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

PART I – Real-Time Flight Experiment Support

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L.D. McMillen, and R.I.B. Osofsky

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TABLE OF CONTENTS

List of Figures.....	iii
Nomenclature.....	iv
Summary.....	1
Introduction.....	1
Part I - Real-time Flight Experiment Support.....	5
HRV Characteristics and Assumptions.....	6
HRV Flight Test Assumptions.....	7
Instrumentation.....	8
Experiment Monitoring and Control.....	8
Candidate Examples.....	9
Boundary Layer Transition Location.....	9
Shock Wave Position Estimation.....	10
Performance Estimation.....	13
Surface Temperature Estimation.....	14
Critical Structural Stress Estimation.....	15
Stability Estimation and Monitoring.....	15
Real-time Estimation of HRV Surface Temperature Example.....	16
Real-time Stability Estimation and Monitoring Example.....	20
Computational Requirements.....	26
Conclusions.....	26
References.....	27
Appendix A Generalized Multiple Scales (GMS).....	29

LIST OF FIGURES

Figure No.	Title	Page
1	Stability Margins of the X-29A Were Estimated in Real-time Using Remote Computation.....	2
2	Remote Computation Concept Could Improve the Real-time Flight Test Support of a HRV.....	3
3	An Extended Range Concept for Real-time Flight Test Support for a HRV.....	4
4	Real-time Flight Test Data Distribution Brings Other Centers into the Active Monitoring Role.....	4
5	Real-time Flight Experiment Support Elements.....	5
6	HRV Will Require Multiple Advanced Technologies.....	6
7	Typical Ground Track for a HRV Flight Test.....	7
8	Mission Control and Test Monitoring Center.....	8
9	Potential Laser Instrumentation Concept to Measure Shock Wave Position.....	11
10	Computational Extrapolation of Shock Wave from Measurement Point.....	12
11	Real-time Monitoring Concept for Critical Structural Stress.....	15
12	Thermal Performance Comparison for Nosecap Cooling Configurations.....	17
13	Peak Temperature Comparison for Nosecap Cooling Configurations.....	17
14	Conceptual Design for a Nosecap with Active Cooling Augmentation and High Performance Heat Pipe.....	18
15	Potential Matrix of Thermocouples on a Nosecap.....	19
16	Real-time Monitoring of Critical Surface Temperatures.....	20
17	GMS Provides Correct Analytical Representation of Space Shuttle Dynamics....	21
18	HRV Dynamic Response Time History Example.....	24
19	Potential GMS Technique for Monitoring HRV Stability.....	25

NOMENCLATURE

AFWAL	Air Force Wright Aeronautical Laboratories
AGARD	Advisory Group for Aerospace Research & Development
AIAA	American Institute of Aeronautics and Astronautics
ASME	American Institute of Mechanical Engineers
ATMS	Automated Flight Test Management System
BTU	British Thermal Units
CRT	Cathode Ray Tube
DoD	Department of Defense
EAFB	Edwards Air Force Base
FMP	Flight Mechanics Panel
FSE	Flight Safety Engineer
FTE	Flight Test Engineer
GMS	Generalized Multiple Scales
GPS	Global Positioning System
HRV	Hypersonic Research Vehicle
JACC	Joint Automatic Control Conference
LTI	Linear Time-Invariant
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane
PSCN	Program Support Communications Network
RCVD	Remotely Commanded Vehicles and Display
WATR	Western Aeronautical Test Range

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

Part I - Real-time Flight Experiment Support

Summary

This report presents the results of a study to identify potential real-time remote computational applications to support monitoring HRV flight test experiments and to define preliminary requirements. In this context, experiment support is used in a broad sense of supporting the flight envelope expansion and specific flight test segments where high quality data are important for flight safety and/or interpreting test results. The study considers a major expansion of the support capability available at Ames-Dryden. The focus is on the use of extensive computation and data bases together with real-time flight data to generate and present high level information to those monitoring the flight. It was determined that a significant extension of the Ames-Dryden real-time flight test support capability through remote computations would be beneficial for monitoring a HRV flight test.

Six candidate examples of potential applications of remote computation to enhance flight test information for experiment monitoring were defined and discussed: 1.) boundary layer transition location; 2.) shock wave position estimation; 3.) performance estimation; 4.) surface temperature estimation; 5.) critical structural stress estimation; and, 6.) stability estimation. Surface temperature estimation and stability estimation were discussed in some detail. Substantial research and validation efforts would be required to develop the techniques identified for the candidate examples. It was impossible to define preliminary computational requirements until the initial research is accomplished.

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 (obtained from NASA). 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⁽⁵⁾ 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*; reported herein; Part II - *Remote Computational Support for Flight Systems Functions*⁽⁶⁾; and, Part III - *Automated Flight Test Management System (ATMS)*⁽⁷⁾.

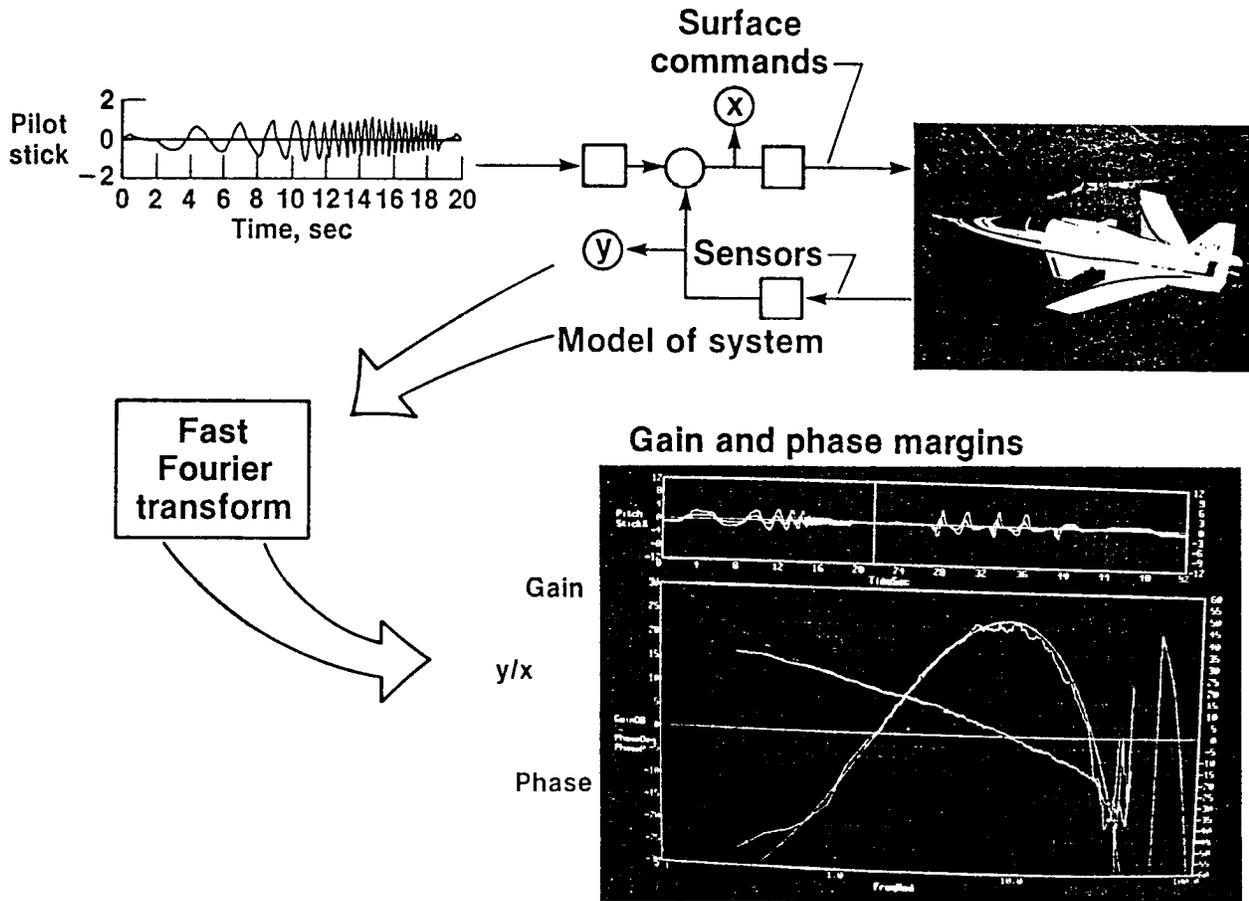


Figure 1: Stability Margins of the X-29A Were Estimated in Real-time Using Remote Computation⁽³⁾

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 on-board 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 on-board. Up links would be used to transmit guidance and control information to the HRV.

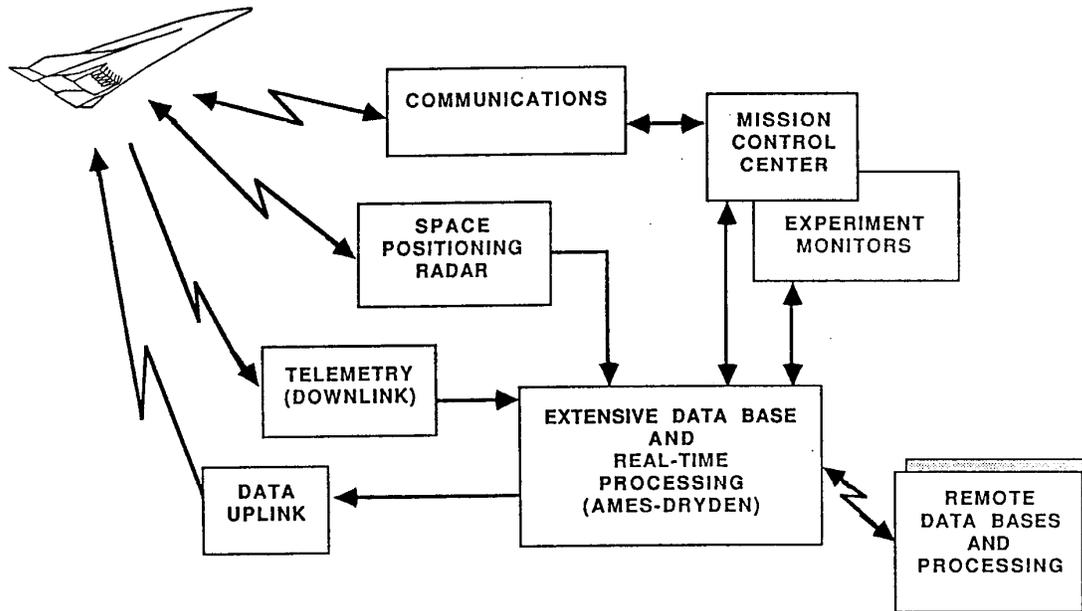


Figure 2: Remote Computation Concept Could Improve the Real-time Flight Test Support of a HRV

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.

