AFOSR 70-1379TR

IS REAL-TIME, ON-LINE OPTIMAL FLIGHT CONTROL FEASIBLE?

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Office of Aerospace Research

June 1970

(1) This document has been approved for public release and sale. Its distribution is unlimited.

86

ABSTRACT

An edited transcript of a special panel discussion "Is Real-time, On-line Optimal Flight Control Feasible?" held by the Theory Committee of the American Automatic Control Council on 5 August 1969 in conjunction with the 1969 Joint Automatic Control Conference, at Boulder, Colorado. The panel considered the problems associated with controlling an aircraft in such a way as to optimize some performance criterion. Specific subjects discussed include optimization theory and techniques, aerospace computer technology, and numerical procedures. A description of a current NASA project in this area is presented. Comments from the audience are also presented.

Qualified requestors may obtain additional copies from the Defense Documentation Center (DDC). All others should apply to the Clearinghouse for Federal Scientific and Technical Information (CFSTI).

DDC
Cameron Station
Alexandria, Va. 22314

CFSTI
U.S. Dept. of Commerce
Springfield, Va. 22151

AFOSR 70-1379TR

IS REAL-TIME, ON-LINE OPTIMAL FLIGHT CONTROL FEASIBLE?

a panel discussion held by
Theory Committee of the American Automatic Control Council
in conjunction with the
1969 Joint Automatic Control Conference
Boulder, Colorado
5 August 1969

Air Force Office of Scientific Research
Office of Aerospace Research, USAF
Arlington, Virginia 22209

June 1970

ACKNOWLEDGMENTS

The Theory Committee gratefully acknowledges the support of

--- the panel members for their individual participation

--- Analytical Mechanics Associates; Grumman Aircraft Corporation; and Autonetics of North American Rockwell, who encouraged their personnel to participate.

--- Air Force Flight Dynamics Laboratory, AFSC
Air Force Office of Scientific Research, OAR
Flight Research Center, NASA
for their participation and other considerations

--- European Office of Aerospace Research, for travel funds for Mr Moelker

--- Professor Gene Franklin, Mrs. Diane Lambert, and Miss Martha J. Leonette, for their valued assistance.

Foreword

The Theory Committee of the American Automatic Control Council has been seeking new ways of stimulating interest in the Joint Automatic Control Conference. After much discussion, members of the Theory Committee determined that a panel discussion on the subject of real-time, on-line optimal flight control would fill this requirement. It is a subject that is both controversal and relevant to current interest of the Air Force and NASA.

A panel of outstanding experts in various areas relating to this topic was selected. Each individual was asked to prepared a short presentation in their speciality. The discussion was held in a special session at the 1969 Joint Automatic Control Conference where approximately 150 people attended. The discussion that followed was quite good in that many different opinions were expressed.

The United States Air Force has a natural interest in this area since the successful performance of many of its missions can be enhanced by flying its aircraft optimally. The Air Force Office of Scientific Research, the extramural basic research agency for the U.S. Air Force, decided to publish an edited transcript of the session with the hope that this publication would stimulate further research in this area. Particularly, it is hoped that germs of ideas for many masters and PhD dissertations are contained within it.

This transcript has been edited only to reduce gross grammatical errors and to insert proper references. The open discussion has not been edited and is presented off-the-cuff in the hope of further stimulating new ideas.

June 1970

ALLEN D. DAYTON
Major, USAF
Applied Mathematics Division
Air Force Office of Scientific
Research

PANEL

Capt. Allen Dayton	A.F. Office of Scientific Research
Lt. Col. Loren Anderson	A.F. Flight Dynamics Laboratory
Dr. Henry J. Kelley	Analytical Mechanics Associates
Dr. Richard E. Kopp	Grumman Aircraft Corporation
Mr. J. J. P. Moelker	A.F. Flight Dynamics Laboratory
Mr. C. F. O'Donnell	Autonetics (N. A. R.)
Mr. Lawrence Taylor	NASA - Flight Research Center

CONTENTS

PANEL DISCUSSION

Captain Dayton: On behalf of the Theory Committee of the American Automatic Control Council I'd like to welcome you to this Session. The Theory Committee has been trying to devise ways to stimulate interest in the Joint Automatic Control Conference. We discussed many different ideas and one of them that we came up with is this subject we are going to discuss tonight. We think it is a controversial one; there are people that are very "pro" and people that are very "con" so perhaps we can get some of the best ideas tonight. I think we have an outstanding panel, I don't include myself, but I think the rest of the people on the panel are experts in their particular areas and I'm very pleased that we could get them here. I'd like to introduce them to you before we start off. On my left is Mr. C. F. O'Donnell from Autonetics who is going to discuss airborne computer systems in 1975 time period. I probably don't need to introduce the individual on my right; Dr. Richard Kopp who has been quite active in Optimization Theory for the past few years from the Grumman Aircraft Corporation. Next to him from the Air Force Flight Dynamics Laboratory is Lt. Col. Loren Anderson who, along with Mr. Moelker sitting next to him, is going to jointly discuss Optimal Display Systems. Mr Moelker is from the National Aerospace Laboratory in Amsterdam, Holland. Then down at the end of the table we have Mr. Larry Taylor from The NASA Flight Research Center at Edwards Air Force Base who has been doing more work in real-time optimal flight control than anyone that I know of.

Maybe some of you know of other people but I think his work, as you will find out when he discusses it, is at least up with the state-of-the-art. Dr. Kelley will be with us in a few minutes.

I am trying to find some place to hang my charts. I thought I would show you my ideas first and it looks like I'm going to have to hold the charts up. You know, we can control a lot of things, but we can't find a simple fastner. The first chart simply asks "Is real-time optimal aircraft flight control feasible?" which is the topic for this evening. We hope to stimulate controversy and discussion and to arrive at a yes or no opinion. Now the next question is, "Why Do You Want to Fly Optimally?" Well, there are many different reasons. First and one of the most obvious is the minimum time problem. Perhaps you know where you are by some sort of estimation procedure, you can put in some terminal conditions which you want to reach for some reason to minimize the time. Second, possibly you would like to fly to a certain point using a minimum amount of fuel. I think this would be particularly important in climbing problems. Third and a little more sophisticated at this point, is where there might be certain military missions, particularly bombing missions, where it is the range that you want to maximize. You want to fly on an aircraft flight profile such that you get the optimum range. A fourth reason might be to maximize the loitering time. I think you can see in Viet Nam that it is quite important that aircraft be able to loiter over certain territory for long periods of time. When we get to the supersonic airliner or supersonic planes, people begin to complain about sonic boom problems so perhaps it is possible to fly profiles such that your sonic boom is minimized at certain points on the ground. And reason number six, air traffic control which Mike Athans[1] talked about this morning and I'm not going to beat a

---

[1] Survey lecture by Michael Athans: Application of optimal control and estimation theory to air traffic control problems - 1969 Joint Automatic Control Conference, August 5, 1969, Boulder, Colorado.

"dead horse" but I think that it's a very important area. Another area involving optimal flight is optimal combat maneuvers and the Frank J. Seiler Research Laboratory at the Air Force Academy has been doing some studies in this area.[2] It turns out that these problems are exceedingly complex differential game problems and they haven't made a great deal of headway, but I think they have at least defined the problems better. If we can't solve the pure differential game problems then perhaps we can solve certain submaneuvers. These, of course are military maneuvers. I understand Grumman[3] has been doing some work in certain types of climbs and turns which should be used in optimal combat. Along with this and more or less going along with what Mike Athans said this morning is the problem of air traffic control of combat aircraft in environments such as Southeast Asia. It's somewhat similar to the aircraft traffic control problem yet the problems are quite different.

Now then, how are we going to develop this "know-how" to fly optimally on-line and in real-time? It is my opinion that we need a three-prong attack and the reason that these speakers are here is because I have more or less used this as the criteria we should go by. One, I think we need to continue our work in optimization research. Two, I think we need more work in numerical analysis and; three, with a big strong emphasis I think we need more work in digital computer research, particularly airborne digital computer research. We need to develop better optimization methods similar to conjugate gradient or random search methods. I don't want to

---

[2] A computer optimization study of a three-dimensional engagement between a surface-to-air missile and tactical aircraft. DeDoes, Senne, Schaefer, and Morgan. Frank J. Seiler Laboratory Report FJSRL 69-051, SRL 69-009, July 1969. See Appendix II.

[3] Formulation and application of a Trajectory Optimization Program for Powered Lifting Vehicles (TOPLV) Grumman Aircraft Corporation. Advanced Development Report No. FSR AD6-06-68.3, December 1968.

emphasize any particular method but I do think we need to do more work in this area. As for numerical analysis, I think we should look at such things as better approximation techniques. Perhaps we don't need to carry out all the long equations. Spline functions fits or orthogonal expansions which I think Mr Taylor will talk about later is one way.[4] And again, in numerical analysis, we need to look at better and faster numerical integration schemes.

(Here someone from the audience suggested "try analog computers")

Captain Dayton: Give us the accuracy and we will be happy to use it.

Someone else said "Do you really need that accuracy?"

Captain Dayton: That is a point I think that is well worth studying. You know, you might do it. However, it is my opinion that most of our hope is going to come from the digital computer side. It will be our salvation. (From the audience..... "Bury that analog man".)

Captain Dayton: Some of the things I think the digital computer people should be investigating for us and perhaps we as control people should be investigating are how do we use digital computers and what types are required. We need faster computation and we need much larger memories. The computer people keep promising that things like large scale integrated circuits and MOS (Metallic Oxide Semi-conductors) are going to give us these memories, perhaps Mr. O'Donnell will give use some words on this later. We need parallel processors. We need modular concepts with special purpose hardware for computing certain functions and we need the software to take advantage of all this hardware; particularly the parallel processors. As far as I know, today we haven't even begun to

---

[4] On the convergence of the Ritz-Galerkin procedure in the calculation of optimal control by the Epsilon technique. Sheng-Choa Huang UCLA Report No. 69-47, AD 695036, August 1969.

come up with any sort of software that can handle parallel processors. I suggest these ideas to start things off and now I am simply going to turn the session over to Dr. Kopp for the next round.

Dr Kopp: Before discussing the feasibility of on-line optimal aircraft flight control, it is appropriate to examine the question, "Is on-line optimal aircraft flight control needed and, if so, where?" I have serious reservations whether this type of control, for example, is required or even desirable for controlling the short period dynamics of an aircraft. In contrast, however, on-line performance and trajectory calculations could have significant implications on tomorrow's high performance aircraft. I believe there is also an in-between area where the computer would determine variable parameter values rather than calculating trajectories or time histories so that a particular performance function would be optimized, thereby leading to what might be thought of as a suboptimal system.

First, I would like to indicate why I have reservations concerning the need for making on-line time history calculations to control short period aircraft dynamics. I cannot help thinking back several years ago to when adaptive controls first became "fashionable." The justification given for the "adaptive approach" was the availability of new engines, with significant increased performance capabilities, enlarged the flight regime to the point where classical control techniques would not be adequate. The adaptive flight control system was to be designed to control an aircraft with unknown time-varying parameters. Many clever and esoteric schemes were proposed to achieve this rather ill-defined goal but few proved practical from an economic or reliability point of view. I believe more progress would have been made if more consideration had been given to the real requirements placed on the control systems, using, rather, an evolutionary type of design approach. By "evolutionary" I mean an iterative design approach that begins with a simple system that can grow in complexity in a systematic way so that the performance of the system is quaranteed to improve with each design iterative terminating at the point of diminishing returns. To illustrate this I would like to discuss briefly a longitudinal control system design for a high performance aircraft that one of my associates examined using realistic aerodynamic data.

Figure 1 shows the natural frequency and damping factor of an unaugmented aircraft for several different flight conditions. The control system designer's problem is to design a control system such that the natural frequency and damping factor of the augmented airframe remain within specified limits for all flight conditions. This region is often referred to as the CAL Thumbprint. As you can see, the unaugmented airframe does not meet the specifications, indicating that some type of control system augmentation is required. An alternate performance criterion is to measure the variation of the time history of a specified linear combination of pitch rate and normal acceleration with that of a desired time history. This criterion, which was recommended by Tobie of Boeing, is known as the C* criterion. For the particular example that I am discussing, the desired time history was chosen as the one corresponding to the center of the CAL Thumbprint. The feedback variables were also chosen as pitch rate and normal acceleration.

The first design in the iterative approach was to select fixed gains for the feedback variables such that the deviation of the C* time history, from the prescribed C* time history corresponding to the center of the CAL Thumbprint, was a minimum in a least squares sense, averaged over many different representative flight conditions. The results of this minimization are shown in Figure 1 as circular symbols for different flight conditions. It is observed that this design is superior to the unaugmented airframe, since the minimization was carried out over the set of parameters that included the unaugmented airframe (zero gains). However, the design does not meet the specifications since several points still lie outside the CAL Thumbprint. The second iterative design was to let the feedback gains take on two different values as a function of another variable. A superficial analysis would show that the damping factor and natural frequency vary predominantly as a function of dynamic pressure, thus this is a natural variable to select to determine which of the two values of gain should be used. A minimization was again carried out to determine the feedback gains (four in this case), with the results shown as the solid squares in Figure 1. It is now observed that, with a simple feedback gain and one switching as a function of dynamic pressure, all points lie within the CAL Thumbprint; the number 1 point corresponds to a power approach condition and is not required to be within the thumbprint but must lie above a specified power approach boundary. Figure 2 shows many more flight conditions with this control system design, which my associate chose to call a discretely adaptive system. If this design still does not satisfy the performance criteria, three sets of gains could be used and the procedure repeated. One might also consider making the gains a function of more than one variable, although I doubt very much that this would be required. The point that I wish to make here is that by using an iterative design approach, the design procedure must improve in each iteration and can be terminated when the point of diminishing returns is reached. In this example, a very simple design resulted.

Today's high performance multimission aircraft are incorporating, in addition to the more standard controlling devices, controlling devices that in the past were very rarely used, such as variable wing sweep, direct lift devices, glove vanes, etc. These devices open up areas where

I believe on-line computer calculations may make significant over-all performance improvements by determining variable gains for a completely integrated control system. In the area of real-time trajectory calculations, two applications immediately come to mind: all weather landing, and collision avoidance. Here, the payoff can be big and thus justify the expense of an elaborate on-board computer. In fact, any emergency situation in which the pilot does not have adequate time to analyze the situation and take appropriate action could benefit significantly through the use of an on-board computer for on-line analysis and display. I am not advocating taking control away from the pilot but merely instructing or assisting him in an emergency situation. The payoff in this situation is even more significant than the one Mike Athens[5] spoke of this morning in regard to relieving the pilot of routine decisions and actions. Another area that comes to mind in which an on-board computer analysis capability might offer a significant contribution, is the problem of flight through turbulent air. An on-board statistical analysis could be made and control gains adjusted appropriately, with pilot performance as the payoff and with structural limits as the constraints.[6]

The last point I would like to make is this: one should consider very carefully the tradeoffs between increased performance, reliability, effect of failure, and cost when considering a rather sophisticated on-board flight control computer. Limited on-line optimal aircraft flight control is feasible today -- but is it worth the price?

Captain Dayton: Thank you, Dick. Dr Kelly is now with us and I would

---

[5] See page 4.

[6] This is somewhat similar to the Aircraft Load Alleviation and Mode Stabilization Program at the AF Flight Dynamics Laboratory. See AFFDL-TR-68-158, DDC 854791.

like to introduce him at the end of the table. He will be talking in just a minute. Next, Mr. O'Donnell is going to tell us what we can expect out of airborne digital computers in the 1975 time period.

Mr O'Donnell: In order to cover the material as rapidly as possible, I will use a number of almost self-explanatory viewgraphs. I should point out first of all that I am obviously an ideal person for a panel like this. I have an almost complete lack of knowledge of anything about flight control. In fact, my sole contact with airframes left me with the impression that they are rather undesirable places to put our very fine digital computers. Some years ago we made the mistake of installing a computer which worked beautifully in the laboratory in an airplane to be tested in the tropics. Test personnel came back with the suggestion that we bore a small hole in the bottom of the pressurized case. The reason was that during ascent from the deck to 50,000' the cooling air, which in those days was blown directly on the component boards, had a high water vapor content which condensed on the boards. It corroded all of our contacts and made big puddles in the bottom of the case. That is when I came to the conclusion that airframes were no place for digital computers.

Fortunately with the reduced power requirements of our later computers and changes in the packaging and cooling systems, we have managed to cope even with the severe environment. I thought then that I would start with the first graph, Figure 3, which makes the uncontroversial statement that the trend in data processing is to all-digital systems which obviously includes adaptive flight control.

In the next chart, Figure 4, I show our development trends in digital data processing. We started using it back in the early 60's due to the high precision required of inertial navigation computers on vehicles operated for extended period of time. It was difficult, if not impossible, to obtain this sustained precision with analog computers. During early work on analog to digital converters at MIT, I had been impressed both with the difficulty of getting analog accuracy of a part in a thousand in the first place and maintaining it in the second place. In addition, I was impressed with the ease of distinguishing between say a zero and a 15 volt level which was all I had to do in the digital system. Circuit tolerance to component parameter drifts was very high in the digital parts of the system. For this reason, if you want precision it seems most logical to add one or two bi-stable circuits with high tolerance to parameter variations rather than to attempt to distinguish between 4.99 volts and 4.98 volts reliably.

Having been forced to digital computers by the requirements for precision in navigation computation, we found it easy to extend the digital computer to take in other functions. At present, as shown in the center section of Figure 4, we include fire control, mission data, and an expanded navigation function plus the flight control operations or rather a part of the flight control operations. We predict that this trend will continue and in the '75-'80 time period, we will include those things shown on the right-hand side of Figure 4.

With this trend in usage, what has been happening to our computer requirements? The next chart, Figure 5 shows the trends in our 3 main areas of concern: speed of operation or how fast can you compute, the input/output or how much peripheral equipment can you handle, and the memory requirements or how big a program can you store.

In addition to the functional trends, I included the cost of on-board computers for representative airframes up to the '75 time period. You can see that while our requirements for speed, memory, and input/output capacity have risen between one and two orders of magnitude per decade, the total computer cost has been decreasing.

I would like to show you why this has been happening. In the next graph, Figure 6, we show the effect on cost and other computer characteristics of the evolution of components used to build computers during this time period. We started with vacuum tubes, went to discrete transistors, then bi-polar integrated circuits and now in computer laboratory models, we have MOS large scale arrays operating. All of thse changes have led to a reduction in both power and weight per equivalent component. Volume reduction has been one of the most spectacular accomplishments. Reliability per component has been increasing, and the cost per component has been dropping at a very acceptable rate. These are the trends that have made it possible to take on the number of on-board computing functions that we are doing today in an economic fashion.

In this next graph, Figure 7, I show some of the changes that are improving the cost-effectiveness of the components we use. This shows the costs of today's bipolar IC's and MOS-LSI. As the clock rates of 10-30 megahertz for bipolar IC's are expected to go still higher, any reasonable or even unreasonable computing speed requirement for on-board computers can be met.

While the MOS devices are slower, they have a very marked advantage in cost; therefore, for some on-board computer organizations it appears that these inexpensive large scale arrays can carry out practically all of the on-board computing requirements.

As shown in the next slide, Figure 8, not only the devices themselves but also the techiques of mounting devices have been evolving. That shown on the left-hand side I regard as obsolescent though not obsolete technology, as it is used in mounting bipolar IC's on multilayer interconnection boards in today's computers. This gives you the equivalent of some 3,000 discrete components on a single board.

