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Hypersonic Research Vehicle (HRV) Real-Time Flight Test Support Feasibility and Requirements Study

PART II – Remote Computation Support for Flight Systems Functions

H.A. Rediess and M.D. Hewett

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PART II – Remote Computation Support for Flight Systems Functions

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TABLE OF CONTENTS

SECTION		*PAGE*
1.0	Summary	1
2.0	Introduction	2
	2.1 Part II - Remote Computation Support for Flight Systems Functions	5
3.0	HRV Characteristics and Assumptions	6
4.0	HRV Flight Test Assumptions	7
	4.1 Instrumentation	8
5.0	"On Board" Flight System Functions	8
	5.1 Trajectory Optimization	10
	5.1.1 Trajectory Optimization Definition & Requirements	10
	5.1.2 Example Problem Formulations	12
	5.1.3 Trajectory Optimization Algorithms	12
	5.1.3.1 POST	12
	5.1.3.2 OTIS	14
	5.1.3.3 Others	14
	5.1.4 Computation Requirements	14
	5.1.5 Data Base Requirements	17
	5.1.6 Precise Test Trajectory Guidance & Control	18
	5.1.7 Data Link Requirements	18
	5.2 Energy Management	19
	5.2.1 Requirements	20
	5.2.2 Normal Operation Example	21
	5.2.3 Emergency Operation Example	21
	5.2.4 Computation requirements	21
	5.2.5 Data Link Requirements	21
	5.3 Autonomous Operations	22
	5.3.1 Example Autonomous Operation System Functions	22
	5.3.1.1 Autonomous Navigation	22
	5.3.2 Computation Requirements	23

TABLE OF CONTENTS (cont'd)

SECTION		PAGE
	5.3.3 Data Link Requirements	23
6.0	Flight Test Management and Control	23
	6.1 AFMS Concept	23
	6.2 AFMS Development	25
	6.3 AFMS Architecture	25
	6.4 Example Problem Formulation	26
	6.4.1 Flight Test Planning	26
	6.4.2 Flight Test Validation	26
	6.4.3 Flight Test Monitoring	26
	6.4.4 Flight Test Replanning	26
	6.4.5 Flight Envelope Expansion	27
	6.4.6 Trajectory Generation	27
	6.4.7 Trajectory Optimization	28
	6.4.8 Energy Management	28
	6.5 The Extension of AFMS to Operational Employment	28
	6.6 Digital Performance Simulation (DPS) Studies	28
	6.7 ATMS Demonstration with HRV Dynamics	29
	6.8 AFMS Example Problem	29
	6.8.1 Example Problem in the Normal Test Mode	29
	6.8.2 Example Problem in the Emergency Mode	31
7.0	Unmanned Operations	33
	7.1 Requirements	33
	7.2 Systems Requirements and Impact	33
	7.3 Operational Issues and Risks	34
8.0	Experimental Vehicle Implications	34
9.0	Conclusions	34
10.0	Recommendations	36
11.0	References	36

Hypersonic Research Vehicle (HRV) Real-time Flight Test Support Feasibility and Requirements Study

Part II - Remote Computation Support for Flight Systems Functions

1.0 Summary

This report assesses the requirements for the use of remote computation to support HRV flight testing. First, we develop remote computational requirements to support functions that will eventually be performed onboard operational vehicles of this type. These are functions which either cannot be performed onboard in the time frame of initial HRV flight test programs because the technology of airborne computers will not be sufficiently advanced to support the computational loads required, or it is not desirable to perform the functions onboard in the flight test program for other reasons. Second, we address remote computational support either required or highly desirable to conduct flight testing itself. We propose the use of an Automated Flight Management System which is described in conceptual detail. Third we discuss autonomous operations and finally, unmanned operations.

In this structure, computational support is discussed for trajectory optimization, energy management and flight test management and control. The use of trajectory optimization is considered essential to successful preflight planning and inflight replanning for HRV operations and flight tests. The type of trajectory optimization required is computer generated open loop control time history solutions to nonlinear two-point boundary value problems. This type of trajectory optimization is computational very intensive. It is not possible in airborne computers today to generate solutions to the class of global optimization problems we are interested in for HRV's within reasonable solution time constraints. Continuous energy management during HRV flight is essential for a number of reasons. For replanning and safety reasons it is essential to know on a continuous time basis where the vehicle can go from its present operational state (location, fuel state, altitude, velocity, etc.). This is required to assure safe vehicle recovery at alternate landing sites in the event of flight emergencies, and to assist in replanning in real time. We must guard against generating a replan which is impossible from an energy management viewpoint to execute. Also, continuous energy management is required as a prerequisite to real time use of trajectory optimization. An optimization algorithm will fail when faced with a problem for which there is no solution which, in turn, will add significantly to solution times and possibly require human intervention in the solution process. Finally, it is highly desirable to provide automated flight test management and control in the form of an advanced Automated Flight Test Management System (ATMS). Such a system would provide knowledge-based expert system supervision of trajectory optimization algorithms, trajectory generators, trajectory controllers, simulations and models. It would provide a total environment for preflight planning and inflight monitoring.

The bottom line is that remote computational support is required to attain the necessary operational flexibility to conduct a flight test program which minimizes testing costs and time. It is not acceptable to operate an HRV in a space shuttle mode in which very little flexibility in the preplanned mission and timeline is allowed. It is most desirable to operate the vehicle in a mode which more closely parallels that of a high performance aircraft wherein the mission can be

replanned in real time to accommodate data, system, human or timeline anomalies in the preplanned mission.

2.0 Introduction

The NASA Ames Research Center, Dryden Flight Research Facility (Ames-Dryden), has a unique real-time flight test support and research capability provided by the Western Aeronautical Test Range (WATR) and the Remotely Commanded Vehicles and Display (RCVD) facility. The WATR consists of the mission control center, communications systems, real-time processing and display systems and tracking systems [1]. The real-time data processing and display systems of the WATR, for example, provide high level flight test information on appropriate engineering parameters[2]. An advanced example of this was the monitoring of the X-29A flight tests[3] as illustrated in Figure 1. During the initial portion of the program, telemetry data were relayed from Edwards, California to Bethpage, New York for the Grumman Engineers to be involved in the real-time flight test monitoring. The RCVD facility provides real-time ground-based computational support for test aircraft command, control and display functions through use of telemetry, ground based computers and uplinks[4]. The RCVD facility has been used, for example, to perform flight controls experiments with the control laws computed on ground-based computers. SPARTA Inc., with the assistance of Systems Technology, Inc. and Information Management, Inc., performed a study[4] for Ames-Dryden considering a major expansion of the real-time support capabilities of these facilities that could significantly enhance flight research. The study reported here is an extension of that study addressing specifically the flight testing of a Hypersonic Research Vehicle (HRV). The study was conducted in three Parts: Part I - *Real-time Flight Experiment Support*[6]; Part II - *Remote Computational Support for Flight Systems Functions*, reported herein; and, Part III - *Automated Flight Test Management System (ATMS)*[7].

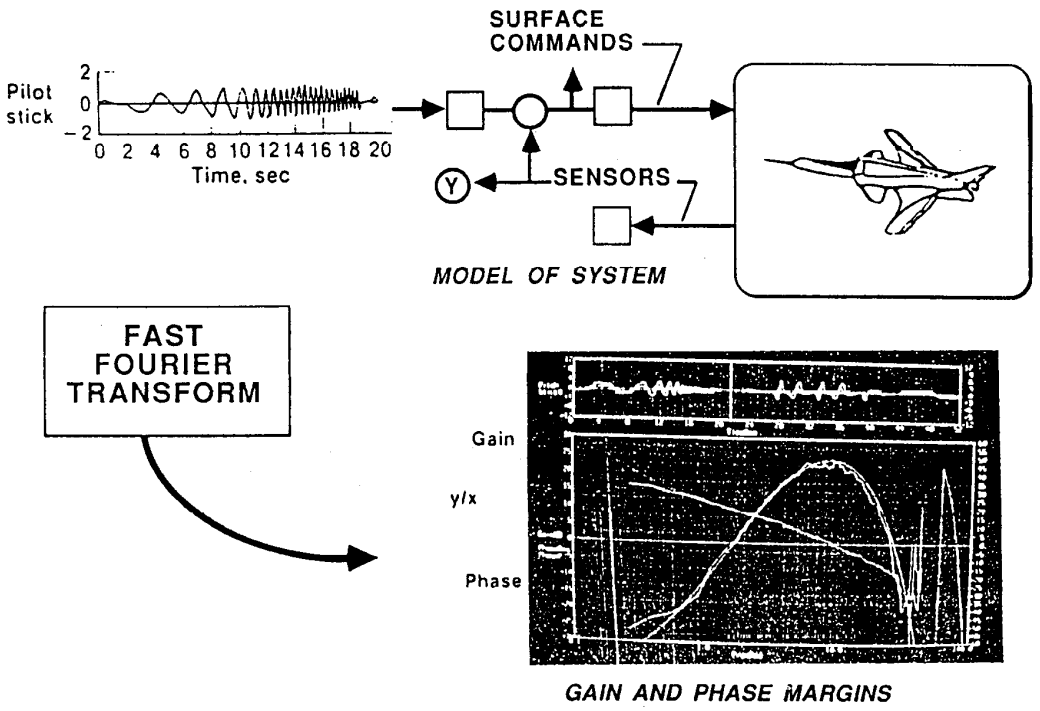

Figure 1: Stability Margins of the X-29A Were Estimated in Real-time Using Remote Computation

The HRV can be thought of as a generic form of the X-30, the experimental flight vehicle in the National Aerospace Plane (NASP), for the purpose of this investigation. By that we mean it is a hypothetical hypersonic vehicle with the same objectives as the X-30 as identified in the open literature. No specific NASP or X-30 data are used in this study. The class of technology necessary for the X-30 are considered and assumptions are made about likely design features and operational characteristics. This "generic" approach seems adequate for investigating this remote computational flight test support concept.

Figure 2 illustrates the general concept of remote computation for real-time flight test support of a HRV. A high data rate telemetry system provides the down link from the HRV and contains all the necessary raw and/or preprocessed flight data. Accurate space positioning data are obtained from a combination of tracking, GPS and onboard systems. These data are provided to the mission control center and the real-time computation center. The real-time computation center would contain an extensive array of computers to support conventional processing, parallel processing symbolic processing, etc. These computers would operate in real-time on flight data, pre-stored data and simulations of the physical processes being investigated to provide a high level of information to assist those conducting the flight tests. The information generated would be used to monitor flight safety, manage the flight tests, assess the quality of the test data, control the experiment, and perform certain flight system functions that would normally be done onboard. Up links would be used to transmit guidance and control information to the HRV.

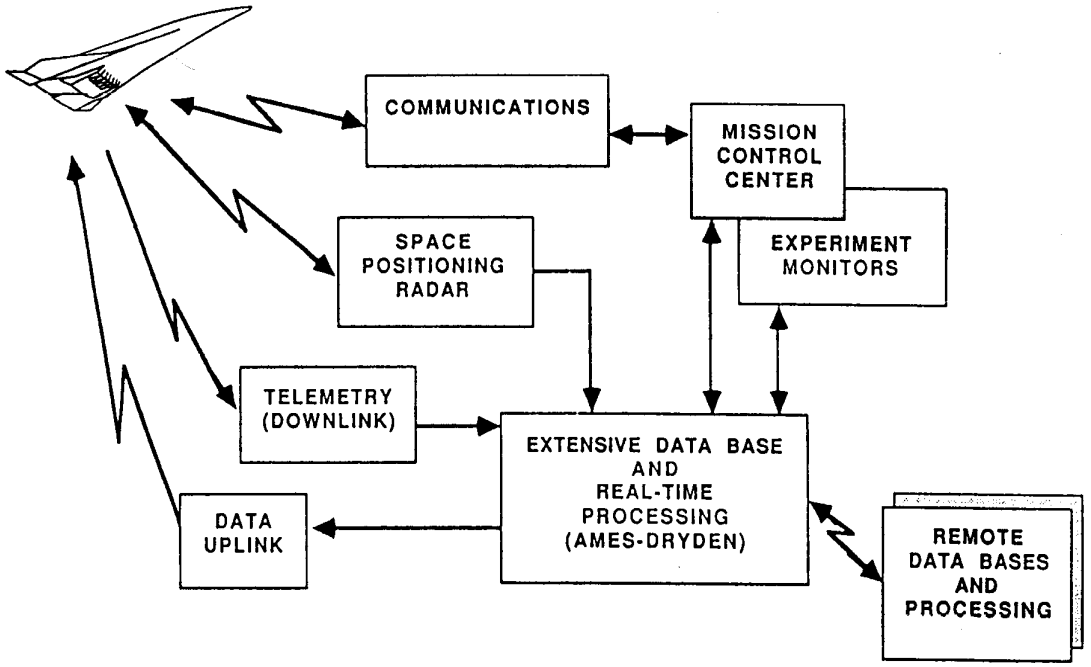

Figure 2: Remote Computation Concept Could Improve the Real-time Flight Test Support of a HRV

Figure 3 shows how this might be done over an extended range. Computations may be required at three levels: (1) onboard; (2) "local" remote; and, (3) primary remote. Only the highest bandwidth computations and flight critical functions would be done onboard. Medium bandwidth non-flight-critical computation that would not tolerate the time delay going to and from the primary computation facility could be performed in a remote but closer location. The bulk of the support remote computations would be performed at the primary location where, presumably, the operational control also resides. An extensive master electronic data base at the primary site would contain the experimental flight data (and possibly ground generated) for easy access by NASA Centers and other laboratories and aerospace companies. Research Centers located around the country, such as Langley Research Center (Langley), Ames Research Center at Moffett Field (Ames), and Lewis Research Center (Lewis) could be tied into the primary site through satellite data links such as the NASA Program Support Communications Network (PSCN) satellite, as shown in Figure 4. Researchers at these facilities could be actively involved in monitoring their experiments during the flight. Each of the remote Centers would have their own electronic data bases and potentially "real-time" flight test support computations relevant to their specific experiment. The master and distributed data buses will have compatible formats for easy exchange of data. This part of the study was not to consider the range implementation issues.