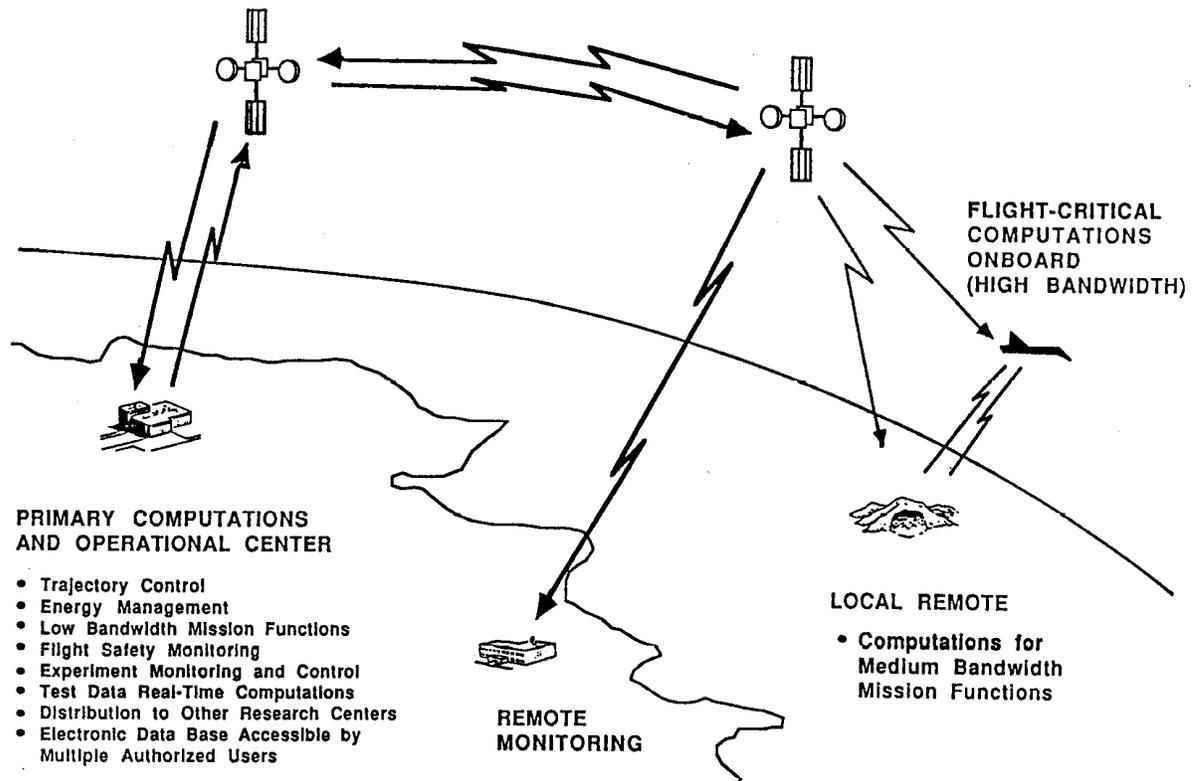


Figure 3: An Extended Range Concept for Real-Time Flight Test Support for a HRV

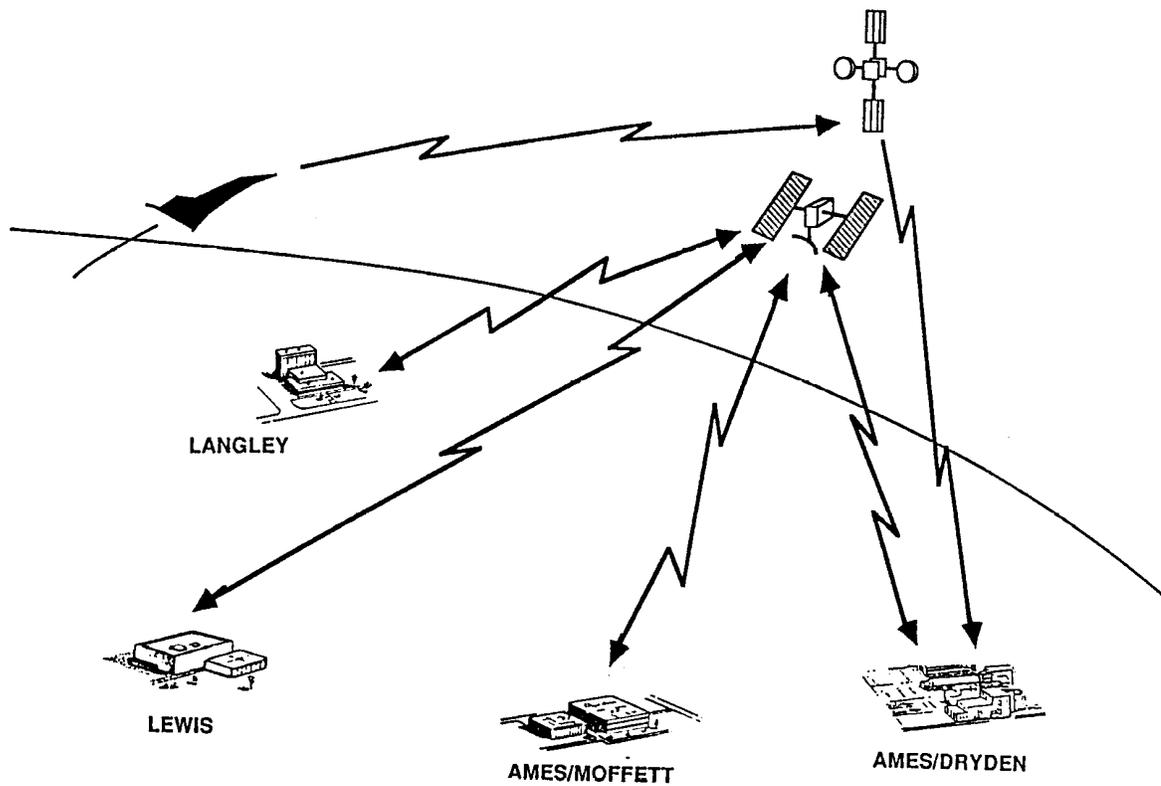


Figure 4: Real-time Flight Test Data Distribution Brings Other Centers into Active Monitoring Role

Part I - Real-time Flight Experiment Support

The use of remote computation would appear to have significant potential for supporting the HRV flight testing and indeed could have significant impact on the experimental vehicle design itself. NASA will need the highest quality flight experiment data possible and yet the conditions under which the test data will be collected may be quite severe. A joint NASA/DOD HRV program would be highly visible in spite of its likely classification. Considerable pressure would exist to accelerate the "experimental" phase and get on to the military mission assessments. Extensive remote computation performed in real-time to monitor and possibly even control the experiments could assure higher quality data and a better understanding of results and anomalies. For example, one might perform simulations of the propulsion system and aerothermodynamic interactions, update the model with real-time flight data, predict the future value of the measured flight parameters and then compare the predicted and measured parameters. Having precise control over the flight experiments and a good understanding of the results in real-time would increase the likelihood of achieving the objectives under a pressured schedule situation.

Figure 5 is a functional diagram of the real-time flight experiment support concept. One would expect the onboard measurements to number in the several thousands of parameters, such as temperatures, pressures and strains at multiple locations; linear and angular rates and accelerations; control effectors positions; fuel quantity and fuel flow rates; various system status parameters; etc. Some onboard processing would be done for those parameters needed by the crew for critical flight operations and for various other purposes, such as data compression to minimize telemetry data rate requirements. Onboard processing requirements are not addressed in this study. The focus of this study is the support provided by the ground system using the telemetry data; real-time simulation, estimation and/or prediction methods; extensive data bases and apriori predictions; and computer generated graphics.

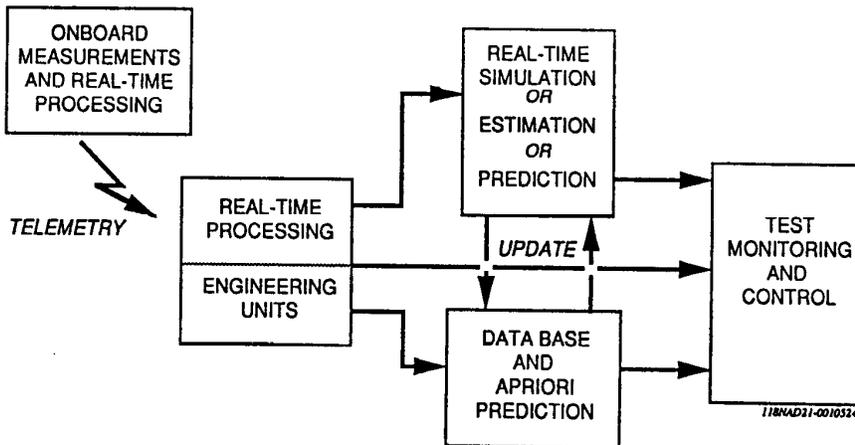


Figure 5: Real-time Flight Experiment Support Elements

The purpose of this part of the study was to determine the feasibility of using this remote computational concept for real-time flight experiment support of a HRV and to attempt to define preliminary computational requirements. The term "experiment support" is used here in a broad context of supporting the flight envelope expansion and specific flight test segments where high quality data is important for flight safety and for correctly interpreting the test results. The scope of the study was at a level to provide credible justification for the concept only.

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⁽⁹⁾. 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^(10,11). 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 6 (illustrative only). At hypersonic speeds, the propulsion mode is a liquid hydrogen-burning scramjet. A rocket engine is assumed for the final stage of orbit insertion and 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.

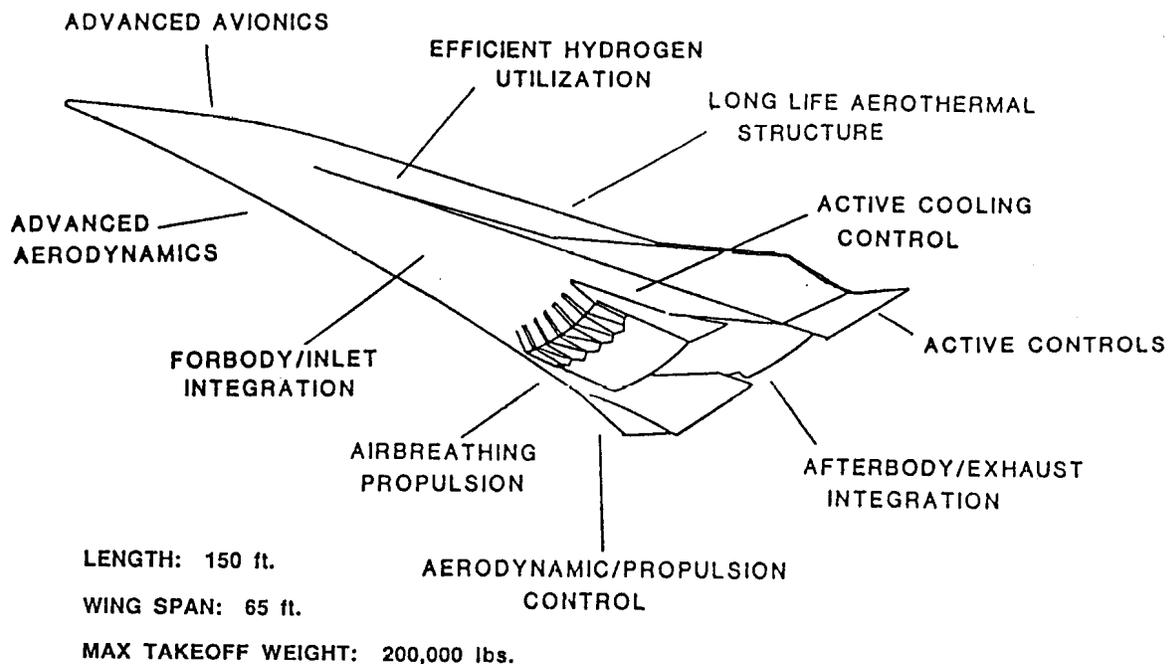


Figure 6: HRV Will Require Multiple Advanced Technologies

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 pre-planned trajectory up to a pre-planned maximum Mach number and altitude, then return on a pre-planned trajectory to EAFB and land horizontally. Figure 7 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 not 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.

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, one can reasonably assume that modest extrapolations from a known data base are good approximations in the nominal cases. The significance of this is that one can use analytical estimation techniques together with onboard measurements to produce a better estimate of the true value of desired flight test parameters than with measurements alone. In some cases it may be possible to make fairly accurate predictions of the parameters for a short period into the future.

One must be prepared to handle off-nominal cases, such as unpredicted phenomena or conditions that require deviation from the pre-planned trajectory (i.e., emergency or significantly different vehicle performance). If assumptions made for the nominal case discussed above are invalid for off-nominal cases, then alternate provisions must be made for the off-nominal cases.