Roughly, two of these boards are now contained in the MOS-LSI board shown in the center of Figure 8. All of the MOS-LSI devices needed for the central processor unit of an on-board computer are mounted on the two sides of this board. It carries all the input/output circuitry needed for interfacing with the various sensors, actuators, and displays. It has the interface circuitry needed for the memory and the input devices whether they be keyboard, tape or other, all on this single board.

The next step, which is still in early development, is to use the beam lead technique illustrated on the right-hand side of Figure 8. Using beam leads or face bonding or some variation, the computer size shrinks to an almost ridiculous level. The latest computer we are programming for about two years from now has a volume as I recall of something like 12 cubic inches.

Computer memories have also been evolving as shown in Figure 9. We started out with disc memories. These having serial access posed problems for the programmers. We went from there to random access magnetic core memories. Originally more expensive, they have now dropped for military applications to the order of $.05/bit and for commericial versions are closer to $.02/bit.

While these less expensive random access magnetic core memories will be with us for some time, plated wire memories will probably overlap and further reduce costs. I don't know whether the projections of something like 1/10th or 1/100th of a cent per bit will be met; nevertheless, random access plated wire memories with non-destructive read-out can soon be packed into a space which is large by comparison with the central processor unit but trivial compared with today's computers. This will allow us to store any reasonable or unreasonable size program required for on-board digital computers.

To further improve the picture for these on-board computers, we are going to read-only memories in addition to the standard read-write memories. Some of these are electrically alterable using approaches such as the MNOS devices; others are read-only diode or MOS-FET arrays. The lower right-hand corner of Figure 10 shows a 128 bit memory of the read-write type used for scratch pad memory. In the lower left corner is pictured a 1024 bit diode array. In both cases the actual devices are on a chip of silicon about 200 mils on a side.

These fixed memories can handle many of the repetitious calculations used during flight, for example, angular transformations. Any instruction will call out the complete sequence needed for angular transformation of a vector into any required reference system. These fixed memories can greatly reduce programming time by comparison with that required for our present computers.

I don't intend to go into Figure 11 in any detail. I have used this slide primarily to make the point that flight control has a relatively low data rate requirement for input and output by comparison with many of the things currently under development. In some cases, we have to deal with data rates of more than 100,000 bits of data/second. In research, we are developing surface acoustic wave devices which can operate up to the gigahertz frequency range. Such devices, some of which are already working in our research labs, make it possible for us to interface with equipment with input/output rates far in excess of anything I see as a potential problem in the flight control area.

Putting all of these components and subsystems together then we have the comparison between present and future avionics computers shown in the next slide, Figure 12. The left-hand side shows a computer which is a composite of those used in today's avionics systems. It has a computing capability quite comparable to the 7094, a relatively recent commercial computer. In the lab we have working prototypes of the D-200 shown on the right-hand side. It continues the trend to very small size and greatly reduced cost for a computing capability which is an improvement over that available in today's computers.

In this next slide, Figure 13, I show the present technique for obtaining fail-soft operation with digital computers in on-board avionics. Either computer can handle those computations considered vital to airframe survival. However, everything funnels into these two computers. This is not the most desirable arrangement from either a software or a hardware point of view.

In this next slide, Figure 14, I have shown both the hardware and the software requirements and schedules for an on-board avionics digital computer. It takes 18 months to develop the hardware and there our experience is sound. The software, however, is very complex. It must be meshed in with the hardware program, and more problems arise due to incompatibility between the software and hardware than almost anything else you care to consider.

This is aggravated by the fact that the Air Force initially always wants a minimum cost program so they squeeze you on speed and memory capacity leading to the sorts of problems shown in this next slide, Figure 15. In spite of the fact that random access memory computers should be easier to program, our system programming costs have been rising. The reason is shown in the next slide, Figure 16, where we see the cumulative effect of a whole series of hurdles a programmer has to clear. Individual programs would be simple. Flight control, fire control, or navigation each by itself is not all that difficult to program, but when you put them all together, combining them in one block and do it with a mixture of inexperienced and experienced programmers, you encounter memory and speed limitations and programming costs rise. It is this combination of problems that is hurting us at the present time.

In addition, we do have an airframe hardware problem as shown in the next slide, Figure 17. I thought this shot which shows the cabling of a late model commerical supersonic transport illustrates our present interconnection problems very well. It adds several tons of weight to the aircraft and makes system changes exceedingly difficult.

I feel that the combination of hardware and software problems shown require that we re-examine our systems organization for on-board avionics. Instead of trying to bring everything into one central computer complex as we do today, perhaps we should revert to some of the analog ways. I do not mean to revert to using analog computers, but rather to take advantage of the low cost digital computer capability coming up to decentralize our computers so that at least preprocessing is done at each sensor in the system. There is no reason why we should not look at flight control as a separate entity with its own data processor, aided in some areas by a central processor complex which controls the overall flow of information. This leads to the organization shown in this next slide, Figure 18, where digital data processors are associated with the individual sensors, displays and actuators. A multiplex system is used to tie the overall system together.

In the next slide, Figure 19, you can see the visible external results of following this philosophy. The mass of cables is replaced by a small number of coaxial cables with the time-division multiplex system. The use of coaxial cables gives you as a bonus, better EMI characteristics, lower cross coupling between unrelated signal leads and other advantages. With proper physical separation and minimum redundancy, vulnerability to accidental or other damage can be reduced at the same time.

This system approach seems to be the proper way to go to make programming an easier job. If you have to fit adaptive flight control programming into a computer along with everything else you are doing on-board, you have a major software problem. This different approach to system organization would break adaptive flight control out as a relatively simple self-contained and manageable program. This I feel would make an adaptive flight control, if it is desirable, something which can be practically included and carried out in on-board digital computers. I do thank you.

Captain Dayton: Mr O'Donnell, I would like to ask you one question which I think is important in the computer area. "What do you think of parallel processing"?

Mr O'Donnell: While multiple processing is more what I am calling for in the system organization above, parallel processing would be an interesting possibility. As you have pointed out, we don't have the software for it today. We have a tremendous problem already in programming on-board computers. If we want to use parallel processing as opposed to a decentralized hierarchy approach, certainly we should invest large sums in research projects to bring parallel processing along very rapidly because we really don't know too much about it at this time.

[NOTE (Capt Dayton): It would appear that the way to go would be to use the decentralized hierarchy approach but along with it to use parallel processing for such special functions as navigation (nonlinear estimation) and optimal profile flight computation]

Captain Dayton: Thank you. We will go on now... Our next speaker is going to be Dr. Kelley.

Dr. Kelley: I just want to say a few words about a particular point of interest in some work I have been doing lately. It is in connection with the long term dynamics of the airplane. I agree with Dick Kopp that the short period stuff can probably be handled with the technology of the 1950's, poles and zeros sort of thing. And optimal control, flight control of the short period modes would probably be gilding the lily or at least there is no obvious large return possible over what can be had with simpler schemes.

Now, in the longer period stuff the situation is quite different, climb to altitude, range performance, and so forth. There has been some work recently in the Air Force on energy maneuverability by Boyd and Christie.[7] Boyd is a Lieutenant Colonel assigned to the F-15 project[8] and Christie[9] is a civilian at Eglin Air Force Base. Their work exploits the energy approach, simplified state system model, and makes some practical use of it. More recently these people have been off on a turning performance kick and they have been able to influence the design of new fighter aircraft to the extent of making turning performance and ability to maintain energy in turns actual design criteria, quite a step forward. It's very hard to put rational numbers of this sort of thing. There are no specs on it yet, except what these people have done. Their approach is kind of semi-empirical. They have tried to take the energy climb approach and extend it to the out-of-plane case by a dimensional analysis sort of idea. And it has some merit.

There are theoretical approaches to the same thing that I have been starting to look at, and I think it has some promise. It looks at least interesting from a research viewpoint, and if we can really have something like a 7090 on board or even half of it, it could be very well applicable to on-board, in-flight real-time path control. There was a paper in one of the sessions earlier today on singular perturbations of differential

---

[7] Contained in the Air Proving Ground Center Report APGC 66-4, AD372287, Classifed Secret. However the section on Energy Maneuverability is reproduced in Appendix I.

[8] Recently moved to Andrews AFB, Maryland.

[9] At the Air Force Armament Laboratory, Eglin AFB, Florida.

equations applied to optimal control.[10] This sort of approach, theoretical approach, it appears might put the energy maneuverability theory on a respectible mathematical level, but, more than that, it might allow it to be extended to out-of-plane applications which are really of interest. Actually, the path control problem in flight is 3-dimensional. Yet, most of the work on flight performance using this approach has been 2-dimensional until quite recently. But I think there is a ray of light here and some possibilities are developing. I, personally, have gotten quite interested in it in the last three or four months, and so I thought it would be worth mentioning here tonight.[11] Thank you.

Captain Dayton: Thank you, Dr Kelley. One of the problems encountered in a airplane with a computer flying under optimal control is the man/machine interaction and how to get the information back to the pilot. To start off on this area, we have Lt Col Loren Anderson to speak about some of the work his group has been doing at the Flight Dynamics Laboratory.

Lt Col Anderson: Thank you very much Captain Dayton. When Captain Dayton called and asked Jack and I to participate in this discussion, he asked us to discuss display projects that are related to optimal control. Therefore I would like to relate several projects in the cockpit display area that might have some growth potential related to the problem under discussion tonight. In these discussions, I will make the assumption

---

[10] Singular Perturbation Methods for Near Optimum Design of High-Order Nonlinear Systems, P. Kokotovic and P. Sannuti. Proceedings of the 1969 Joint Automatic Control Conference, Boulder, Colorado, page 257.

[11] See "Energy Climbs, Energy Turns and Asymptotic Expansions" by H. J. Kelley and T. N. Edelbaum, also "Flight Path Optimization with Multiple Time Scales" by H. J. Kelley, both to appear in the AIAA Journal of Aircraft.

that the blending or automaticity, augmentation, and manual control is such that manual control capability is required. Assuming we accept the manual control requirement, the problem resolves to several questions. What are the system display requirements? What information transfer and processing is required and how do you achieve this?

We have an interesting device developed in conjunction with the vertical take-off and landing advanced development program. This device illustrates the flight profile indicator (FPI) concept that started with the idea the pilot needs some sort of display to give a big picture in the vertical plane during the penetration and final approach of both conventional aircraft and vertical take-off and landing aircraft including helicopters. Initially we mechanized this concept with an electro-mechanical instrument in a simulator. Mechanical limitations resulted in poor performance. Subsequently we got a Heath kit and generated the display you see here. (Figure No. 20). The final approach and penetration paths are generated and placed in proper perspective in the vertical plane. The dashed line emanating from the vehicle is a velocity vector with true direction either increasing in length or decreasing in length depending upon the instantaneous acceleration or deceleration along the flight path.

Currently, the FPI is installed in a CH-3C helicopter flying against the Honeywell State equipment which has localizer capability and also DME. From the DME signal we can generate range and range-rate and from the altimetry gear aboard the helicopter altitude and altitude rate are available. With these parameters we can generate the FPI display.

In addition to the CH-3 flight test program several simulator efforts are investigating the human performance parameters involved. When is the best time to change the scale? What scale should be used? And what are some of the other human factors aspects of the problem? (Figure 21)

This panel is the basic pilot factors panel. The pilot factors (PIFAX) program was a joint Air Force-FAA program which had a basic objective of putting the pilot most effectively in the control loop. The PIFAX work has been extended to the VTOL vertical take-off and landing problem area using essentially the basic pilot factors display plus a flight profile indicator as shown on the right of the viewgraph. This is the type panel used in the CH-3C helicopter. The cross-hairs on the attitude indicator are used for precise guidance and the flight profile indicator is used for the big picture orientation. We may extrapolate this approach to the problem under discussion today in that the more complicated flight paths will probably need some sort of a big picture situation display such as a flight profile indicator. In the 2-dimensional problem a display very similar to the flight profile indicator is appropriate. The 3-dimensional problem brought up earlier is a very real and much more complicated problem. We do not have a solution to the 3-dimensional problem at this time; however, some work has been done in this area.

In addition to the component projects such as the FPI we are interested in the overall problem of computer display feasibility for flight performance optimization as a logical extension of the component work. We were very fortunate to have Mr. Moelker from the National Aerospace Laboratory in Amsterdam spend a year (August 1967 to August 1968) with us under the Exchange Engineer Agreement of NATO. Under his technical supervision a computer display feasibility study for flight performance optimization was accomplished. This was a joint effort between the Flight Control Division and the Flight Mechanics Division of the AF Flight Dynamics Laboratory. At this point, I would like to turn the discussion over to Mr. Moelker who will discuss the conclusions of that study. Thank you very much.

Mr. Moelker: The study that was just referred to by Lt Colonel Anderson is published in a report. The title of the report is Computer Display Feasibility Study for Flight Performance Optimization.[12] The approach that was taken in the study is somewhat similar to the one mentioned in the session[13] on air traffic control problems. We were not primarily interested in air traffic control problems, but this certainly is an interesting area of work. When I came over from Holland last Friday, it took me 28 hours to get from the Hague to Dayton. In considering the area in which most of the work should be done, it is necessary to look at the operational requirements. This is covered briefly in the report.

Before embarking on a system development program, however, more thought should be given to defining the requirements. The minimum time, minimum fuel, maximum range, maximum endurance, range-time, altitude rendezvous and zoom climb optimal flight maneuvers are considered important.

The main assumptions made in the study are the following:

(a) The aircraft can be represented by a point mass

(b) Perfect information is available from the sensors, therefore, Kalman filtering techniques were not considered.

(c) The study was further limited to aircraft motions in the vertical plane only.

(d) The last limitation relates to the control variables. The flight path optimization system was developed for the F-104C instead of the F-111 or any other airplane with more control variables than just throttle and elevator.

For the stated open loop problem a literature survey was made on the

---

[12] AFFDLTR-68-125, AD844 468.

[13] See page 4, survey lecture by Michael Athans dealing with the three-dimensional problem.

state-of-the-art optimization programs. Several methods listed in the report use the exact model for the point mass. Others use a simplified model. One of these has been discussed; the energy maneuverability theory. This technique was not solved for the variable thrust problem at the time of the report. Unfortunately, there are some painful restrictions in the simplified model. There appear discontinuities in the solutions and these are difficult to fly; so fairings are needed and that complicates the method. The question remains as to how to generate the path that is produced by a program.

What is needed is a program that gives the ability to compute the path in real time, on-board the aircraft. Another possibility is to store solutions on board the aircraft and select a nearly similar optimal solution from a dense enough family of pre-calculated solutions to the problems expected. The last possibility is a mixed version of the other two.

The second approach was taken because the first one was not feasible and insufficient information was available on mixed versions. Irrespective, however, of the method in which you generate the path, the pilot has to fly it. A literature search was made and it was found that besides the automatic handling and terrain following problems, there had not been much done to get a solution for flying a predetermined path that is not a straight line. Some of the paper and pencil work is given in the report. As mentioned by Lt Col Anderson, several programs are going on that are related to this one. It is hoped that more work can be done in this area in future years. Thank you very much.

Captain Dayton: As Dr. Kelley mentioned earlier, some interesting work has been done by the group at Eglin Air Force Base under Lt Col Boyd and Tom Christie in energy maneuverability. The report describing this work came out in 1966 by the Air Force Armament Laboratory and I have a copy of the report back in my office which doesn't do much good now. The report is classified, however, the section on energy maneuverability in the back is not classified. It can be obtained from DDC by anyone who has a security clearance. And like I say, the section on energy maneuverability is not classified.[14] There has been some very interesting work done, also on energy maneuverability, by Voss and Stettler in the Advanced Development Group of the Grumman Aircraft Corportion. I don't have the number of those reports, but they are classified confidential.[15] The reason they are classified is because they consider particular aircraft such as the F4C or F-111 and give performance characteristics. But they compare the energy maneuverability methods versus a conjugate gradient method in one of them and a more or less standard gradient method in the other. For anyone that is going to work in real-time optimization, I think these reports are extremely valuable. You will have to weigh in your own mind whether we should be using algebraic criterions such as energy maneuverability or just trying to maximize certain performance indices such as

---

[14] See Appendix 1.

[15] Comparison of Optimization Techniques on a Minimum Time-To-Climb Problem of an FX/VFAX Type Aircarft: Part I - The Energy Maneuverability Method vs. the Modified Gradient Penalty Function Method by J. Voss and A. DaPuzzo, Grumman Advanced Development Note ADN 06-06-68.1, April 1968 (CONFIDENTIAL).

Comparison of Optimization Techniques on a Minimum Time-To-Climb Problem of an FX/VFAX Type Aircraft: Part II - The Modified Gradient Penalty Function Method vs. The Davidon Conjugate Gradient Method by M. Stettler and J. W. Voss, Grumman Advanced Development Note ADN 06-06-68.2, April 1968 (CONFIDENTIAL).

Comparison of the Energy Maneuverability and an Accelerated Gradient Method for Estimating the Maneuvering Performance of Supersonic Fighter Aircraft by J. W. Voss, Grumman Advanced Development Report ADR 06-06-69.1, March 1969 (CONFIDENTIAL).

minimum fuel. We have one more speaker and then we'll open the session for general discussion. Mr Taylor has been doing some work in this area for NASA of the Flight Research Center at Edwards Air Force Base and he has previously given one of his papers[16] at the meeting of the AIAA in New York back in January. That's where I first ran across it. So, I will turn it over to Mr. Taylor.

Mr Taylor: After that build-up, I wasn't sure he had the right man. But, I would like to outline some of the things we are trying to do at the Flight Research Center in this area. Our interest has been specifically this, to generate solutions fast enough for real-time optimal profile system. We first became interested in this when we found that through an application of dynamic programming, we were able to generate solutions very fast. And having an Alert computer around and a stable-table and an F-104 and the possibility of putting them all together, the program was initiated. The program consists of three phases: One, ground-base calculations just designed to speed up the calculation process using several schemes. The second is to simulate those methods of creating the optimal profiles that appear to be suitable for real-time applications, and find out if they are going to be fast enough and what problems each particular method has. And finally, the flight test of the methods that prove out in the simulation. Now, for the methods that are in competition right now or we're planning on trying. First we are going to go through an exercise with just a canned profile. Now, what I mean actually is more than just a single canned profile, but rather a family of profiles

---

[16] Experience using Balakrishman's Epsilon technique to compute optimum flight profiles, by Lawrence W. Taylor, Jr., Harriet J. Smith and Kenneth W. Iliff presented at the AIAA 7th Aerospace Sciences Meeting, New York, New York, Jan 20-22, 1969.

as you would have generated with dynamic programming. You have a whole tree of profiles coming from a starting condition or converging to an end condition. So, that if you would find yourself off the particular branch of the tree that you had intended to follow, then you are on another branch that will give you the optimal profile from that condition rather than continuing to go back to some pre-computed nominal. Simulation of this caused us to think. We thought this was going to be a very routine job, we were so nieve. Then we started seeing double-valued functions of velocity and altitude appearing and didn't figure that we could really talk about errors in those quantities. So what we have gone to is a desired flight path angle as a function of altitude and Mach number. Then you present to the pilot a zero reader, and he tries to nullify this error between the desired flight path angle and the actual flight path angle that he is experiencing. By so doing he will follow these branches of the optimal profile to the end condition. So we have used dynamic programming to generate these trees. This can be done very fast. You have complete freedom in a trade between the quality of the tree that you generate and the speed of computation. We are talking now about discrete state space, i.e. at combinations of altitude and velocity you have nodes through which you are routing. The grid you select can be very course with a relatively small number of nodes enabling the calculations to be performed very fast or a higher quality tree can be achieved by selecting a fine grid and taking a longer time to perform the calculations. So dynamic programming is fast but it is cruder than we would like. Another method that looks very promising is what we call the Epsilon Technique of Balakrishan. It's a modification of the standard gradient technique that eliminates the need for solving the adjoint equations and enables you to compute the gradients much faster and requires much less memory on the part of the computer. In the New York paper that Captain Dayton was referring to, we tried to make some sort of a comparison of computation times. It's impossible to make any direct comparisons with the information I have been able to find in the literature, but we have tried. And it (Balakrishman's Epsilon Technique) appears to be somewhere from 4 to 100 times as fast as the more classical approaches. The flight test will not be starting until the end of this year and that will be the canned profile and what sort of scheduling and troubles we'll have is anybody's guess. That is about all I have to say.

