Cost ($)	FUPC
Initial Baseline MTBF (Hours)	MTBF
Number of LRUs	NLRU
LRU Cost/Equipment Cost (for each LRU)	FC_j
Equipment MTBF/LRU MTBF (for each LRU)	FM_j
Fraction of Repairs Performed at I-Level (for each LRU)	RTS_j
Weight (Pounds for each LRU)	W_j
I-Level Repair Time (Manhours for each LRU)	BRT_j
D-Level Repair Time (Manhours for each LRU)	DRT_j
I-Level Support Equipment Development Cost ($)	SDB
First-Unit Acquisition Cost for I-Level SE ($)	FUCB
D-Level Support Equipment Development Cost ($)	SDD
First-Unit Acquisition Cost for D-Level SE ($)	FUCD

5.5.4 Incorporation of Standardization Considerations

The standardization factors defined in Table 5.5-4 also enter the STEP LCC computations. The initial values indicated are the assumed values for a new item of equipment that has yet to be utilized in an aircraft program. When existing equipments are included in the STEP data base, the factors are initialized in accordance with the procurement experience and current utilization of the equipment.

TABLE 5.5-4

EQUIPMENT STANDARDIZATION FACTORS

T-1320

DEFINITION	STEP SYMBOL	INITIAL VALUE
Initial Inventory Introduction Switch	ISS(1)	1
Quantity Procured to Date	NQ	0
Current Acquisition Cost	PC	FUPC(3)
Cumulative Subsystem Usage at Start of Year K (Hours for each Year K in the Analysis Time Horizon)	T_K	5000(all K)
Baseline MTBF at Start of Year K (Hours for each Year K in the Analysis Time Horizon)	$MTBF_K$	MTBF(3) (all K)
Quantity of I-Level SE Procured to Date	NSEB	0
Current I-Level SE Acquisition Cost ($)	PSEB	FUCB(3)
Quantity of D-Level SE Procured to Date	NSED	0
Current D-Level SE Acquisition Cost ($)	PSED	FUCD(3)
I-Level SE Base Location Switches (for each USAF Base Location)	ISB_i(2)	0
Peak Return Rate of LRU j to Depot (Returns/Month for each LRU)	PRR_j	0
Current Level of LRU j Depot Spares (for each LRU)	$NSDP_j$	0

NOTES:

(1) $ISS = \begin{cases} 0 & \text{if equipment has been applied in a previous aircraft} \\ 1 & \text{if current aircraft is the initial application} \end{cases}$

(2) $ISB_i = \begin{cases} 0 & \text{if equipment I-Level SE is not currently located at base i} \\ 1 & \text{If equipment I-Level SE is currently located at base i} \end{cases}$

(3) As defined in Table 5.5-3

The fundamentals of the standardization update functions are discussed below; detailed equations are documented in Appendix A.

Initial Introduction - When an equipment is applied on an aircraft program for the first time, the inventory introduction switch is thrown which effectively zeros out the one-time LCC elements (development, SE development, nonhardware acquisiton) when that equipment is utilized in subsequent aircraft programs.

Production Learning Curve - The basis of learning curve cost analysis is the assumption that each time the production quantity for an item of equipment doubles, the cost per item decreases by a constant percentage of its previous cost. Empirical data exist supporting this assumption, although uniform agreement as to what the real learning factors are does not exist. Incorporation of this effect in the G-LCC computation is illustrated in Fig. 5.5-2. The first aircraft utilizing an equipment incurs acquisition costs based on the initial portion of the learning curve. The equipment cost is then updated by moving down the learning curve based on the acquisition quantity. The updated cost is applied in subsequent aircraft applications.

Learning curves are also used in establishing the support equipment costs. In general, these curves will differ from those used on the installed avionics equipment since they will be based on different empirical data. It is not maintained herein that standardization in itself reduces acquisition costs in this manner, only that the potential for cost reduction exists if an appropriate procurement method can be established.

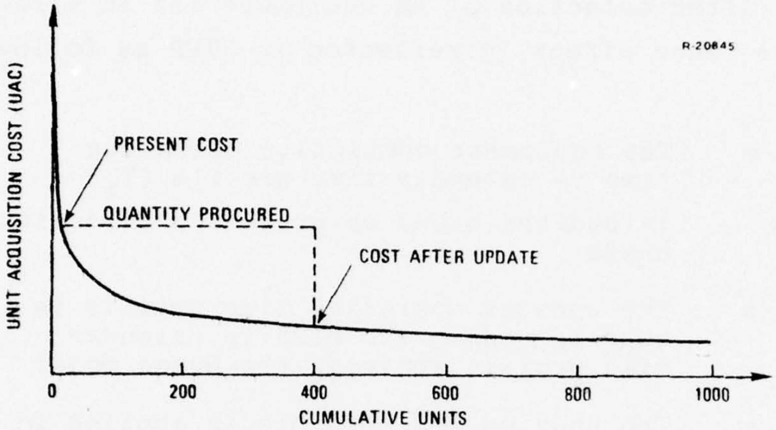

Figure 5.5-2 Unit Acquisition Cost vs Cumulative Production Quantity

Reliability Improvement - Empirical data (Refs. 45, 46, 47) exist demonstrating that if an equipment reliability improvement program is sustained during operational usage, than equipment MTBF grows with cumulative operating time in the manner displayed in Fig. 5.5-3. This behavior is often referred to as following a Duane model of reliability improvement.

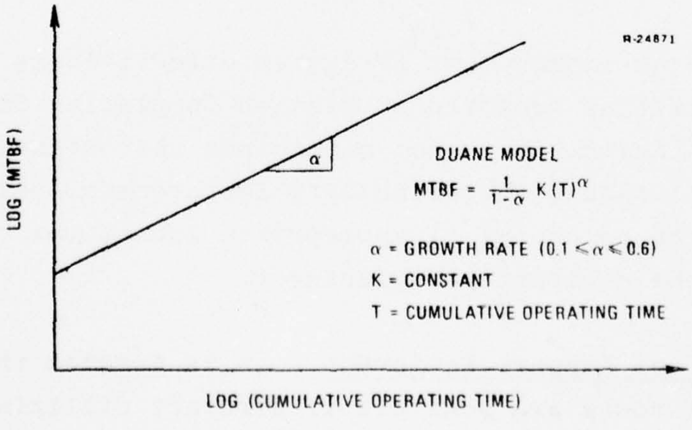

Figure 5.5-3 MTBF vs Cumulative Operating Time

After selection of an equipment for an aircraft program, the Duane effect is reflected in STEP as follows:

- The equipment cumulative operating time vs calendar time profile (T_k) is updated based on projected aircraft usage
- The updated operating time profile is used to update the MTBF vs calendar time profile applying the Duane model
- The updated MTBF profile is applied in subsequent aircraft LCC computations.