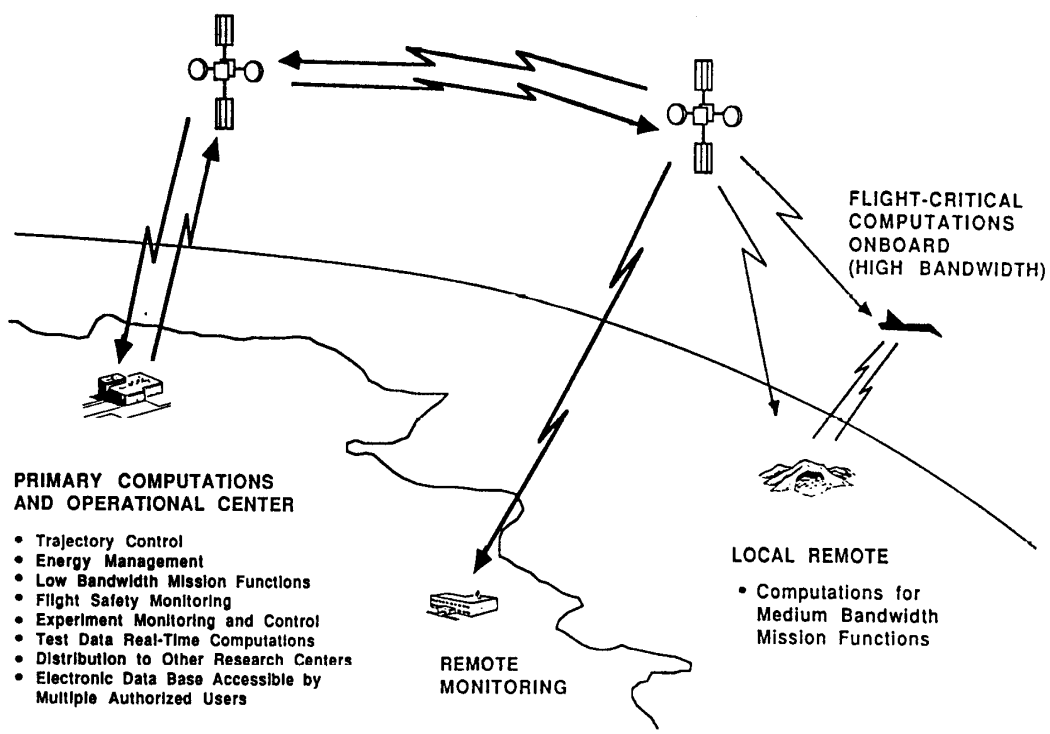

Figure 3: An Extended Range Concept for Real-Time Flight Test Support for a HRV

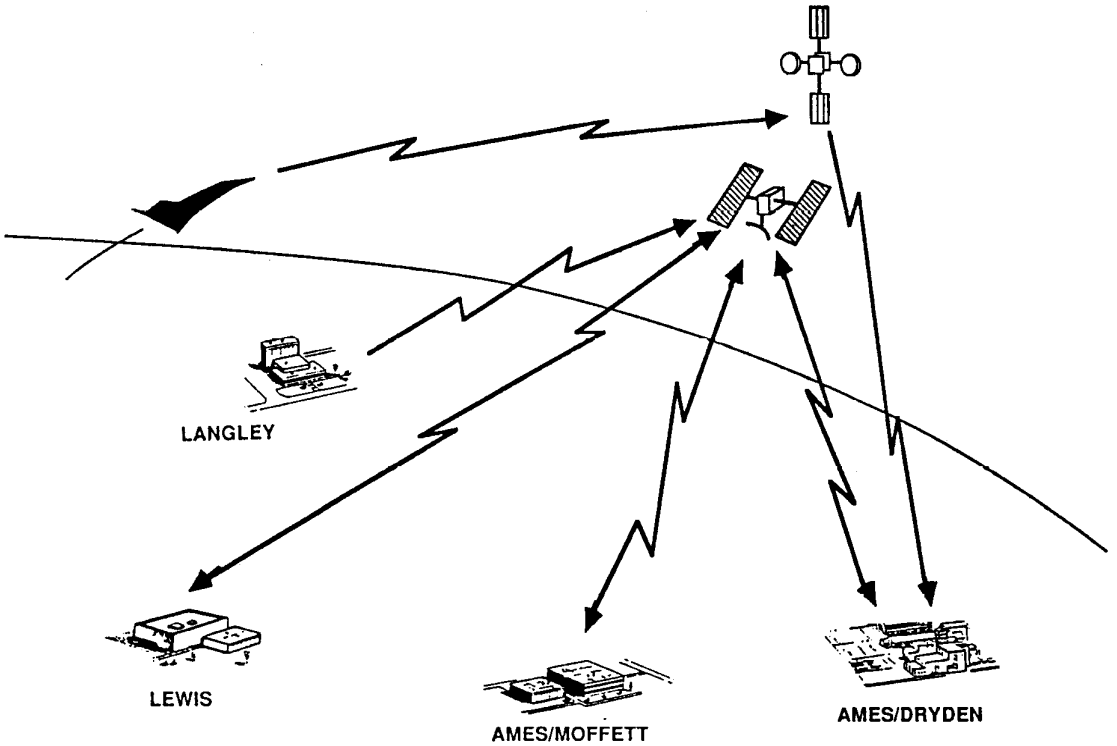

Figure 4: Real-time Flight Test Data Distribution Brings Other Centers into Active Monitoring Role

2.1 Part II - Remote Computation Support for Flight Systems Functions

Ames-Dryden has demonstrated the feasibility and benefit of performing certain flight systems functions in flight experiment programs through remote computations (e.g., F-8 DFBW controls research, HiMAT, and projections for HIDEC). Many of the flight systems functions that would be needed for the HRV could potentially be performed through remote computation and off-load the onboard computation requirements. If that could be done, there would be two significant benefits. First, the onboard system could be minimized without compromising the functional objectives. The savings in weight and space could be significant. Secondly, the level of technology from an algorithmic standpoint that could be investigated in flight, would not be tied to specific flight-qualified hardware/software systems. For example, advanced architectural computers required for performing certain autonomous operations functions may not be available in compact flight-qualified versions in time for a HRV flight test program. One would only have to have the necessary sensors and pilot interface media onboard the vehicle and perform the computations on the ground with this approach. Concepts could be investigated in flight ten years before flight qualified equipment is developed. The remote computational approach would allow multiple concepts to be evaluated rather than just one since it would not be locked in by the specific onboard hardware configuration.

A second way in which "remote computation" for flight systems functions can be beneficial for HRV flight testing is the preflight planning, replanning during the flight and precise trajectory guidance and/or control (manned or unmanned operations) in support of the flight test program. Whereas the first class of applications discussed above deal with using the remote computational to investigate algorithms that would eventually be implemented onboard in an operational vehicle, this class is directed totally at ground based computations to aid the flight test engineers and/or to provide command guidance to the pilot during the experimental flight test program. Remote computations with uplinks to the vehicle could be used in an operational situation if adequate onboard backup systems are provided to take over if the data links are lost or autonomous operations are required. The study did not treat this potential operational situation.

Part II is to study the feasibility and develop the preliminary requirements for remote computational support for: 1.) certain (onboard) flight systems functions (ones that would normally be performed by dedicated onboard hardware/software systems generally involving sensors, extensive computations and in some cases pilot interfaces, e.g., displays and controls.); 2.) flight test management and control functions to aid the flight test engineer or pilot; and, 3.) unmanned operations. The principal aspects of each of these that are considered here for illustrative purposes are trajectory guidance and control (G&C) and energy management.

The report first defines the HRV characteristics and flight test and assumptions made, then addresses each of the three types of support mentioned above and finishes with conclusions and recommendations.

3.0 HRV Characteristics and Assumptions

For the purpose of this study, the HRV is assumed to be a "generic" form of the X-30; that is, it has the performance capability to meet the design goals of the X-30 indicated in the open literature[8]. Its objective is to have the capability to take off horizontally, accelerate to high hypersonic Mach numbers using airbreathing propulsion, fly into low Earth orbit, reenter the atmosphere and descend to a powered horizontal landing. Since such a vehicle has not yet been designed, a number of assumptions must be made about its potential characteristics in order to perform this study[9,10]. It is assumed to have an airbreathing multi-mode propulsion system which is integrated into a highly swept delta wing-body configuration of the nature shown in Figure 5 (illustrative only). At hypersonic speeds, the propulsion mode is a liquid hydrogen burning scramjet. A rocket engine is assumed for the de-orbit maneuver. The HRV structure is assumed to be a hybrid of advanced materials, fabrication techniques, hot structures and actively cooled structures. It may contain advanced metallic alloys, inter-metallic composites, metal-matrix composites, advanced carbon-carbon composites, ceramics and ceramic matrix composites. Portions of the structure, such as the nose cone leading edges and the engine cowl, are expected to require some form of action cooling using liquid hydrogen.

Once the HRV reaches the speed where the scramjet takes over, it must fly a corridor of dynamic pressure between the minimum required to sustain engine operation (plus some margin) and the maximum allowable due to flutter, structural and/or aerothermodynamic loads limits. The scramjet has the best performance flying at maximum dynamic pressure, about 1,500 pst for this class of vehicles. At that dynamic pressure the surface temperature could reach 2,000°F. The heat flux into the structure from aerodynamic heating is sensitive to the boundary layer transition point as well as dynamic pressure, both of which are functions of the flight conditions. Precise control of the flight path trajectory will be very important.