Captain Dayton: Thank you Mr Taylor. We realize that we probably haven't covered all of the work that's going on in this area and I would now like to open the discussion at this point to anyone who feels like they have done any work that they'd like to discuss. Please feel free to come up and tell us about it. If we have no takers, I would like to ask a question just to get things started and then I think we can open it up. I'd like to ask, would anyone on the panel care to make any comments about the estimation problem that would be required before you can fly optimum profiles? In other words, it looks to me that if you are going to solve a two point boundary value problem you will need to know where you are and where you want to go. Does anyone want to say anything about this? No takers. All right, I'll let somebody else ask the questions.

Dr Kelley: Tell us about your Flight Test Program. What airplane are you flying there?

Mr Taylor: Mine?

Dr Kelley: Yes.

Mr Taylor: O. K. we are flying the F-104 and we've got an Alert computer which is a Honeywell derivative. I would like to indicate the sort of computation times we're thinking about for updating the dynamic programming tree. A new table of desired flight path angle as a function of altitude and Mach number, is expected to require 4 or 5 seconds with the class of computer we're talking about in the Alert. Now, that's only an estimate because we haven't exercised the program on that computer. We've worked with a computer having similar speed but we could get some surprises in going to the Alert computer. The Epsilon technique requires about 10 iterations to go from just a straight line connecting the end conditions to a final solution. But you don't have to do that each time. You are updating the trajectory from where you are to where you want to go. So, an update in terms of just one iteration requires on the order of twelve seconds time. Now, we have fit these programs into computers of similar memory that we are talking about tonight. But I say I still have to hedge my bets because we haven't gone through a detailed development and debugging on the actual computer we intend to use in flight.

<u>Captain Dayton</u>: Does the panel have any other questions? Anybody on the panel? O.K. we'll open it for general questions from the floor. Would you please stand up and state your name and who you represent. O.K. you've got your hand the highest.

I am Ed Bristol of the Foxburrough Co. which is a process industry so you can see how far off I am. But I am kind of the sympathies obviously of the second speaker who had the feeling there ought to be simpler ways of doing these things. And if I were approaching the kind of problem we talked about here, off the top of my head, the kind of thing that would come to mind to me is I would develop an alphabet or a dictionary of basic trajectories if you will which I would then optimize or provide the perturbation method specially designed to handle each one of these trajectories. And I would think in terms of an on-line conversational language if you will where a pilot could tie together a number of these useful trajectories to do what he eventually wanted them to do. Now how much of this sort of thing would follow the thinking of the gentlemen up there in terms of both in man-machine communication problems and their approach to this whole problem of getting effective use of optimization in an on-line environment.

Captain Dayton: Since Dr Kelley did some of the first optimal trajectory work in this country, I think it would be appropriate to ask him to answer the question?

Dr Kelley: I'm not sure I get the gist of it.

Mr Bristol: The gist of it is this, I would like to create an alphabet or a set of basic trajectories which we can analyze. These would then be available for a pilot to compound linguistically to do a variety of things.

Dr Kelley: I think that sort of think is possible and its a sweat right now to do these things on the ground even with plenty of time. But with these more rational approximation schemes like the asymptotic approximation thing I mentioned, I think you might wind up with an on-board in-flight scheme that would store segments of trajectories, say, mai: energy arcs and you would be in a mode of either getting on it or getting off it by some transition logic, or following it. And this is the same sort of thing I think you have been talking about. So, I certainly agree with you, that you have to simplify. I'm not pushing in-flight solution of the Euler equations. It's hard enough to do it on the ground with plenty of time. You've got to make drastic approximations and I think we've got a lot to learn to know how to do that.

Mr Bristol: There are two factors here I'm getting at. One of course is the computational side of it, the other is the side of it of the particular pilot who is trying to achieve some end. And he needs very much to understand how these things compound, and both of these I think probably would end us up with something appreciably short of the on-board subroutines.

Captain Dayton: I think the energy maneuverability methods were really derived from this viewpoint. They're to compare one airplane against the other but they're also used to indicate to the pilot which type of maneuvers generally he should fly and they've done fairly well. Are there any other questions? You had your hand up, didn't you?

Andrew Nassir, Consultant, representing the Rand Corporation here this evening. Some of the work I have done previously in previous assignments with the Air Force Space and Missiles Systems Organization and The Office of the Secretary of the Air Force-Special Projects while on active duty until this June I think might be of interest in supporting some of of the discussion here this evening. One of the things we looked at very carefully was state-of-the-art in aerospace computers, primarily for the spaceborne mission, but it also applies almost equally as well for the manned application. I think the comments Mr O'Donnell was making about the trends in the equipment certainly are very valid, we see it coming down the line. I think though one thing that was commented on from a language point of view that hasn't been mentioned here this evening, is the development of a higher order language for space programming that is called SPL or Space Programming Language.[17] And the concept here is to

---

[17] Space Programming Language (SPL/J6) programmer's manual, Nov 68, System Development Corporation, Santa Monica, California. SAMSO-TR-68-383 AD 679136.

make it easier to program, easier to actually use the airborne computers, to re-program, to validate, and actually to implement the programs you're interested in getting into the machine in a quicker time basis. I think one of the things that also is of interest is we began to see it become practical to get more of a real-time control in the spacecraft particularly. Here though, we don't have the man in the loop upstairs. And so it was very necessary to try to establish real-time control, either ground control or relinquish it to the satellite as we have considered doing for future satellites. In the case of the man though, real-time airplane control, the question is a little bit different. The question is how much do you want to really give the man or how much does he want to actually have at his disposal upstairs and I think the key to it is maybe not so much that you want to just take the emergency paths, give him emergency control, but you want to give them routine control over the vast majority routine paths that he has that actually become numerous in many cases to the point that its desirable to have computer control, computer system control if it can be easily implemented for him. So, this I think is the trend as we have seen it in some of our recent studies and it certainly supports the concept that we really can operate. Yes, as far as feasibility, we're certainly getting there real quick.

Captain Dayton: Thank you. Does anybody else have any questions?

My name is Noel DeLesso from Bell Telephone Laboratories. Mr. O'Donnell mentioned that he thought in the future we would go to many separate processors perhaps, instead of one large central processor. Captain Dayton mentioned perhaps what you call parallel processing. Wouldn't it seem feasible that, depending upon the application involved to, in fact, use a combination? There are large multi-processor systems under development now, both commercial and military, that may enable you do parallel and multi-processing depending on how you.... The defintions here are hazy depending upon whom you are talking to, but it would seem to me that with the progress one has seen with multi-processing up to now it should be relatively feasible to do them in an airborne computer since it seems to be going on quite well in ground computers. And I would also like to make one other comment. Some experience that I've gained in some work I have done with digital displays, where there are very large numbers, indicate that when you get all done and add up the total cost compared to the system, the system type work as opposed to the display type work, separating the display costs where you go to the digital displays as opposed to the older analog types can get astronomically high. Enough to scare you.

Captain Dayton: I'd like to say one short word on the difference to me, and I may be all wet here, between parallel processing and multi-processing, I see multi-processing as Mr O'Donnell said where each processor is handling an independent function, like one for navigation, one for flight control and so on. I see parallel processing, and this is not well understood at all, where perhaps you could have one of the parallel processors for each state of the system.[18] This is something I think would have to be investigated. There is independence involved here and other problems. Any other questions?

Peter Frost, General Electric Process Computer Department. Mr O'Donnell mentioned that he had a two-computer system and he had a kind of fail-soft

---

[18] For instance you could us a parallel processor to solve the non-linear estimation problem in the navigation system with each subprocessor assigned to a state of the system.

system. With his distributed system that he mentioned a little later as the future thing, I was wondering about the fail-soft aspects of multiplexing. Can you visualize it taking care of the programming end? It sounds like it's just about as bad as any kind of multi-processing as I can think of.

Mr O'Donnell: In any system you can find points such as the actuators, for example, in a flight control system which must function reliably; all other precautions are useless. Paralleling of components has always been considered in order to reduce failure possibilities. At some point it becomes uneconomic. An example from the early digital computer days is first of all putting logical diodes in series to guard against shorts and then putting two additional diodes in parallel to guard against an open circuit in any one diode. This led to excessive voltage drop and current drain in the logic units requiring higher driver power and resulting in a less reliable system showing the dangers inherent in unthinking approaches to system reliability, but within limits redundancy can be used to make a system fail soft. With individual processor costs coming down to something like a couple of thousand dollars each, you should be able to afford redundancy in the critical areas of the decentralized system and so still have the fail-soft possibility.

Captain Dayton: Any other questions?

My name is Chuck Wells, Wolf Management Services. I recently participated in a study sponsored by NASA, Ames, on the application of modern control theory to on-board real-time control of the SST trajectories. And, in this study, we looked at the application of linear perturbation theory to control the aircraft along a pre-computed nominal trajectory. I missed some of the initial discussion, so I don't know if this was mentioned at all. We came up with very interesting results in that it appears that you can take a very large optimization program like the STOP[19] program at Boeing. Recompute a nominal trajectory based on the performance criteria you would like to optimize for the particular flight, taking into account all known parameters, aircraft weight, the total load of the aircraft, winds aloft forecast and temperature aloft. I put these into the STOP program or some similar optimization program and come up with a pre-computed nominal. The problem then is pretty simple; to control in any number of control variables and state variables if you would like using linear perturbation control theory. And some of the stuff that we came up with was just basically a formulation of what that controller looks like and as Mike Athans mentioned this morning, it's simply a linear controller about this nonlinear optimal trajectory. The controller structure itself for a three control system where you control thrust, elevator, and say wing positions. All this involves is a three-dimensional Ricatti equation for the weighting gains on the controller and it appears that these weighting gains can be computed in real-time with very little difficulty on the computers that they have available today. There is also another technique for possible implementation of on-board real-time controllers and that is a technique called multi-point control. In this particular case, the multi-point controller originally developed by Dave Salmon, where the objective is to take the non-linear equations of motion, solve them for all possible variations, or at least a range of parameters of interest and then develop a control that is insensitive to these parameter changes so that the on-board controller now may take

---

[19] STOP - A computer program for supersonic transport trajectory optimization by Lawrence H. Stein, Malcolm B. Matthews and Joel W. Frank. The Boeing Company NASA Contractor Report CR-793 May 1967.

a very simple form like a polynomial expression of the state variables that is relatively insensitive to the parameters and then this can be implemented as your on-board controller. So, I just wanted to point out some further refinements and further developments that has been applied to the SST real-time control problems that are basically applications of the technique that Mike Athans talked about this morning.

Question: Is this available in a report?

Wells: This will be available in a report in about six months.

Question: Can you indicate how well it worked and how large a perturbation you can make this linear for?

Wells: This was basically a theoretical study at this time.

Question: You didn't make actual comparisons?

Wells: The actual results, the only results, numerical results were a slightly different way to calculate nominal trajectories. And the nominal trajectories were calculated only in single state variable. And it was again energy. There was a new twist to that and basically the follow-on studies will apply the stochastic controller to the pre-computer nominals that are available in this report.

Captain Dayton: Thank you.

Dr Kelly: I would like to comment on the perturbation scheme. I have had some experience with perturbation schemes in guidance, optimal guidance and also with the atmospheric flight problem. And I don't think you'll know what you have really got by the tail until you've tried to calculate some numbers with this thing. The Euler equations for atmospheric flight are very poorly conditioned, very unstable, and the linearized Euler equations which you are playing with are just as bad and have some pretty bad numerical error propagation properties. I think it is presumptious to get up and say off-hand "we have made a theoretical study" without having tried it and indicate there really are some possibilities here. I think you have only taken the first step. And the second step is the one that is going to tell what the real difficulties in this particular approach are, its pretty hard.

Wells: I would like to comment some more. As I said, the Ricatti equations in the particular example where you have three control variables are simply three by three. You will have numerical computation problems. But I don't think that these are that difficult. We have tried this linear perturbation control on other systems beside nonlinear aircraft systems and it seems to work with very little difficulty. And, although there are problems, I don't think they are unsurmountable.

Dr Kelley: Art Bryson is here, I notice, and he has some experience with Ricatti equations, not in real-time with airplanes though. Maybe he would make a comment.

Captain Dayton: He's hiding over there I think....

Art Bryson: No, I was simply going to comment, maybe I can get around to that. But I think you are talking about linear perturbations. Of course, I'm an enthusiast for linear perturbations around nominal paths. Some of the recent work I have been doing with Kaman Avidyne for

NASA/ERC deals with entry gliders which are unpowered of course. The terminal part of the flight coming into landing. We made an approximation there which is again in line with the kind of thing Henry Kelley was talking about and Kokotovich[20] this morning in simplifying the system. We discovered that in looking at some of the flight test data and some of the simulations for these entry gliders, that they essentially became quasi-steady in velocity and flight path angle below a certain altitude. And so we tried, with our fingers crossed to get by treating these as though you could deduce them from the other variables of the problem, altitude being the principal one. So we simplified the problem to a point mass three dimensions, from 6 state variables down to 4 and then we used one of the state variables, altitude as the independent variables which turned out to be...what we're trying to do is bring the glider into the begin-flare point just before you come onto the runway and so our state variables turned out to be the XY coordinates looking down on the ground relative to the end of the runway and the heading angle. Of these three quantities as state variables, the velocity and flight path angle can be deduced from altitude. We calculated a nominal path and some feedback gains which were keyed to altitude, not time. A straight in flight and a 90 degree turn are the two we investigated to some extent. And with the feedback gains then which were variable and discrete, time we interpolated, and the success was quite great in the sense that we could take very large perturbations in the initial conditions..... large perturbation in winds, large perturbation in density, versus altitude and still bring this entry glider which was an M2F2 right into the begin-flare point within very tight conditions

---

[20]. See page 20.

of the desired condition at that point. This paper is going to be presented[21] at the AIAA meeting a couple of weeks from now at Princeton where these things were worked out. Also, along the same lines, Jason Speyer and I did a paper a couple of years ago in which we, I think, made an improvement on the perturbation scheme by estimating the time-to-go and Henry Kelley had before that talked about a kind of performance index to go as a way of indexing your feedback gains. There's a great improvement in either one of these over using just clock time as your index variable for your feedback gain. Estimate the time-to-go and then key it to time-to-go so that you don't run out of gains or have some gains left over when you get to the end of the flight. And again, just this simple modification opened the tube around the nominal on which you could control, just unbelieveably for an entry glider which goes in at 36,000 feet we could take perturbation of plus or minus 20,000 feet per second, and this is unlikely that you get perturbation that are that large and still bring down to one single nominal into one desired end condition. Now that's not the whole problem, of course, but you may want to change your end conditions and you don't have the right path, you may need several. I have always been a great enthusiast for nominal paths with feedback gains and simplified models. We're also doing work[22] in energy state and three dimensions in which we use two state levels: energy state and heading angle. Of course, the energy combines altitude and velocity under one variable. We're getting very

---

[21] A Terminal Guidance Scheme for Lifting Body Entry Vehicles, William Hoffman, Arthur E. Bryson Jr., and John Zvara, AIAA Guidance, Control, and Flight Mechanics Conference, Aug 18-20, 1969, Princeton, New Jersey.

[22] Energy State Approximation of Supersonic Aircraft, A.E. Bryson, Jr., M.N. DeSai, W.C. Hoffman, In Journal of Aircraft, vol 6 no 6, Nov-Dec 1969, pp 481-487.

good results with this computing optimal paths and my students are doing this out at Stanford.

Captain Dayton: Thank you, Art.

Mr Mitter: I have made some studies integrating the Ricatti equations that arise out of neighboring optimal feedback control. I would like to reiterate what Dr Kelley was saying, they often turn out to be very delicate and very hard to integrate. In fact, the behavior of these equations are remarkedly very different from the ones one gets from the standard neighboring optimal control problems, the linear quadratic type of problems, because the coefficients being the various derivatives, the second order derivatives of the Hamiltonian. Essentially, the linearized solution corresponding to some nonlinear optimal control problem that cannot be understood just by solving some linear quadratic problem which you can set out right in the beginning. But it is possible that the way the Ricatti equations have been solved up to now, that is, by working with the necessary conditions corresponding the continuous problem may lead to additional stability problems when solving these linearized feedback gains. It may very well be that once you discretize the problem first and then derive, solve the discretized problem and then by some experience to think these Ricatti equations may be better behaved from the viewpoint of discretizing the problem first. I would like to ask what sort of other problems you have solved for; these initially nonlinear problems with neighborhood optimal feedback control or did you start with a linear quadratic problem?

Wells: We started with a nonlinear chemical reaction which had fairly bad exponential nonlinearities. The linearization was done about the nominal trajectory at each point in time and the discrete equations were used at all times. The Ricatti equations give us no trouble at all. They were very simple algebraic manipulations that we had to do to solve the real-time gains. Of course, we had to relinearize at each data point so that we were never very far from the nominal and we almost had a linear system at every point in time. So for this reason we had no trouble at all in solving the ....(Mitter interrupts).......is there any test for calculating the time varying gains or the steady state?

Wells: We calculated them to the end conditions at each point in time, but we only used the one we just calculated and we relinearized and solved the problem again, calculate the new gains applied to the next point in time and in the calculation of the Ricatti equations from the end point to that time there was no trouble at all in numerics in the recursive equation for the Ricatti equation. So that's why I have only had experience in the discrete Ricatti equations over time intervals of up to about 200 time intervals. And I never came out with any trouble.

Mitter: In a chemical reactor, aren't your effective eigenvalues in the linearized system, aren't they very well damped?

Wells: Yes, they are very well damped.

Mitter: And they're not spread over a wide range.

Wells: No, I had quite a high frequency component in the reactor.

Mitter: Yes, but they are well damped and I think that's part of the difference.

Captain Dayton: Does anyone else have any other comments or questions?

Harry Turing, Electronics Research Center. I am not Professor Bryson's customer, so I do not complain against linear perturbation approach. I think that some recent experience that I had working on the Apollo problem and what little I've seen of V/STOL type work at Electronics Research Center that we're getting started in, one of the major problems is operational. We are so uncertain about what result you are going to have from any given place. You have about considerations and this sort of thing. But the mechanism put into the machine to take care of all the contingencies require that you have a lot more sophisticated machinery there than you need for the linear perturbation problem, if you want to go with that approach. So, I argue that the way to go in any sort of flexible variable problem like most flight control problems are except in restrictive cases like re-entry gliders is an explicit approach which I guess can be related as energy maneuverability problem where you try to introduce algebraic characteristics and also is related to your work in developing dynamic program algorithms which you can generally resolve as you go along. And using approaches like this you're not chained to some particular nominal or some canned nominal or even a set of canned nominals which may begin to blow all out of proportion when you have to consider a large number of possibilities. It seems to me that one major reason why more ideas of people haven't been explored and the linear and second variational approach haven't been applied is because they don't have the inheriant capabilities that explicit techniques have. I think it might be well worth going further into explicit type techniques and exploring that area more.