The following LCC elements for subsequent aircraft programs are reduced as a result:

- D-Level Support Equipment Acquisition
- Initial Spares
- Recurring Maintenance
- Packaging and Shipping

There is also an improvement in system effectiveness for subsequent aircraft as measured by Mission Completion Success Probability. Again, it is not maintained that standardization in itself will result in reliability improvement, only that it provides the potential if appropriate incentives can be provided to the equipment manufacturer.

<u>I-Level Support Equipment</u> - It is assumed that savings in I-Level SE costs are possible if aircraft utilizing the same equipment are colocated. This is recognized in STEP through the SE Base Location Switches. After an equipment is selected for application in an aircraft program, these switches

are thrown at each base location where the aircraft is deployed to indicate the presence of the SE at these locations. As a result, subsequent aircraft programs applying the same equipment will not be required to acquire I-Level SE for those locations where the SE exists as a result of previous programs.

D-Level Spares and Support Equipment - Standardization can reduce overall SE and spares requirements at D-Level. In effect, this is due to the fact that greater logistics support efficiency is achievable with large SE and spares pools than with several small pools. This effect is recognized in STEP by maintaining the status of these pools (NSED and $NSDP_j$ in Table 5.5-4) as aircraft programs are sequentially analyzed. When an aircraft program applies a previously utilized equipment, the D-Level SE and spares requirements are computed as the incremental quantities required on top of the existing pools to satisfy logistic support objectives. All other things equal, this incremental requirement generally decreases as the size of the existing pool is increased.

SECTION VI

STANDARDIZATION CONCEPT EVALUATION

6.1 DATA BASE APPLIED IN CONCEPT STUDIES

A data base was developed to illustrate typical standardization tradeoff analyses using STEP. The standard cost factors defined in Table 5.5-1 were developed from AFLC documents (Ref. 48) and other source material. Based on the force structure data described in Chapter 2, aircraft data records in the format of Table 5.5-2 were developed for the following aircraft:

- Tactical (F-16, A-10A, A-10B, Follow-On Interceptor, Advanced Tactical Fighter)
- Tanker and Cargo Transport (ATCA, AMST, KC-135)
- Strategic Bombers (B-52, B-1)

Based on a number of sources equipment data records in the format of Table 5.5-3 were developed for several generic types of navigation equipments.

Alternative navigation suites, comprised of generic equipment included in the data base, were synthesized for each of the above aircraft. These suites were the basis for conducting the representative standardization tradeoff studies.

6.2 STANDARDIZATION CONCEPTS STUDIED

The DSPC option of STEP was applied to identify areas in the initially proposed suites where additional redundancy was required to satisfy MCSP objectives. The suites modified as such were then examined for potential standardization alternatives. For purposes of demonstrating the methodology, the standardization concepts summarized in Fig. 6.2-1 were identified for analysis.

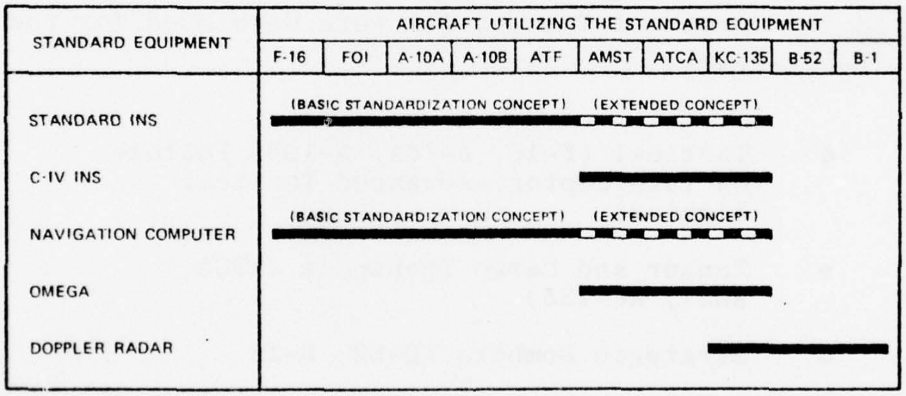

Figure 6.2-1 Standardization Concepts Analyzed

As shown, two ranges of standardization were considered for the standard INS and for the navigation computer. The basic INS standardization concept is over tactical aircraft; the extended concept includes tanker and cargo/transport aircraft. The extended concept is traded off against the alternative of applying the Carousel-IV commercial INS on the tanker and cargo/transport aircraft. The same alternative ranges were considered for the airborne navigation computer. The basic concept reflects the application of a standard, relatively simple, fire control computer in tactical aircraft. The extended concept reflects application of a more complex computer to perform the navigation/weapon delivery function on tactical aircraft and the navigation management function on tanker and cargo/transport aircraft.

6.3 STEP APPLICATION TO STANDARDIZATION CONCEPTS

STEP was then utilized to assess the relative global life-cycle cost benefits of the standardization options identified. A specific option was evaluated by establishing STEP navigation suite definition data identifying the candidate standard item of equipment with the appropriate aircraft suites. STEP was then exercised in each of the following modes:

Mode 1:	The standardization factor update function is executed after each suite/aircraft LCC evaluation
Mode 2:	The standardization factor update function is bypassed after each suite/aircraft LCC evaluation

This procedure is illustrated in Fig. 6.3-1.