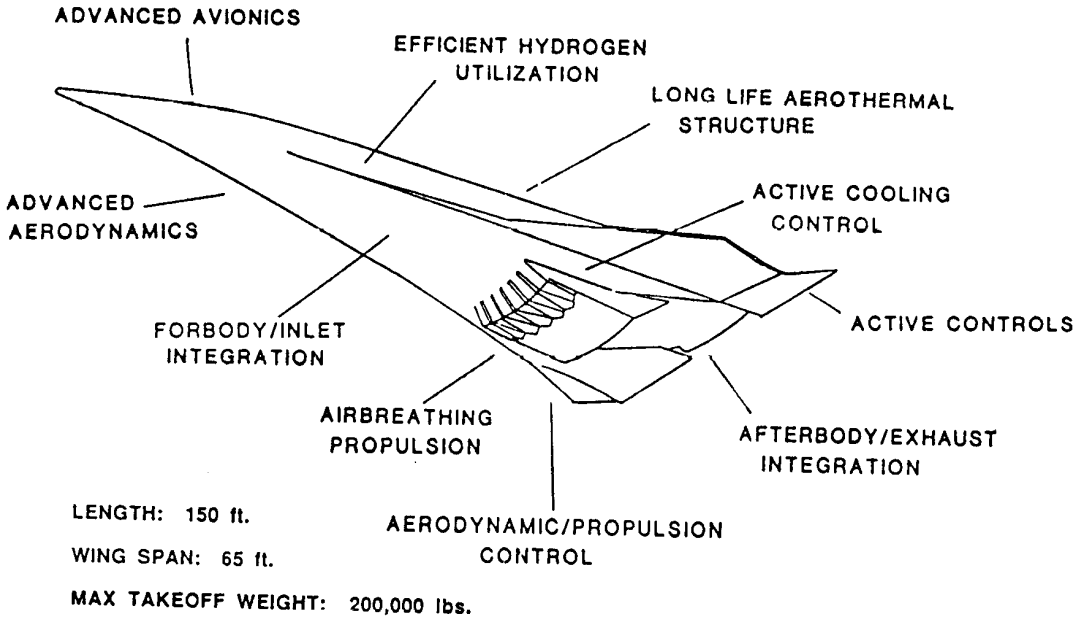

Figure 5: HRV Will Require Multiple Advanced Technologies

4.0 HRV Flight Test Assumptions

The flight test program is assumed to be conducted from Edwards Air Force Base (EAFB). The HRV would take off horizontally, fly a preplanned trajectory up to a preplanned maximum Mach number and altitude then return on a preplanned trajectory to EAFB and land horizontally. Figure 6 is an example of what a typical ground-track might look like during the envelope expansion phase. The Figure shows one potential method[5] for maintaining continuous telemetry and uplink coverage by using relays via mobile remote ground units and a remote airborne platform. A satellite relay may be needed for the highest performance flight conditions. The range considerations for providing telemetry coverage was included in this part of the study. It is assumed here that it is possible to have telemetry coverage at the flight conditions of interest. Efforts of potential time delays using relay stations are discussed.

It is assumed that the flight test program would progress in the typical experimental aircraft manner of gradual envelope expansion. For example, the first phase would be low-speed tests with the turbojet engine (mode) to check out many of the systems, subsystems, instrumentation, telemetry, flying qualities, landing characteristics and performance would be confirmed before proceeding to less certain hypersonic speeds and scramjet (mode) operation. Extensive flight simulation and analyses, updated at each step by flight test data, would support this envelope expansion. It is assumed that there would be an extensive pre-flight data base on all disciplinary aspects of the HRV and that it would be updated with test data from each flight. The key point for this study is that as long as the HRV is close to the planned trajectory and flight test plan on each flight, you are only making modest extrapolations from a known data base.

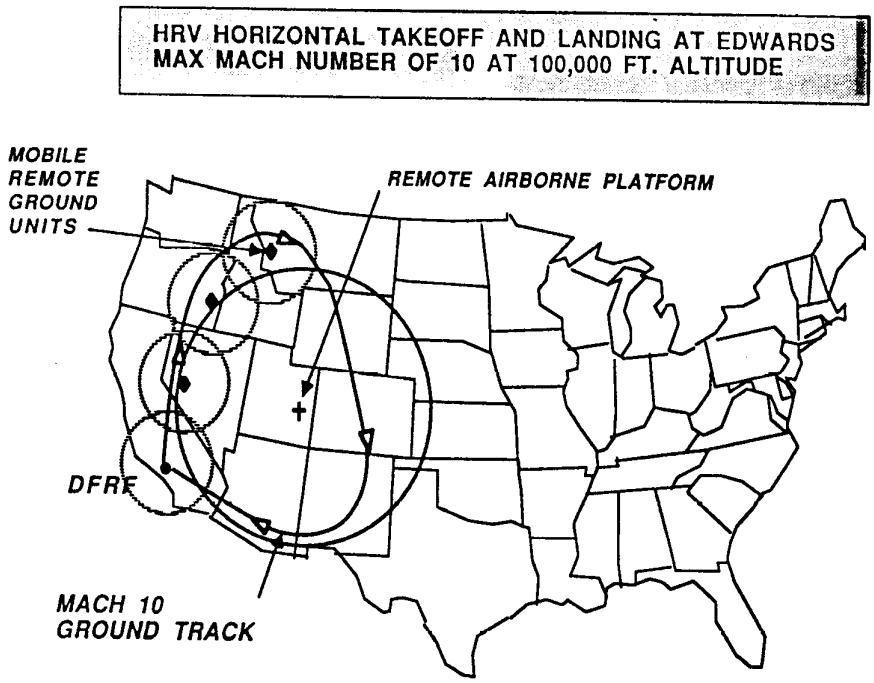

Figure 6: Typical Ground Track for an HRV Flight Test

4.1 Instrumentation

The flight test instrumentation is, of course, critical to the real-time monitoring and control process. It is often difficult if not impossible to measure a parameter you want where you want it. The problem will be particularly difficult in hypersonic flight with scramjet propulsion. The NASP program recognizes this and has one element of the program devoted to developing instrumentation concepts for the most challenging problems. In performing this study, certain assumptions had to be made about instrumentation and measurement techniques which should be available for a HRV. For example, we do not address the measurement of free-stream flow field conditions, i.e., static and dynamic pressure, Mach number, etc., but rather assume that accurate measurements of those parameters are available. We assume that the typical state and control variable measurements are available via telemetry as well as range data from the NASA tracking facilities. Other vehicle and systems parameter measurements, such as vehicle configuration, fuel status and flow rate, critical structural temperature and total stress, etc., are assumed available on the ground.

5.0 "On Board" Flight System Functions

In this section we develop the remote computational requirements for functions that will be eventually performed onboard operational flight vehicles. We will show that these functions are important for the flight test and that they cannot be implemented on today's generation of airborne computers and are not likely to be implementable in time to be incorporated into the first HRV flight tests. In addition, it is likely that as time goes on, the demands for computational power to implement increasingly advanced concepts will increase. Of course, the capabilities and performance of airborne computer hardware will also increase in parallel. In fact, it can be shown that for the past twenty years computer throughput has doubled every year for a fixed physical CPU size. Figure 7 illustrates this phenomenon. The Figure shows the increase in integrated circuit density as a function of time since 1960. The phenomenon is not likely to change for the foreseeable future.

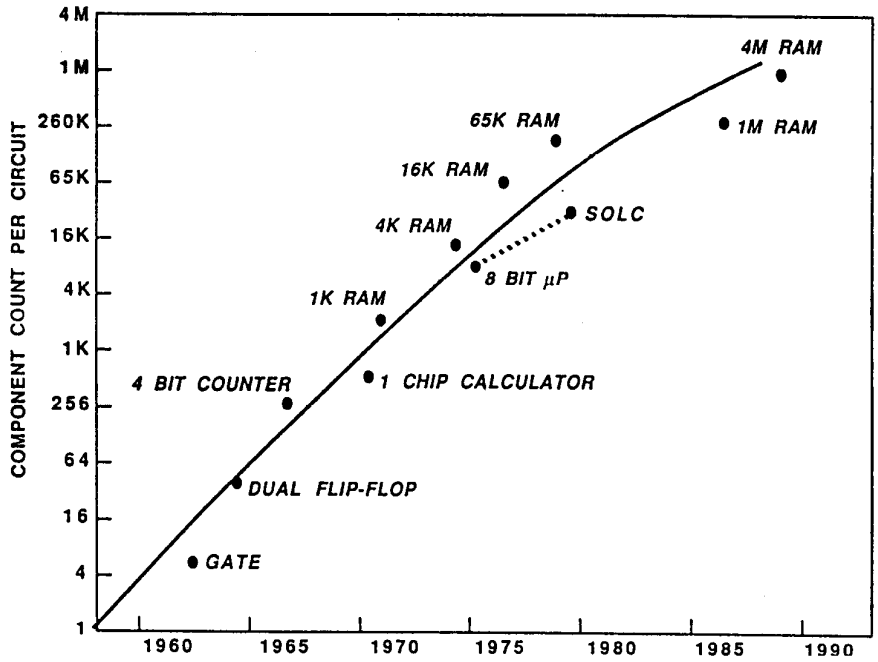

Figure 7: Integrated Circuit Density is Doubling Every Year

It is also a well observed phenomenon that the computational demands of advanced concepts arising out of research and development activities always exceed current computer hardware capabilities. In other words, there will always be the need to use remote computation to demonstrate increasingly advanced functions no matter how capable airborne computers become. The assumption here, of course, is that ground based computing systems will always be able to support more throughput than airborne computers because of the unlimited space available in a ground based system and the lag between applying the latest computer technology to ground based general purpose computers and airborne special purpose computers. This lag is typically two to six years and is a function of market demand (very low for airborne computers), commercial vs. government application (commercial applications are much more financially rewarding to a developer), and the necessity to flight qualify and flight harden all airborne computer equipment.

In addition, remote computation allows the implementation of advanced concepts in code which does not have to meet stringent V&V requirements and which can be modified comparatively easily.

In the following sections, we develop the rational and requirements for remote computation to support three types of onboard flight system functions; trajectory optimization, energy management and autonomous operations.

5.1 Trajectory Optimization

From a computational viewpoint, trajectory optimization is by far the most demanding of G&C functions. We consider the generation of energy management trajectories to be trajectory optimization problems from this computational viewpoint. We formulated two trajectory optimization problems which are appropriate for the HRV and for potentially illustrating the benefits of the remote computation approach. We surveyed ARC, LaRC and other sources for existing optimization algorithms for solving the problems formulated and identified two leading candidates (POST[11] and OTIS[12]) suitable for use in generating optimal trajectories for the HRV. We studied these algorithms to assess the computational requirements for real-time optimization solutions.

5.1.1 Trajectory Optimization Definition & Requirements

It is our view that an HRV must have access to highly developed trajectory optimization algorithms and the necessary computing power to exercise these algorithms in real time for inflight replanning. The purpose of these algorithms would be to generate flight trajectories which the HRV would follow to accomplish some goal. First, let us define what we mean by trajectory optimization.

The class of problems we are considering in trajectory optimization in this application is the deterministic, nonlinear, two-point boundary-value class of problems. We seek computer generated numerical solutions for optimal control time histories and their associated flight trajectories which minimize (or maximize) some performance measure (a functional which might include time, control energy, etc) subject to equality constraints (the dynamic equations of motion of the flight vehicle), state inequality constraints (limitations on vehicle states such as angle-of-attack, load factor, dynamic pressure, Mach number, aero-heating, etc.), control inequality constraints (limitations on thrust, control deflections or forces, etc) and boundary conditions. The equations of motion cannot be linearized typically because the range of operating conditions encountered is too large in a given problem. In addition the inequality constraints play a heavy roll and prevent for all practical purposes the linearization of the problems of interest. Thus, an optimal control law solution cannot be generated analytically, e.g., through solution of a Riccati equation. If we could generate an optimal control law (controls which are a weighted linear combination of vehicle states) or even a family of optimal control laws, the problem would be over. We could do all trajectory optimization on board the flight vehicle. There would be no need for remote computation to do trajectory optimization.

Also, we are not talking about the class of problems here which are concerned with tracking a trajectory once one is generated. The tracking problem can also be formulated as an optimal control problem. In this application, it is the stochastic optimal linear feedback problem: an extension of the linear regulator with a quadratic performance measure which minimizes tracking errors and control energy. An optimal control law is generated and the computations can be done on board a flight vehicle as we shall see. This is the correct application of optimal control theory for the problem discussed in section 5.1.6 below.

The dynamic equations of motion used in trajectory optimization problems of the type discussed herein are typically of the 3 degree-of-freedom (DOF) variety with pseudo degrees-of-freedom added to better simulate limitations on angular rates, which we will term 3 DOF+. Typically these pseudo degrees-of-freedom take the form of first order lags in parameters such as roll rate, pitch rate, yaw rate, thrust rate of change, etc. Occasionally, a trajectory optimization problem requires the use of a full 6 DOF simulation to obtain acceptable results. Since these optimizations require a great deal of computer CPU time typically, it is wise to use only the level of

model sophistication required to generate a meaningful solution (optimal control time history and associated trajectory). Using this solution as the norm, the stochastic optimal linear feedback problem can then be formulated by linearizing the equations of motion about the norm and solving a Riccati equation to generate a tracker optimal control law (section 5.1.6). This control law produces control increments which must be added to the control time history at any given point in time to yield the total control deflections or forces.