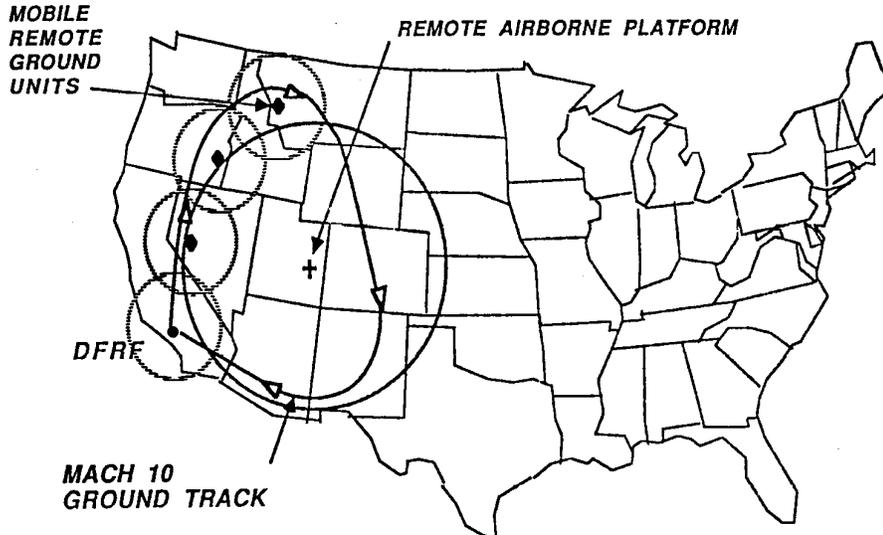


Figure 7: Typical Ground Track for an HRV Flight Test

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, density, Mach number, temperature, constituents, 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 via telemetry. Any assumptions about specific in-flight measurements associated with the candidate examples are discussed in Section 5.1.

Experiment Monitoring and Control

Flight test monitoring and control would occur in the mission control center, which might look like Figure 8 ⁽⁵⁾, for example. Information for flight safety and test monitoring would be presented on video monitors on the flight safety engineers' (FSE) consoles and the flight test engineers' (FTE) consoles and/or projection screens. The focus of this study is to consider use of extensive computation and data bases together with real-time flight data to generate and present to those monitoring the flight high level information or more accurate information than the raw data which would aid them in making rapid decisions effecting the flight. Six candidate examples which illustrate this concept and the potential benefits are discussed in Section 5.1. Because of the limited scope of this study, it was only possible to consider two of these in some detail (Sections 5.2 and 5.3). Flight safety monitoring aspects are discussed within each example. These techniques are only identified conceptually and have not been developed to any extent.

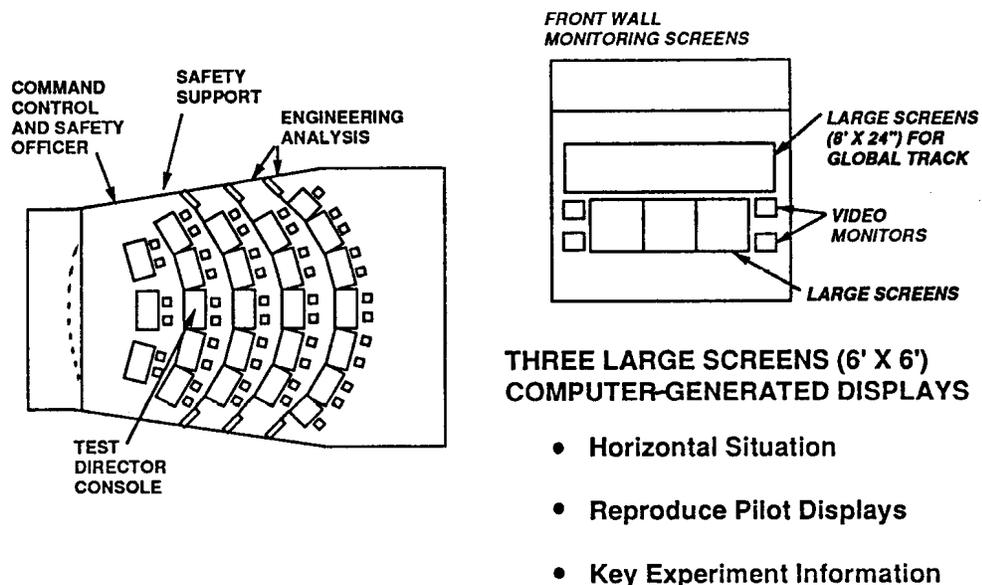


Figure 8: Mission control and Test Monitoring Center

Candidate Examples

The six candidate examples of potential applications of remote computation to enhance the flight test information for experiment monitoring were selected because of their importance to HRV flight test and the difficulty of getting accurate information directly from standard instrumentation alone. The importance of the problem areas and possible solutions were generated from discussions with specialists working in hypersonic vehicle technology at NASA Ames Research Center (both at Moffett Field and Dryden Flight Research Facility) and NASA Langley Research Center. The common characteristic of these examples is the integration of mathematical modeling of some physical process, pre-flight data base, and real-time measurements from onboard instruments. A rough analogy is the use of Kalman filtering as a state estimator where a model of the physical process is used to generate the optimal filter. *Probably the most important idea presented in this study is the consideration of instrumentation and computation techniques as a unified process when devising the flight test measurement system.* The objective is to develop the best estimate of the true value of a parameter or sets of parameters which are most useful in monitoring the flight tests. In some cases, it may also be possible to predict values of the parameters several seconds into the future so as to anticipate and avoid potential critical situations. The real-time estimates/predictions must be presented to the FSE's and/or FTE's in a simple and unambiguous manner for quick and accurate interpretation.

Boundary Layer Transition Location

The condition of the structure and state of the boundary layer at certain points on the vehicle were identified by several NASA researchers as being very important to have knowledge of during the HRV flight test. Knowledge of the location of the boundary layer transition is most important because of the drastic change in heat transfer through the boundary before and after transition. Structure of the boundary layer is an important factor in the operation of the scramjet engine. For example, a turbulent boundary layer at the inlet provides better high-pressure recovery and mass capture, and also reduces the susceptibility to engine unstarts. If the transition point moves well aft, the inlet may ingest a thick boundary layer, and the performance may be significantly reduced. The boundary layer problem is further complicated by the need to know when re-laminarization occurs as the vehicle re-enters the atmosphere. At the present there is little confidence in being able to accurately predict the point at which re-laminarization occurs.

Measuring the location of the boundary layer transition in flight will be a very challenging problem. Surface pressure measurements are not sensitive enough to locate the transition point. Acoustical measurements have been suggested as a means to detect the transition point; however the ambient noise environment may be so high, particularly in the region of the engine inlets, that it may not be possible to extract the noise signature of the boundary layer transition. Temperature gradient along the surface is a potential way of detecting the transition point because of the much higher heat transfer through the turbulent boundary layer. However, an abrupt temperature change on the surface could result from other sources, such as an unexpected shock impingement. A laser instrument that could scan the local flow near the surface could be effective, if the in-flight installation problem can be solved.

It may be possible to use distributed acoustical measurements and sophisticated computational techniques, such as adaptive filtering or pattern recognition techniques to extract the boundary layer transition signature. This is difficult to assess at this time because it will depend on the characteristics of the acoustic environment at the surface due to the engine and other sources. It will be highly dependent on the engine/inlet design, the structural design, acoustical transmission/isolation of the structure and subsystems (fuel pumps, etc.) design. Experimental measurements using full-scale hardware would be necessary to develop an adequate data base to develop and assess this approach.

An alternate concept might be to use a combination of temperature and pressure measurements, together with logic algorithms to estimate the transition location. Surface temperature would be the primary indicator of the transition location and pressure would be used to discriminate against abrupt temperature change being due to shock impingement, which would also have a corresponding abrupt change in pressure.

A promising laser instrument development is underway at Sandia Labs⁽⁸⁾ that uses electron-beam and laser-induced fluorescence in the airstream. From measurements of the backscatter from the fluorescent nitrogen, atomic nitrogen, and nitric-oxide, one can determine the density and velocity profile through the boundary layer. It would provide enough information to determine whether the flow is laminar or turbulent at that instrument location. It may be possible to use a few such instruments in key locations and use computational techniques to estimate the location of the boundary layer transition within some reasonable region around the measurement point or between measurement points.

Shock Wave Position Estimation

Knowing the position of shock waves that impinge on some portion of the structure in real-time is important from flight safety and engine performance standpoints and can be useful in interpreting flight test results. At hypersonic speeds, shock wave impingements on the vehicle surface can cause severe local aerodynamic heating and structural damage. A vivid example⁽¹²⁾ occurred on flight 2-53-97 of the X-15 on October 3, 1967, when NASA was testing a dummy ramjet configuration at a speed near $M=7$. The dummy ramjet was mounted on the lower vertical stabilizer and was instrumented to measure local flow characteristics. Near the maximum speed an apparently unexpected interaction of the ramjet/vehicle stabilizer shock waves and the boundary layer caused such high skin temperatures (over 2,700° F estimated) on the dummy ramjet pylon leading edge as to destroy the ablator and melt the Inconel-X skin. There was also some melting of the ramjet skin and structure. The pylon acceleration and pressure instrumentation were also lost due to the heating. The high temperature also caused three of four explosive bolts holding the dummy ramjet to the lower vertical to fire and jettison the ramjet prematurely. If techniques were available at that time to continuously track the location of shock waves in the vicinity of the dummy ramjet and lower vertical, test engineers may have been able to warn mission control of the approaching problem. Surface pressures alone are not adequate to measure the shock position. There were pressure measurements on the leading edge of the pylon of the dummy ramjet, but by the time they registered the pressure change due to the shock, it was too late. Ideally, one would want a continuous three-dimensional (3D) and physical characterization representation of shock waves in potentially critical regions of the vehicle. A test engineer could then track their movement and anticipate potential problems.

A possible measurement approach is to develop an optical instrument that would directly measure the shock wave position by detecting the large density change across the shock wave. This would be very challenging instrumentation task, particularly for obtaining the three-dimensional position at multiple locations around the vehicle. Research is underway⁽⁸⁾ to develop non-intrusive optical diagnostics instrumentation for hypersonic flight research using electron-beam and laser-induced fluorescence techniques. The current focus is on measuring characteristics in the boundary layer. For this study, it will be assumed that an optical instrument could be developed for measuring the shock position and will be referenced to as a laser instrument.

Two possible approaches to use laser instruments are illustrated in Figure 9. For typical HRV configurations, a scanning laser would most likely have to operate at shallow angles in order to "see" critical regions, such as around the inlets, from another location on the vehicle. That means the laser must have a range of several meters, and the backscatter signal off the shock density wave will be very weak unless a higher power laser is used. Weight and volume constraints

essentially rule out high-power lasers. Even with a scanning laser, several would be required to cover all the potential critical areas. An alternate approach is to use a series of fixed lasers normal to the surface to map out the shock position in two dimensions as shown in Figure 9. Knowing the shock position in one plane provides a lot of useful information, but in complex shock interaction regions it may not be sufficient. Using lasers normal to the surface to measure shock position may be better than a scanning laser from the power standpoint since the range would be only a meter or less. However, many laser positions would be needed to cover all the potential critical regions on a HRV. Another challenge in using lasers is to provide "windows" in the structure at locations which may have very high heat flux and temperature gradients. Joining the window material to actively cooled structures may be difficult.