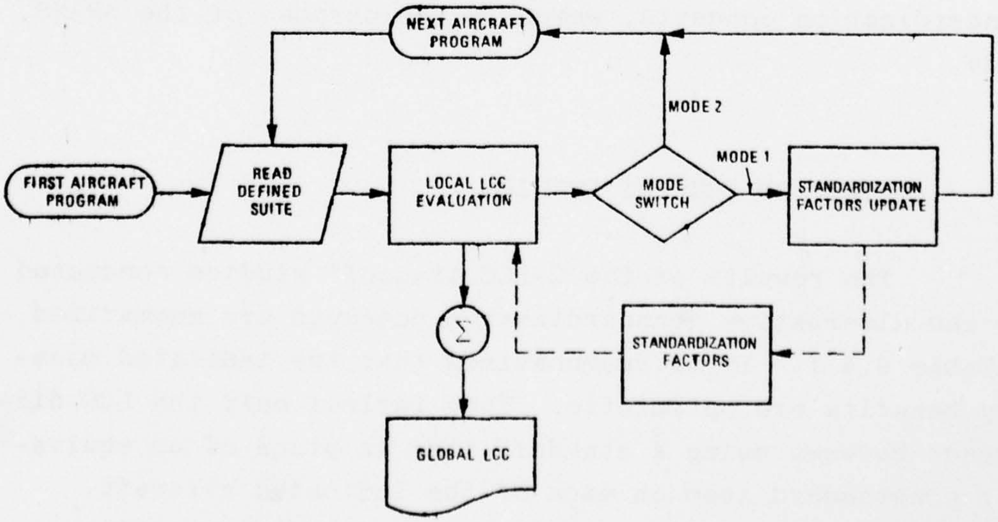

Figure 6.3-1 Modes of STEP Operation

The G-LCC output resulting from Mode 1 operation reflects the effects of standardization concepts established in the suite definition. Since the standardization factors update is bypassed in Mode 2, the G-LCC output reflects, in effect, the application of nonstandard equipment throughout. Accordingly the LCC benefits of the standardization concept is measured by the difference between the Mode 1 and Mode 2 G-LCC.

In an absolute sense, this is an optimistic measure of the standardization benefits since it does not account for the effects of optimizing equipment selections at the individual aircraft program level instead of applying a standard. To study this effect, distinct records in the navigation equipment file must be established for the locally optimal equipments. G-LCC comparisons may then be performed between navigation suites utilizing these equipments and suites implementing the standardization concept. An example of such a comparison is presented in Section 6.4. However, the G-LCC difference between Mode 1 and Mode 2 STEP operation provides a meaningful measure of the relative benefits of alternative standardization concepts, which is the purpose of the SPANS study.

6.4 RESULTS OF CONCEPT STUDIES

The results of the G-LCC tradeoff studies conducted for the alternative standardization concepts are summarized in Table 6.4-1. It is reemphasized that the indicated monetary benefits are optimistic. They reflect only the LCC difference between using a standard item in place of an equivalent nonstandard item on each of the indicated aircraft, based on the assumed effects of standardization on LCC as described in Section 5.5.4.

TABLE 6.4-1

GLOBAL LCC BENEFITS OF ALTERNATIVE STANDARDIZATION CONCEPTS

T-1336

ASSUMPTIONS

- CASE 1: STANDARD SUBSYSTEM APPLIED IN EACH AIRCRAFT
- CASE 2: NEW SUBSYSTEM DEVELOPED FOR EACH AIRCRAFT
- COST CHARACTERISTICS OF EACH NEW SUBSYSTEM AND STANDARD SUBSYSTEM ARE INITIALLY IDENTICAL

NAVIGATION SUBSYSTEM	*APPLICABLE* AIRCRAFT	CASE 1 GLOBAL LCC	CASE 2 GLOBAL LCC	BENEFITS	
				(Case 2 - Case 1)	$\% = \frac{(\text{CASE 2} - \text{CASE 1})}{\text{CASE 2}}$
INERTIAL NAVIGATION SYSTEM	F-16, A-10A, A-10B, FOI	$310 M	$560 M	$250 M	45%
INERTIAL NAVIGATION SYSTEM	F-16, A-10A, A-10B, FOI, AMST ATCA, KC-135	$402 M	$718 M	$316 M	44%
NAVIGATION COMPUTER	F-16, A-10A, A-10B, FOI	$160 M	$280 M	$120 M	43%
NAVIGATION COMPUTER	F-16, A-10A, A-10B. FOI, AMST, ATCA, KC-135	$210 M	$357 M	$147 M	41%
OMEGA	AMST, ATCA, KC-135	$ 14 M	$ 20 M	$ 6 M	30%
DOPPLER RADAR	B-52, B-1, KC-135	$ 28 M	$ 42 M	$ 14 M	33%

To illustrate the areas in which standardization reduces life-cycle costs, the G-LCCs for the extended INS standardization concept are broken down into constituent elements in Table 6.4-2. It is seen that a substantial portion (45%) of the G-LCC benefits are attributable to savings in recurring maintenance costs for the system. This is a result of reliability improvement that is assumed to occur with maturity of the standard system (it does not reflect improved maintenance personnel efficiency which will also probably occur). Recurring maintenance cost savings were found to be higher for inertial equipments than for other types of avionics. This is probably due to the high maintenance costs generally associated with these items (Ref. 49).

TABLE 6.4-2

BREAKDOWN OF GLOBAL LCC BENEFITS
FOR INS STANDARDIZATION

T-1335

ASSUMPTIONS

- GLOBAL LIFE-CYCLE COSTS CONSIDERED OVER F-16, A-10A, A-10B, FOI, AMST, ATCA, KC-135
- CASE 1: STD INS USED IN EACH PROGRAM
- CASE 2: NEW INS DEVELOPED FOR EACH PROGRAM
- COST CHARACTERISTICS OF EACH NEW INS AND STD INS ARE INITIALLY IDENTICAL

LCC ELEMENT	CASE 1 STANDARD INS	CASE 2 NON-STANDARD INS
ONE-TIME COSTS*	$ 13 M	$ 91 M
HARDWARE ACQUISITION	$160 M	$210 M
SUPPORT EQUIPMENT	$ 12 M	$ 25 M
SPARES	$ 44 M	$ 77 M
RECURRING MAINTENANCE	$173 M	$315 M
TOTAL	$402 M	$718 M

*Development, Technical Data, Initial Training, Contractor Support, etc.