<u>Captain Dayton</u>: Thank you. Anybody have any comments or disagreements?

<u>Mr. Taylor</u>: I'd like to address a very mundaine problem we're going to have to face. That is, we're trying to. One of the reasons we're

interested in updating the optimal profile is that we are encountering an atmosphere that's not nominal. It's a non-standard atmosphere; every day it's a non-standard atmosphere. And, it's not a single scalar to be added to the nominal temperatures at all altitudes. It's some other function and we need some ideas. We've gone along and encountered this hunk of atmosphere, how do we cleverly predict what's going to be up there? When you look at some of the curves of altitude versus the temperature, these things are liable to do anything up there. They're fairly well behaved for the lower altitudes but in the tropopause or higher they're just liable to do anything. So we need a little help. Encountering the atmosphere this far, what's it going to do up here... got the answer right in person! (Referring to Mr. Moelker who was pulling out a chart.) We got some averages. (Figure 22)

Mr Taylor: We need these to establish the nominal, but when we find ourselves off of that, are we going to figure the whole curve is shifted? We have to do something, but we know that is not going to be the case, just looking at the individual curves and you find these things quite variable.

Person 1: No discontinuities.

Mr Taylor: I kept the chalk on the board.

Captain Dayton: Up to the tropopause, I would agree with you. But above that it looks pretty wild to me.

Boxenhorn: Well, then you may have to have it smaller increments for estimation.

Mr Taylor: We need a sensor about 10,000 feet higher than the airplane.

Person: You have any reason to believe that there is correlation between what's happening down low. If there is no correlation, you're not going to be able to fit it in no matter what you do.

Person: You can include that in your estimation.

Taylor: That's what I need, more complications.

Captain Dayton: Does anybody else have any suggestions? Ways to go to solve these problems? Well, if not I guess we should close. One thing that would be interesting is to come back here in 1975 and see what's actually been done and where we stand at that point. We could play the tapes back and then we can laugh or say we haven't made any progress, but tonight, I think we've accomplished our purpose. We've presented some controversial items and we'll just have to wait and see what happens. On behalf of the Theory Committee, I would like to thank you again for attending and particularly to thank the panel who put forth such great energy to come here.

APPENDIX I

ENERGY-MANEUVERABILITY *

PART I. BASIC ENERGY-MANEUVERABILITY COMPUTER MODEL

DERIVATIONS

INSTANTANEOUS MANEUVERABILITY. For any given aircraft, maximum load factor (normal acceleration) may be computed as a function of altitude and airspeed:

$$n_L = \frac{qSC_{L_{max}}}{w},$$

where n_L = maximum normal acceleration (dimensionless)

$q = \frac{1}{2} \rho V^2$, dynamic pressure (lb/ft^2)

ρ = atmospheric density ($slugs/ft^3$)

V = true airspeed (ft/sec)

S = reference wing area (ft^2)

$C_{L_{max}}$ = maximum coefficient of lift (dimensionless)

w = aircraft weight (lb)

Since calibrated airspeed (CAS) is more meaningful to the pilot than true airspeed, the G-V diagrams depict maximum normal acceleration versus CAS.

SUSTAINED MANEUVERABILITY. Energy Rate. The energy (E) possessed by an aircraft is the sum of its potential energy (E_p) and its kinetic energy (E_k). Mathematically,

$$\begin{aligned} E &= E_p + E_k \\ &= wh + \frac{1}{2} mV^2 \\ &= w\left(h + \frac{V^2}{2g}\right), \end{aligned}$$

---

* Extracted from APGC-TR-66-4 Vol 1

where

h = altitude (ft)

m = aircraft mass (slugs)

g = 32.174 ft/sec^2, the gravitational acceleration

The expression, $E = w \left(h + \frac{V^2}{2g}\right)$ gives us a measure of the energy state of an aircraft at any altitude-airspeed combination. However, since the main interest lies in comparing aircraft with different weights at the same altitude-airspeed combination, it is more meaningful to make the above expression independent of aircraft weight. Dividing both sides of the above expression by w yields

$$\frac{E}{w} = h + \frac{V2}{2g} .$$

The term E/w can be regarded as specific energy (E_s), with the result that the energy state of an aircraft can now be expressed as a function of altitude and airspeed:

$$E_s = h + \frac{V^2}{2g} .$$

The problem of managing energy involves controlling the rate of transfer between energy levels. Differentiating the above expression results in

$$\dot{E}_s = \dot{h} + \frac{V\dot{V}}{g},$$

where the dot (.) indicates the derivative with respect to time, $\frac{d}{dt}$. To provide more insight into energy rate, $\dot{E}_s$, we may employ Figure II-1 and write a force balance equation along the flight path.

$$m\dot{V} = T_a - D - w \sin \gamma,$$

or

$$T_a - D = w \sin \gamma + \frac{w}{g} \dot{V},$$

or

$$\frac{T_a - D}{w} = \sin \gamma + \frac{\dot{V}}{g}.$$

Multiplying both sides of this expressions by V yields

$$\left(\frac{T_a - D}{w}\right) V = V \sin \gamma + \frac{V\dot{V}}{g}.$$

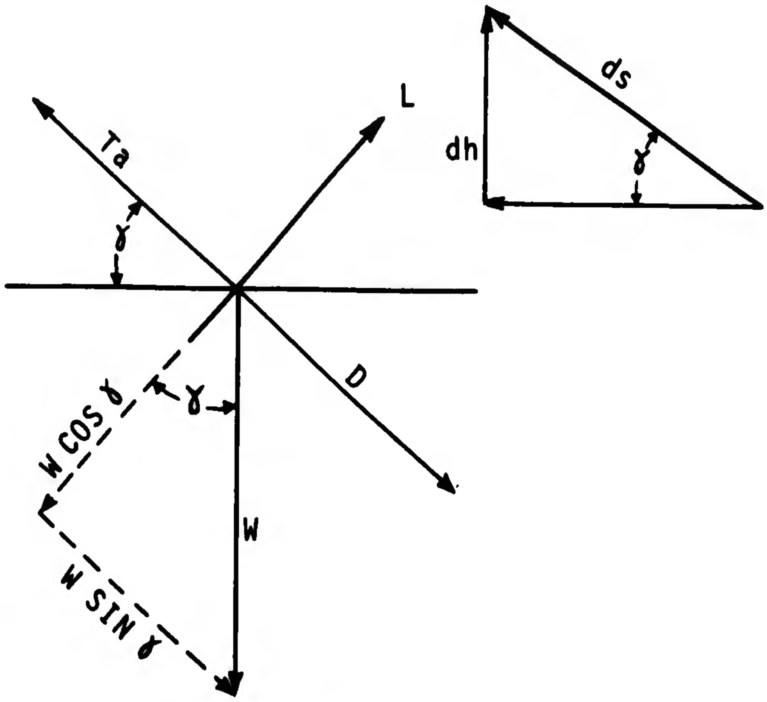


Figure II-I. Aircraft Force-Balance Diagram.

BLANK PAGE

Since $\dot{h} = V \sin \gamma$, we may write

$$\left(\frac{T_a - D}{W}\right) V = \dot{h} + \frac{V\dot{V}}{g} \; . = \dot{E}_s$$

The right side of the above expression is equal to $\dot{E}_s$. Recalling that work is accomplished in transferring from one energy level to another, and that power, by definition, is the time rate of doing work, the left side of the above equation may be equated to specific excess power, P_s :

$$P_s = \dot{E}_s = \left(\frac{T_a - D}{W}\right) V.$$

In an attempt to counter an immediate threat, the energy-oriented fighter pilot will strive to increase his maneuvering energy as quickly as possible. This amount to maximizing the rate of transfer between energy levels, which is equivalent to maximizing integral

$$E_s = \int_{t1}^{t_2} P_s dt.$$

According to Rutowski (reference 1), this is accomplished when

$$\left[\frac{\partial P_s}{\partial V}\right]_{E_s = k} = 0,$$

or

$$\left[\frac{\partial P_s}{\partial h}\right]_{E_s = k} = 0.$$

In the altitude-Mach number plane, these relationships are satisfied at those points where the E_s contours are tangent to the 1-g P_s contours. Connecting these points results in an approximate minimum time path.

Energy-Maneuverability Efficiency (E-ME). If the above-mentioned threat is not as imminent, the pilot will attempt to increase his maneuvering energy while conserving internal energy (fuel) for future maneuverability. This is achieved by maximizing the integral

$$E_s = \int_{w_1}^{w_2} \frac{dE_s}{dw} \, dw.$$

Since $dE_s = P_s dt$,

and $dw = -\dot{w}_f \, dt$ ($\dot{w}_f$ = fuel flow - lb/sec)

we see that $\frac{dE_s}{dw} = -\frac{P_s}{\dot{w}_f}$,

and

$$E_s = -\int_{w1}^{w2} \frac{P_s}{\dot{w}_f} \, dw.$$

Again, by employing Rutowski's technique, we obtain

$$\left[\frac{\partial(P_s/\dot{w}_f)}{\partial V}\right]_{E_s=K} = 0,$$

or

$$\left[\frac{\partial(P_s/\dot{w}_f)}{\partial h}\right]_{E_s=k} = 0.$$

These relationships are satisfied at those points in the altitude-Mach number plane where the E_s contours are tangent to the 1-g $P_s/\dot{w}_f$ contours. Connecting these points results in an approximate minimum fuel path.

The $P_s/\dot{w}_f$ contours suggest a measure of efficiency in view of the fact that they depict the amount of <u>specific</u> energy gained per pound of fuel expended. In order to acquire a more meaningful measure of efficiency, these contours can be modified to portray the amount of <u>maneuvering</u> energy gained for the internal energy (fuel) expended. This is done by multiplying the $P_s/\dot{w}_f$ contours by the weight of fuel available, w_{fa}, to obtain the resulting expression for Energy-Maneuverability Efficiency:

$$E\text{-}ME = \frac{P_s^*}{\dot{w}_f} w_{f\,a}$$

where P^*_s = the average P_s over the fuel weight interval

$w_{fo} - fc \geq w_f \geq w_f \geq w_f\ r$ (ft/sec), and $w_{f\ a} = w_{f\ o} - fc - w_{f\ r}$,

where w_{fo} = initial fuel weight (lb)

fc = fuel consumed in flying from some reference energy level to any given altitude-Mach number point (lb)

w_{fr} = fuel reserve (lb)

RANGE. For any altitude-airspeed combination, available range for cruise condition may be expressed as

$$R = \frac{w_{f\ a}}{\dot{w}^*_C}\ V + x,$$

where $\dot{w}^*_C$ = the average cruise fuel flow, $\dot{w}_C$, over the fuel weight interval $w_{f\ o} - fc \geq wf \geq w_{f\ r}$ (lb/sec),

and x = the horizontal distance traversed in flying from some reference energy level to any given altitude combination.

COMPUTATIONS

ENERGY RATE DIAGRAMS. For any given aircraft, an Energy Rate diagram may be constructed by dividing the altitude-Mach number plane into a rectangular grid, computing energy rate (P_s) values at all of the points of intersection of the grid lines, and then connecting points of equal P_s. The contour defined by $P_s = 0$ represents the steady-state boundary of the aircraft. An aircraft cannot operate outside this contour without losing energy, either in the form of altitude, airspeed, or some combination of both. The steady-state boundary is further restricted on the left by the buffet boundary (obtained by connecting points where $C_L = C_{L_{max}}$), and on the right by placard limits (a combination of pressure (structural) limits and engine temperature limits).

Considerable insight into the effects of pulling g within the aircraft's flight envelope can be gained by constructing Energy Rate diagrams of more than 1 g. These diagrams contain both positive and negative P_s contours within the 1-g steady-state envelope. As such, they provide a measure of sustained maneuverability as a result of pulling g within the envelope.

E-M EFFICIENCY DIAGRAMS. Computational aspects of the diagram proceed in the same manner as for the Energy Rate diagrams, except that now we compute and connect points of equal E-ME. Two different types of E-ME diagrams are constructed. The first type is referred to as the path independent (constant fuel) E-ME diagram. Computations for all points in the envelope are based on 50% fuel weight. Since fuel weight is held constant, the expression

$$\text{E-ME} = \frac{P^*_s}{\dot{w}_f} w_{fa}$$

reduces to

$$\text{E-ME} = \frac{P_s}{\dot{w}_f} w_{fa} \ .$$

The diagram is called path-independent since the amount of fuel at the altitude-Mach number points where computations are made is independent of the paths required to reach these points.

In the second type of E-ME diagram, called the path-dependent (variable fuel) E-ME diagram, the amount of fuel required to reach any given altitude-Mach number point is subtracted from the total fuel weight before E-ME computations are made. The assumption is that the pilot has flown a minimum fuel path from some reference energy level (we use $E_{s_{REF}} = 3000$ feet) to the altitude-Mach number point under consideration. A more detailed discussion of this assumption will be given later in this appendix and in Appendix III.* Additionally, the amount of fuel upon which the

---

* See AFGC TR-66-4 Vol 1.

path-dependent E-ME computations are based is reduced by a suitable reserve (normally 5% of full internal plus 20 minutes loiter at 10,000 ft).

RANGE DIAGRAMS. Again, the computational aspects of this diagram are essentially the same as for the Energy Rate and E-M Efficiency diagrams. To compute range, the program requires, as an additional input, a partial power setting table, i.e., a table of cruise fuel flow as a function of altitude, Mach number, and drag (thrust required). The subsonic and supersonic portions of the envelope are computed using partial military and partial afterburner power settings, respectively. A transient region is observed between the subsonic and supersonic portions of the envelope. In this region, level unaccelerated flight is not possible as the thrust required is greater than military thrust available, yet less than minimum afterburner thrust available.

For range, only a path-dependent (variable fuel) Range diagram is constructed. For this addition the amount of fuel available at any given altitude-Mach number point is reduced by the amount of fuel required to fly a minimum fuel path from some reference energy level (again, we use $E_{s\ REF}$ = 3000 feet) to the point under consideration, and by a suitable fuel reserve (e.g., 5% of full internal plus 20 minutes loiter at 10,000 feet). The horizontal distance traversed in flying the above-mentioned minimum fuel path, x, is considered part of the available range. A discussion of the method used to compute fuel consumed and horizontal distance traversed is given later in this appendix and Appendix III.

(Extracted from APGC-TR-66-4 Vol 1)

APPENDIX II

REFERENCES

Definition and Analysis of Flight Command Functions and Computations
A. S. Marino, W. E. McAdams, R. C. Chojhacki
Hughes Aircraft Company
Technical Report AFFDL-TR-68-145, AD 847201
November 1968

Frank J. Seiler Research Laboratory Reports on Analysis of Tactical Aircraft and Missile Engagements

A.

SRL Report No.	Title
68-0017	The Application of the Method of Steepest Descent to a Pursuit-Evasion Problem
69-0007	Determination of Realistic Performance Trade-Offs in the Air-to-Air Role
69-0008	The Snap-Shoot Gunsight
69-0013	An Investigation and Design of Improved Guidance Schemes for Air-to-Air Missiles (U) (Confidential Report)
69-0014	Energy-Maneuverability Applied to Air Combat Tactics

B.

ABSTRACT

A Computer Optimization Study of a Three-Dimensional Engagement Between a Surface-to-Air Missile and Tactical Aircraft

Frank J. Seiler Research Laboratory Report 69-0009, July 1969

This report discusses a computer optimization study of the engagement between the Soviet surface-to-air missile, the SA-2, and tactical aircraft. The study was an outgrowth of a request by DDR&E for the US Air Force to investigate the application of modern mathematical optimization techniques in the analysis of tactical aircraft-missile engagements. The reasons for the choice of the particular engagements are its applicability to the problem of evading a surface-to-air missile (SAM), the availability of computer simulation results for this type of engagement from the Air Force Armament Laboratory, and the large amount of data available from actual Southeast Asia (SEA) firings.

The specific aim of this study was to determine the optimum evasive flight path that a pilot should select in order to maximize the miss distance between his aircraft and the SAM. Hence, the problem considered was the control problem of determing evasive strategies in a one-on-one encounter between two aerodynamic vehicles. In view of the experience of conducting air operations in SEA the authors realize that the assumption of a one-on-one encounter is often unrealistic; however, without this restriction there appears to be little hope of determining optimal evasive maneuvers. However, as is shown in the report, solutions to the one-on-one problem provide significant insight as to the structure of "good" evasive maneuvers.

The method of solution employed was to formulate the engagement as a one-player differential game. Open-loop optimal controls for the aircraft, i.e., throttle setting, roll rate, and load factor are then determined by iterating on "guessed values" for those quantitites until certain necessary conditions are satisfied. The problem then becomes one of determining whether the control so derived is globally optimal. The mathematical optimization technique employed was the method of steepest ascent. The method of solution for obtaining the optimal controls was to simulate a very realistic three-dimensional engagement of the SA-2 and a tactical aircraft by means of a digital computer program that also included the method of steepest ascent.

The paper discusses the results from the particular engagements of the SA-2 and two different tactical aircraft: a high-speed one and a low-speed one. These results are used as examples to provide insight toward answering the following questions.

1. How close to optimum are the evasive maneuvers that have evolved in SEA and how can they be improved?

2. Can one determine the quantitative influence of aircraft design parameters on the outcome of an encounter with a SAM?

The emphasis in the report is on the answers to these two questions.