Historically, trajectory optimization methods have been successfully used in a wide variety of applications including off-line non-real time trajectory optimization for flight vehicles. The most common methods in existence are:

1) First order gradient methods (the method of steepest descent)
2) Second order gradient methods (Newton-Raphson)
3) Variation of exteremals
4) Quasi-linearization
5) Dynamic programming
6) Epsilon methods

A number of algorithms are available in the aerospace industry, commercially, in the academic world and in government which employ all of these techniques. In section 5.1.3 we discuss two of the most promising for the HRV application. In addition, work is in progress at Honeywell to develop real-time trajectory optimization algorithms.

The primary requirement of a suitable trajectory optimization program to qualify it for use in HRV flight testing is that of flexibility. The algorithm must be able to generate optimized trajectories for an extremely wide range of performance measures, flight conditions, and constraints. A large variety of flight test maneuvers will be formulated involving energy management, envelope expansion, capture maneuvers, structural maneuvers, aerodynamic heating tests, stability and control tests and many others. In addition the data base used by the simulation in the program must be easily accessed so that new data can be input daily during the flight test program. Finally, the program must be able to generate trajectories rather quickly on available computer systems so that real-time trajectory optimization can be effectively performed during a flight test in response to some flight anomaly.

As an example of the complexity of HRV flight testing as opposed to standard high performance flight testing, consider the case of executing a simple capture maneuver from the end condition of one maneuver to a trim point for the next maneuver. In an F-18, the capture maneuver is performed manually with little consideration other than normal operating procedures to the flight path chosen to perform the capture. It is easy to design a flight test trajectory controller to perform the maneuver automatically. This was done in the ATMS[7] program. No optimization was involved. In the HRV the flight path chosen to perform the capture is a major problem - an optimization problem. Many constraints and limitations are involved including aerodynamic heating, Scramjet operational limits, major concerns about fuel consumption, operating area considerations, etc. It cannot be left to the test pilot to simply fly to and stabilize on the next trim point.

Trajectory optimization will be required to perform in-flight replanning. The replanning requirement arises out of the desire to be able to generate revised trajectories in response to flight test anomalies such as data dropouts, instrumentation failures, unexpected data, vehicle emergencies, vehicle system failures which are not emergencies but which affect the remaining time line, weather, scheduling conflicts (particularly with air-route traffic), fuel consumption anomalies and many other factors. Replanning must be accomplished fast. We envision that real time trajectory optimization algorithms must be able to generate solutions in five to ten seconds of CPU time.

5.1.2 Example Problem Formulations

The two optimization problems formulated are given below:

1. HRV Reentry

This problem involves HRV reentry trajectory analysis. It is a derivative of sample problem 2 formulated in Reference 11. The simulation is initiated at the entry interface at 400,000 feet geopotential altitude and terminated when the vehicle has descended to 50,000 feet geopotential altitude. The trajectory control time history attempts to minimize total heat flux by capitalizing on an assumed capability of the thermal protection system to withstand a high heat rate for a short period of time. This assumption is based on a similar design on the space shuttle. The basic optimization strategy is to attain the prescribed maximum heat rate as early as possible on entry into the atmosphere. This limit is followed until an acceleration constraint is encountered. A bank angle linear-feedback steering algorithm is then switched from controlling heat rate to controlling the acceleration profile. The acceleration limit is then followed until it is necessary to deviate from the limit to achieve the specified crossrange.

2. Minimum Fuel Acceleration from Mach 5 to Mach 20

This problem involves an acceleration from a low hypersonic Mach to a high hypersonic Mach at a high altitude. The altitude is not constrained to be constant during the maneuver. The algorithm attempts to maintain dynamic pressure within specified limits and keeps the stagnation point heat flux below some maximum while minimizing the fuel required to perform the maneuver.

These two problems are similar to the sample problems in Reference 11. We extrapolated from the results of running the sample problems given in Reference 11 (which are totally suitable for the space shuttle) to estimate the throughout required to run the above problems in a variety of computers.

5.1.3 Trajectory Optimization Algorithms

The purpose of this work was to identify the best possible, available algorithms for performing the optimizations and determine the relative merits, capabilities and disadvantages of each. Of all the available optimization algorithms reviewed, two emerged as having the necessary capabilities and performance. Both developments were government sponsored and the algorithms with documentation are available from COSMIC at nominal cost. They are:

1. Program To Optimize Simulated Trajectories (POST)

2. Optimal Trajectories By Implicit Simulation (OTIS)

Both OTIS and POST have the capability of generating trajectories under a very wide variety of conditions, constraints, performance measures. This is an absolute requirement if they are to be suitable for use in HRV flight testing as discussed in section 5.1.1.

5.1.3.1 POST

POST[11] was designed, developed, coded and delivered to NASA Langley by Martin Marietta Corporation. It is a generalized point mass, discrete parameter targeting and optimization FORTRAN program. POST provides the capability to target and optimize point mass trajectories for a powered or unpowered vehicle near an arbitrary rotating, oblate planet. POST has been used successfully to solve a wide variety of atmospheric ascent and reentry problems, as well as exoatmospheric orbital transfer problems. The generality of the program is evidenced by its N-phase simulation capability which features generalized planet and vehicle models. This flexible simulation capability is augmented by an efficient discrete parameter optimization capability that includes equality and inequality constraints.

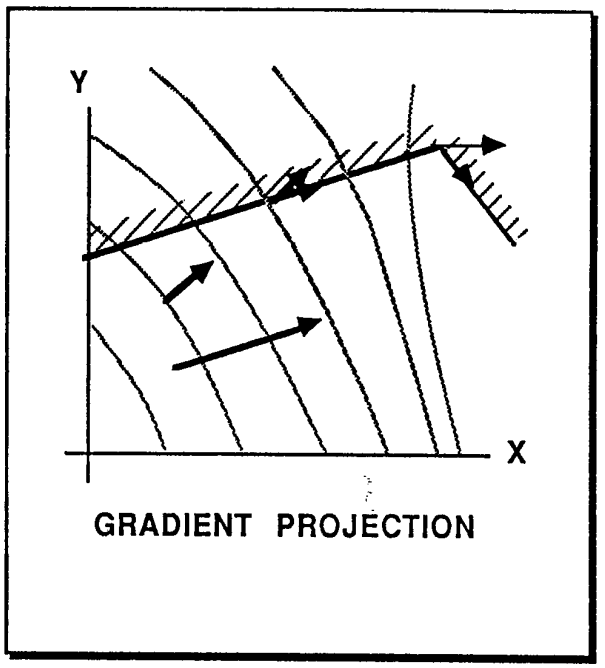

Figure 8: Rosen's Gradient Projection Automatically Treats Inequality Constraints

The optimization routine used by POST is a modified first order gradient projection method of Rosen[15]. The technique is shown for a simple two parameter function optimization in Figure 8. The function f(x,y) is to be minimized with two inequality constraints active. Within the admissible region we minimize in the direction of the maximum negative gradient, however, on a constraint boundary we project the maximum negative gradient at that point onto the boundary to obtain the direction of minimization, etc.

Rosen's gradient projection is an excellent technique ideally suited to a generic nonlinear trajectory optimization algorithm because it handles inequality constraints in a very natural way and has excellent convergence properties.

5.1.3.2 OTIS

OTIS[12] was designed, developed, coded and delivered to the Air Force Wright Aeronautical Laboratories by Boeing Aerospace Corporation. OTIS is a FORTRAN program for simulating and optimizing point mass trajectories of a wide variety of aerospace type vehicles. The program is designed to simulate and optimize trajectories of launch vehicles, aircraft and missiles with provision made for cruise legs, flight in a low air density environment, free and fixed end constraints, specified waypoints and path constraints. OTIS was developed to provide an easy to use trajectory analysis tool. OTIS was assembled using a modular architecture to facilitate program upgrades and modifications. OTIS can be used to solve optimal control problems without extensive optimization expertise.

The optimization technique used in OTIS is a nonlinear gradient projection method similar to that employed in POST.

5.1.3.3 Others

Other algorithms considered included a number of available dynamic programming algorithms, an algorithm featuring Balakrishnan's Epsilon Method[13], and the COPES algorithm[14] featuring a conjugate direction method by Fletcher and Reeves. None of those considered had the extensive simulation, modeling and optimization feasibility and environment provided by OTIS and POST.

5.1.4 Computation Requirements

The most demanding requirement for performing trajectory optimization in real time for inflight replanning is computer throughput. In turn, this requirement dictates whether one can perform real-time trajectory optimization in an onboard airborne computer in time for implementation in a prototype HRV or whether it must be done on ground computers in a remote computation mode. With this in mind a computer throughput study was performed based on using OTIS and POST as the optimization algorithms.

POST and OTIS were installed in a MicroVAX II at SPARTA's Laguna Hills Office. The sample problems supplied with both programs were run and CPU times were recorded. POST is supplied with three sample problems involving trajectory optimization on a space shuttle ascent, a reentry and an orbital transfer. OTIS is supplied with six sample problems ranging from a minimum time-to-climb for a supersonic fighter to an air launched LTSAT problem. The sample problems described in section 5.1.2 were not run per se: rather, a comparison was made between the problem formulations for the sample problems supplied with each program and the problems described in section 5.1.2. An extrapolation was then made to estimate CPU run times for these problems on the MicroVAX II. These estimates were further extrapolated to estimate run times on other machines of arbitrary throughput in terms of MFLOPS. Table 1 shows the CPU run times of the sample problems supplied with POST and OTIS on the MicroVAX II, a 0.9 MFLOP machine. The table also shows the extrapolated CPU run times for these sample problems on several other computers suitable for remote computation available at NASA Ames Dryden including a MASSCOMP 5400, a CYBER 750, an ALEXI 6400 and a SEL 32/97. In addition, a transputer based configuration of 100 advanced transputers is included. Extrapolated run times for three

airborne computers are also shown including a Nordon MILVAX, a Rolm HAWK and a transputer based computer with 16 advanced processors. In the case of the transputer based systems 50% parallelism is assumed to be achievable. We consider the MILVAX and the HAWK because they are flight qualified general purpose computers specifically built for onboard computation. We consider a transputer based computer because transputers allow parallel processing architectures to be constructed which are very high in throughput (assuming one can take advantage of the parallelism available), very low in cost and configurable in terms of size, shape and the number of processors installed. In addition, NASA has a project ongoing to build and flight qualify a transputer based computer for flight test use onboard a flight test aircraft.

Table 1
CPU Times (minutes) for Sample Problems Supplied With The Programs

	Remote Computers						Airborne Computers		
	Micro VAX II	MC 5400	CYBER 750	ALEXI 6400	SEL 32/97	T-xxx* (100-50%)	MIL VAX	HAWK	T-xxx** (16-50%)
MFLOPS	0.9	2.5	11	5	10	200	2	1.4	32
POST									
Prob. 1 6D	6.1	2.2	0.5	1.1	0.5	0.03	2.7	3.8	0.17
Prob. 1 3D	6.9	2.5	0.6	1.2	0.6	0.03	3.1	4.3	0.19
Prob. 2 3D	4.7	1.7	0.4	0.8	0.4	0.02	2.1	2.9	0.13
Prob. 3 3D	36.3	13.1	15.0	6.5	3.3	0.16	16.3	22.5	1.00
OTIS									
Prob. 1	13.0	4.7	1.1	2.3	1.2	0.06	5.9	8.1	0.37

* Note: Assumes 25 board advanced (second generation) transputer computer CPU (100 transputers) with 50% parallelism achieved

* *Note: Assumes 4 board advanced (second generation) transputer computer CPU (16 transputers) with 50% parallelism achieved

The sample problems supplied the programs are formulated briefly below:

<u>POST 6D</u>

Problem 1: This problem optimizes a reentry trajectory segment (10 seconds) for a shuttle orbiter vehicle. The optimization strategy is to attain a prescribed maximum heat rate as soon as possible.

<u>POST 3D</u>

Problem 1: This problem is a shuttle ascent optimization problem to determine maximum payload capability of various configurations.

Problem 2: This problem optimizes a shuttle orbiter entry from 400,000 feet to 50,000 feet. The optimization scheme attempts to minimize total heat by capitalizing on the ability of the thermal protection system to withstand a high heat rate for a short

period of time. The strategy is to achieve maximum heat rate as early as possible in reentry.

Problem 3: This problem optimizes the location, duration and attitude of two thrusting maneuvers that transfer an orbital vehicle from a near-Earth parking orbit to a near-geostationary orbit.

OTIS 3D

Problem 1: This is the traditional minimum time-to-climb problem for a supersonic fighter.

Table 2 shows extrapolated CPU times for the problems described in section 5.1.2.