Further insight is gained by breaking down global life-cycle costs by individual aircraft programs as displayed in Fig. 6.4-1. Since it is assumed that the standard INS and non-standard INS are equivalent systems, the LCCs are identical for the A-10A, the initial aircraft program. The life-cycle costs of the standard INS drop significantly relative to the nonstandard INS in subsequent aircraft programs. While the magnitude of the LCC savings is greatest on the larger aircraft programs such as the F-16, on a normalized basis (e.g. savings per aircraft) the savings are greater on smaller programs such as the AMST. This is attributable to the fact that for the nonstandard case one-time costs are amortized over fewer aircraft and acquisition costs are incurred over the initial portion of the production learning curve. Hence a preliminary conclusion that can be drawn from studies of this nature is that small aircraft programs should utilize existing equipment to the extent possible.

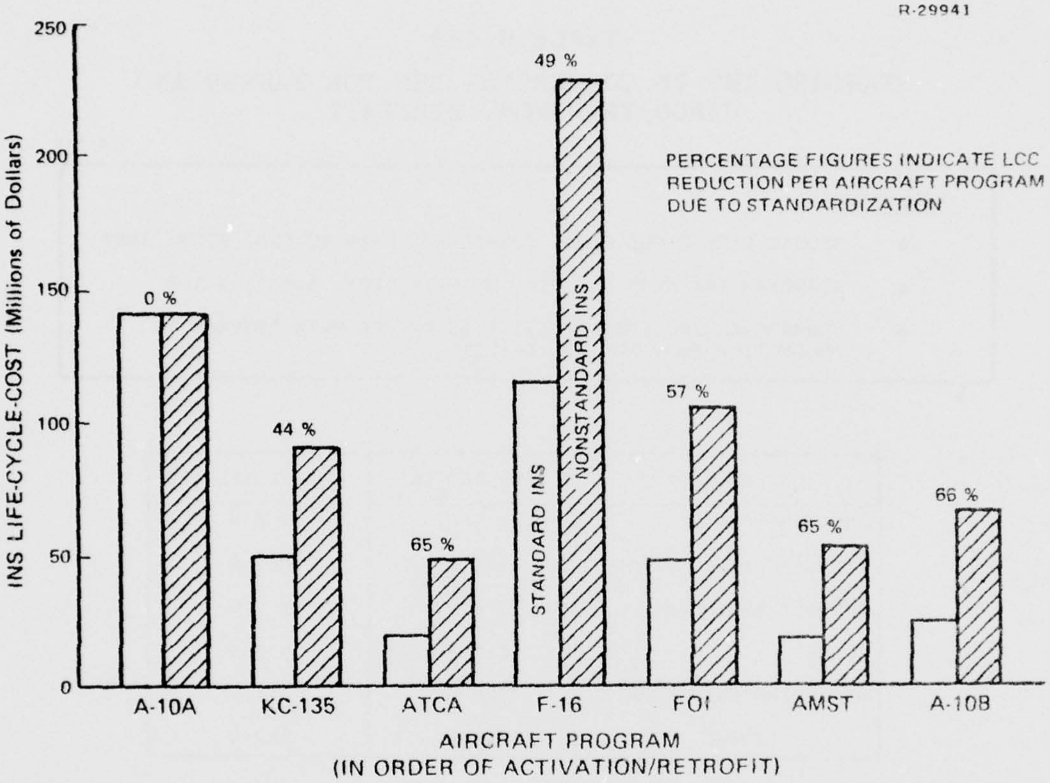

Figure 6.4-1 Standard vs Nonstandard INS LCC by Aircraft Program

The extended INS standardization option example is carried one step further to illustrate the tradeoff methodology. When the standard INS is considered for application on tanker and cargo/transport aircraft, it must be compared against the Delco Carousel-IV commercial INS recently selected by the Air Force for retrofit of the C-141. This is a mature system, both in terms of production cost and reliability, as a result of widespread commercial airlines application on the Boeing 747. An LCC data record for this system was established based on current cost and reliability data. STEP was then used to compare its life-cycle costs on tanker and cargo/transport aircraft against the standard INS, assuming that the standard INS was also procured and utilized on tactical aircraft. The results of this comparison are presented in Table 6.4-3.

TABLE 6.4-3

STANDARD INS VS COMMERCIAL INS FOR TANKER AND CARGO/TRANSPORT AIRCRAFT

R-29408

ASSUMPTIONS

- GLOBAL LIFE-CYCLE COSTS CONSIDERED OVER KC-135, ATCA, AMST
- STANDARD INS ALSO UTILIZED ON F-16, FOI, A-10A, A-10B
- COMMERCIAL INS (CAROUSEL-IV) IS MATURE WITH RESPECT TO PRODUCTION COST AND RELIABILITY

LCC ELEMENT	STANDARD INS	COMMERCIAL INS
ONE-TIME COSTS	$ 0 M	$ 0 M
HARDWARE ACQUISITION	$44 M	$58 M
SUPPORT EQUIPMENT	$ 6 M	$ 7 M
SPARES	$11 M	$ 5 M
RECURRING MAINTENANCE	$26 M	$11 M
TOTAL	$87 M	$81 M

The standard INS is seen to be favorable from the standpoint of acquisition costs. This is a result of production experience which would be gained in tactical aircraft programs. However the reliability maturity resulting from tactical applications is not sufficient to "catch-up" with the commercial INS, as reflected in the difference in initial spares and recurring maintenance costs. The difference in total LCC for the two systems is not judged to be significant.

6.5 CONCLUSIONS AND RECOMMENDATIONS

The major result of the SPANS study was a demonstration of a quantitative approach to standardization issues.

It was proven feasible to analyze and compare alternatives within the three dimensions of avionics standardization -- equipment, aircraft, and time. The methodology was also illustrated to have potential application in ongoing aircraft equipment standardization programs in the following capacity:

- To identify candidate aircraft program applications for the standard
- To compare the standard against alternative equipments for specific aircraft
- To guide development effort and acquisition strategy for the standard to maximize its competitive position.

The applications of the SPANS methodology to date, as described herein, have been simplistic in nature, directed more at proving the analysis process than at deriving firm conclusions. In the dynamic environment of emerging navigation technologies, aircraft program cancellations, etc., it is believed that the methodology is more significant than any preliminary conclusions with respect to specific standardization options which could easily be negated in the near future. However, the early results do provide insight into avionics standardization and its payoffs. For example, one of the fundamental problems associated with standardization, that of justifying the initial aircraft application of a standard, is displayed in a visible manner.