APPENDIX III

ATTENDENCE LIST

Name	Address
Dr Eugene E. Yore	Honeywell Inc. Minneapolis, Minn.
Edward Haug	U.S. Army Weapons Command
George Lance	The University of Iowa
Bob Walljasper	U.S. Army Weapons Command, Rock Island, Illinois
Duane McRuer	Systems Technology, Inc., Hawthorne, California
Greg Hofmann	Systems Technology Inc. Princeton, N.J.
Dr David H. Wakelin	J&L Steel Corp., Pittsburgh, Pa.
Noel X. Delesso	Bell Telephone Labs, Whippany, N.J.
Cecil L. Smith	Louisiana State University
Dennis F. Wilkie	Ford Motor Co., Dearborn, Michigan
Russ Hannen	Air Force Inst. of Tech, Wright-Patterson Air Force Base
Robert L. Swain	Grisson Hall, Purdue University
Carol Kallina	Mobil R&D - Princeton, N.J.
R. Gran	Grumman Aerospace, Bethpage, N.Y.
B. Friedland	Singer-Kearfott, Little Falls, N.J.
S. Margolis	State U of N.Y. Buffalo
Robert Heidemann	University of Calgary
John Donnelly	University of Calgary
Michael D. Canon	IBM Research, San Jose, California
Donald P. McCown	IBM, San Jose, California
W. H. Phillips	NASA-Langley
Roger D. Jones	ABEX Corp, 1220 Dublin Rd. Columbus, Ohio
E. J. Hinman	Applied Physics Lab, Silver Springs, Md.
J. M. Undrill	General Electric Co., Schenectady, N.Y.
J. R. Redus	NASA-Marshall SFC
D.G. Stidimt	Martin-Marietta, Denver, Colorado
Dean K. Fredinik	Rensselaer Poly. Inst., Troy, N.Y.
S. M. Seltzer	Lockheed Missiles & Space Co., Sunnyvale, California
N. E. Thompson	University of British Columbia, Vancouver, Canada
David R. Frost	G. E. Process Computer Dept, Phoenix Arizona
Richard G. Brusch	G. D. Convair, San Diego, California
Eugene M. Cliff	University of Arizona, Tucson
Thomas L. Vincent	University of Arizona, Tucson
James L. Melsa	SMU, Dallas, Texas
Burton Boxenhorn	MIT Instrumentation Lab, Cambridge, Massachusetts
Andrew M. Nassir	Rand Corp-Consultant, Santa Monica, California
Don Vander Stoep	Boeing Co., Seattle, Washington

W. J. Vetter	U of Waterloo, Ontario, Canada
George G. Etzweiler	EE Dept. Pennsylvania State U
Stephen Kahne	EE Dept. U Minnesota
Mr & Mrs M. P. Burgess	Dupont, Aiken, South Carolina
John Pokoski	EE Dept. U of New Hampshire, Durham, New Hampshire
Dave Limbert	M. E. Dept. U of New Hampshire
Michael K. Sain	EE Dept. U of Notre Dame
T. M. Carney	NASA-Electronics Res. Cent. Cambridge, Massachusetts
C. H. Wells	Wolf Mgt. Svc., 260 Sheridan Ave. Palo Alto, California
D. M. Salmon	Wolf Mgt. Sve., 260 Sheridan Ave. Palo Alto, California
R. E. Larson	Wolf Mgt. Svc., 260 Sheridan Ave. Palo Alto, California
R. N. Clark	EE Dept., U of Washington, Seattle, Washington
Gerald E. Bergmann	Flight Control Staff, Boeing Co. Wichita, Kansas
John S. Pazdera	Electrical Engineering, U of Missouri, Rolla, Missouri
Jason L. Speyer	Analytical Mechanics Associates, 179 Fifth Street, Cambridge, Massachusetts
Gene F. Franklin	Stanford U. ERL Stanford, California
Lloyd Stevenson	NASA/ERC 575 Technology Sq., Cambridge, Massachusetts
Donald Gray	NASA/ERC 575 Technology Sq., Cambridge, Massachusetts
Louis F. Kazda	Elec. Eng. Dept., U of Michigan, Ann Arbor, Michigan
Ed Rynaski	Cornell Aero Lab., 4455 Genesse St Buffalo, N.Y.
Barney L. Capehart	U of Florida/Genesys, 7300 Lake Eugner Drive, Orlando, Florida
Jerry M. Mendel	McDonnell Douglas Astronautics, Western Div., 3000 Ocean Park Blvd, Santa Monica, California
Palmer McCurdy	Process Computer Dept., General Electric Co., 2255 W. Desert Curve Rd., Phoenix, Arizona
Juergen Ackermann	DFVLR-113, 803 Oberpfaffenhofen, Germany
Sam Walters	Mechanical Engineering, 345 E. 47th St. New York, N. Y.
H. A. Spang	G. E. Res. & Dev., Schenectady, N.Y.
Prof J. Nuishel	National Research Council, ME Fuel Lab., Montreal Rd., Ottawa, Ontario
P. F. Petiowits	Chandler-Evans Control Systems, Hart, Conn.
R. Layton	Chandler-Evans Control Systems, Hart, Conn.
E. E. Pentecost	Autonetics, Anaheim, California
R. K. Bogne	NASA Flight Research Center, P.O. Box 273, Edwards, California
W. L. Othling	AF Flight Dynamics Lab., AFFDL/FDMC Wright-Patterson AFB, Ohio
Major G. M. Anderson	AFIT SE-B, Wright-Patterson AFB, Ohio

John Paul Hyde	Frank J. Seiler Research Laboratory, USAF Academy, Colorado
Prof L. R. Young	MIT, Room 37-155, Cambridge, Mass.
Major C. S. Summers	USAFA-DFEE, Colorado
Samuel L. Hazen	27 Joseph Street, Cheektowaga, N.Y.
Henry P. T. Corley	P.O. Box 3043, Richmond, Virginia
Art Bryson	Stanford University
S. K. Mitter	Case-Western Reserve
Major Nicholas P. Callas	Air Force Office of Scientific Research, Arlington, Virginia

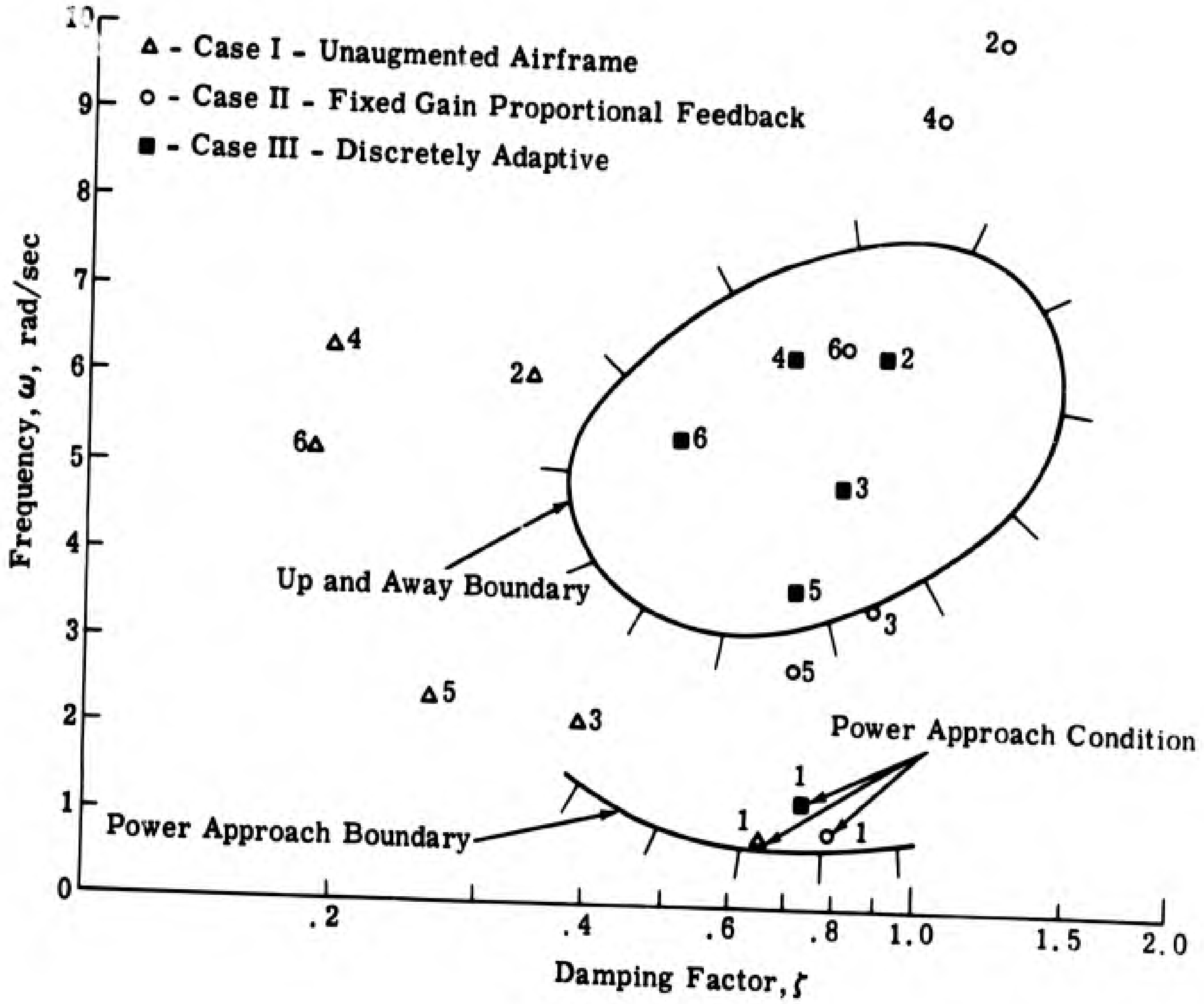


Fig. 1 CAL Thumbprint Criterion

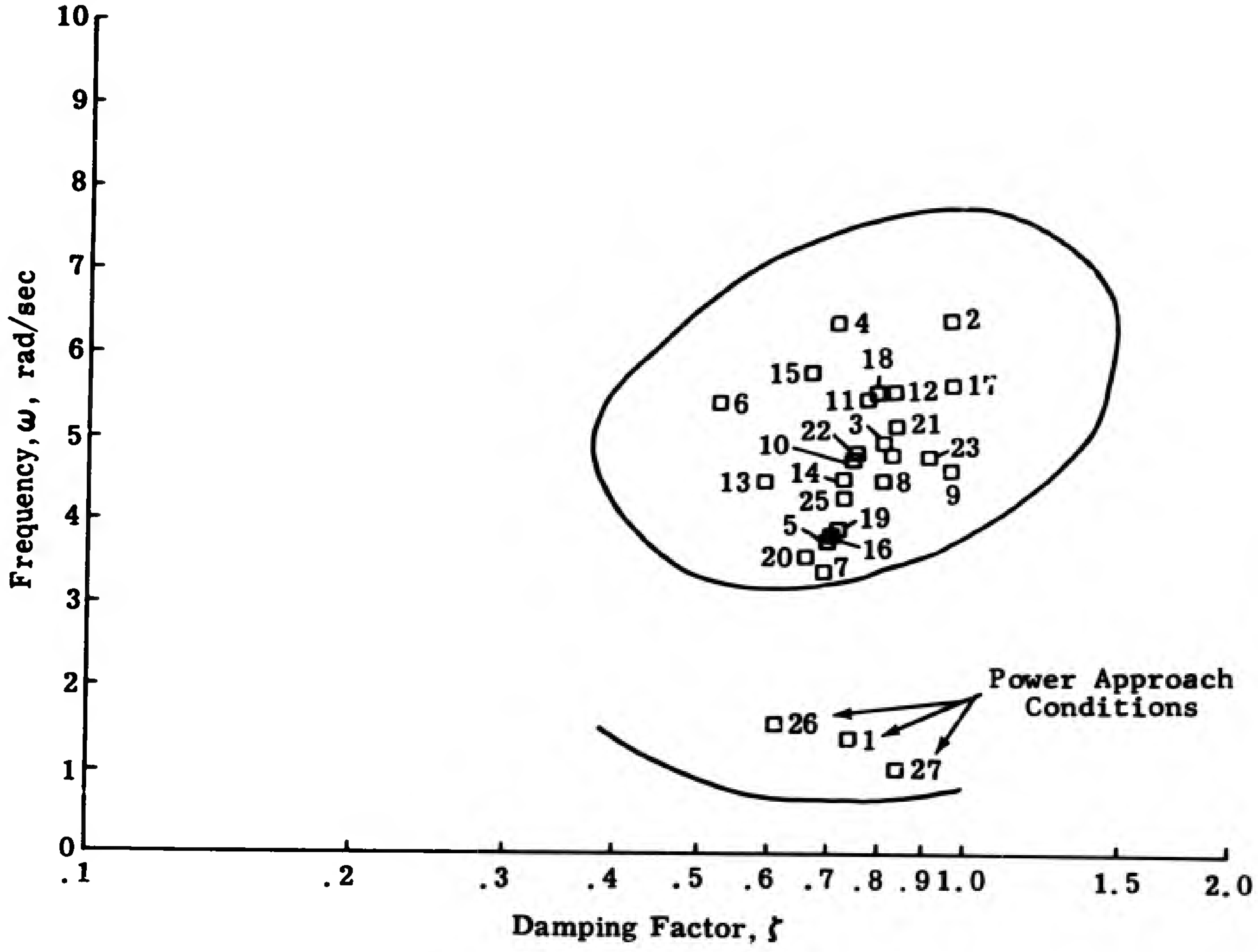


Fig. 2 Case III for Increased Number of Flight Conditions

TREND DATA PROCESSING

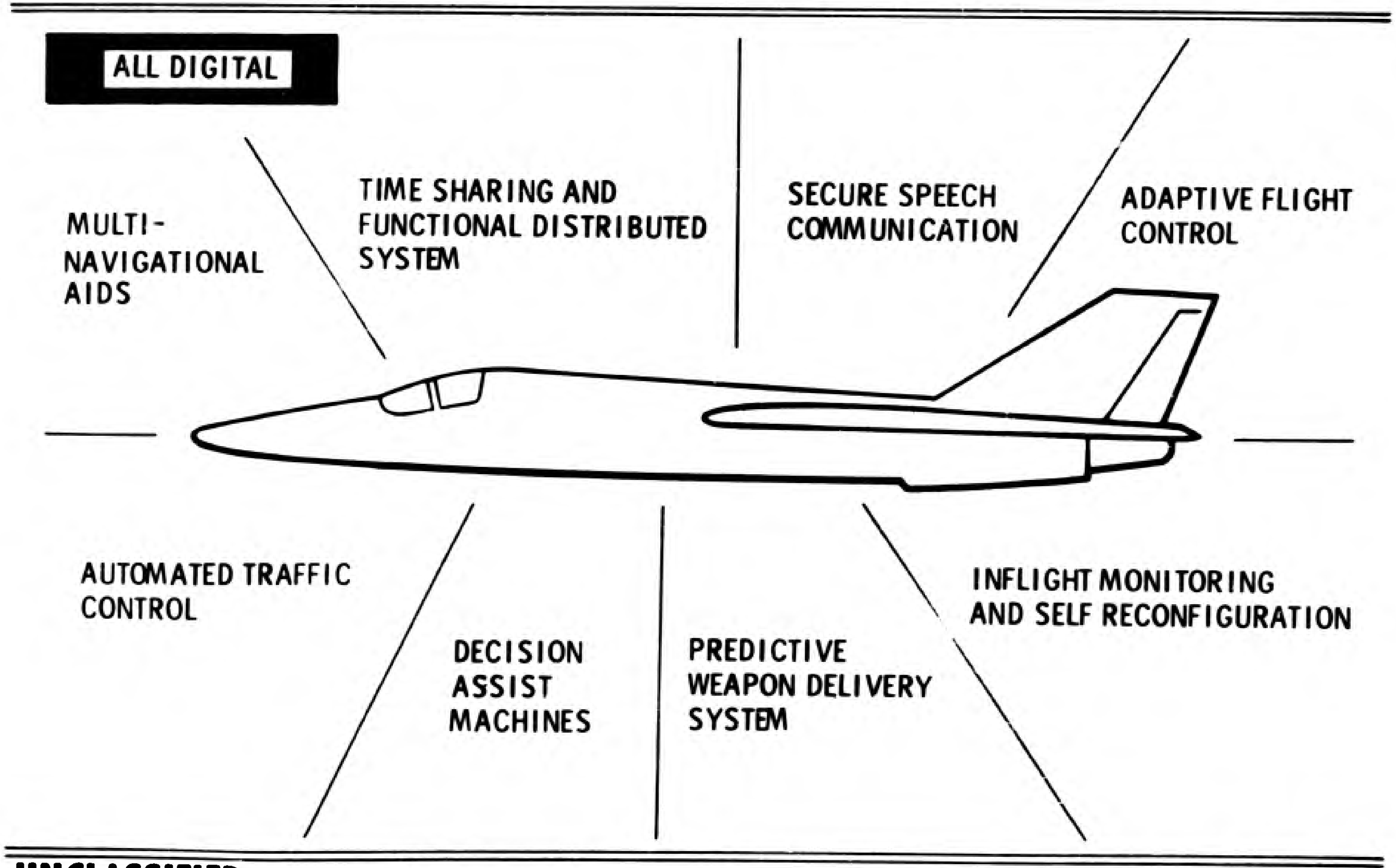
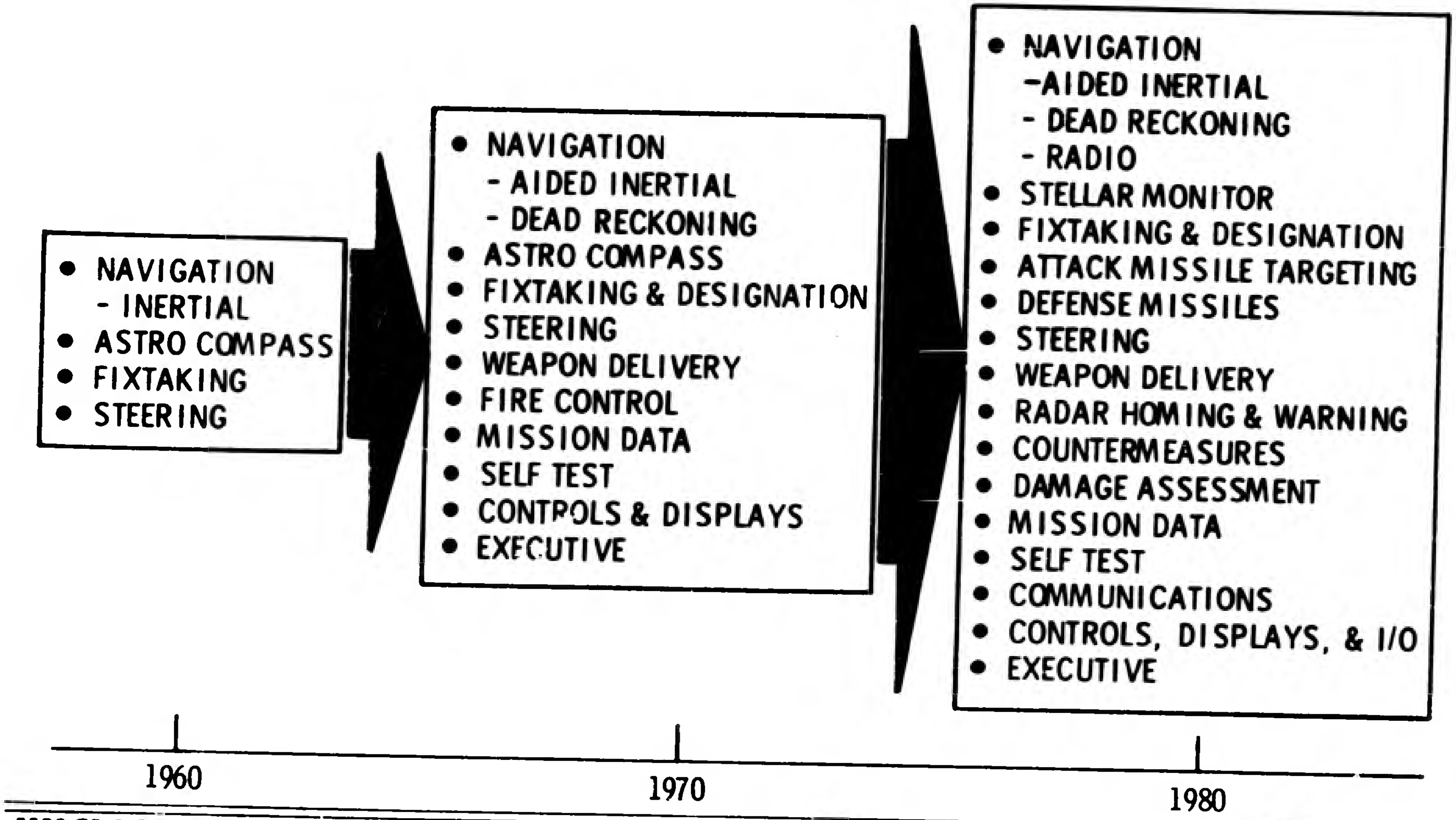