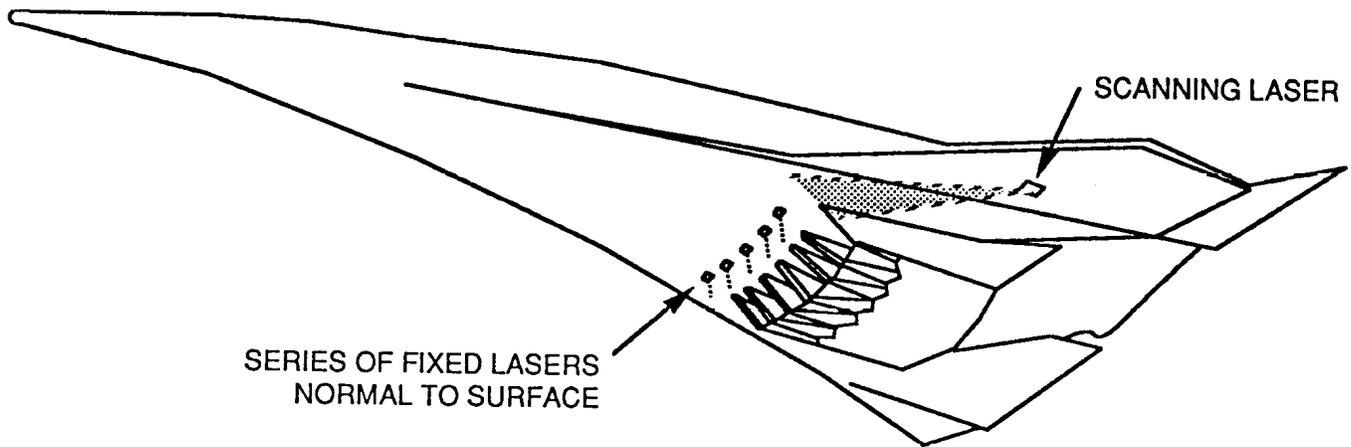


Figure 9: Potential Laser Instrumentation Concept to Measure Shock Wave Position

If a viable flight qualified laser instrument can be developed for measuring shock wave position at discrete locations, remote computation techniques could be used to interpolate between and extrapolate beyond the discrete measurement points. One possible approach is the following (see Figure 10): (1) compute and store very accurate estimates of the shock waves and boundary layer interactions, if appropriate (3D shape, orientation, and position), in the critical regions of the vehicle to be monitored where there are discrete laser measurements; (2) compute and store sensitivity functions for how the shock waves and boundary layer interactions would change about the nominal estimates computed in step 1 with changes in the local flow characteristics, e.g., particulate composition, flow temperatures, free-stream conditions, etc.; (3) compute the differences between the measured shock position and flow characteristics and the nominal pre-computed estimates; (4) compute estimated changes in the shock waves and boundary layer interactions (3D shape, orientation, and position) in real-time using the sensitivity functions (step 2) and differences (step 3); and (5) construct a new 3D estimate of the shock waves and boundary layer interactions, if appropriate, from results of step 1 and step 4 which best fits the discrete laser measurements of the shock position. Steps 1 and 2 are pre-computed for the critical flight conditions on the nominal flight path prior to flight and stored in a manner which can be accessed in real-time during the flight.

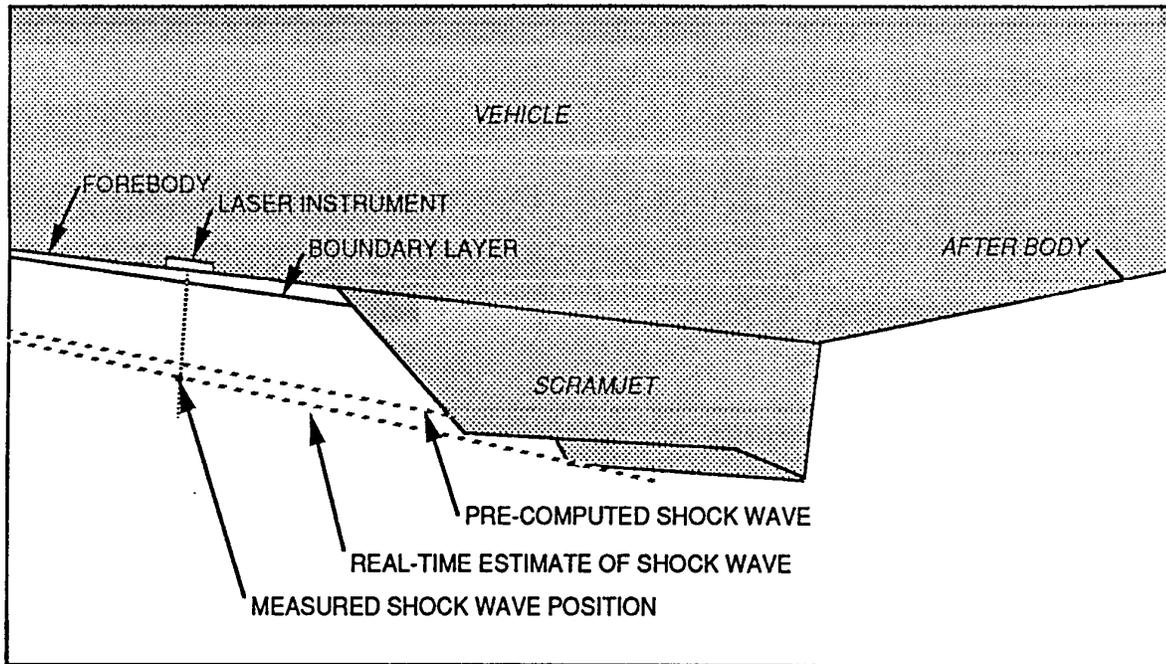


Figure 10: Computational Extrapolation of Shock Wave from Measurement Point

The final product of this approach would be a real-time estimate of the 3D shape, orientation and position of shock waves and boundary layer interactions which can be presented pictorially to flight test engineers on a monitoring screen through computer-generated graphics. One would also present the pre-computed 3D estimates (pre-flight predictions) in the same format, but different color, for easy comparison. The test engineer could select whether the pre-computed estimates are displayed or not. Also displayed would be a computer-generated 3D pictorial of the critical region of the vehicle being monitored. The 3D shock wave estimates would be superimposed on the vehicle pictorial to show possible shock impingement, for example. Both the vehicle and shock waves could be rotated by the test engineer in real-time for better viewing. The laser measurement points would be identified on the display so that the monitor would always have the actual position measurements as well as the computed extrapolations. The measured local flow and free-stream conditions would be available to display if the test engineer needed to refer to them for interpreting the pictorial display. Another useful piece of information to present to the test engineer is an estimate of how good the real-time estimates of shock waves and boundary layer interactions are. One should be able to develop such an estimate, or at least an upper bound on the estimate using the sensitivity functions (step 2) and the differences between measured shock position and flow characteristics and the nominal pre-computed estimates (step 3). The test engineer would use this measure of goodness to determine the degree to which the extrapolations can be relied upon.

The test engineer's monitor could also present surface temperatures or temperature margins (Section 5.2) on the same display. The combination of a pictorial display of the shock waves impinging on a structural member and a color-coded surface temperature or margins on that structural member would be a very effective way to monitor the flight tests. The test engineer could quickly assess potential problems.

It may be possible to use other flight measurements in addition to the discrete laser measurements to develop better estimates of the shock wave and boundary layer interactions in critical regions. For example, measured surface pressures and temperatures could be compared to predicted pressures and temperatures for the estimated shock position and interactions. If different, the estimated position and interactions would be changed according to sensitivity functions to provide a better match with the measurements.

Recall that this concept is based on the HRV flying a prescribed flight path along which predictions of the shock characteristics and sensitivity functions have been pre-computed and stored for use in real-time. During normal envelope expansion this is not only a reasonable assumption, but also a very prudent flight test approach for an experimental aircraft. The companion to this report ⁽⁶⁾ addresses methods for precisely controlling the HRV to a prescribed trajectory. If one has to deviate from the planned flight path and the shock position estimation technique becomes invalid, you just revert back to the standard flight measurements and fly a conservative flight path to an appropriate recovery site.

Performance Estimation

One of the major challenges in developing a HRV capable of going from earth to orbit is to produce an integrated propulsion system and configuration with the necessary performance at hypersonic speeds. Three-fourths of the energy needed to go into orbit must be added to the vehicle above Mach 8. The required net propulsive thrust to accelerate at hypersonic speeds will be a small difference between two very large forces, the ram drag and gross thrust. The net thrust may only be 5% to 7% of the gross thrust. The uncertainty in predicting the total vehicle drag and gross thrust above Mach 10, at best, will probably be from 5% to 10% of gross thrust. That means that the vehicle could end up having zero or negative forward acceleration at some point and not be able to achieve its desired performance. Real-time estimation and prediction of the performance is important for effective energy management and trajectory control of a HRV during envelop expansion. The energy management and trajectory control problems are treated in the companion report⁽⁶⁾. A common requirement is to have good estimates of the vehicle's performance (engines on and off) and aerodynamic characteristics over the allowable set of trajectories. If the vehicle's performance is significantly less than predicted, it may have to deviate from the planned flight path. Accurate real-time re-planning of the best alternate trajectory would require an updated estimate of the vehicle's performance. From an energy management standpoint, it is always important to know your current energy state. Reduced performance translates directly to reduced productive energy (i.e., ability to convert stored energy to either kinetic or potential energy) which may reduce the options in an emergency situation.

From an energy management and trajectory control standpoint, one would want real-time estimates of lift, drag, and thrust. These estimates would be used to update the mathematical model in real-time to use in the energy management and trajectory control computations for the remainder of the flight. Techniques are available⁽¹³⁾ to determine performance parameters from flight test data which could be used in the early phase of the envelope expansion with the jet engine mode. Yechout's⁽¹³⁾ techniques involve a series of quasi-steady-state accelerations and decelerations at different power settings. This is a relatively slow process to be considered real-time. Certainly the processing can be real-time, but the final estimates would not be available until the end of the maneuver sequence. The gross thrust estimates involve using an engine deck model. Yechout was able to measure performance parameters within 5% on a subsonic jet aircraft.

It is not apparent that any techniques exist for estimating the performance parameters from flight test data for a HRV operating in the ramjet/scramjet modes. This is an excellent topic for

innovative research. In formulating the problem one should keep in mind that it is not necessary to estimate the absolute values of thrust and drag, but only the difference as a function of the vehicle's state variables, flight conditions, and control variables. If this is possible, the accuracy would be much better than taking the difference between two very large numbers (ram drag and gross thrust). The detail formulation will depend on the characteristics of the HRV configuration and ramjet/scramjet. If a detail model for the engine and its integration with the airframe are necessary to achieve the desired accuracy, extensive real-time processing will be needed.

The other aspect of energy management mentioned earlier is to always know the current vehicle energy state. One can assume that there will be adequate measurements of velocity, altitude, and vehicle mass to accurately calculate the kinetic and potential energy at all times. The vehicle mass is not actually measured, but rather estimated from a combination of the original preflight measurements and in-flight measurements of volume pressure and temperature of remaining fuel and fuel-flow rates. Estimating the productive energy potential of the remaining fuel (liquid or slush hydrogen) may be more difficult because it is used for active cooling of the structure as well as for propulsion. The hydrogen would be loaded in a liquid or slush state. Thermal energy is added through the active cooling system such that the hydrogen is at the proper state and temperature for injecting into the ramjet/scramjet. There are indications that an active system for cooling the structure may require a higher use rate of hydrogen than the engine needs for propulsion. The excess would have to be jettisoned.

One possible method for estimating the productive energy potential of the remaining fuel would be to measure the efficiency of converting fuel into vehicle kinetic and potential energy; i.e., energy change per fuel flow rate. The efficiency would be a function of the vehicle state variables and atmospheric parameters along the trajectory flow. The measured efficiency could be stored as a function of flight conditions and used to update models along alternate trajectories.