The standardization concept identification process with a System Analyst in the loop also proved to be enlightening in uncovering significant issues such as:

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STANDARDIZATION POTENTIAL ACROSS NAVIGATION SYSTEMS (SPANS).(U)
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UNCLASSIFIED   TASC-TR-840-1   AFAL-TR-77-188   NL

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- Whether to standardize inertial equipment at the IMU or INS level
- Whether to standardize the computation function at the central computer or microcomputer level.

These two issues were found to be interrelated in that standardization at the IMU level tends to complement central computer standardization, and INS standardization tends to complement standardization at the microcomputer level.

Having developed and proven an analytic approach to the problem, the next recommended step is to refine the methodology and extend the data base so that in-depth analyses of specific standardization issues confronting the USAF today are possible. Recommended methodology refinements include:

- Development of an improved, systematic way of incorporating effectiveness measures in the methodology
- Incorporation of F^3 standardization considerations and the effect of competition on acquisition cost
- Incorporation of RIW considerations and the effect on reliability improvement.

In the area of data base extension, the greatest need is for data relevant to the cost <u>disadvantages</u> of standardization. In particular, locally optimized equipments which could be applied in aircraft in place of standards should be identified and their costs quantified. Also, data is needed for estimating the incremental cost associated with interfacing a standard in the different types of aircraft.

GLOSSARY OF TERMS

A/C - Aircraft

ADF - Automatic Direction Finding Equipment

ADPI - Air Defense Point Intercept

ADS - Air Data System (used to describe a rudimentary air data data sensing/computing subsystem which is less comprehensive in function than a CADC)

AEP - Avionics Evaluation Program

AFAL - Air Force Avionics Laboratory (AFSC)

AFLC - Air Force Logistics Command

ASFC - Air Force Systems Command

AGE - Aerospace Ground Equipment

AHARS - Advanced Heading-Attitude Reference System (A specific type of AHRS)

AHRS - Attitude-Heading Reference System

AMST - Advanced Medium STOL Transport

ASD - Aeronautical Systems Division (AFSC)

ATC - Air Traffic Control

ATCA - Advanced Tanker/Cargo Aircraft

Baseline Mission Profile - Representative flight profile for a specific mission

BIT(E) - Built In Test (Equipment)

CADC - Central Air Data Computer

CARP - Computed Air Release Point (System mode of operation during air drop supply)

CAS - Close Air Support

CAT I - Category I landing conditions (>200 ft cloud base, > 0.5 mile visibility)

CAT II - Category II landing conditions (100-200 ft cloud base/ 0.25-0.5 mile visibility)

CCIP - Continuously Computed Impact Point

CER - Cost Estimating Relationships

CIV - Carousel IV Inertial Navigation System (Commercial INS)

Colocation - Location of more than one type of aircraft at a single base

CONUS - Continental U.S.A.

CSD - Common Strategic Doppler

CTOL - Conventional Take-off and Landing

DAIS - Digital Avionics Information System

DS - Defensive Strike (Volatile Target)

DSPC - Design to System Performance/Cost (Model developed by Directorate of Aerospace Studies, Kirtland AFB)

EI - Escort Intercept

EMP - Electromagnetic Pulse (Associated with nuclear explosion)

ESG - Electrostatically Suspended Gyro

EWO - Emergency Wartime Operations

FAA - Federal Aviation Agency

(FAA)AC - (Federal Aviation Agency) Advisory Circular

FAC - Forward Air Control

FAC-X(A-10B) - Forward Air Control Aircraft (Projected)

FAR - Federal Aviation Regulation

FOI - Follow-on Interceptor

Force Structure - The entire complement of aircraft in the USAF operational inventory at any specified point in time

F^3 INS - Form, Fit and Function Standard Inertial Navigation System

GCA - Ground Controlled Approach

Global LCC (G-LCC) - Total life-cycle cost for developing, acquiring, installing and supporting the avionics equipment selected for <u>all</u> aircraft in the USAF force structure

GPS - Global Positioning System

ICAO - International Carrier Airlines Organization

ICAOR - International Carrier Airline Organization Regulation

IDNE - Inertial-Doppler Navigation Equipment

ILT - Intertheater Logistics Transport

IMC - Instrument Meteorological Conditions

INS - Inertial Navigation System

Interim CAS - Limited Close Air Support Capability

IST - Intratheater STOL/CTOL Transport

JTIDS - Joint Tactical Information Distribution System

K-Factor - Reliability degradation factor for equipment operating in severe environments. (In this report K=1 for the Cargo/Transport cruise flight environment and K>1 for Strategic Bomber, Attack and Air Superiority Aircraft)

Laydown - Low Altitude Delivery of High Drag Bombs

LCC - Life-Cycle Cost

Local LCC (L-LCC) - Life-cycle cost for developing, acquiring, installing and supporting the avionics equipment selected for a single aircraft type

LRU - Line Replaceable Unit

MCSP - Mission Completion Success Probability (Probability of Aircraft arriving in mission objective area with sufficient equipment operative to complete mission)

Meaconing - Transmitting actual or simulated radio navigation signals for the purpose of confusing navigation.

MILS - Milliradians (in weapon delivery, the angle subtended by weapon miss distance at the aircraft's position at the instant of weapon delivery)

MIRA - Multifunction Inertial Reference Assembly

Mission Area - Generalized mission role

Mission Phase - Segment of the mission profile requiring specific avionics system/subsystem utilization and performance

MMR - Multi-Mode Radar

MTBF - Mean Time Between Failures

Navigation Subsystem (User Equipment) - A generic, functional element of the navigation suite, e.g., Inertial Navigation Subsystem, Doppler radar subsystem, navigation computer.

Navigation Suite - The entire complement of navigation avionics equipment on an aircraft.

OMEGA - Long range radio navigation system.

PAR - Precision Approach Radar.

PPS - Preplanned Deep Strike

Redundancy - Provision of two identical pieces of equipment performing parallel functions to provide a single-fail-operative mission capability.