Fig. 3

SYSTEM MECHANIZATION: FUNCTIONAL GROWTH



- NAVIGATION
  - INERTIAL
- ASTRO COMPASS
- FIXTAKING
- STEERING

- NAVIGATION
  - AIDED INERTIAL
  - DEAD RECKONING
- ASTRO COMPASS
- FIXTAKING & DESIGNATION
- STEERING
- WEAPON DELIVERY
- FIRE CONTROL
- MISSION DATA
- SELF TEST
- CONTROLS & DISPLAYS
- EXECUTIVE

- NAVIGATION
  - AIDED INERTIAL
  - DEAD RECKONING
  - RADIO
- STELLAR MONITOR
- FIXTAKING & DESIGNATION
- ATTACK MISSILE TARGETING
- DEFENSE MISSILES
- STEERING
- WEAPON DELIVERY
- RADAR HOMING & WARNING
- COUNTERMEASURES
- DAMAGE ASSESSMENT
- MISSION DATA
- SELF TEST
- COMMUNICATIONS
- CONTROLS, DISPLAYS, & I/O
- EXECUTIVE

Fig. 4

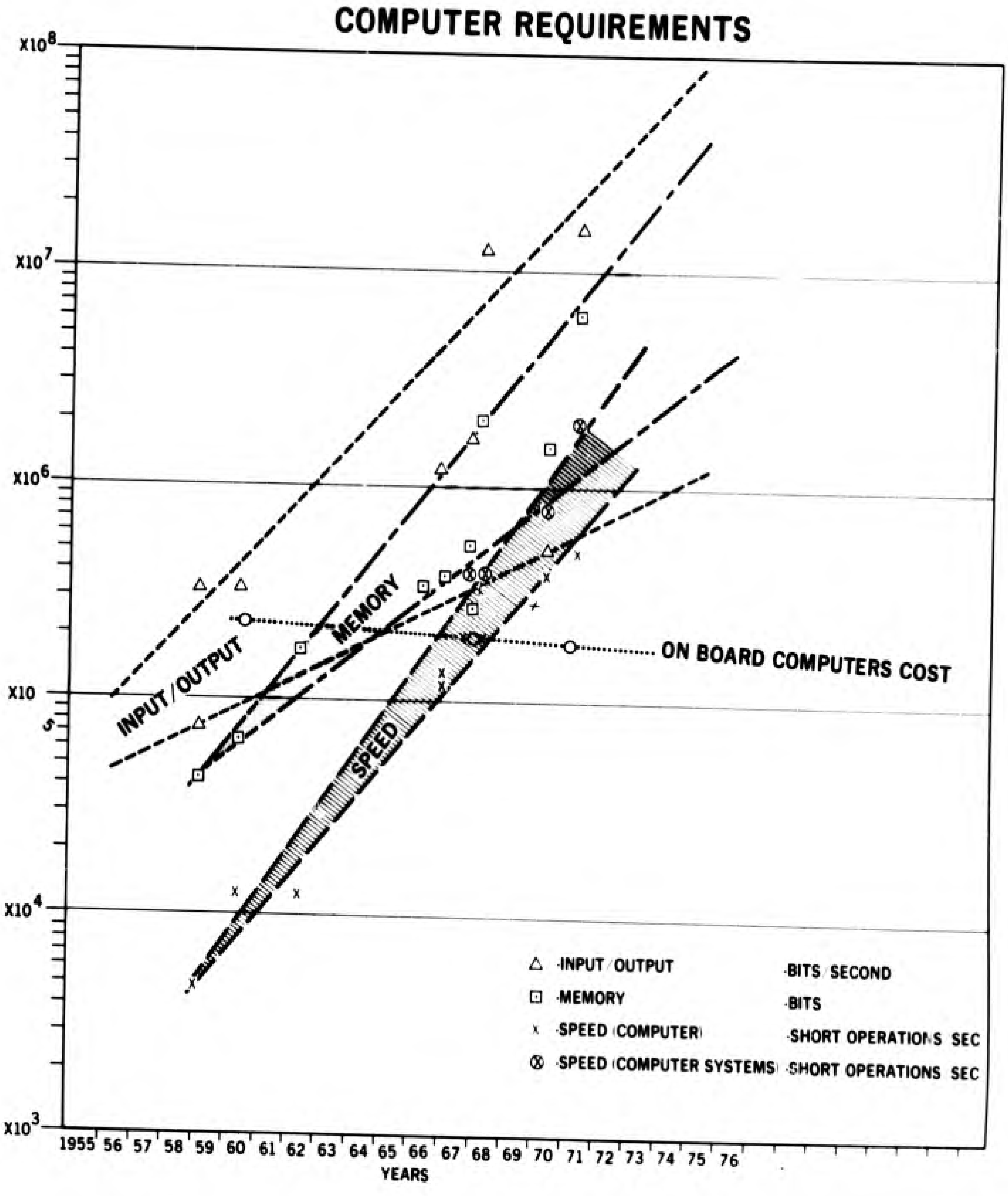
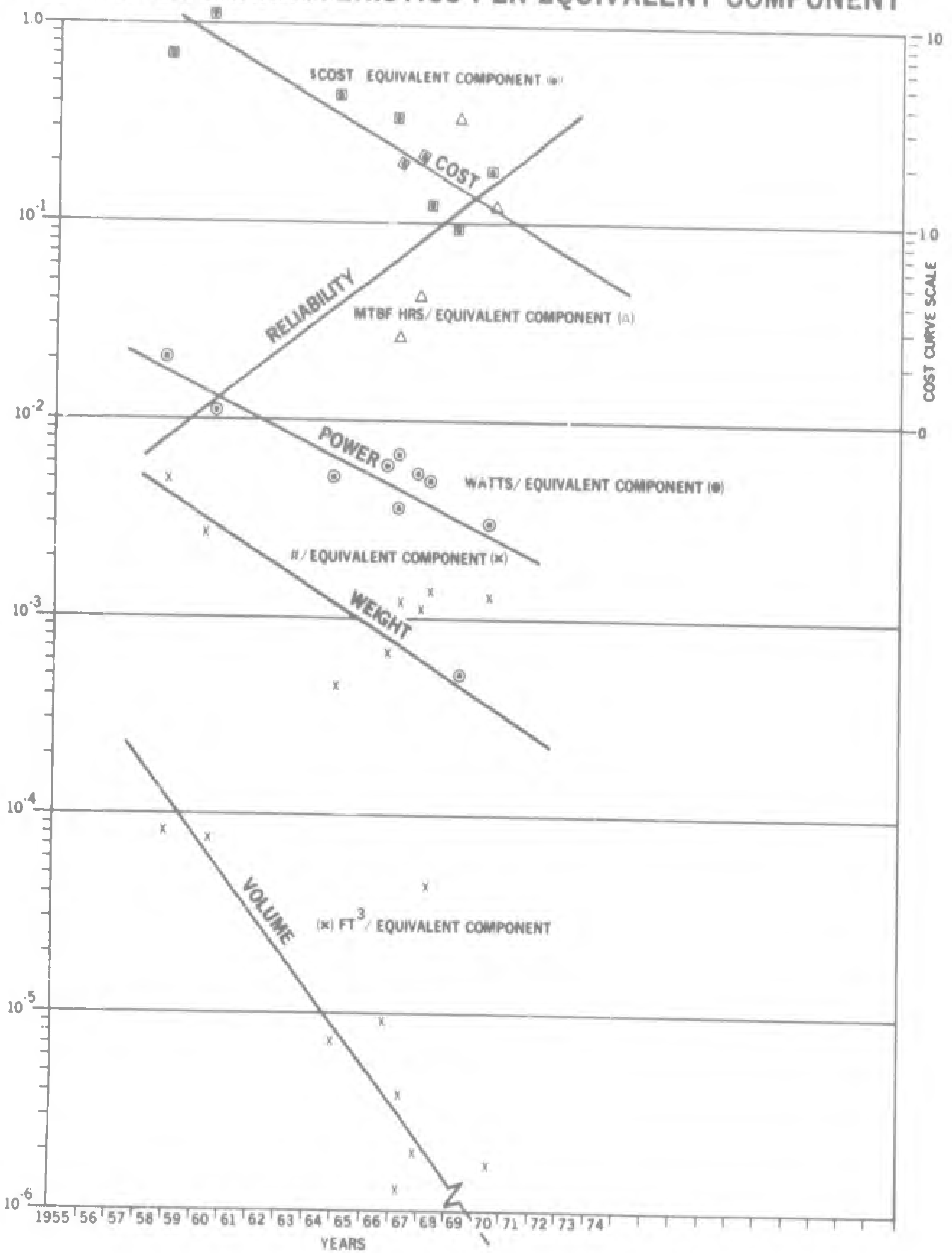

COMPUTER REQUIREMENTS
X10^8
X10^7
X10^6
X10
5
X10^4
X10^3
INPUT/OUTPUT
MEMORY
SPEED
ON BOARD COMPUTERS COST
△ ·INPUT/OUTPUT ·BITS/SECOND
⊡ ·MEMORY ·BITS
x ·SPEED (COMPUTER) ·SHORT OPERATIONS/SEC
⊗ ·SPEED (COMPUTER SYSTEMS) ·SHORT OPERATIONS/SEC
1955 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76
YEARS

Fig. 5

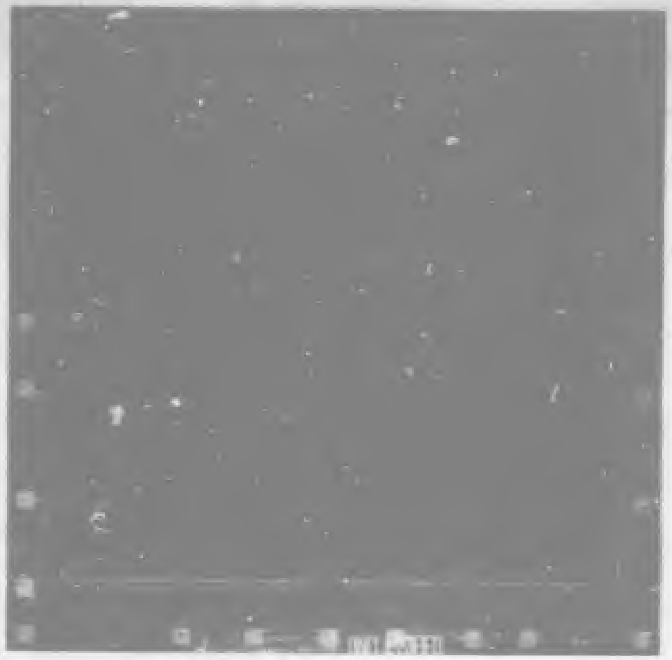


COMPUTER CHARACTERISTICS PER EQUIVALENT COMPONENT

Fig. 6

CIRCUITRY TRENDS

BIPOLAR I C



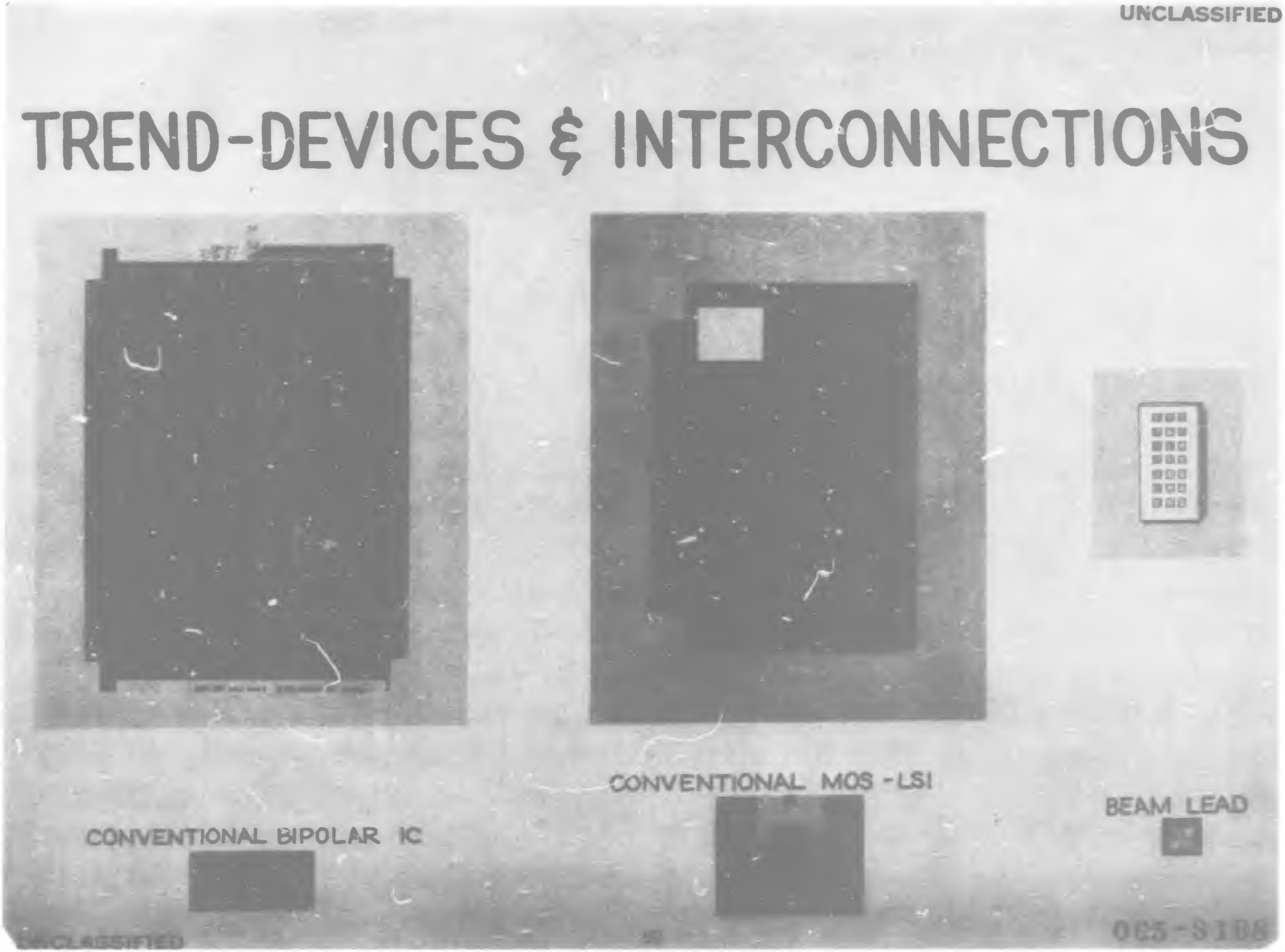
MOS/LSI

BIPOLAR I C 1969	BIPOLAR I C 1975		MOS/LSI 1969	MOS/LSI 1975
10-30 MHz	50-60 MHz	SPEED	1-2 MHz	5-10 MHz
75 ¢	25 ¢	COST/GATE	5-10 ¢	2-5 ¢
10-50 mw	5-20 mw	POWER/GATE	50 μW	50 μW
50 - 100	250 - 500	GATES/CHIP	150 - 200	500 - 1000
		RADIATION TOLERANCE		
$\approx 10^8$ RADS/SEC	$\approx 10^{11}$ RADS/SEC	GAMMA RATE	$\approx 10^7$ RADS/SEC	$\approx 10^{11}$ RADS/SEC
$\approx 10^6$ RADS	$\approx 10^7$ RADS	GAMMA DOSE	$\approx 10^4$ RADS	$\approx 10^7$ RADS
$\approx 10^{13}\ \eta/\mathrm{CM}^2$	$\approx 10^{14}\ \eta/\mathrm{CM}^2$	NEUTRONS	$\approx 10^{14}\ \eta/\mathrm{CM}^2$	$\approx 10^{14}\ \eta/\mathrm{CM}^2$