From a flight test engineer monitoring standpoint, it will be useful to compare the vehicle's measured trajectory parameters (acceleration, velocity, altitude, range, and cross-range) as functions of time to a real-time computer simulation output with the measured control variables (engine and flight control) as inputs. Deviations between the actual and simulated trajectory parameters provide a qualitative indication of discrepancies between the vehicle and predicted performance parameters. Various levels and types of simulations could be used from simplified point mass trajectory simulation to a complete nonlinear six degree-of-freedom simulation. Measured Mach number, angle-of-attack, side-slip angle, air density, dynamic pressure, etc., can be used in the calculation of aerodynamic parameters.

Surface Temperature Estimation

Monitoring the vehicle surface temperature at potentially critical locations, such as the nose cap, wing leading edges, scramjet inlet cowl lips, forebody compression surfaces, shock/boundary layer interaction points, shock/control surface interactions, control surface gaps, etc., will be very important from a flight safety standpoint during the envelope expansion phase. If the temperature approaches a level which could cause possible structural damage, the flight profile would have to be changed to reduce the heat flux into the vehicle. However, it will be difficult, if not impossible, to measure the surface temperature directly at all the potentially critical places. Surface-mounted thermocouples may burn off. Imbedded and "back-face" thermocouples can probably be used, but with actively cooled structures proper interpretation of the measurements will be important because of very high thermal gradients at the thermocouples. The concept suggested here is to use modeling and computational techniques to provide very accurate estimates of surface temperatures from a matrix of imbedded and back-face thermocouples. The technique would also provide estimates between and beyond the discrete measurement points. This example was selected to be explored in more detail in Section 5.2.

Critical Structural Stress Estimation

The stress experienced on HRV structure will be due to a combination of aerodynamic, gravitational, inertial, and thermal loads. The critical stress limits for flight safety will be a function of temperature of the material under stress. Having a continuous estimation of the total stress and the temperature-dependent stress safety criteria in real-time would enhance flight safety. Figure 11 is a cartoon of a real-time stress-monitoring concept. In-flight measurements would be made of strain, temperature, and acceleration (up to acoustic frequencies) at several locations in the region of interest. With high sampling rates, it might be possible to employ a high-speed simulation of the system dynamics to calculate stress at points between the measurement locations and to predict future behavior (based on assumed forcing functions). Some kind of modal model might be good for handling spatial variations (although changing temperatures provide a significant challenge), as well as temporal variations. The safety monitoring would consist of comparing the estimated stresses to the temperature-dependent allowable stresses; joint and seal integrity monitoring; and acoustic fatigue monitoring. The experiment monitoring would include estimated aero, thermal and inertial load contributions; thermal and acoustic loads (intensity and frequency) compared to the predicted; vibration characteristics (frequency, damping, and mode shapes); and possibly material and joint degradation.

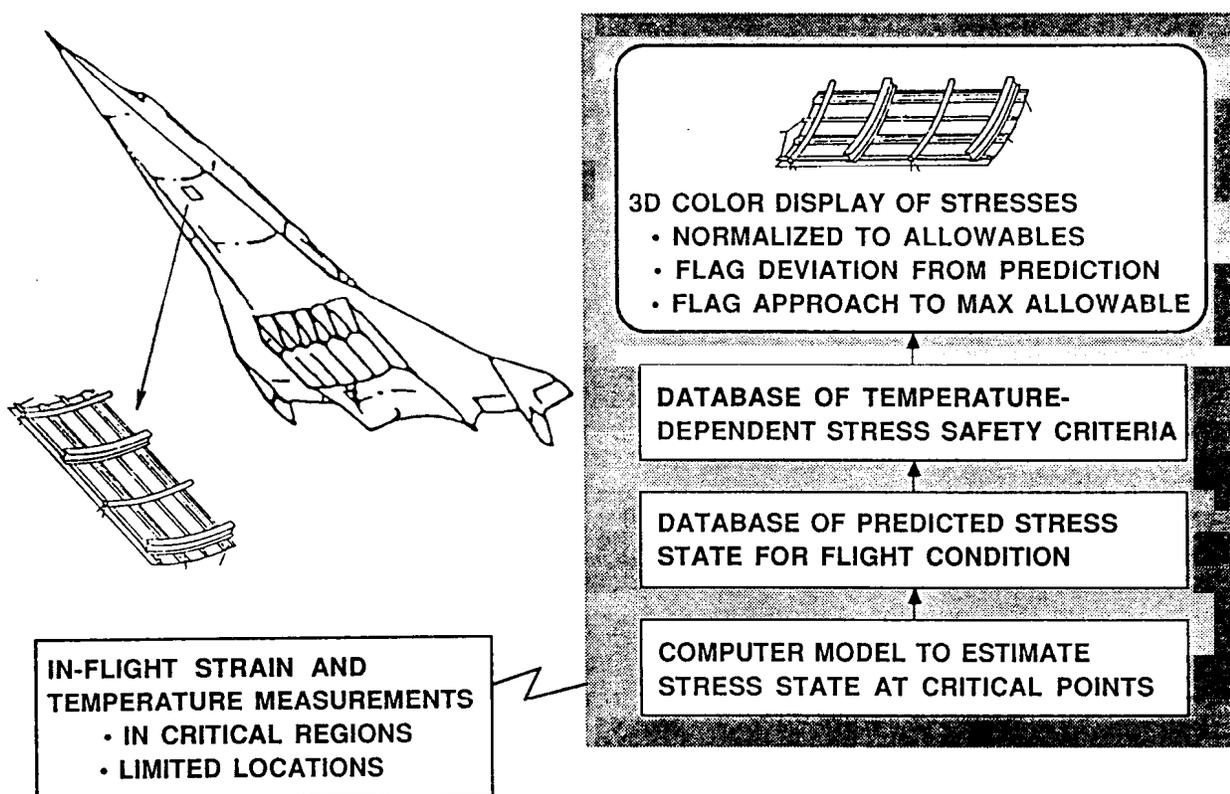


Figure 11: Real-Time Monitoring Concept for Critical Structural Stress

Stability Estimation and Monitoring

The ability to accurately estimate and monitor the stability of a HRV in real-time would be highly beneficial to flight safety and efficiency of accomplishing the envelope expansion. In the past, stability was monitored by a test engineer observing the vehicle dynamic response to pilot

inputs and/or external disturbances on a strip-chart recorder and trying to deduce whether there is a stability problem. On the X-29A flight test program⁽³⁾, the response of a simulated model to actual pilot control inputs was calculated and compared to the actual response in near real time. If the calculated response differed from the actual response, one could conclude that the aircraft differed from the analytical model. This gives a qualitative indication of stability, which may be adequate for the linearized time-invariant case. The concept suggested here is to make a quantitative estimate of the stability in real-time with the best available time-varying dynamical systems analysis techniques and presenting simple measures of the stability to the test engineer on a CRT display. Predictions of the expected stability along the current trajectory can also be made for several time increments into the future. These estimates can be made for both the augmented and unaugmented vehicle. The test engineer monitoring these stability predictions could observe the trends and warn the test director if a potential stability problem is approaching.

This concept was selected to be developed in more detail in Section 5.3. It involves telemetry of the vehicle state information to the ground station, extensive modeling of the vehicle characteristics, and real-time estimation of the stability using the Generalized Multiple Scales (GMS) method discussed below⁽¹⁴⁾. Conventional linearized time-invariant analysis methods are not adequate for this class of vehicles.

Real-time Estimation of HRV Surface Temperature Example

The requirement to fly at high dynamic pressure for maximum efficiency of the scramjet at hypersonic speeds creates a severe aerothermodynamic environment for the structure. Tauber and Adelman⁽¹⁵⁾ estimated ascent peak stagnation point and equilibrium wall temperatures for the wing leading edge of a transatmospheric vehicle can be as high as 6700°F and 4900°F respectively. The corresponding peak heat flux was estimated to be as high as 1100 and 425 BTU/Sec/ft² respectively; and a total heat load of around 26KBTU/ft². For comparison, the total head load for a typical Space Shuttle entry is about 6KBTU/ft². The extremely high heat flux and total heat load drives the materials and structural design concepts for a HRV. Ablators (e.g., Apollo) and insulators (e.g., Shuttle) do not satisfy the HRV operational requirements. Figure 12 is a calculation of the heat flux at the nose cap for a typical HRV ascent trajectory and the relevant thermal management approaches which are considered appropriate for an operational HRV. The cooling capability of various thermal management schemes is shown in Figure 13 as a function of incident heat flux. It is clear from Figures 12 and 13 that multi-mode thermal management approaches are likely to be used on a HRV. Even with sophisticated thermal management, surface temperatures above 2000°F are quite likely at critical locations on the vehicle. Unexpected shock wave and boundary layer interactions could cause extreme local heating to much higher temperatures as in the case of the X-15 dummy ramjet pylon leading-edge experience⁽¹²⁾ discussed in Section 5.1.3.

If an accurate map of the surface temperatures at potential critical areas can be developed and extrapolated a short time into the future, it may be possible to avoid potential structural damage due to aerothermodynamic heating. The high temperatures, complexity of multi-mode thermal management techniques, and high thermal gradients make the process of measuring surface temperatures directly almost, if not, impossible and the process of estimating the surface temperature at all potential critical locations very challenging. High temperature thermocouples, such as Platinum-rhodium, operate accurately at temperatures up to 2700° F and possibly 3000°F^(c). Surface-mounted, or even imbedded or back faced mounted thermocouples could not be used in those areas if the temperature at the thermocouple could exceed 2700°F. Imbedded or back-faced-mounted thermocouples, of course, only measure the temperature at their location, which can be substantially different from the surface temperature. Temperature gradients across the thickness of the external surface material can be several 100's degrees Fahrenheit depending on the type of material, thickness, thermal management system, and the incident heat flux. Backface temperatures

measured in-flight could be used in inverse thermal models to backout surface heat flux and temperatures. The complexity and accuracy of inverse methods is a strong function of material properties and the thermal management concept used.