RNAV - Area Navigation (Requirement in domestic airspace)

RIW - Reliability Improvement Warranty

RLG - Ring Laser Gyro

RMS - Root Mean Square

ROC - Required Operational Capability (document)

R_{50} - 50th percentile of the radial error distribution (CEP)

R_{95} - 95th percentile of the radial error distribution

SAM - Surface-to-Air Missile

SBP - Strategic Bomber, Penetration

SBS - Strategic Bomber, Standoff

SE - Support Equipment

Standard Cost Factors - Cost parameters associated with equipment entry into USAF inventory and equipment support which are independent of the aircraft program considered, e.g., maintenance labor rates, data management costs, packaging and shipping costs.

Standardization - Use of a standard subsystem on more than one aircraft type

STEP - Standardization Evaluation Program

STOL - Short Take-Off and Landing

TA - Terrain Avoidance

TD - Time Difference (coordinate system)

TDS - Tactical Data System

TF - Terrain Following

TS - Tanker, Strategic

TTA - Tanker, Tactical/Airlift

UHF/DF - Ultra-High Frequency Direction-Finding Equipment

User - Aircraft operating element of the USAF

UTM - Universal Transverse Mercator (coordinate system)

VLF - Very Low Frequency

VMC - Visual Meteorological Conditions

VOR/ILS - Vertical Omni-Range/Instrument Landing System Equipment

VOR/TAC - Composite Civil/Military VOR/TACAN Facility

VSTOL - Vertical/Short Take-off and Landing

WX - Weather (normally used in this report to indicate proximity to severe weather conditions)

X-Band Beacon - Aircraft rendezvous radar beacon

APPENDIX
LIFE-CYCLE COST AND UPDATE EQUATIONS

A.1 OVERVIEW AND NOTATION

This appendix documents the life-cycle cost equations which comprise the global LCC model in the Standardization Evaluation Program (STEP). The equations are applied sequentially to specific equipments in specific aircraft programs. To minimize cumbersome notation, the subscripts identifying the equipment and the aircraft program are omitted. There is no resulting ambiguity since in any given execution of the equations, there is only one equipment and one aircraft under consideration.

All independent variables in the equations are traceable to one of the following sources:

- Standard Cost Factors File (Table 5.5-1)
- Aircraft Data File (Table 5.5-2)
- Equipment Data File (Table 5.5-3)
- Standardization Factors Table (Table 5.5-4)
- Navigation Suite Definition.

The notation (S), (A), (E), (F), and (N) will be utilized in the definitions to refer to these sources. All variables are defined once, the first time in which they appear in an equation.

A.2 TOTAL LIFE-CYCLE COST

The total life-cycle cost (LCC) of the specified equipment on the specified aircraft is

$$LCC = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_8 + C_9 \quad \text{(A.2-1)}$$

where

C_1 = Hardware Development Cost
C_2 = Support Equipment Development Cost
C_3 = Hardware Acquisition Cost
C_4 = Support Equipment Acquisition Cost
C_5 = Nonhardware Acquisition Cost
C_6 = Initial Spares Cost
C_7 = Recurring Maintenance Cost
C_8 = Packaging and Shipping Cost
C_9 = Support Equipment Operation and Maintenance Cost.

Each of these LCC elements is developed subsequently.

A.3 LCC ELEMENT EQUATIONS

A.3.1 Hardware Development

The cost of equipment development for a particular technology is program input. It is assumed that only the first aircraft program utilizing the equipment incurs this cost.

$$C_1 = ISS \times DC \qquad (A.3\text{-}1)$$

where

ISS = Equipment inventory introduction switch (F)*

DC = Equipment development cost in dollars (E)

A.3.2 Support Equipment Development

Support equipment development cost for a particular equipment technology is also program input and incurred only in the initial aircraft application.

$$C_2 = ISS \times (SDB + SDD) \qquad (A.3\text{-}2)$$

where

SDB = Development cost in dollars for I-level support equipment (E)

SDD = Development cost in dollars for D-level support equipment (E)

A.3.3 Hardware Acquisition

Equipment acquisition costs are based on a "learning-curve" computation as follows:

$$C_3 = FUPC \times \sum_{K=NQ+1}^{NQ+NA\times NPA} K^{\log(LC)/\log(2)} \qquad (A.3\text{-}3)$$

$$^{*}\ ISS = \begin{cases} 0 & \text{if equipment has been previously introduced to the USAF inventory} \\ 1 & \text{if current aircraft is the first application of the equipment} \end{cases}$$

where

FUPC = First-unit production cost of the equipment (E)

NQ = Quantity of the equipment procured prior to the current aircraft program (F)

NA = Total number of aircraft on which the equipment is to be installed (A)

NPA = Number of equipment installed per aircraft (N)

LC = Exponent of unit learning curve for the equipment technology (S)

Accordingly, equipment acquisition costs decrease as the cumulative procurement quantity associated with previous aircraft programs increases.

A.3.4 Support Equipment Acquisition

Acquisition cost for Support Equipment (SE) at both the I-level and D-level to provide an in-house support capability for the equipment is based on a learning-curve computation as follows:

$$C_4 = \text{FUCB} \times \sum_{K=\text{NSEB}+1}^{\text{NSEB}+\text{NBR}} K^{\log(\text{LCSE})/\log(2)} + \text{FUCD} \times \sum_{K=\text{NSED}+1}^{\text{NSED}+\text{NDR}} K^{\log(\text{LCSE})/\log(2)} \qquad \text{(A.3-4)}$$

where

FUCB = First-unit acquisition cost for I-level support equipment (E)

NSEB = Quantity of the I-level SE item procured prior to the current aircraft program (F)

NBR = Quantity of I-level SE that must be procured in the current program (computed below)

LCSE = Exponent of the unit learning curve for support equipment (S)

FUCD = First-unit acquisition cost for D-level support equipment (E)

NSED = Quantity of the D-level SE item procured prior to the current aircraft program (F)

NDR = Quantity of D-level SE that must be procured in the current program (computed below)

The following paragraphs describe the computations of NBR and NDR respectively.