OG5-3196 Fig. 7

UNCLASSIFIED

TREND-DEVICES & INTERCONNECTIONS



CONVENTIONAL BIPOLAR IC

CONVENTIONAL MOS -LSI

BEAM LEAD

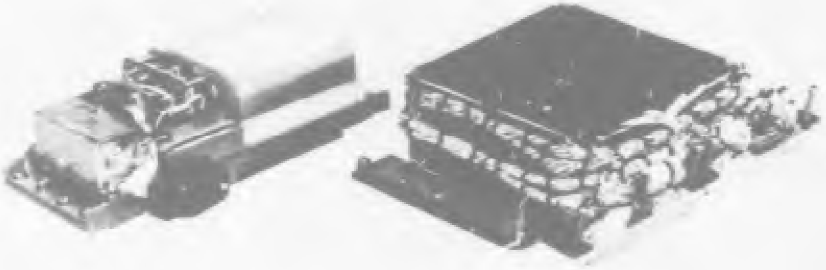
UNCLASSIFIED

065-S188

Fig. 8

UNCLASSIFIED

COMPUTER MEMORIES



Magnetic Core

Disk Memory

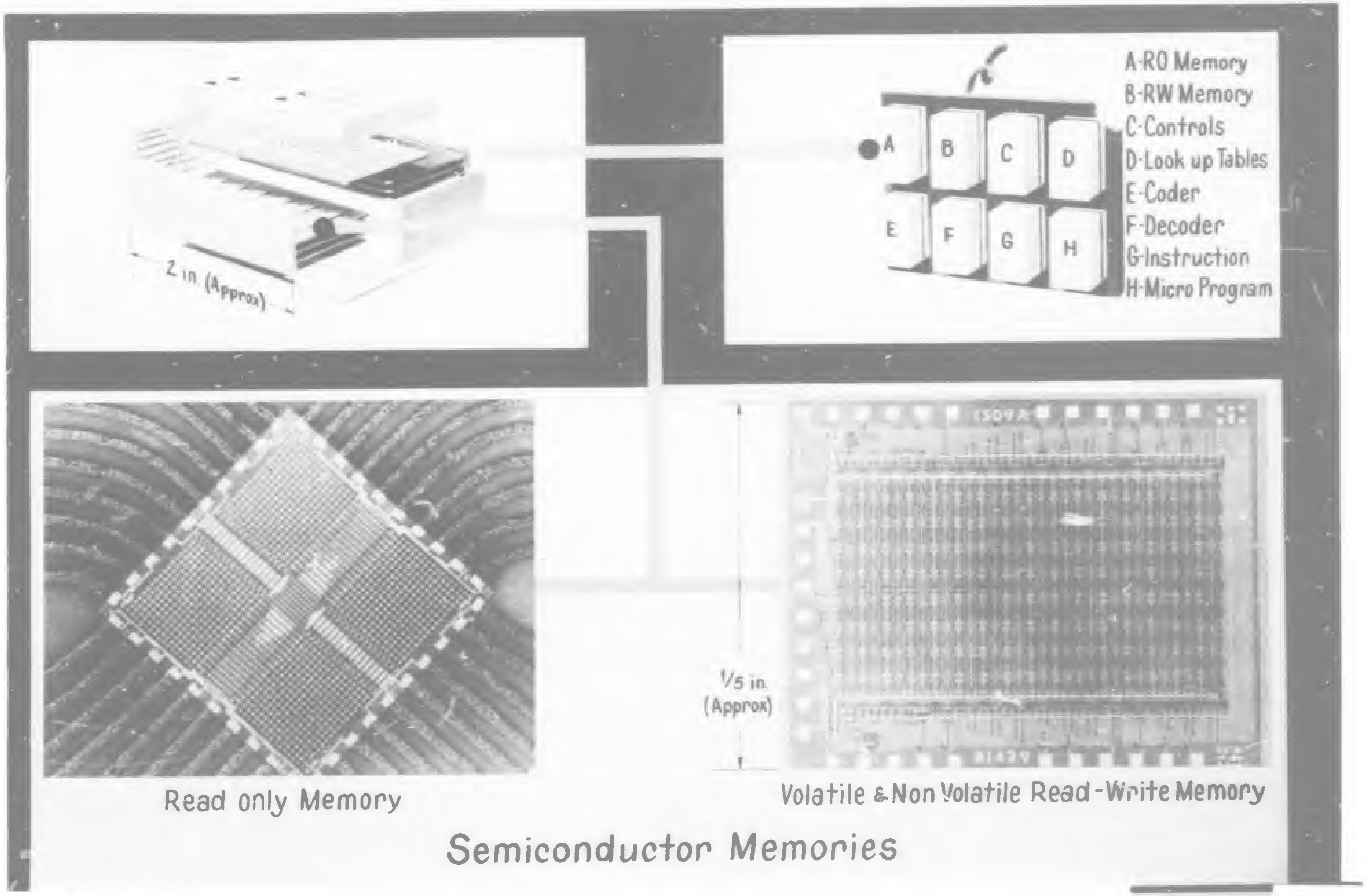
Plated Wire Memory

UNCLASSIFIED

5G9-3100

Fig. 9

TREND MEMORY APPLICATIONS



Read only Memory

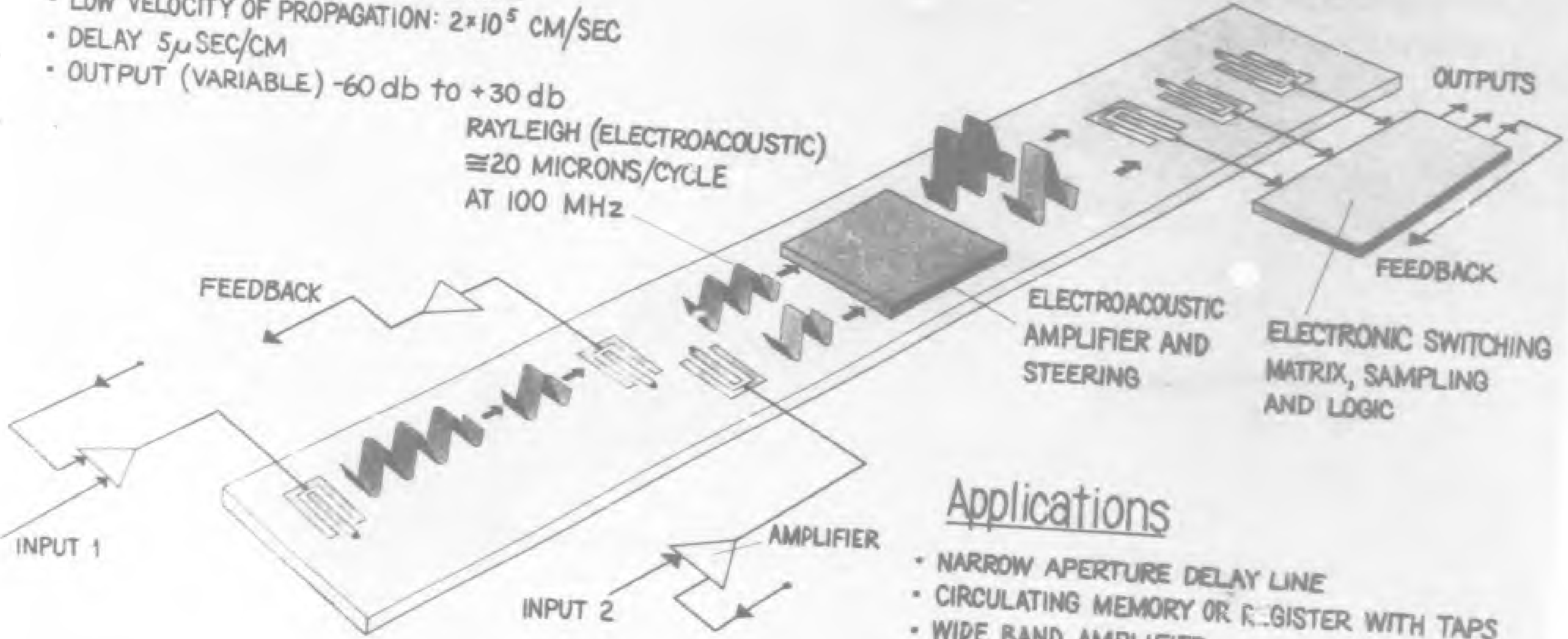
Volatile & Non Volatile Read-Write Memory

Semiconductor Memories

SURFACE ACOUSTIC WAVE TECHNOLOGY

Characteristics (typical)

- HIGH FREQUENCY: 100-500-1000 MHz
- LOW VELOCITY OF PROPAGATION: 2×10^5 CM/SEC
- DELAY 5 μSEC/CM
- OUTPUT (VARIABLE) -60 db to +30 db



Applications

- NARROW APERTURE DELAY LINE
- CIRCULATING MEMORY OR REGISTER WITH TAPS
- WIDE BAND AMPLIFIER
- HIGH SPEED CORRELATOR
- HIGH SPEED DIGITAL FILTER
- LOGIC
- HIGH SPEED DATA SCANNING & PROCESSING

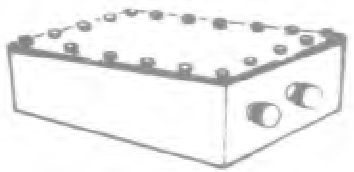
Fig. 11

UNCLASSIFIED

DATA PROCESSOR EVOLUTION

CURRENT AVIONICS COMPUTER

D200-10 COMPUTER



CURRENT AVIONICS COMPUTER		D200-10 COMPUTER
.9 CU FT	SIZE	.1 CU FT
50 LBS	WEIGHT	5 LBS
230 WATTS	POWER	5 WATTS
1500 HOURS	MTBF	3000 HOURS
CORE 16-24 BITS 16K WORDS	MEMORY	ALL MOS 16 BITS 2 - 8K WORDS READ-ONLY 256 - 1024 WORDS R/W
7 μSEC	ADD TIME	4 μSEC
32 μSEC	MULTIPLY TIME	34 μSEC

UNCLASSIFIED

5659 18623

Fig. 12

CENTRAL COMPUTER

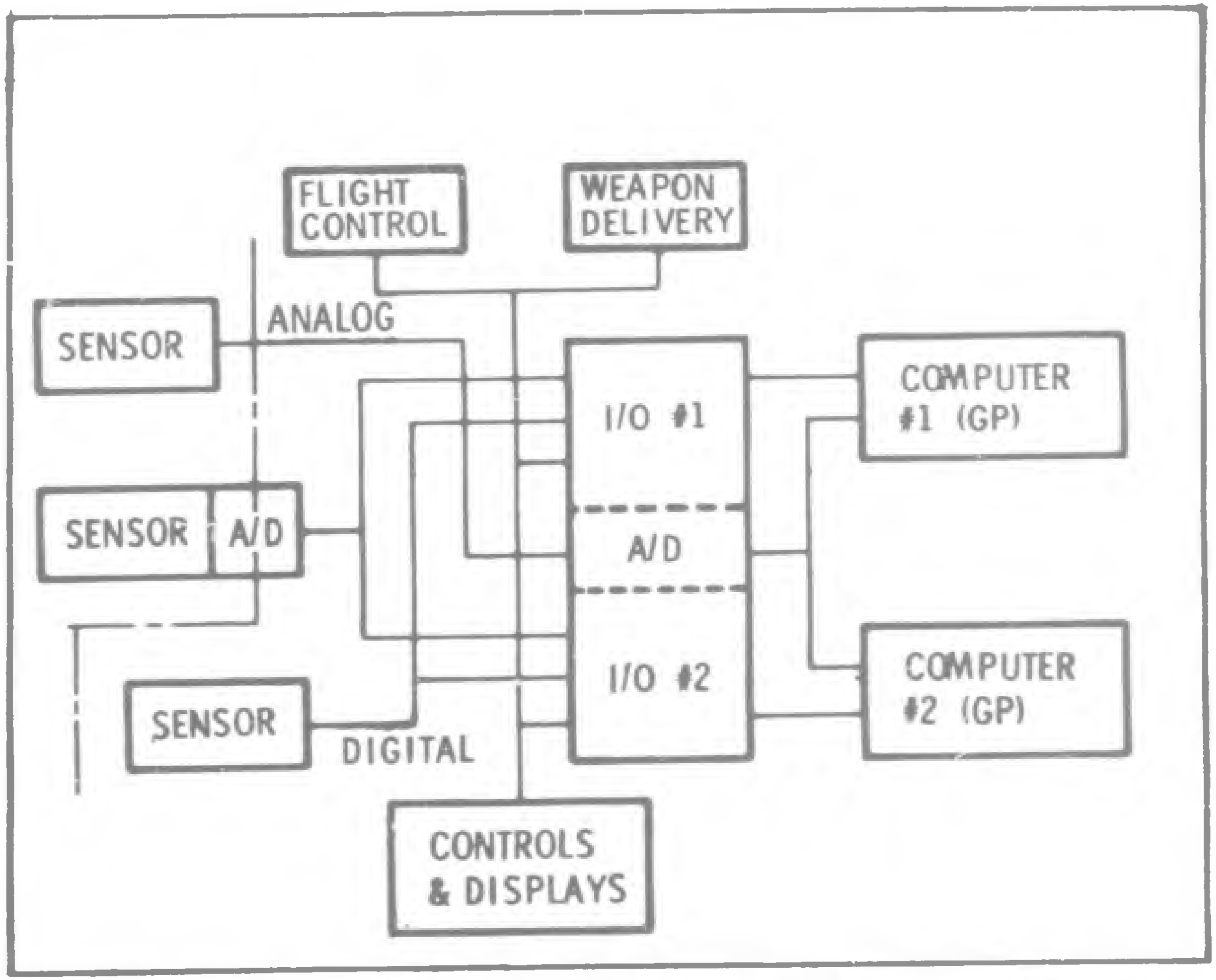


Fig. 13

REAL-TIME PROGRAM DEVELOPMENT

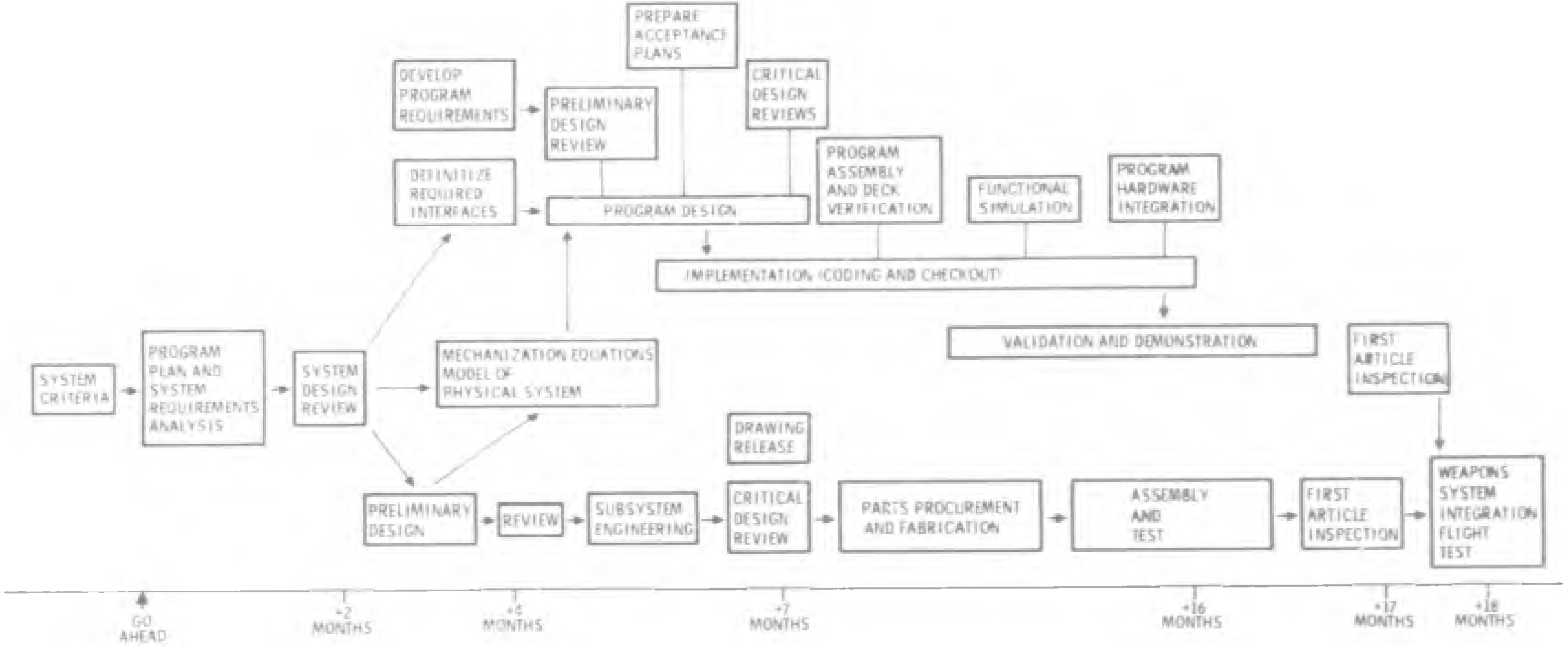


Fig. 14

DOLLAR PROGRAMMING COSTS

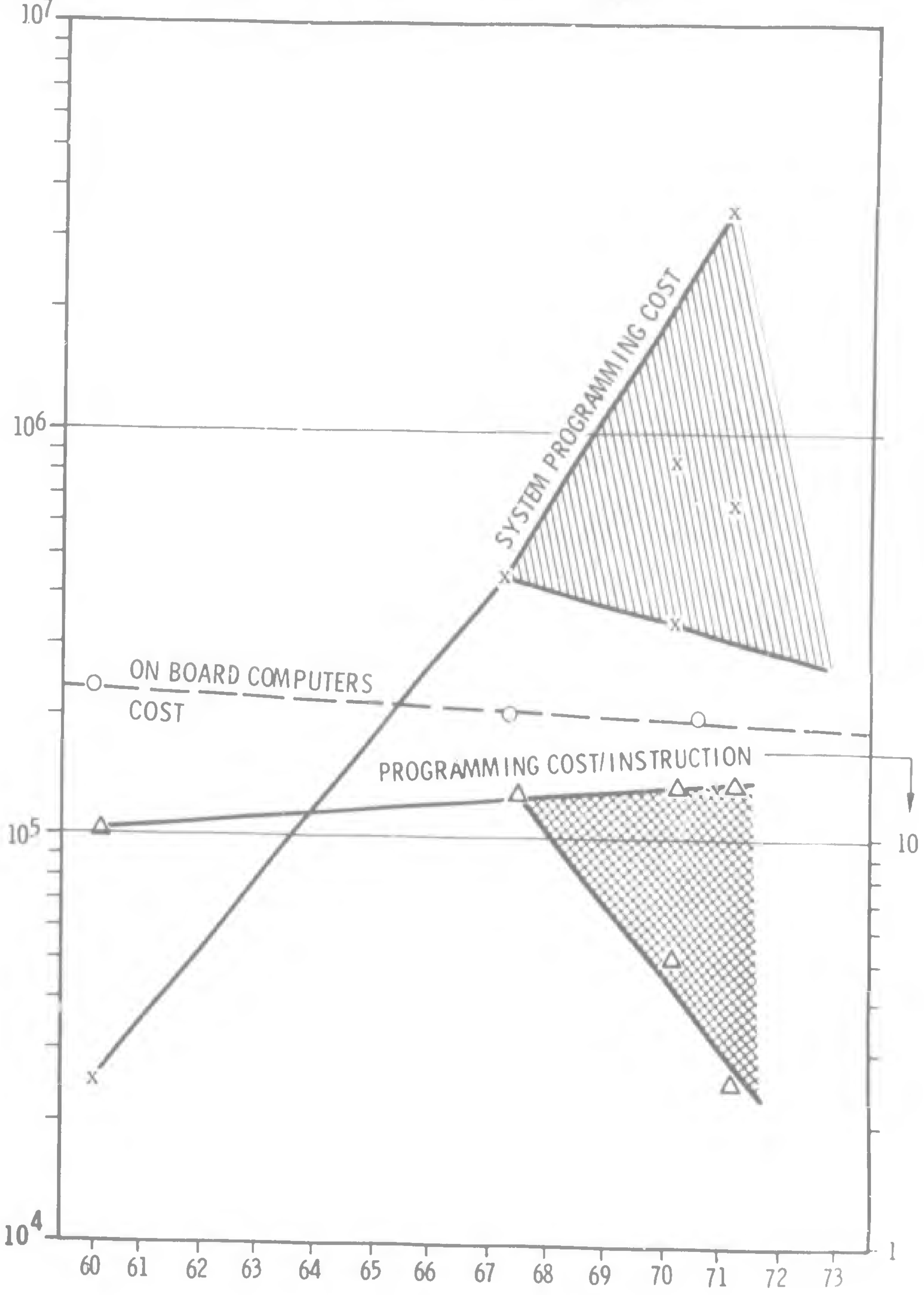
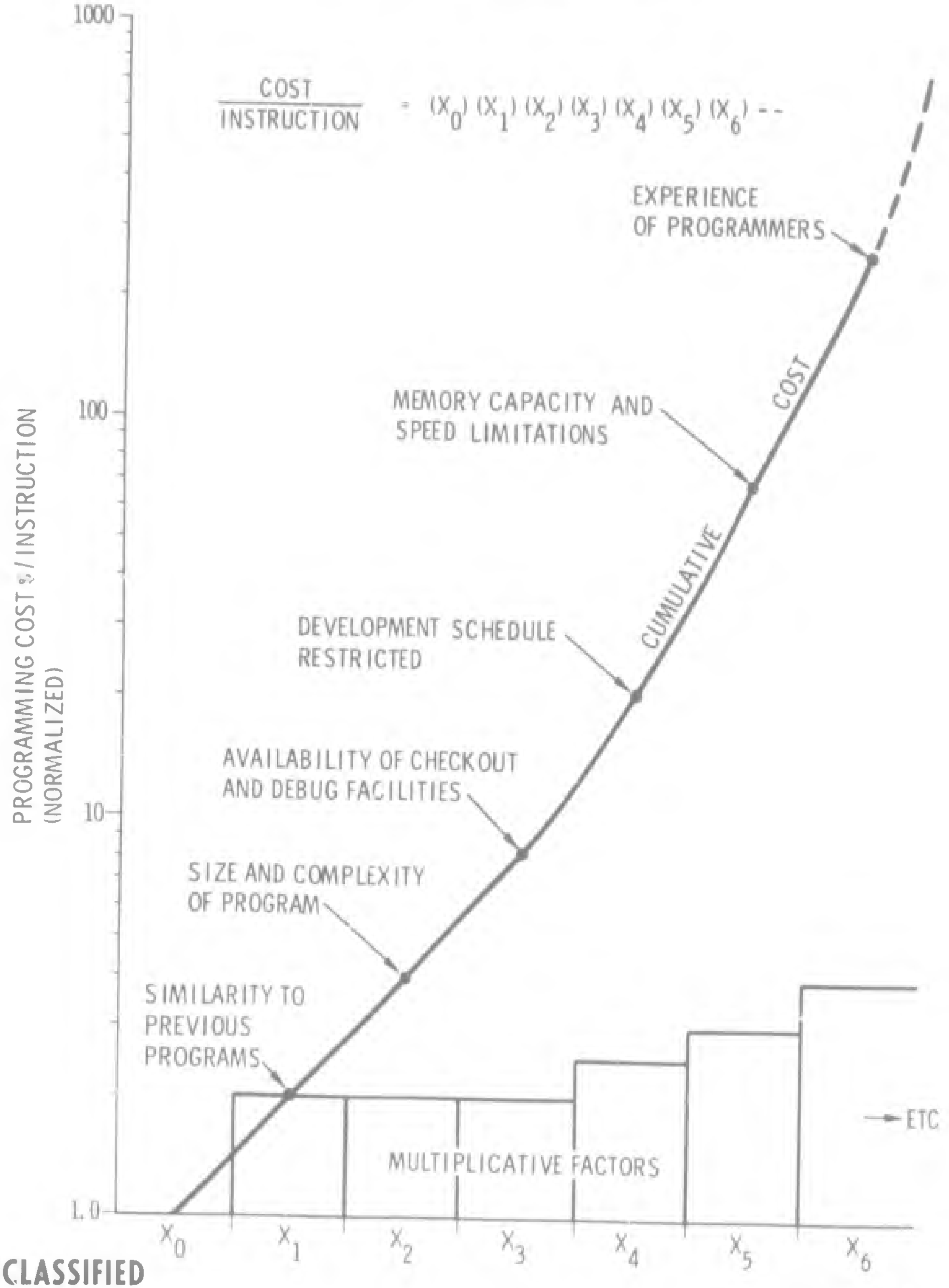