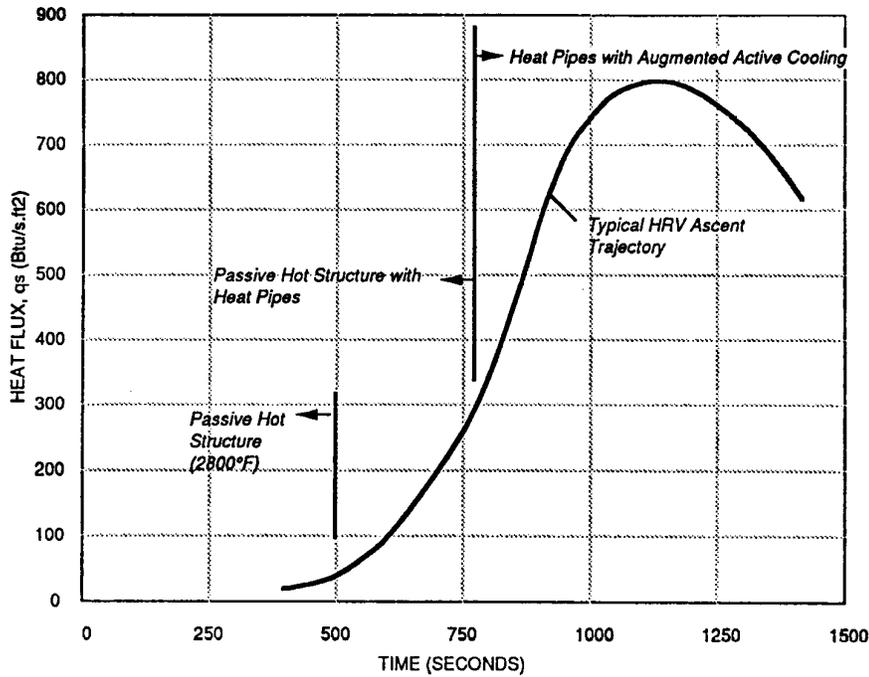


Figure 12. Thermal Performance Comparison for Nosecap Cooling Configurations

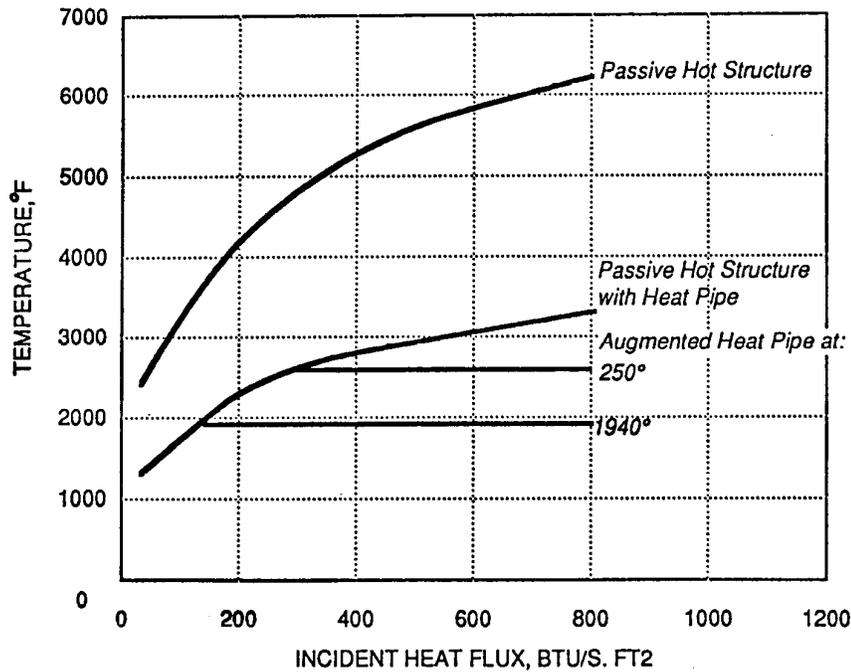


Figure 13. Peak Temperature Comparison of Nosecap Cooling Configurations

Fiber-optic devices for measuring surface temperatures above 2700°F are available commercially for laboratory measurements. Flight-qualified versions may also be available, or if not could probably be developed. The fiber-optic sensor must be positioned such that it can observe the emissivity of the surface. Such an instrument could possibly be mounted in a position to measure the temperature at the "back side" of the vehicle's surface material. It would be difficult, if not impossible, to mount it such that it could directly observe the external surface, (for example, at the tip of the nosecap). As in the case with thermocouples, the most likely measurements are at the back side of the structure rather than at the external surface.

Actively cooled structures add more complexity to the problem of measuring or estimating the vehicle's surface temperature. Figure 14 shows a SPARTA conceptual design for a HRV nosecap using active cooling augmentation and high performance heat pipe. This concept could also be used for wing leading edges. It was designed for peak heat flux of over 800 BTU/sec-ft². A heat pipe is used to transfer the heat from the nose, which is exposed to the highest heat flux, to a convectively cooled heat exchanger. The heat pipe operates with liquid lithium being vaporized at the hemispherical cap by the intense heat flux, which increases the pressure at the cap end of the chamber; the lithium vapor is drawn to the lower pressure end and condenses on the coated carbon-carbon composite surface, which is convectively cooled by liquid hydrogen through a heat exchanger; the liquid lithium fills the grooved arteries on the cone and is drawn by capillary action back to the cap where it is again vaporized. This concept has been demonstrated in laboratory tests.

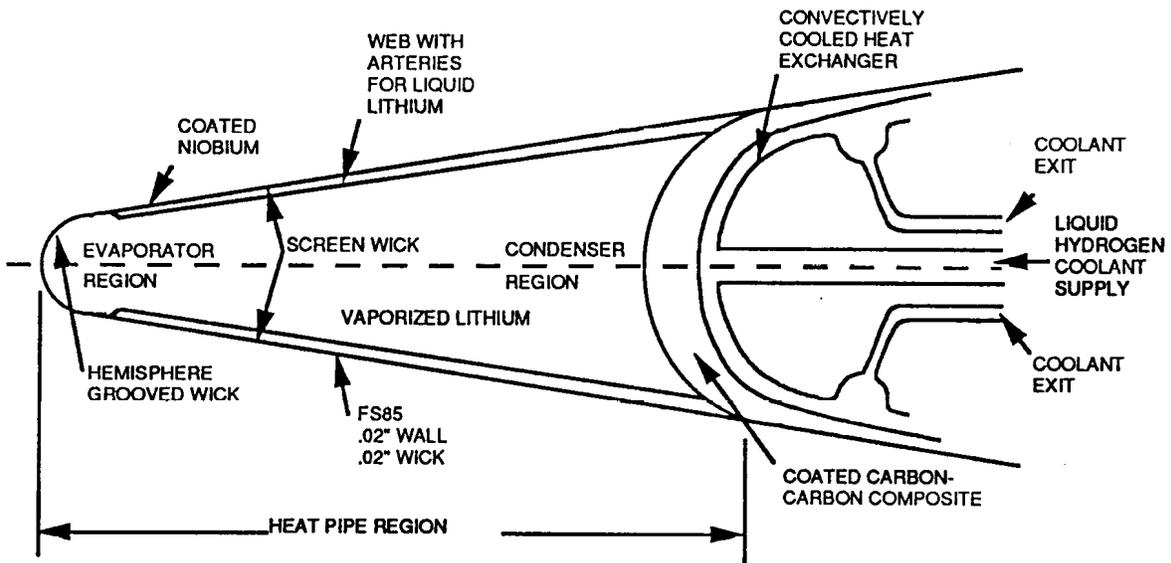


Figure 14: Conceptual Design for a Nosecap with Active Cooling Augmentation and High Performance Heat Pipe

Instrumenting a design such as Figure 14 to measure the outside temperature over the entire nosecap surface would indeed be challenging. The suggestion here is to use a combination of imbedded thermocouples, modeling of the local thermodynamics, extensive data base of the predicted surface temperatures, and real-time computational techniques with inverse models to provide very accurate real-time estimates of the surface temperatures and heat flux. Figure 15

illustrates how a matrix of thermocouples might be imbedded on the backface of the actively cooled structure. The best locations for the thermocouples relative to the grooved arteries, ribs, and liquid lithium would have to be investigated and tested. The intent would be to develop mathematical models that will estimate the exterior surface temperature from the imbedded thermocouple measurements. It is not at all clear that such inverse methods can be developed to operate in real time and give accurate estimations and would have to be the subject of a research program. Existing techniques used to calculate surface temperatures of actively cooled structures at hypersonic speeds, such as finite element codes, ABAQUS or TOPAZ3D, divide the problem into many small segments of a grid and perform numerical solutions of the local thermodynamics. The computations for a section of the structure depicted in Figure 14 typically run about 1 to 15 minutes on a Convex C120 supercomputer, depending upon model fidelity and geometric complexities and, therefore, would not be appropriate for real-time applications. A suggested approach for research is to consider developing linear or possibly non-linear estimators based on the local thermodynamics, and pre-computed and stored predictions of the temperatures along the nominal flight path that are corrected to the measured actual flight condition. The estimators would operate on the measured imbedded thermocouple temperatures to extrapolate them to the surface at the measurement points and between them. The estimators may require measurements of the thermal management system state variables as well. It may be necessary to restrict the region of validity for a particular estimator and use multiple estimators to cover the area of interest. For example, one might be restricted to the liquid metal heat pipe area and another in the flange area.

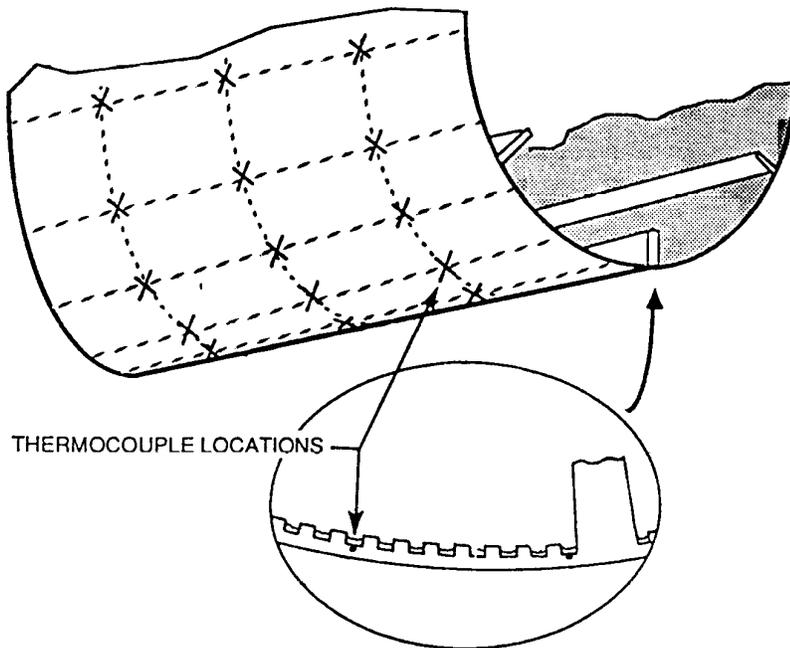


Figure 15: Potential Matrix of Thermocouples on a Nosecap

Figure 16 illustrates the suggested approach for real-time monitoring of critical surface temperatures on an actively cooled nose cap. A 3D color display of the temperature distributions estimated in-flight and predicted could be presented to the flight test engineer monitoring the flight. The estimated temperatures would be compared to critical limits continuously, and if a limit is approached a flag would appear.

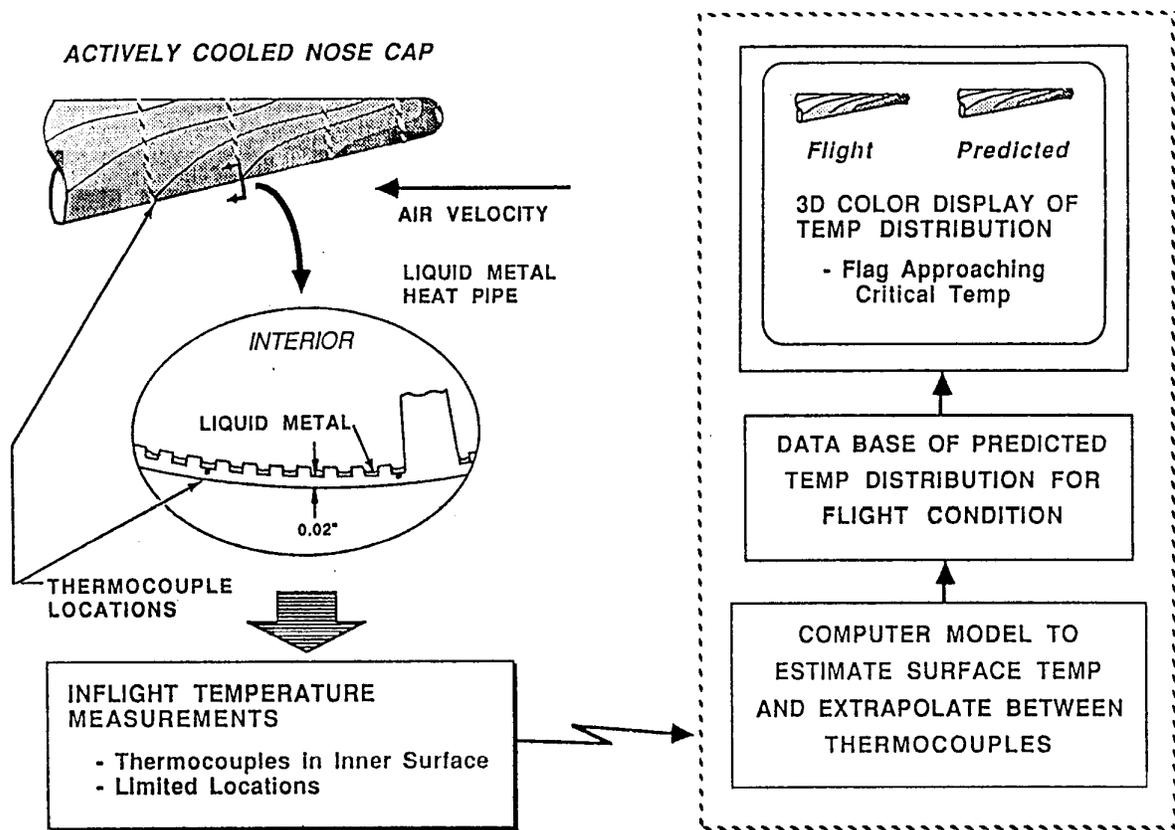


Figure 16: Real-time Monitoring of Critical surface Temperatures

Real-time Stability Estimation and Monitoring Example

The flight dynamics of an HRV present a number of challenging problems to the dynamicist who is used to dealing with conventional flight vehicles at a prescribed flight condition. The departure from conventional description could potentially be so pronounced and different that considerable care is necessary in developing a basic understanding of the complex flight dynamics of a hypersonic vehicle.