Table 2
Extrapolated CPU Times (minutes) for the HRV Formulated Problems (section 5.1.2)

	Remote Computers						Airborne Computers		
	Micro VAX II	MC 5400	CYBER 750	ALEXI 6400	SEL 32/97	T-xxx* (100-50%)	MIL VAX	HAWK	T-xxx** (16-50%)
POST									
Problem 1	5	2	1	1	1	0.03	2	3	0.2
Problem 2	33	12	3	6	3	0.14	15	20	0.9
OTIS									
Problem 1	6	2	1	1	1	0.03	3	4	0.2
Problem 2	42	15	3	7	4	0.19	18	25	1.2

* Note: Assumes 25 board advanced (second generation) transputer computer CPU (100 transputers) with 50% parallelism achieved

**Note: Assumes 4 board advanced (second generation) transputer computer CPU (16 transputers) with 50% parallelism achieved

The problems formulated in Section 5.1.2 were:

Problem 1: This problem is similar to sample problem 2 above. An HRV reentry trajectory is sought which minimizes total heat flux.

Problem 2: This problem generates a trajectory which accelerates the vehicle from Mach 5 to Mach 20 while minimizing the fuel required, keeping dynamic pressure within specified limits and stagnation heat flux below some maximums.

The 50% percent parallelism figure for the transputer based computer system is based on the assumption that, on the average, the optimization algorithms can be recoded such that, on the average, 50% of the total CPU time available can be utilized when the optimization algorithms are in execution. In order to take advantage of parallelism, the optimization algorithms would have to be rewritten in the occam language.

Assuming that the current rate of computer throughput growth illustrated in Figure 7 is maintained, and assuming POST is implemented in an onboard computer for trajectory optimization, a five second solution to a significant trajectory optimization problem would be attainable in 1993 using on an advanced (second generation) transputer configuration. However, a qualified airborne computer based on this technology is not likely to be available until 1995-2000. The second generation transputer processor will be available in late 1988. The basis of this projection is the 0.9 minute solution time for the airborne T-XXX computer. Halving that number every year, we arrive at a 3-4 year period to reduce that solution time to 5 seconds.

The advantages for transputer technology are clearly shown in Figure 9. Not only is throughput capability very high but cost is relatively low. In addition the number of nodes (processors) in a configuration is limited practically only by the user's ability to write software which takes advantage of the nodes available.

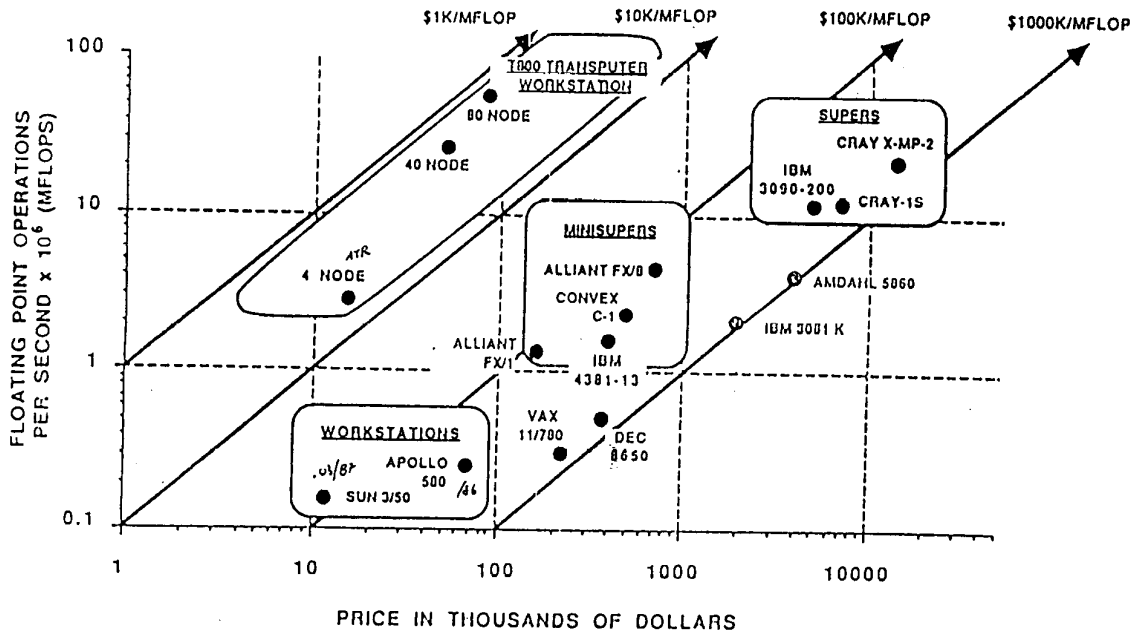

Figure 9: Transputers Provide Lots of Throughput for the Dollar

5.1.5 Data Base requirements

In addition to computer throughput, a second requirement for performing trajectory optimization in a real time replanning mode is the requirement to constantly (and in real time) change/modify the data base used in the POST and OTIS dynamic simulations. Both POST and OTIS have generic simulations preprogrammed which can be tailored to represent any flight vehicle. The OTIS simulation is a 3+ DOF+ simulation with pseudo degrees-of-freedom added. POST has two simulations: a 3 DOF version and a 6 DOF version. The simulations can be modified by a flight test engineer (FTE) working at a workstation if the programs are hosted in a ground based computer.

5.1.6 Precise Test Trajectory Guidance & Control

Once a trajectory is generated using OTIS or POST, the HRV must be precisely flown on the trajectory. Many trajectories may be able to be flown with adequate precision by the test pilot. Others may require a very high performance maneuver autopilot or flight test trajectory controller to fly the maneuver under fully automatic control. For example, during the flight envelope expansion flight testing, precise trajectory control particular during critical test conditions will be very important for three reasons: 1.) to assure the safe and efficient envelope expansion ; 2.) to avoid exceeding critical limits inadvertently ; and, 3.) to provide precise test conditions for verification of predicted performance and technical data, i.e., aerothermal, propulsion parameters, structures, etc.

If the test pilot is performing the maneuver, some type of display must be available to show tracking errors in some format so that the pilot can zero them. ILS type needles, or a pathway-in - the-sky type HUD display are possible.

In the fully automatic mode, a number of design approaches can be taken to design the trajectory controller. As a general approach, we are suggesting a stochastic optimal state feedback tracking formulation be used. For specific instances wherein it is possible to define rather accurately the precise maneuver to be performed, a classical design approach for that specific maneuver might be preferred. More than likely, both design approaches to the trajectory controller should be employed even in parallel in some cases.

Our experience indicates that remote computation is not required to implement such a controller even for HRV prototype testing. We recommend that the controller be implemented onboard in a general purpose flight test computer based on transputer technology. Guidance data generated from ground-based trajectory generators or optimization algorithms would have to be uplinked to the HRV to drive either the display or provide the autopilot input.

5.1.7 Data Link Requirements

The data link requirements are discussed herein. With all all trajectory optimization except trajectory tracking done in remote computation we envision that the data link requirements for uplink and downlink to the HRV will not require significant expansion over what is currently available on the RAV system.

UPLINK - Currently, the RAV facility uses two of its eleven message streams on the 1553 bus for uplink encoding at a maximum encoder rate of 97k bits/sec. The two streams consist of a 16 bit parallel data stream and a 32 bit parallel control stream. The uplink transmit rate is 256Hz with 21 bits/word and 18 words/frame. For each word, 16 bits are data bits and 5 checksum bits. Similarly, each frame has 16 data words and 2 for control and synchronous information.

Even though this current data rate will need to be vastly improved to support the HRV, they will only need to be improved slightly for remote trajectory optimization. Therefore, this function will not be the driving requirement for HRV uplink requirements.

DOWNLINK - It is envisioned that the amount of data and the data rate necessary for performing will not increase significantly over current remotely augmented vehicle (RAV) levels. This data link would not have to be maintained continuously during flight testing, but it would be desirable to do so. Periods of noncoverage would mean some limitations imposed on real-time replanning during these periods, no data monitoring, no on-line data analysis. If it is possible to continue to provide communications during data link noncoverage, one could still do replanning

based on predicted present position and operational state, however, uplink could not be used to automatically update the onboard tracker until the link is restored.

5.2 Energy Management

We define energy management as follows: knowing the following parameters about the flight vehicle at any given point in time:

1. the vehicle's kinetic energy,
2. the vehicle's potential energy,
3. the vehicle's flight path vector,
4. the stored energy state (fuel state - for each fuel type and/or engine if more than one are involved),
5. the vehicle's geographic position,
6. the propulsion system status,
7. the vehicle's performance and aerodynamic characteristics,
8. all other restrictions on vehicle performance,
9. landing site locations and characteristics;

where can the vehicle go in space (and land safely some place after going there), or where can it land. We define items 1 through 5 as the operational state of the vehicle. We include items 6 through 8 in the vehicle's operational data base.

Energy management is an operational and safety issue. In prior applications for vehicles such as the X-15, the space shuttle and the like, energy management has been used to determine power-off footprints for landing site alternatives. In these applications only the vehicle's kinetic and potential energy states, and the vehicle's aerodynamic performance characteristics (lift and drag) were required to calculate footprints. The footprints typically took the shape of cardioids with one axis along the horizontal flight path vector.

Energy management for an HRV is a much more involved and computationally intensive issue. It is absolutely necessary to provide an on-line capability to determine where the vehicle is capable of going at any point in time in order to provide any flexibility whatsoever in mission or flight test replanning for contingencies. It is a necessary adjunct to trajectory optimization. It is a total waste of valuable time and resources, for example, to attempt to find an optimal trajectory to get to some final condition (such as a runway threshold at a specified landing site) if it is impossible from an available energy point of view to get there from here. Thus the analytic expression given by equation (1) is no longer valid. Propulsion effects must be included. In addition, energy management principles must be extended to cover not just landing site alternatives, but an available three dimensional volume of attainable space of which the cardioid previously referred to becomes a curved surface intersection of the the earth and the volume. The concept is shown in Figure 10. The volume should be computationally carried along with the vehicle. It changes shape continuously as a function of the vehicle's operational and data base state.

We envision a continuous computation of this volume which is a function of not only a changing operational state but also a changing operational data base. The data base is shared by the trajectory optimization algorithms which are used to generate optimal trajectories between operational states within the volume. The AFMS system described in section 6.1 encompasses this energy management capability in addition to trajectory optimization. It is an integral part of preflight planning and in-flight replanning.

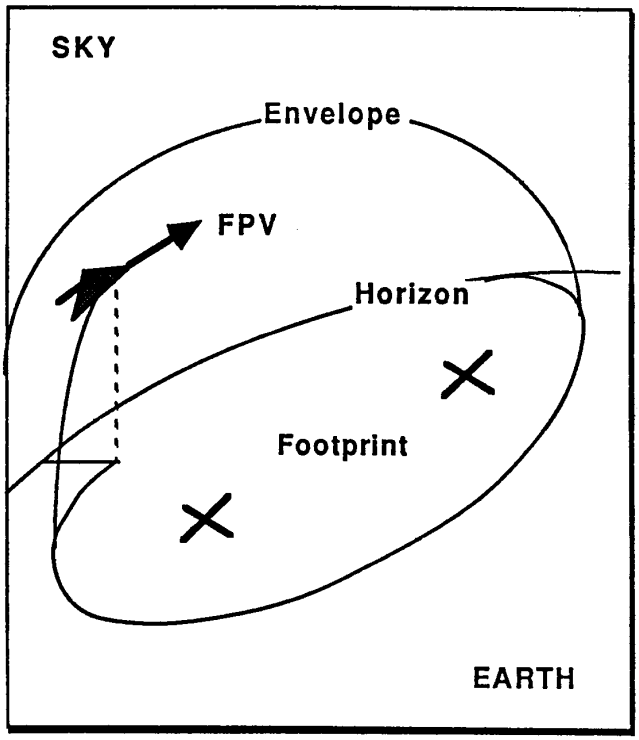

Figure 10: An Attainable Space Volume is Continuously Calculated

5.2.1 Requirements

Energy management requires the employment on-line and during planning of algorithms which predict the total operating space which can be reached from any given operational state. It is implicitly understood (and must be taken into account in the algorithms) that one must be able not only to reach an operational point but to be able subsequently to land safely somewhere in order for the operational point to be considered as within the available operational space. For example, if we decide to accelerate from Mach 5 to Mach 20 along some operational line such as constant dynamic pressure, we must be confident that if we get there, we still have enough fuel left to land somewhere. Planning this in advance and simulating it in the NASA SIM facility is one matter, but suppose that a situation has arisen in which we would like to depart in-flight from the preplanned timeline due to some anomaly or an emergency. We must have a way of being able to predict the operational space available quickly. Trajectory optimization does not do this job efficiently.