Fig. 15

UNCLASSIFIED

SOME FACTORS AFFECTING COST OF PROGRAMMING



UNCLASSIFIED

Fig. 10

CABLiNG - LATE MODEL SUPERSONIC TRANSPORT

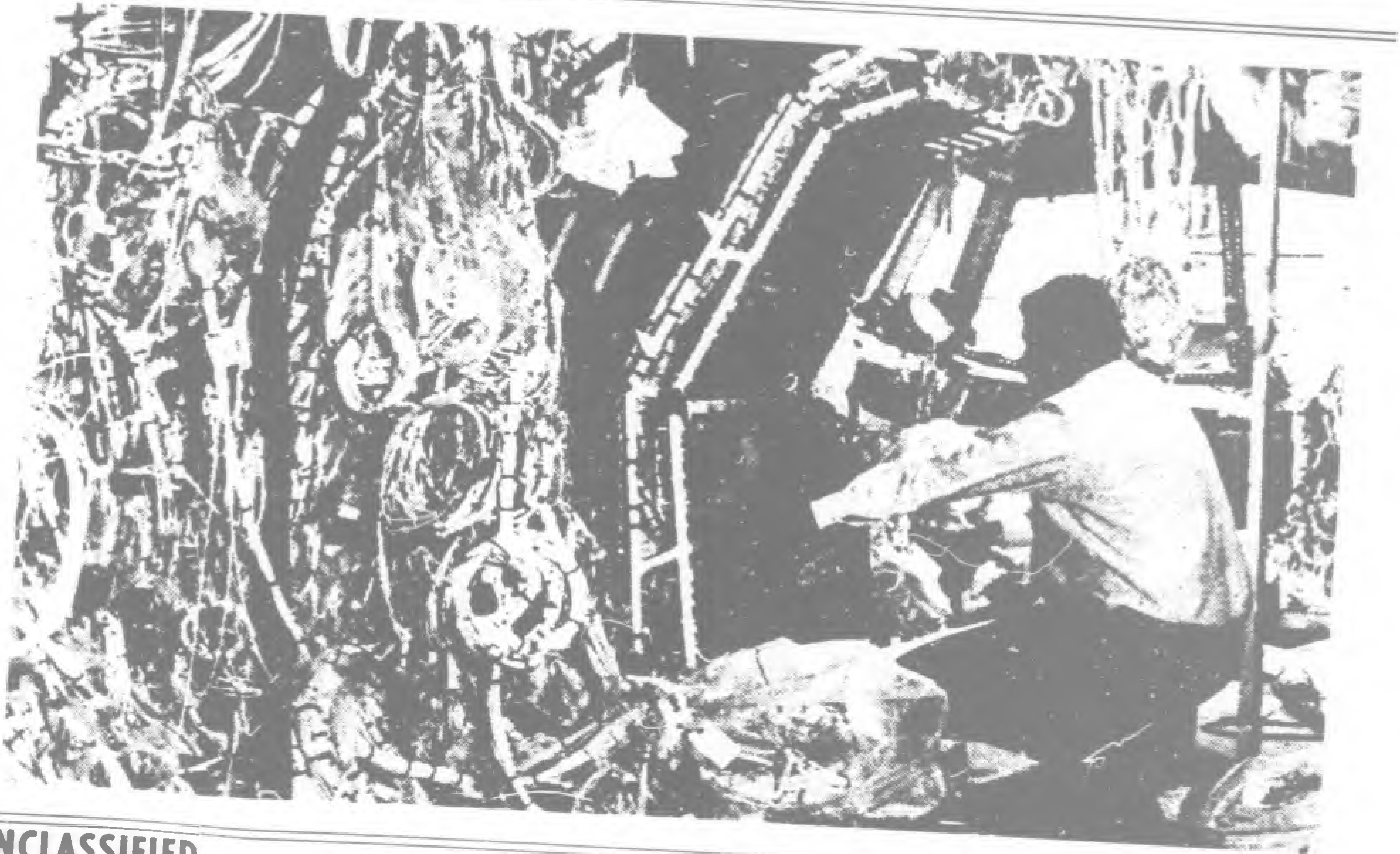
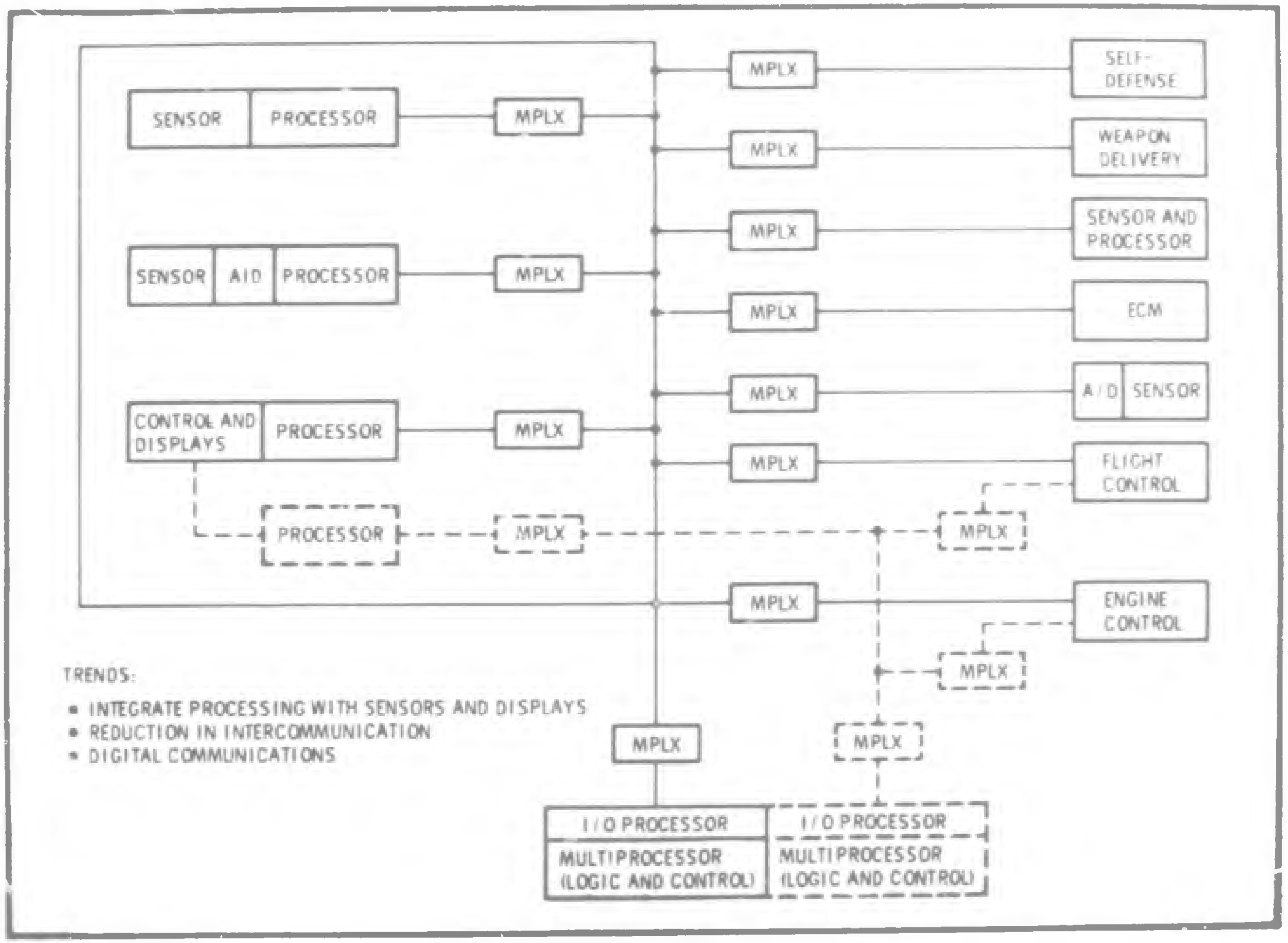


Fig. 17

DISTRIBUTED COMPUTERS



TRENDS:

- INTEGRATE PROCESSING WITH SENSORS AND DISPLAYS
- REDUCTION IN INTERCOMMUNICATION
- DIGITAL COMMUNICATIONS

OGS9 18668A

Fig. 18

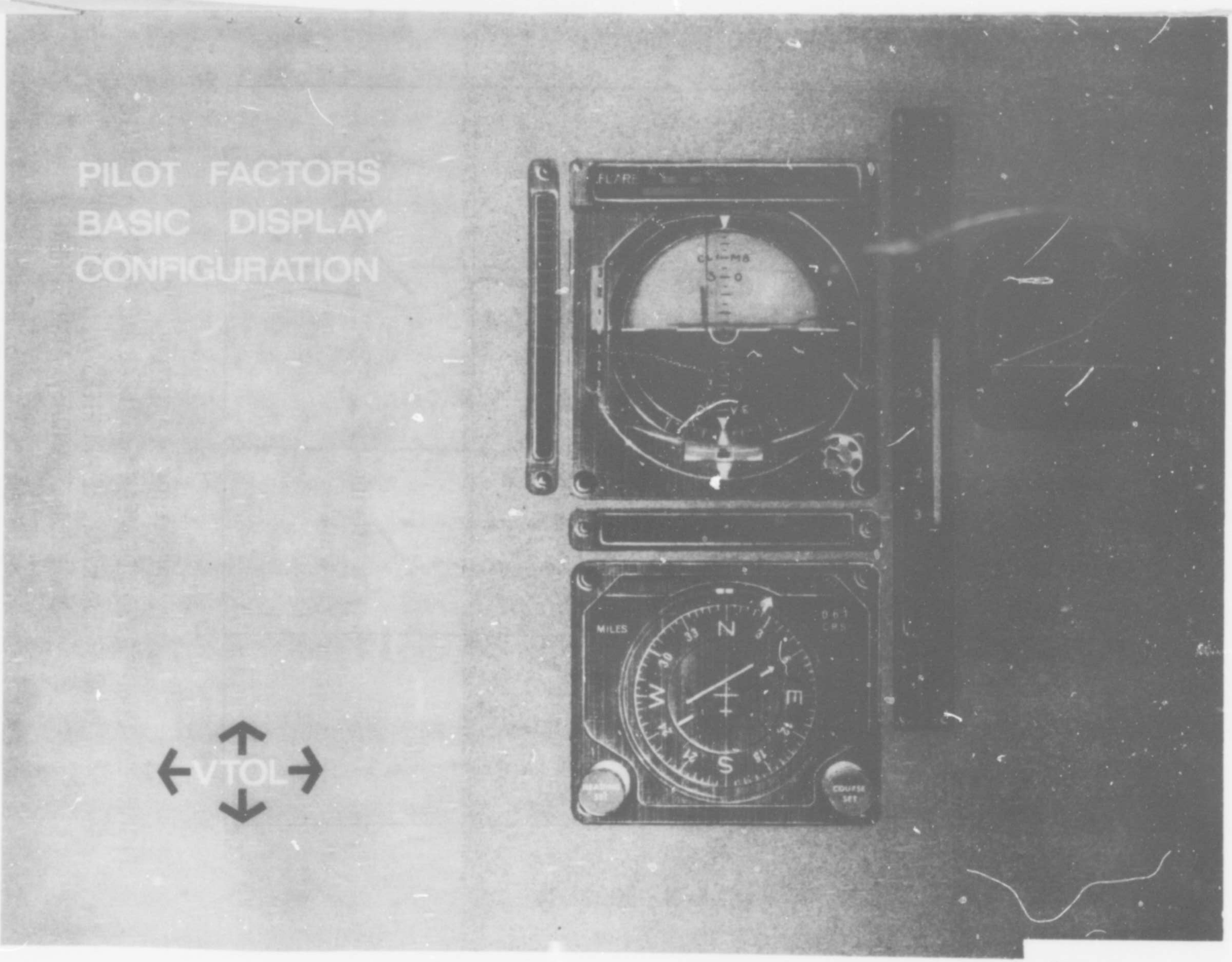
AIRCRAFT CABLING USING SIGNAL MULTIPLEXING

Advantages

- Less Weight, Less Volume, Lower Cost
- Less Vulnerable to Operational Damage
- Less Susceptible to Electromagnetic Interference
- Greater Instrumentation Tie-In Flexibility

Fig. 19

Fig. 20


PILOT FACTORS
BASIC DISPLAY
CONFIGURATION

VTOL

Fig. 21

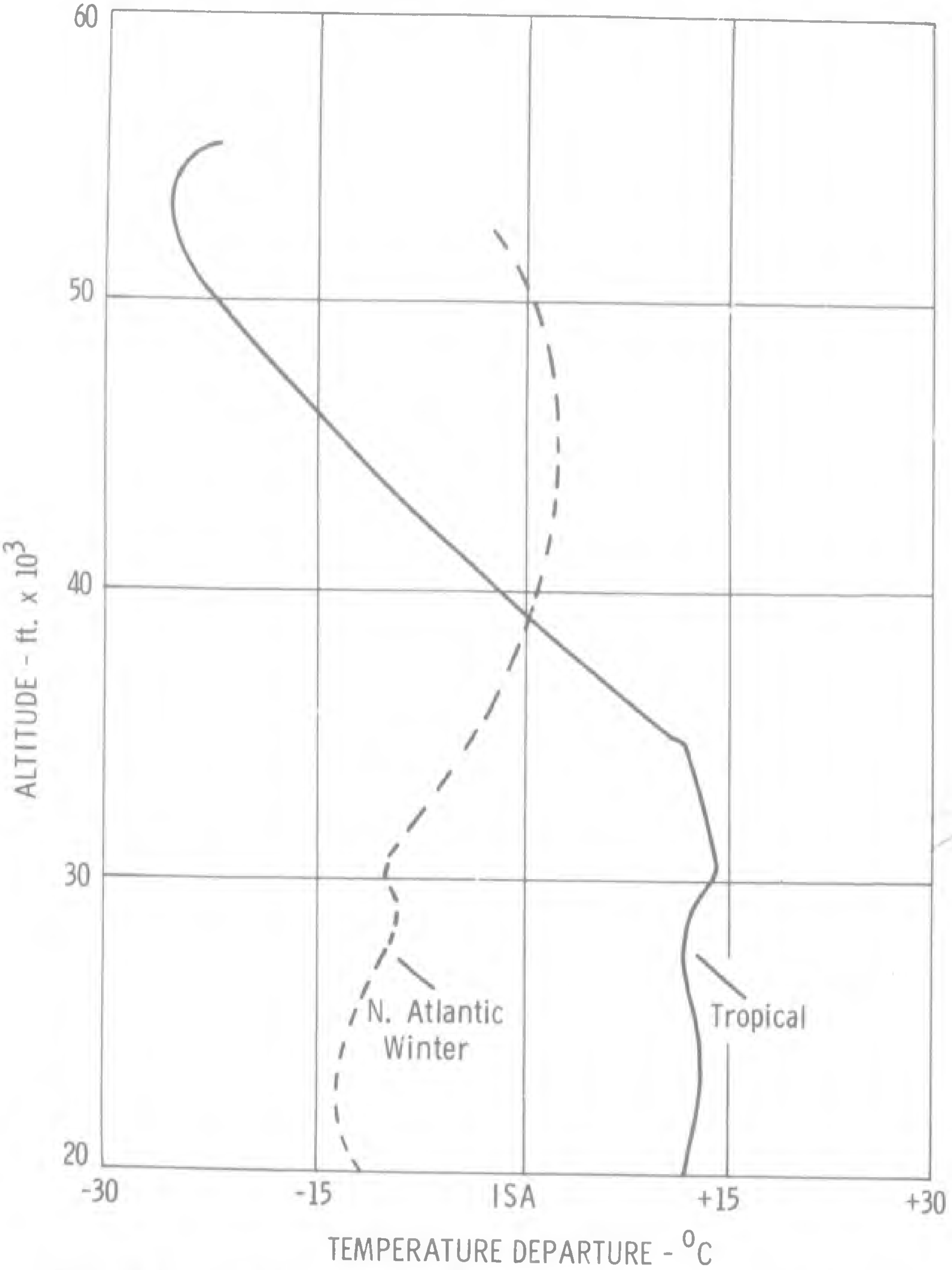


FIGURE 22 COMPARISON OF MEAN TROPICAL AND NORTH ATLANTIC WINTER TEMPERATURE PROFILES WITH THE INTERNATIONAL STANDARD ATMOSPHERE

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Air Force Office of Scientific Research
Applied Mathematics Division
Arlington, Virginia 22209

2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

3. REPORT TITLE

IS REAL-TIME, ON-LINE OPTIMAL FLIGHT CONTROL FEASIBLE?

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Scientific Special

5. AUTHOR(S) (First name, middle initial, last name)

Allen D. Dayton (Editor)

6. REPORT DATE

August 1969

7a. TOTAL NO. OF PAGES

56

7b. NO. OF REFS

--

8a. CONTRACT OR GRANT NO.

IN-HOUSE

b. PROJECT NO.

9749-01

c. 61102F

681304

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

AFOSR 70-1379 TR

10. DISTRIBUTION STATEMENT

1. This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES

PROCEEDINGS
Theory Committee of the American Automatic Control Council with the 1969 Joint Automatic Control Conference, Boulder, Colo, 5 Aug 69

12. SPONSORING MILITARY ACTIVITY

Air Force Office of Scientific Research (SRMA)
1400 Wilson Boulevard
Arlington, Virginia 22209

13. ABSTRACT

An edited transcript of a special panel discussion "Is Real-Time, On-line Optimal Flight Control Feasible?" held by the Theory Committee of the American Automatic Control Council on 5 August 1969 in conjunction with the 1969 Joint Automatic Control Conference, at Boulder, Colorado. The panel considered the problems associated with controlling an aircraft in such a way as to optimize some performance criterion. Specific subjects discussed include optimization theory and techniques, aerospace computer technology, and numerical procedures. A description of a current NASA project in this area is presented. Comments from the audience are also presented.