The dynamics of a conventional flight vehicle at a particular flight condition are usually analyzed by linearizing the equations of motion at the flight condition. The stability and dynamics of the vehicle are then described on the basis of linear time-invariant (LTI) systems theory. For instance, the system stability is assured if the eigenvalues have negative real parts. Further, the local stability of the nonlinear system (i.e., the vehicle) is also represented by the linearized system, however, with some exceptions. Control systems are then designed based on standard LTI methods.

When the flight conditions vary drastically and continuously as with an HRV, the above approach is not strictly valid. The differential equations of motion vary as the flight conditions change. In this case, the nature of the flight dynamics becomes considerably more complex, and cannot be determined by the usual LTI methods. Notwithstanding this difficulty, the dynamics and control engineers endeavor to apply LTI stability and control methods to approximate the true behavior, at least for slowly varying systems. Such simplistic approaches could potentially lead to serious misrepresentations of the true system behavior.

The basic approach can be illustrated by the following example⁽¹⁶⁾. Consider the motion of the Space Shuttle along a steep entry trajectory. As the center of mass travels along an optimal trajectory (minimizing the overall thermal protection system weight, for example), the angle-of-attack oscillations exhibit a continuously increasing frequency (Figure 17). This motion cannot be described by conventional methods. A common approach is to "freeze" the system and treat it as a time-invariant system. Stability and response analyses are then carried out using standard methods of stability and control analysis. However, such a simplistic approach often leads to a complete misrepresentation of the true system dynamics. Ramnath solved this problem using GMS methods⁽¹⁶⁾. He separated the fast and slow aspects of the time-varying dynamics on multiple time scales. The variable frequency of the motion is described on the fast scale. The slower amplitude variations are described on a slow time scale. A combination yields the composite description. These solutions are depicted in Figure 17. This Figure shows four solutions, all satisfying the same initial conditions. The four solutions are:

- (1) "Exact" or Numerical Solution
- (2) GMS Fast-Scale Solution
- (3) GMS Fast-and-Slow Solution
- (4) "Frozen" Solution

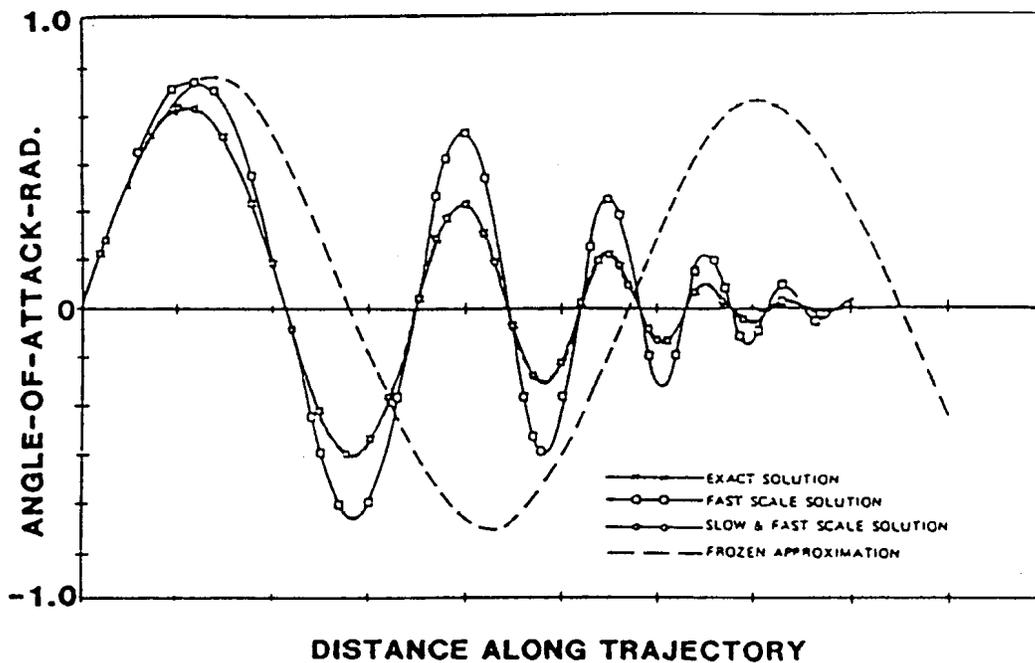


Figure 17: GMS Provides Correct Analytical Representation of Space Shuttle Dynamics

It is clear from the Figure that the GMS-Fast Solution represents the frequency very accurately, as evidenced by the zero-crossings of the solution in comparison with the numerical solution. This because the frequency variation constitutes the rapid part of the oscillations, and is accurately described by the fast solution. The error in amplitude, being slower, is picked up on the slow time scale. The combined GMS Fast and Slow solution shows excellent agreement in both the amplitude and frequency in comparison with the numerical solution. The accuracy is so good,

in fact, as to be indistinguishable from the "exact" solution. The "frozen" solution, based on a constant-coefficient approximation, is highly inaccurate. Indeed, it totally misrepresents the behavior even before the first half-cycle of the oscillation.

Stability of the HRV

The dynamics and stability of an HRV depend on a number of factors, including the vehicle characteristics, the environment, the trajectory, and the velocity profile. As a baseline, we may consider a velocity profile accelerating from Mach 2 to Mach 15, and a trajectory after a take-off from Edwards AFB northward, climbing, turning and accelerating. Other trajectories may involve flight at constant-altitude or re-entry and landing. With this scenario, it is clear that the vehicle will exhibit a wide variation in its characteristics. Because of the possibility of peculiar and counter-intuitive behaviors, it is of great importance that a capability be developed to predict the stability and response characteristics, at least for a short time into the future. It is of further benefit if it could be done in real time. Because of the limitations of conventional methods, a strong and clear need exists for a more sophisticated method to overcome the difficulties of standard methods. The Generalized Multiple Scales(GMS) method, developed by Ramnath⁽¹⁴⁾, is ideally suited to address and solve both these important problems. This technique makes use of the inherent time constants existing in the system dynamics to develop simple and accurate representations of the system dynamics. A brief description of the GMS method is presented in Appendix A.

Based on the information available, the GMS approach enables us to predict accurately the dynamic behavior and stability of an HRV in terms of simply calculable functions. The non-intuitive stability and response are rendered transparent by the GMS theory. Further, because the calculations are simple, the computations can be carried out efficiently and rapidly. Therefore, real-time computations are achievable.

Some of the potential peculiarities of an HRV can now be enumerated as follows. Among the number of effects, the four major areas are:

- (1) Stability
- (2) Response
- (3) Bifurcation
- (4) Turning Points

The stability of a hypersonic vehicle during acceleration cannot be predicted simply by the location of the eigenvalues. In principle, the eigenvalues may have negative real parts and the system could be unstable. The GMS theory predicts the stability correctly.

The acceleration results in continuously modifying the frequency and damping of the response. Indeed, even the notion of frequency has to be interpreted properly. During these maneuvers, in contrast to the steady flight case, the phase of the oscillatory dynamics changes nonlinearly, and the damping is usually more complicated, being described by exponentials of nonlinear arguments. The climbing, turning, accelerating flight introduces deviations from the usual descriptions of a flight vehicle in regard to the coupling between the longitudinal and lateral-directional flight modes. Unfamiliar modes may be introduced, thus complicating the representation. A correct prediction of the response should include such a variation in the frequency and damping of all the modes. The GMS method achieves such a uniform description.

Under certain conditions, it is possible that the vehicle could exhibit essentially nonlinear oscillations which cannot be predicted by linear theory⁽¹⁷⁾. At certain critical flight velocities, the vehicle can experience a bifurcation from one solution branch and jump to another branch suddenly. Such a sudden jump could potentially have serious implications in regard to stability

and control. At other times, the vehicle motion could suddenly change from a limit cycle of constant-amplitude constant-frequency oscillations to diverging oscillations. Such complex motions have to be analyzed carefully.

Under certain other conditions, it is possible that the vehicle exhibits "turning points". These are points at which the character of the dynamics changes from non-oscillatory motion to one of oscillations, or vice versa. In these situations, the phase of the dynamics is lost and this would potentially have a significant effect on the stability, control, and dynamics prediction.

The stability and control of HRV's is treated with the GMS method specifically for the Air Force Wright Aeronautical Laboratories in Reference 18. The GMS method allows us to accurately predict the stability of a HRV during the flight test regardless of whether these important non-conventional problems exist or conventional linear time-invariant conditions apply.

Monitoring Stability During Flight Tests

In the following, an approach is discussed to provide a simple stability criteria displaced in real time for monitoring by a flight test engineer. It will enable him to observe the current estimated stability and predictions of the stability several seconds in to the future. The advantages are that such a display could serve the important and useful purpose of anticipating the complex dynamic modes of the vehicle which could possibly be exhibited during the flight envelope of the vehicle. The transition to particular motions such as nonlinear resonances and instabilities are usually subtle and insidious. Such a behavior is counter-intuitive and cannot be predicted by standard analysis methods, as discussed earlier.

Stability Monitoring by Means of GMS Theory

The motion of an HRV is described accurately in terms of simply calculable functions using the GMS theory. Further, these descriptions display systematic separation of the rapid and slow aspects of the dynamics. Thus, the frequency variations are described on the fast time scale and the slower amplitude behavior on the slow-time scale. Because of this highly desirable feature, the system stability can be described on a slow-time scale and is, therefore, simple. Based on this approach, we can develop simple descriptions of the system stability which can be used in a predictive capacity.

In particular, a parameter, $p(t)$, can be developed to describe the stability of the HRV in time-varying flight conditions along an arbitrary trajectory. We will define $p(t)$ as the time derivative of the log of the amplitude envelope of vehicle dynamic response to an impulse function. Conceptually, this can be thought of as the ratio of the time rate of change of the amplitude envelope, $\dot{A}(t)$, to the amplitude envelope, $A(t)$; i.e., $p(t) = \dot{A}(t)/A(t)$. See Figure 18. In steady flight (LTI), this reduces to the familiar damping parameter, $\zeta\omega_n$, which is a constant. When the flight conditions are changing rapidly; i.e., accelerating or decelerating, $p(t)$ is a function to time. The stability criteria of the time varying system (HRV) can be stated simply as

$$\begin{aligned} p(t) < 0 &\text{ implies stability} \\ p(t) > 0 &\text{ implies instability} \end{aligned}$$

The parameter, $p(t)$, can be expressed analytically using the GMS theory. It uses a mathematical model for the HRV flight dynamics linearized about the time varying trajectory being flown. The model could include the stability augmentation system so that estimates of stability could be made with or without augmentation. At the first level of sophistication, the model would use the best a priori stability and control derivatives. A second level of sophistication would be to

update the model in "real time" using a parameter identification technique. The aerodynamic characteristics would be stored as functions of the flight conditions (M, α , etc.). the model would use the actual trajectory parameters (altitude, velocity and acceleration).