The requirements for energy management arise in just about all flight phases. In takeoff and ascent, for example, energy management is critically important to allow instant decisions on abort fields. In space shuttle and other space systems, abort field decisions are carefully planned in advance in a "canned" fashion. That is, if the vehicle is between a and b the abort field will be x for example. These decisions are determined by extensive ground simulation. Although such planning will also be done in HRV testing and operational employment, the use of on-line energy management computations will allow much more flexibility in replanning and added safety margins. It will allow a bridging of the gap between a vehicle which is very narrowly constrained to an extensively (and expensively) preplanned flight path and timeline (space shuttle) to a vehicle

which can be operated in a much more flexible way (as one would operate a high performance fighter).

5.2.2 Normal Operation Example

The sub-orbital cruise phase of the flight test program will consist of a series of flight test maneuvers planned, hopefully, with the help of a fully developed AFMS system (an advanced ATMS system discussed in section 6.1). Any number of circumstances could occur which require inflight replanning to be done. These circumstances might include a flight emergency requiring immediate recovery, a vehicle malfunction which dictates a change in flight plan not requiring an emergency landing, on-line data analysis which affects the flight plan (such as fuel consumption which is greater than planned requiring a real time replan), and a host of other circumstances. Real time replanning would require energy management calculations to immediately determine what it is possible to do and a trajectory optimization algorithm to optimize it.

For example, a sensor failure causes the loss of certain data which precludes performing a series of planned maneuvers, however, other maneuvers can be substituted which do not require this sensor, so that the flight is not lost. Substituting the new set of maneuvers for the remainder of the flight significantly alters the planned trajectory. An on-line replan must be done. This function cannot be presently done on airborne computers due to throughput limitations.

5.2.3 Emergency Operation Example

The same system functions in the event of a flight emergency. The most common type of emergency for which energy management will be of greatest assistance is one in which the vehicle must land as soon as possible. For example, the vehicle loses significant or total propulsion while at sub-orbit speed. The energy management algorithm displays a ground footprint which, hopefully, includes a suitable landing site. The trajectory generation algorithm generates an optimal trajectory to get there. It might be required that the maneuver be done in minimum time, or more likely, that the maneuver be done so as to maintain airspeed within some rather narrow range throughout the maneuver. Typically, one desires the end point of the maneuver to be at a "high key" over the desired landing point at maximum L/D airspeed. For these type vehicles "high key" is usually in excess of 40,000 feet AGL.

5.2.4 Computation Requirements

The computational requirements are discussed herein. As described previously, the energy management algorithm for continuously generating the attainable volume of space as a function of the vehicle's operational state and data base state is envisioned to be very computationally intensive. If we estimate the computational throughput required as being on the same order as the trajectory optimization algorithm, we will be in a conservative ball park. The basis of this is the following argument. We propose that an updated envelope should be calculated every second during flight. The calculation would include the boundary definition, graphical software to generate and display a graphical image of the attainable volume and a constantly updated data base of operational information derived from the envelope such as attainable landing sites.

5.2.5 Data Link Requirements

The data link requirements to support remote energy management computers are not expanded over those described in Section 5.1.7.

5.3 Autonomous Operations

Manned operational hypersonic vehicles may need to operate autonomously, that is without communications or data links, for significant periods of time for certain military missions. Not having access to classified military requirements for such vehicles, we made the following assumptions about the requirements and associated flight systems functions for the purpose of this study:

AUTONOMOUS CAPABILITIES	FLIGHT SYSTEMS IMPLICATIONS
1. Fly from mid altitude into low earth orbit (LEO)	Autonomous 3D navigation
2. Rendezvous with a satellite in LEO	Precise 4D autonomous navigation and guidance
3. Dock with a satellite - cooperative - non-cooperative	Precise relative range, range rate and bearing
4. Reenter and skip to a new orbit	Accurate orbital parameters, trajectory guidance, and energy management
5. Reenter and fly to a designated recovery location	Accurate orbital parameters, trajectory guidance and energy management
6. Atmospheric flight to a specific location at a specific time	Precise 4D autonomous navigation, trajectory guidance and energy management

It appears that all of the above could be demonstrated degree on the HRV using remote computation for the critical algorithms except the actual docking maneuver. One could even do a limited demonstration of docking guidance but not actual docking, which may not be necessary in the HRV flight test program. The trajectory guidance and energy management functions are similar, with respect to remote computational support, to the examples discussed in sections 5.1 and 5.2. The principal new elements are the autonomous navigation, accurate orbital parameters determination and precise relative position determination for docking. An interesting and beneficial aspect of the remote computational approach is that several alternate implementations of these autonomous capabilities could be demonstrated on the HRV with essentially one set of core hardware and possibly different sensor sets.

5.3.1 Example Autonomous Operation Systems Functions

5.3.1.1 Autonomous Navigation

The key feature of autonomous navigation is the use of onboard self contained precision position determination system, such as a stellar navigation system, to update the inertial nav system. It would be possibly to have only the star tracking system and inertial measurement unit (IMU) onboard, do the computations on the ground and data link the results to the HRV.

5.3.2 Computation Requirements

Trajectory optimizations and energy management must be performed onboard. We envision that operations will be simplified and restricted to place less computational demand on onboard computers. Trajectory optimizations for replanning, particularly for emergencies, will be possible. We might limit energy management calculations to footprint predictions only.

5.3.3 Data Link Considerations

Data link to ground facilities would not be increased over those discussed in Section 5.1.7 to support autonomous operations demonstrations.

6.0 Flight Test Management and Control

A significant result of this study is the identification of the necessity to develop an automated flight management system to provide multiple levels of automated flight and system management for HRV. We suggest the development of a knowledge based automated flight and mission management system (AFMS). AFMS is envisioned as an extension of the Automated Flight Test Management System (ATMS)[7], being developed by NASA for aiding the Flight Test Engineers during the HRV flight tests. ATMS is a flight test oriented system. The AFMS concept extends ATMS beyond flight testing to operational employment. The AFMS concept could be developed for the flight test program, extended, perfected and demonstrated in the flight test program, and then applied and extended further to cover both military and commercial planning/replanning in the vehicle's operational employment.

6.1 AFMS Concept

AFMS is envisioned as an integrated symbolic /conventional processing environment which provides several levels of automation for performing flight test planning and real time replanning, mission planning and real time replanning, trajectory guidance and control, trajectory optimization, trajectory generation, energy management, flight system management and data system management. AFMS provides the total man-machine interface between mission/flight test control personnel, the flight vehicle and all remote computational facilities in addition to managing all autonomous operations. AFMS represents the highest level of automated flight system management for NASP and allows multiple levels of human interface, intervention, observation and supervision. The concept is shown in Figure 11.

The AFMS concept is discussed in the context of trajectory guidance and control for illustration purposes. OTIS and POST would be totally integrated into the ATMS system to form the AFMS environment. Research engineers would use AFMS with OTIS and POST to generate optimized flight test maneuver subproblems for a number of flight test maneuvers. The FTE's workstation would allow the FTE to choose between these subproblems, choose specific flight conditions and define a trajectory by optimizing within a subproblem. That is, the FTE would not be working with raw OTIS or raw POST formulating. That work would be done by research engineers. The FTE would be constrained by subproblem definitions already set up by the research engineer. Within those selectable definitions the FTE would perform optimization for planning or replanning in flight.

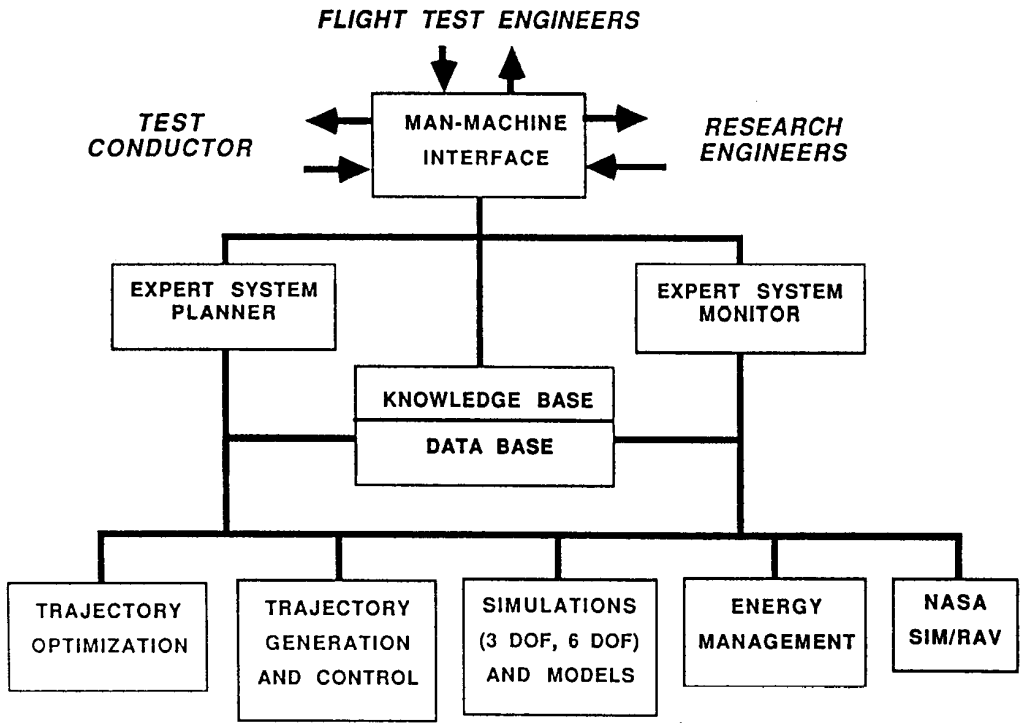

Figure 11: AFMS Concept

The FTE workstation, the simulation validation workstation, and the flight system concepts developed for ATMS would be extended to AFMS. In essence, AFMS would provide knowledge-based, expert system assisted supervisory management of a number of algorithmic tools to perform trajectory optimization, data analysis, data reduction, flight and data monitoring, weather monitoring, and other functions to aid the FTE, test conductors and test pilots in conducting successful flight tests which maximize available flight time utilization, flight resource utilization and minimize flight testing costs.

The AFMS system using the knowledge-based expert system planner, the energy management algorithm, the trajectory optimization algorithm, the flight test trajectory controller and the 3 DOF+ vehicle simulation is used to create flight plans and trajectories. The planner supervises the coordinated use of these algorithms under the oversight of the FTE. The FTE is allowed to interact with the system as it is performing the real time replanning function to provide his guidance, input and approval. In essence, computational power and an advanced, highly integrated set of conventional and knowledge-based algorithms are used to perform in a semi-automated fashion, the job several FTE's (and the test conductor) would be doing in a near panic mode and very inexactly, when faced with a flight or data anomaly.

6.2 AFMS Development

We envision AFMS to be developed in three phases. First, ATMS would be fully developed as a flight test engineer's flight test planning, replanning and monitoring tool for HRV flight testing. Second, AFMS would be completely developed as a natural extension of ATMS and used to support NASP flight testing. Third, AFMS would be expanded to support NASP mission management in the operational environment.

6.3 AFMS Architecture

A suggested AFMS architecture is shown in Figure 12 as implemented in SUN workstations.