I-Level SE Requirements - The I-level SE computation recognizes bases at which the current aircraft is colocated with other aircraft for which the subject equipment has already been procured and assumes that no additional SE will be required at these locations.

$$NBR = NB - \sum_{i=1}^{NB} ISB_{IB_i} \qquad (A.3\text{-}5)$$

where

NB = Number of base locations at which the current aircraft is (to be) deployed (A)

IB_i = Index of aircraft base location i (A)

ISB_{IB_i} = SE base location switch for base IB_i (F)*

D-Level SE Requirements - The SE requirements at D-level are based on the projected peak demand for the SE. The computation takes into account that SE may already be positioned at depot as a result of previous aircraft programs, but that additional sets may be required to meet the demand increase due to the current aircraft.

$$NDR = \sum_{j=1}^{NLRU} \frac{(PRR_j + NA \times NPA \times U \times FM_j \times XK/MTBF_{IFY}) \times DRT_j}{DHM \times UTIL} - NSED \qquad \text{(A.3-6)}$$

(Rounded upward to next integer)

where

NLRU = Number of Line Replaceable Units (LRUs) comprising the navigation equipment (E)

PRR_j = Peak return rate of LRU j to depot in returns per month (F)

U = Equipment usage on the aircraft in hours per month per aircraft (N)

FM_j = Proportion of equipment failure rate attributable to LRU j (E)

XK = Ratio of baseline† equipment MTBF to the MTBF in the current aircraft operational environment (A)

IFY = First year in which all installs will have been completed in the current aircraft program (A)

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* $ISB_i = \begin{cases} 0 \text{ if SE is not currently positioned at base i} \\ 1 \text{ if SE is currently positioned at base i} \end{cases}$

†The baseline utilized is the cargo/transport aircraft operational environment.

$MTBF_K$ = Baseline* Mean Time Between Failure in hours of the equipment at the start of year K (F)

DRT_j = Repair time at D-level for LRU j in hours (E)

DHM = Depot working hours per month (S)

UTIL = Support equipment utilization in usable time per available time (S)

A.3.5 Nonhardware Acquisition

Included in the nonhardware acquisition element are nonrecurring costs such as technical data, repair manuals, training materials, etc. The cost is assumed to be proportional to the first-unit acquisition cost for the equipment and incurred only by the first aircraft program applying the equipment.

$$C_5 = ISS \times ROH \times FUPC \qquad (A.3\text{-}7)$$

where

ROH = Ratio of nonhardware acquisition costs to first-unit production cost (S)

A.3.6 Initial Spares

It is assumed that spare Line Replaceable Units (LRUs) will be provisioned at I-level and D-level to support equipment removals from the aircraft. The initial spares cost is based on a learning-curve calculation as follows

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*The baseline utilized is the cargo/transport aircraft operational environment.

$$C_6 = \sum_{j=1}^{NLRU} \left[FC_j \times FUPC \sum_{K=NQ+NA\times NPA}^{NQ+NA\times NPA+NSB_j+NSD_j} K^{\log(LC)/\log(2)} \right]$$

(A.3-8)

where

FC_j = Fraction of equipment acquisition cost attributable to LRU_j (E)

NSB_j = Number of LRU_j spares required at I-level (computed below)

NSD_j = Number of LRU_j spares required at D-level (computed below)

The computations of NSB_j and NSD_j are described in the following paragraphs.

<u>I-Level Spares Requirements</u> - LRU spares requirements at I-level are determined in accordance with a specified aircraft availability objective at each base where the aircraft is deployed. The peak demand rate for spares of LRU_j at base m (D_{jm}) is given by

$$D_{jm} = NBA_m \times NPA \times U \times FM_j \times XK/MTBF_{IFY} \quad (A.3\text{-}9)$$

where

NBA_m = Number of aircraft deployed at base m (A)

The average time to replenish the I-level supply at base m after an LRU_j spare has been removed to fulfill a demand (RT_{jm}) is given by

$$RT_{jm} = RTS_j \times TAT + NRTS_j \times RST_m \quad (A.3\text{-}10)$$

where

RTS_j = Fraction of LRU_j failures that are repaired at I-level (E)

TAT = Repair turnaround time at I-level in months (S)

$NRTS_j = 1 - RTS_j$

RST_m = Resupply time to base m from depot in months (S)

The I-level spares requirements for LRU_j at base m ($NSPB_{jm}$) are then computed as the minimum N such that

$$\sum_{K>N} (K-N)(D_{jm}RT_{jm})^K \, e^{-D_{jm}RT_{jm}}/K! \leq$$
$$(1-AO) \times NBA_m/(NSSYS \times NLRU) \qquad (A.3\text{-}11)$$

where

AO = Aircraft availability objective (A)

NSSYS = Number of distinct subsystems in the navigation suite (N)

and the total I-level requirements for LRU_j are

$$NSB_j = \sum_{m=1}^{NB} NSPB_{jm} \qquad (A.3\text{-}12)$$

D-Level Spares Requirements - LRU spares requirements at D-level are computed in accordance with an objective probability of having a spare available. It is assumed that the depot supply supports all aircraft on which the subsystem is applied. The number which must be procured in the current program is the incremental amount needed to maintain the objective. The peak demand rate on the depot supply of LRU_j spares from the current program alone (RR_j) is

$$RR_j = NA \times NPA \times U \times FM_j \times XK \times NRTS_j / MTBF_{IFY} \qquad (A.3\text{-}13)$$

The number of additional D-level LRU_j spares which are procured for the current program is then computed as

$$NSD_j = (RR_j + PRR_j) \times (BDS + DTAT) + DSF \sqrt{(RR_j + PRR_j) \times (BDS + DTAT)} - NSDP_j \qquad (A.3\text{-}14)$$

where

PRR_j = Demand rate in demands per month on the D-level LRU_j spare supply from earlier aircraft programs applying the subsystem (F)

BDS = Base to depot shipping time in months (S)

DTAT = Repair turnaround time at D-level in months (S)

DSF = Depot stock safety factor in standard deviations (S)

$NSDP_j$ = Current level of LRU_j spares at D-level to support earlier aircraft programs applying the equipment (F)

Standardization impacts the initial spares cost element in three ways:

- Reduced I-level and D-level requirements due to reliability improvement
- Reduced overall D-level requirements because large supplies are more efficient against surges in demand
- Reduced spares acquisition costs due to the learning curve effect.