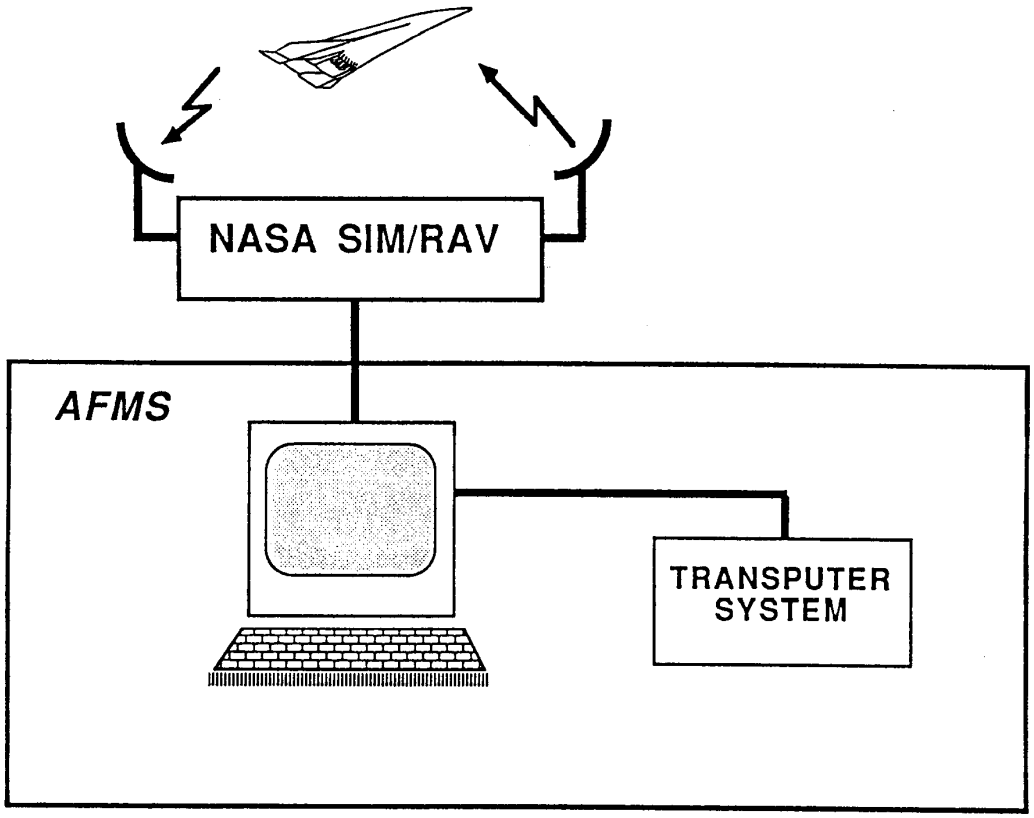

Figure 12: AFMS Architecture

We envision a networked system of computers to host AFMS based on SUN workstations. We envision that the man-machine interface to the system with all its associated display and interface software is hosted in a minicomputer workstation such as a SUN 3/50 on a customized communication network with other computers in the AFMS system. By the same token we envision that the trajectory optimization algorithms, flight test trajectory controllers and simulations

be also hosted on separate workstations on the same customized communication network in the AFMS system.

We envision that each workstation would require a transputer interface to a transputer "box" with an expandable number of transputers to increase the computational throughput of the workstation. As described in section 5.1.4, the computational throughout required to support trajectory optimization is 400 MFLOPS. This is attainable with a SUN 3/50 with an adjunct transputer system of 128 transputers provided full parallelism is realizable. This assumes we would like to be able to solve a significant optimization problem in 5 seconds of CPU time. A equivalent system would easily handle the energy management function.

6.4 Example Problem Formulations

This section contains several examples of uses of the proposed AFMS system as an aid to conducting HRV flight testing.

6.4.1 Flight Test Planning

An HRV type vehicle will be expensive to fly and always fuel critical. Efficient flight planning will be crucial to keep flight test costs under control. AFMS provides this capability with a dedicated workstation environment independent of the NASA SIM facility. Like ATMS, AFMS would allow the FTE the ability to string together in the most fuel efficient way a series of flight test maneuvers. AFMS would not only allow preprogrammed flight test maneuvers to be ordered efficiently but also would the use trajectory optimization algorithms to generate optimum paths. Contingency plans could also be easily generated.

Flight test planning is done with the aid of an expert system planner as demonstrated in the ATMS prototype system.. The planner includes a set of rules for ordering maneuvers in the most fuel efficient or time efficient way. The system integrates knowledge-based expert systems with conventional trajectory optimization, controller and simulation algorithms.

6.4.2 Flight Test Validation

As with ATMS, AFMS contains a communication interface between the workstation computer and the NASA SIM facility to validate flight plans generated with the workstation in real time piloted simulation. Actual flight test is then just one step away: a substitution of the HRV flight vehicle for the 6 DOF simulation.

6.4.3 Flight Test Monitoring

AFMS allows automated monitoring of downlinked flight data from the HRV vehicle and tracking data from range facilities. Flight data from specific flight test maneuvers can be analyzed in real time and decision made with the aid of an expert system monitor on the quality of the data obtained from the maneuver. Health Monitoring of vehicle systems can also be done.

6.4.4 Flight Test Replanning

In the event that the flight test monitor shows some test or time line anomaly or an emergency, real time replanning can be done automatically. The expert system replanner efficiently

uses energy management calculations and trajectory optimization algorithms to formulate replans quickly and with improved accuracy compared to decisions arrived at by FTE's under time pressure. The concept utilizes the replanner not as a replacement for FTE involvement in the replanning process but as an aid to improve their judgement under time pressure. The system allows FTE's to be involved at a higher management level in this replanning process thereby improving the quality of decision reached and reducing the risk of making incorrect replanning decisions.

6.4.5 Flight Envelope Expansion

The following problem is an example of envelope expansion. The technique requires on-line data reduction and analysis to correct the stability and control parameters in the aerodynamic simulation to match the responses to control inputs at each test point (Mach number). The simulation is then extended to the next flight condition and simulated responses to control inputs are obtained and analyzed prior to actually flying the aircraft to the next data point. Trajectory optimization is required in real time with the constantly changing simulation parameters to derive new trajectories between the data points. This is a case of the HRV trajectories being potentially much more complicated with more constraints to be obeyed than in the case of simple level accelerations between data points with a high performance fighter.

This problem involves stringing together a series of flight test segments which must be performed with minimum fuel subject to the following conditions and constraints:

a. Dynamic pressure equal to some constant unless constraint b (below) is violated, in which case dynamic pressure is to be greater than some minimum.

b. Stagnation point heat flux is less than some maximum.

c. The following Mach profile is commanded:

1)	$t = t_0$	$M = 5$
2)	$t_0 \rightarrow t_1$	accelerate to $M = 6$
3)	$t_1 \rightarrow t_2$	$M = 6 + 0.05$
4)	$t_2 \rightarrow t_3$	accelerate to $M = 8$
5)	$t_3 \rightarrow t_4$	$M = 8 + 0.05$
6)	$t_4 \rightarrow t_5$	accelerate to $M = 10$
7)	$t_5 \rightarrow t_6$	$M = 10 + 0.05$
8)	$t_6 \rightarrow t_7$	decelerate to $M = 5$

6.4.6 Trajectory Generation

We envision trajectory generation as being performed in the AFMS system. Trajectory generation differs from trajectory optimization in that trajectories are generated without the use of an optimization algorithm. This is the way it is currently done in the ATMS prototype system. Flight test maneuvers are preprogrammed to force the vehicle to follow prescribed state variable conditions to reproduce for example, a windup turn. Closed loop control is exercised over observed states to produce the maneuver specified. The ATMS Flight Test Trajectory Generator (FTTG) includes capture and exit segments to capture the desired trim condition and restore level flight after the maneuver.

6.4.7 Trajectory Optimization

Trajectory optimization is an alternative form of trajectory generation which we view as absolutely required for HRV flight testing. For example, trajectory optimization is required to compute reentry trajectories which are optimal from an aerodynamic heating viewpoint. The optimal policy must consider the design of the thermal protection system and the best way to employ it during reentry. For example, in space shuttle reentry it is best to maximize the heat flux as early in the reentry as possible.

Since fuel will always be critical in HRV flight, minimum fuel trajectories will be sought routinely. Merely transitioning from one flight condition to the next, a trivial maneuver in a high performance flight test airplane, will in all likelihood require a minimum fuel trajectory optimization solution.

6.4.8 Energy Management

Continuous energy management calculations are required to assure that test conductor personnel, flight crew and FTE's know at all times where the HRV is capable of going from its present position considering its operational state and fuel status. This is important to allow continuous awareness of immediately available landing sites. It is also important to replanning so that a replan is not suggested from which safe recovery to a landing site is not possible.

The implementation of this level of energy management will allow the HRV to be flown in both a flight test and operational mode more similar to that of a high performance airplane than, for example, a space shuttle. During space shuttle flight (and for that matter all previous space vehicles) flight plans are very seldom altered from those planned and rigorously simulated prior to flight. Replanning is a major effort and is done with extensive human resources and with great care. Ground simulation is used extensively in replanning and the activity takes a lot of time. AFMS imposes automation on some percentage of the effort. An energy management algorithm provides the necessary tool to enable replanning to be done quickly. Without the algorithm, trajectory optimization could be far more time consuming because many optimization attempts using impossible sets of end conditions would fail.

6.5 The Extension of AFMS to Operational Employment

AFMS is a natural operational employment tool for planning, monitoring, controlling and supervising the operational flights of HRV type operational vehicles. Extending the AFMS flight test system to military or commercial operations would provide a cost effective way of developing and testing not only the vehicle but also an automated tool for employing it.

6.6 Digital Performance Simulation (DPS) Studies

DPS[16] was hosted on a MicroVAX II and on the TI EXP-LX at SPARTA to conduct energy management studies. Simplified Keplerian dynamics were added in addition to] Generic Hypersonic Computer Simulation Aerodynamic Model (3 DOF) (GHAME). The Keplerian dynamic modification consisted of adding a correction term into a gravity calculation to reduce "g" by centrifugal force. No modifications were made to include a round earth. Thus, any results obtained from this simulation are valid for short flight segments only. (include other changes made to accommodate HRV model). A number of trajectories were generated using DPS maneuver options 1, 2, 3, etc.

It quickly became apparent in this effort that DPS was not an appropriate tool for HRV trajectory studies of any type. DPS is a true 3 DOF simulation without any pseudo degrees-of-freedom added for incorporating rate limits. As such it is not suitable for inclusion in an optimization routine for trajectory generation. Our conclusion from this study was that DPS is not suitable for inclusion into the AFMS structure: that OTIS and POST are much more suitable and capable for any trajectory studies in the HRV program.

6.7 ATMS Demonstration With HRV Dynamics

The GHAME 3 DOF simulation was integrated into the ATMS system developed under separate contract. The HRV appears as a selectable flight vehicle under the AIRCRAFT menu. The only other working selection on this menu is the HIDEC F-15 which was used for all the ATMS development and demonstrations. A limited demonstration was developed showing a hypothetical abort situation from an altitude of 200,000 feet over Lancaster and a subsequent landing at Edwards. DPS (modified for the HRV) was used to generate the trajectory. Trajectory optimization was simulated.

The demonstration illustrates how a trajectory optimization algorithm triggered by the ATMS flight test monitor expert system could be utilized to generate a zero thrust trajectory. The trajectory generated would be displayed on the ATMS monitor for the FTE and test conductor's observation. Then upon receiving approval in response to a prompt, the system would trigger the tracker/controller to follow the trajectory generated, or give guidance commands to the test pilot through ILS type needles or a pathway-in-the-sky HUD display. The pilot could then fly the maneuver manually.

6.8 AFMS Example Problems

Two example programs are formulated in the following sections which illustrate how AFMS would be used in HRV flight testing. The extensions of this to production system operations are obvious.

6.8.1 Example Problem in the Normal Test Mode

In this example we envision an HRV in the midst of performing envelope expansion at some test altitude. The remaining test plan after the envelope expansion consists of a descent to a lower altitude, a series of speed-power points and, finally, a descent to a landing. Let us suppose that we encounter a higher than expected fuel consumption during the envelope expansion maneuver. The higher fuel consumption dictates a landing earlier than planned. The challenge is to use the remainder flight time as efficiently as possible considering the currently planned remaining maneuvers and their relative priorities and maneuver conditions, and the alterations required to the ground track to accomplish the earlier landing. Without AFMS, we are limited to exercising one of a set of well preplanned contingencies. The more flexibility we want, the more contingencies we have to preplan and validate individually in simulation. With AFMS we are able to replan in flight without excessive contingency preflight planning. In addition, we realize considerable improvement in mission flexibility. Also, by validating the AFMS system in simulation instead of each individual contingency plan for each individual flight test, we save considerably on engineering and simulation time. The increase in flexibility attainable and the decrease in the amount of preflight contingency planning required both reduces the cost of flight testing considerably while increasing operating safety margins.

In Table 3 a sample timeline of events is given for the formulated problem described in the previous paragraph.

Table 3: Replan Timeline - Fuel Consumption Problem

Time (sec)	Event
0	Fuel anomaly discovered by AFMS monitor expert system. System alerts FTE with message.
0+	AFMS recommends that a replan be initiated.
2	FTE initiates replan using AFMS interface (keyboard response to a prompt). FTE selects planning parameters or defaults.
2+	AFMS starts planing function. Monitor function is temporarily suspended.
3	Planning expert system: - uses management algorithm to calculate effect on landing site if any, - uses planer rules to determine priorities between cutting off envelope expansion maneuver or limiting speed-power points, - uses trajectory optimization algorithm (with 3 DOF+ simulation) to truncate maneuvers in accordance with planner priority and to make alterations to remaining trajectory so that the best use is made of the remaining flight time, - uses energy management algorithm again to confirm trajectory optimization solution is feasible.
12	AFMS uses 6 DOF simulation and FTTG/C to validate trajectory. Trajectory is displayed on the AFMS map and timeline displays.
15	FTE approves replan and instructs AFMS to exercise the plan.
15+	AFMS issues revised plan to FTTG/C. Altered guidance commands begin driving pilot displays for manual control or controller for automatic vehicle control depending on the mode of operation previously selected.

The original and altered timelines are shown in Figure 13 assuming that the planner chose to limit the envelope expansion maneuver as a result of an anomaly in fuel consumption noted at point A. The planning activity is shown completed at B.

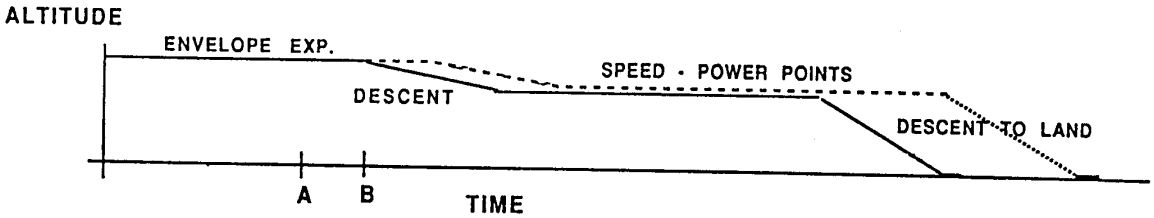

Figure 13: Replanning is Accomplished Within 15 Seconds

6.8.2 Example Problem in the Emergency Mode

In this example, we envision an HRV in the midst of performing envelope expansion at some test altitude. The remaining test plan after the envelope expansion consists of a descent to a lower altitude. The remaining test plan after the envelope expansion consists of a descent to a lower altitude, a series of speed-power pints and, finally, a descent to a landing. Let us suppose that a flight control computer malfunction occurs. Prudence dictates an immediate precautionary landing at the nearest available and suitable landing site. Without AFMS, we are limited to a few well planned contingencies. We will have planned abort sites all along the preplanned trajectory. Any replanning as described in Section 6.8.1, is severely limited because of the necessity to remain close to the preplanned trajectory so as not to invalidate the contingency planning for emergencies such as this one. AFMS relieves this requirement considerably and provides improved flexibility as a result.

In Table 4, a sample timeline of events is given for the formulated problem described in the previous paragraph.

Table 4: Replan Timeline - Emergency Abort Problem

Time (sec)	Event
0	Flight control computer fails.
2	FTE initiates replan by telling AFMS to immediately plan landing at the nearest site in minimum time.
2+	AFMS starts planning function. Monitor function is temporarily suspended.
3	Planning expert system: - uses energy management algorithm to determine closest landing sites, - uses planer rules to select best of available lading sites, - uses trajectory optimization algorithm (with 3 DOF+ simulation) to determine optimal path to chosen landing site, - uses energy management algorithm again to confirm if trajectory optimization solution is feasible.
10	AFMS uses 6 DOF simulation and FTTG/C to validate trajectory. Trajectory is displayed on the AFMS map and timeline displays.
12	FTE approves replan and instructs AFMS to exercise the plan.
12+	AFMS issues revised plan to FTTG/C. Altered guidance commands begin driving pilot displays for manual control or controller for automatic vehicle control depending on the mode of operation previously selected.

The original and altered timelines are shown below. Point A denotes the pint of system failure detection. The planning activity is shown completed at B.

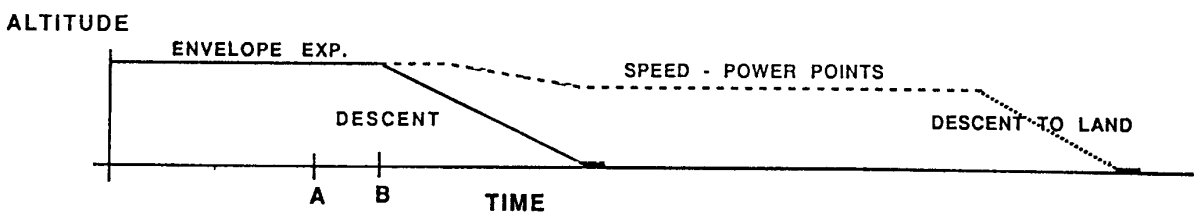

Figure 14: Replanning is Accomplished Within 12 Seconds

7.0 Unmanned Operations

Although the principal focus of the study was on manned vehicle flight, we were asked to consider the additional implications on remote computational support for unmanned operations. Unmanned operations are defined as operations with no flight crew onboard and the vehicle operates under the supervision/control of a ground based system and/or pilot, i.e. remotely piloted vehicle (RPV).

7.1 Requirements

Unmanned operations require, at a minimum, electronic interfaces to the vehicle systems that a crew member would have provided. It's generally held that a manned HRV would have most if not all of the systems automated and the crew could operate principally as a monitor and take over in an emergency. If that's the case one might think that going to unmanned operations would be simple. It could be if a higher program risk is acceptable. One could use the RPV mode as the emergency mode to backup the onboard automated systems. What one looses is the infinite adaptable and reasoning of the human insitu that is most beneficial in the emergency situation. It's virtually impossible to reproduce the flight and systems environments adequately on the ground for a pilot to be as effective as in flight. That means that it's more likely that an emergency could arise that an RPV pilot could not adapt to fast enough to avoid a critical situation; hence there would be more risk to the program.

We will assume that an RPV pilot would be used and in a similar manner as an onboard crew. Information would be required on the ground for monitoring and possibly control all vehicle systems including:

1. Propulsion system;
2. Flight path control;
3. Fuel system and fuel transfer;
4. Navigation system;
5. Configuration control;
6. All onboard sensors;
7. All onboard avionics;
8. All subsystems;
9. Instrumentation; and,
10. Others

Under normal operating conditions, this information would be telemetered to the mission control center even for manned vehicle operations for monitoring purposes. The remote computations for supporting flight systems functions discussed in the previous sections would be used. Trajectory guidance commands would be uplinked and tied directly into the autopilot as well as displayed to the RPV pilot. Similarly with other functions.

7.2 Systems Requirements and Impact

We believe the following additional functions would have to be added to the vehicle if it's unmanned:

1. Benign emergency autopilot modes in case of a data link failure;
2. Onboard systems health monitoring and critical action systems;
3. Backup RPV operating mode,possibly from an airborne platform.

7.3 Operational Issues and Risks

The risks associated with creating full dependence on automated systems with no onboard flight crew backup available seem to far outweigh the potential benefits achieved for this type of flight vehicle. The risks include loss of the vehicle due to:

1. Loss of data link;
2. An emergency set of conditions not anticipated for which onboard systems cannot provide required information to troubleshoot; and,
3. A combination of 1 and 2 above.

These risks increase the probability of loss of the vehicle to the point of causing restrictions on airspace use by agencies such as the FAA. Political considerations and public perception might prohibit the use of continental airspace or for that matter, overland flight anywhere.

8.0 Experimental Vehicle Implications

The implications on the vehicle design and cost of using remote computational support to perform the flight management functions discussed herein as opposed to performing these functions onboard are difficult to assess to any degree of accuracy. The following considerations are germane:

1. The design and development of an onboard computing system to perform these functions for the first HRV will be very expensive and very technically risky.

2. The development of a ground based environment to support remote computation as described herein is relatively inexpensive and of low technical risk. This is because the essential components of the system are already in place and the concept of remote vehicle control has been exhaustively flight tested and used routinely by NASA Ames Dryden for ten years. NASA is already developing an automated flight test management system which has all of the components required. The Phase I ATMS system has been demonstrated in simulation.

3. Vehicle weight considerations are considered minimal. There appears to be no significant difference between supporting remote computation with its associated data link equipment and adding a very capable computer system to perform all computational functions onboard.

9.0 Conclusions

In this section we present the conclusions reached in Part II of the contract concerning the advantages and requirements for remote computational support for HRV flight testing.

1. It is feasible and beneficial to perform the trajectory optimization, energy management and trajectory generation computations for the HRV flight test program with remote computers i the mission control center and data links to the HRV. The following benefits were concluded:

    a. Although it should be possible to build a computer architecture capable of performing realistic trajectory optimization and/or energy management onboard in

real-time based on 1993 transputer technology, there is some program risk of getting such a computer flight qualified before the late 1990's.

b. Ground-based implementation allows a much more complete modeling of the HRV performance and the atmospheric conditions that is likely with onboard computers which would be available in the mid-1990 time period.

c. Ground-based implementation provides greater flexibility for investigating several alternate optimization and guidance techniques with little or no impact on the vehicle and vehicle development schedule. Even algorithms specifically designed for onboard implementation could be evaluated by this method. Also, these software packages will be much less costly to develop and validate since they do not have to be flight qualified.

d. The capability to test onboard trajectory optimization and energy management algorithms using ground-based computers would inherently be available in an automated flight management system discussed in Conclusion 2.

2. An automated flight management system (AFMS) is highly desirable and beneficial for the HRV flight test program. The key benefits identified are as follows:

   a. Significant improvement in flexibility during flight testing leading to more efficient use of flight time especially in the event that changes in a flight plan are required to accommodate emergencies or time line anomalies.

   b. Significant decrease in required contingency preflight planning and associated flight plan validation simulation.

   c. Reduced cost of flight testing due to the savings realized in a and b above.

3. Transputer technology provides a very cost effective potential for both onboard real-time flight systems functions and extensive ground-based computations necessary for trajectory optimization and energy management. The key factors and benefits identified area as follows:

   a. Transputers are easily parallelized into configurations of an unlimited number of mods (processors), thus, providing expandable parallel processing capability.

   b. Transputers support occam, a language and operating system which supports parallel processing.

   c. Transputers provide very high throughput at very low cost.

   d. Transputer-based computers are configurable in terms of size and weight and, as a result, are natural candidates for airborne applications.

   e. Transputer technology is being developed for even higher throughput devices.

4. Autonomous operations can be demonstrated using remote computation support. Remote computation can be used to demonstrate many alternate implementations using ground-based computers. In terms of onboard computational support required for autonomous operations, the three previous conclusions apply. It may be desirable to provide less capable optimization and energy management algorithms onboard for autonomous

operations. For example, energy management might be restricted to provide landing site availability and reachability only as opposed to a full replanning capability.

5. Unmanned operations of a HRV disguised for manned flight are possible but are highly discouraged for HRV missions. Besides the requirement for providing quad redundant data links for all flight management and system monitoring functions, the political and public implications of flight testing and operating an unmanned HRV vehicle over the continental United States and other public lands are enormous, particularly when the public realizes that most of the time the vehicle is at suborbital velocities which implies that many emergencies may force the vehicle to find a place to land quickly.

10.0 Recommendations

The following actions are recommended as a result of this study:

1. Use remote computation in HRV flight testing to:

   a. provide the functions described herein without attempting to build an expensive onboard system in the first vehicle,

   b. expand significantly the operational flexibility of the vehicle,

   c. reduce significantly the risks attendant with HRV flight testing.

2. Aggressively pursue the development of ATMS technology to HRV flight testing (AFMS).

3. Continue to investigate the application of transputer technology to both an onboard flight research computer and as augmentation to NASA Ames-Dryden's remote computation capability.

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16. Abstract

This report assesses the requirements for the use of remote computation to support HRV flight testing. First, we develop remote computational requirements to support functions that will eventually be performed onboard operational vehicles of this type. These are functions which either cannot be performed onboard in the time frame of initial HRV flight test programs because the technology of airborne computers will not be sufficiently advanced to support the computational loads required, or it is not desirable to perform the functions onboard in the flight test program for other reasons. Second, we address remote computational support either required or highly desirable to conduct flight testing itself. We propose the use of an Automated Flight Management System which is described in conceptual detail. Third, we discuss autonomous operations and finally, unmanned operations.

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