A.3.7 Recurring Maintenance

Recurring maintenance costs are computed for equipment maintenance at the intermediate and depot levels. These costs are computed on an annual basis in order to factor in reliability improvement over the equipment life cycle. The computation is based on the expected number of LRU removals and the maintenance cost per removal as follows:

$$C_7 = \sum_{k=1}^{LIFE} \sum_{j=1}^{NLRU} ENR_{jk} \times (RTS_j \times BRC_j + NRTS_j \times DRC_j) \qquad (A.3\text{-}15)$$

where

LIFE = Projected inventory usage period of the aircraft in years (A)

ENR_{jk} = Expected number of removals of LRU_j in year k (computed below)

BRC_j = I-level repair cost in dollars for LRU_j (computed below)

DRC_j = D-level repair cost in dollars for LRU_j (computed below)

The expected number of LRU removals is computed as

$$ENR_{jk} = \sum_{i=1}^{12} NAM_{ik} \times NPA \times U \times FM_j \times XK/MTBF_k \qquad (A.3\text{-}16)$$

where

NAM_{ik} = Cumulative number of equipment installs on the current aircraft through month i of year k (A)

and the repair costs as

$$BRC_j = BRT_j \times (SBR + SBMC) \qquad (A.3\text{-}17)$$

$$DRC_j = DRT_j \times (SDR + SDMC) \qquad (A.3\text{-}18)$$

where

BRT_j = I-level repair time in hours for LRU_j (E)

SBR = Standard labor rate at I-level in dollars per manhour (S)

SBMC = Standard materials consumption rate at I-level in dollars per manhour (S)

SDR = Standard labor rate at D-level in dollars per manhour (S)

SDMC = Standard materials consumption rate at D-level in dollars per manhour (S)

Standardization impacts the recurring maintenance costs through reliability improvement and consequently fewer equipment failures to be repaired over its life-cycle.

A.3.8 Packaging and Shipping

The cost to pack and ship units between base and depot is computed as

$$C_8 = \sum_{k=1}^{LIFE} \sum_{j=1}^{NLRU} 2 \times ENR_{jk} \times NRTS_j \times W_j \times (FOS \times SPSO + FC \times SPSC) \qquad (A.3\text{-}19)$$

where

W_j = Weight in pounds of LRU_j (E)

FOS = Percentage overseas deployment of the aircraft (A)

SPSO = Overseas packaging and shipping cost in dollars per pound (S)

FC = Percentage CONUS deployment of the aircraft (A)

SPSC = CONUS packaging and shipping cost in dollars per pound (S)

Again the impact of standardization is realized through fewer overall shipments as a result of reliability improvement.

A.3.9 Support Equipment Operation and Maintenance

The recurring cost of operating and maintaining support equipment required for the subsystem is estimated as a percentage of the SE acquisition cost.

$$C_9 = \text{LIFE} \times \text{CSEM} \times C_5 \qquad \text{(A.3-20)}$$

where

CSEM = Annual cost to operate and maintain an item of support equipment expressed as a fraction of the acquisition cost (S)

A.4 STANDARDIZATION FACTORS UPDATE

The updating of the standardization factors for an item of navigation equipment is an integral function in the global LCC model. After selection of an equipment for application in an aircraft, the equations in this section are applied to the standardization factors corresponding to that equipment. All equipment variables below refer to the selected equipment and all aircraft variables refer to the most recent aircraft program, i.e., the one generating the update. As a notational convention, primed symbols below refer to the values of standardization factors prior to the update in process. For example, the expression

$$x = x' + y$$

denotes that the updated value of the standardization factor x is equal to its old value plus the quantity y.

$$\text{ISS} = 0 \tag{A.4-1}$$

$$\text{NQ} = \text{NQ}' + \text{NA} \times \text{NPA} \tag{A.4-2}$$

$$\text{PC} = \text{FUPC} \times \text{NQ}^{\log(\text{LC})/\log(2)} \tag{A.4-3}$$

$$\underset{(k=1,\text{LSPAN})}{T_k} = \begin{cases} T_k' & \text{for} \quad 1 \le K \le \text{IBY} \\ T_k' + 6 \times \text{RP} \times (\text{K}-\text{IBY}) \times \text{U} \times \text{NPA} & \text{for} \quad \text{IBY} < \text{K} \le \text{IFY} \\ T_k' + T_{k-1} + 12 \times \text{NA} \times \text{U} \times \text{NPA} & \text{for} \quad \text{IFY} < \text{K} \le \text{IBY} + \text{LIFE} \\ T_{\text{IBY}+\text{LIFE}} & \text{for} \quad \text{IBY} + \text{LIFE} < \text{K} \le \text{LSPAN} \end{cases} \tag{A.4-4}$$

where

T_k = Cumulative usage in hours of the equipment on all aircraft through the start of year k (F)

IBY = Initial year of aircraft activation/retrofit schedule (A)

RP = Aircraft activation/retrofit rate in installs per month (A)

LSPAN = Length in years of the SPANS analysis horizon (program constant)

$$\underset{(k=1,\text{LSPAN})}{\text{MTBF}_k} = (T_k/T_{\text{IYA}})^{\alpha}\, \text{MTBF}_{\text{IYA}}/(1-\alpha) \tag{A.4-5}$$

where

IYA = Initial year that equipment is available for operational use (E)

α = Slope of the Duane reliability growth curve for the equipment (S)

$$\underset{(j=1,NLRU)}{PRR_j} = PRR'_j + NA \times NPA \times U \times FM_j \times XK/MTBF_{IFY} \qquad (A.4\text{-}6)$$

$$NSEB = NSEB' + NB - \sum_{i=1}^{NB} ISB'_i \qquad (A.4\text{-}7)$$

$$PSEB = FUCB \times NSEB^{\log(LCSE)/\log(2)} \qquad (A.4\text{-}8)$$

$$NSED = \sum_{j=1}^{NLRU} (PRR_j \times DRT_j)/(DHM \times UTIL) \qquad (A.4\text{-}9)$$

(rounded upward to next integer)

$$PSED = FUCD \times NSED^{\log(LCSE)/\log(2)} \qquad (A.4\text{-}10)$$

$$\underset{(i=1,NB)}{ISB_{IB_i}} = 1 \qquad (A.4\text{-}11)$$

$$\underset{(j=1,NLRU)}{NSDP_j} = PRR_j \times (BDS + DTAT) + DSF \sqrt{PRR_j \times (BDS + DTAT)} \qquad (A.4\text{-}12)$$

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