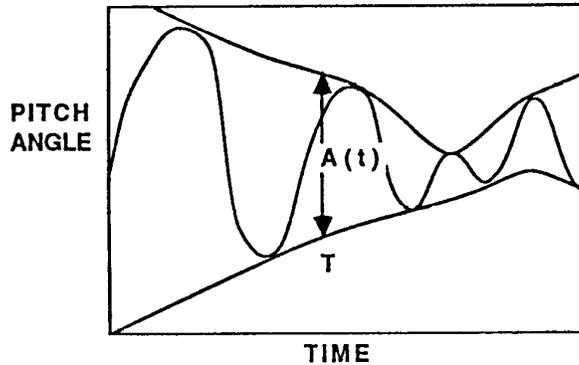


Figure 18: HRV Dynamic Response Time History Example

The parameter could be displayed to the flight test engineer on a bar chart representing the HRV stability with and without augmentation. Furthermore, $p(t)$ could be calculated at various times into the future, assuming the HRV continues along the prescribed trajectory or along a potential alternate trajectory which the test engineer chooses. Figure 19 illustrates how this might be displayed. Color would be used to highlight important aspects, for example the bar could turn yellow when approaching the stability margin bandage, then red if it exceeds the boundary.

One could still display the dynamic response of the HRV to pilot inputs for the model and actual vehicle as was done on the X-29A⁽³⁾. The model used here could use the same data base as that for the $p(t)$ calculations.

Another important aspect of this theory is that even the problem of parameter uncertainties can be treated within the confines of this approach. It is well known that even with the best mathematical models of a flight vehicle, the actual system shows differences in comparison. Therefore, the actual flight vehicle motion might depart from the predicted response which is based on the best mathematical model available. In order to quantify and track these effects, we appeal to sensitivity theory of variable systems⁽¹⁹⁾. The sensitivities of the vehicle motion with respect to critical parameters during accelerated flight can be evaluated by the GMS theory, as shown by Ramnath⁽¹⁹⁾. This allows us to introduce another "buffer" bound on top of the present bound on $p(t)$. This means that the effect of parameter uncertainties on the flight vehicle motion can be accounted for and factored into the stability prediction during acceleration flight.

A natural extension of this approach is to consider finite changes in the parameters. This problem was also investigated and solved by Ramnath⁽¹⁹⁾. In this case, the GMS theory enables us to develop analytical, or quasi-analytical, expressions for the higher order sensitivities. If needed, these can also be factored into the stability bounds.

In studying the dynamics of a hypervelocity vehicle flying along steep trajectories (for example, ballistic ones as in re-entry), the frequency of the angle-of-attack oscillations increases continuously. However, under certain conditions, these oscillations can become unstable at a particular altitude. This critical altitude, marking a transition to instability, can be estimated accurately by the GMS method, as shown by Ramnath⁽¹⁸⁾.

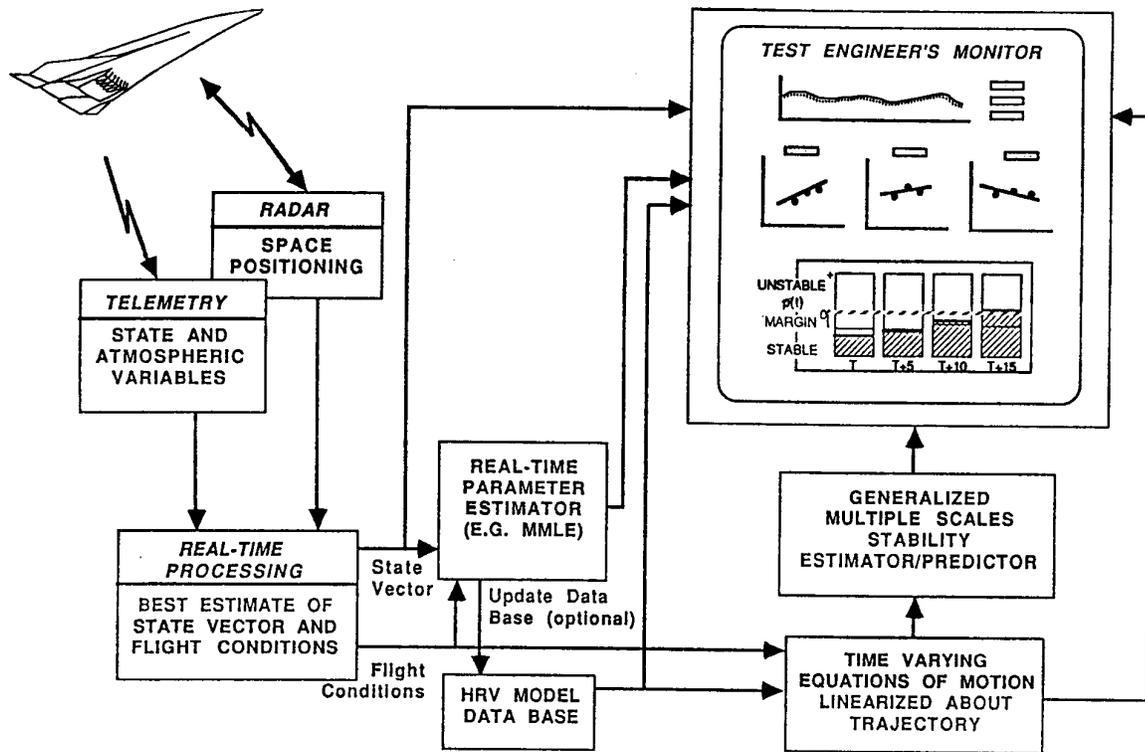


Figure 19: Potential GMS Technique for Monitoring HRV Stability

In the present context, the stability of the oscillations is described by the slow-time scale solution, representing the variation of the envelope of the oscillations. In this case the envelope decays, thus showing that the angle-of-attack oscillations are stable. While the complete solution may be quite complex, the stability information, by itself, is relatively simple. We can make use of this property in developing simple criteria to predict the stability of the flight dynamics of a hypervelocity vehicle in important flight situations such as accelerating flight. These can be utilized by the test flight engineer and the pilot to ensure a safe and successful completion of the flight test program.

Flight Test Data Requirements

The flight test data required in real time is modest by Ames-Dryden standards. The following would be required:

- | | |
|-----------------|---|
| air data: | density, static pressure, Mach number, angle-of-attack, sideslip, etc. |
| kinematic data: | flight path angle, attitude angles, angular rates and accelerations, linear accelerations, etc. |
| vehicle data: | mass, inertia, control deflections, etc. |

From these, calculations would be performed in real time to project the stability and response of the vehicle into the near future.

Benefits

The advantages of such a capability would be several. Primarily, the element of surprise in the dynamic behavior of the vehicle is obviated. Possibilities of peculiar behavior are well recognized and could be anticipated. One could then prepare to avoid or meet such events. Potentially serious or catastrophic consequences could be avoided. The full flight capability of the vehicle could be realized, leading to enhanced mission success.

Computational requirements

The original intent of this study was to make preliminary estimates of the computational requirements. In particular, the potential of using supercomputers for supporting the experiment monitoring was to have been addressed. Unfortunately the level of definition possible within the scope of this study was not adequate to define the computational tasks. Substantial research and validation effort will be required to investigate the concepts suggested here before the computational tasks can be defined. The type of numerical simulations that are used on supercomputers for calculating aerodynamic and aerothermodynamic effects for a HRV are non-real-time and inappropriate for this application. In several of the candidate examples, new real-time estimators are suggested which need to be explored in some depth.

Conclusions

Six candidate examples of potential applications of remote computation to enhance flight test information for experiment monitoring were defined and discussed: 1.) boundary layer transition location; 2.) shock-wave position estimation; 3.) performance estimation; 4.) surface temperature estimation; 5.) critical structural stress estimation; and, 6.) stability estimation. Surface temperature estimation and stability estimation were discussed in some detail. The conclusions were:

- 1.) significant extensions of the Ames-Dryden real-time test support capability through remote computations would be beneficial to monitoring a HRV flight test;
- 2.) one should take an end-to-end view of the measurement/estimation process for real-time flight test monitoring;
- 3.) new flight-qualified instrumentation will be needed for effective boundary transition location and shock-wave position estimation whether remote computation is used or not;
- 4.) substantial research and validation efforts will be needed to explore the concepts suggested in this report and develop the most promising and beneficial ones; and,
- 5.) it is not possible to estimate computational requirements until the identified techniques are developed further.

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APPENDIX A

GENERALIZED MULTIPLE SCALES (GMS) METHOD

This technique is particularly useful in the study of a phenomenon which exhibits a mixture of rapid and slow motions. The inherent time constants present in the dynamics of such systems are systematically separated, leading to simpler representations. Such a separation of the fast and slow motions is achieved by employing a number of independent "observers," each using a "clock" (or scale) which counts time (or a spatial variable) at a different rate. Each observer perceives a different aspect of the phenomenon. A combination of the different aspects yields a composite description of the dynamics. The method is fairly recent in its development, but has already been applied to study a great variety of phenomena with considerable success.

The main idea of the GMS method is to extend the independent variable into a new space. The dependent variable is also suitably extended. The problem is solved in the new space and the solutions are expressed in the original problem variables. In other words, the solution of a differential equation is sought by first extending it into a new space and then solving it in the new space. The solution to the original problem is directly obtained by restricting the extended solution to the original problem variables.

The GMS technique consists of enlarging the domain of the independent variable time into a space of higher dimension by means of 'clocks' or scale functions. The differential equations describing a dynamic phenomenon are extended into a set of partial differential equations. A small parameter $\epsilon (\ll 1)$ is identified as the ratio of the fast and slow time constants. By means of this parameter the extended equations are solved order by order and lead to asymptotic solutions. Thus, the concept of transformations forms a particular case of this general process of extension.

Extension: Given a function $f(t, \epsilon)$ and another function $F(\underline{\tau}, \epsilon)$ of the n independent variables $\tau = \tau_0, \tau_1 \dots \tau_n$ (each of which can be an n -dimensional vector), we can say that $F(t)$ is an extension of $f(t)$ if, and only if, there exists a set of relations

$$\tau_i = \tau_i(t, \epsilon)$$

i.e.,

$$\tau_i = \{\tau_1(t, \epsilon), \tau_2(t, \epsilon), \dots, \tau_n(t, \epsilon)\}$$

such that when inserted into $F(\underline{\tau}, \epsilon)$ yield $F(\underline{\tau}(t, \epsilon), \epsilon) = f(t, \epsilon)$.

In applications we extend

$$\begin{matrix} t & \{\tau_0, \tau_0 \dots\} \\ x(t, \epsilon) & x(\tau_0 \tau_1 \dots, \epsilon) \end{matrix}$$

where $\tau_i = \tau_i(t, \epsilon)$ are the time scales and are chosen to yield accurate asymptotic solutions.

There are many dramatic phenomena where the choice of linear scales is inadequate. Examples are those which are described by time varying and nonlinear differential equations. In such cases, the solution process by the GMS method requires greater freedom in the choice of scale functions. The method was generalized by Ramnath and Sandri⁽¹⁴⁾ to include nonlinear and complex scales.

This generalization is tantamount to the use of "accelerating" or "decelerating" clocks; i.e., time is counted at an increasingly faster or slower rate, depending on the phenomena. By this means, simple and uniform representations of the dynamics are obtained. These ideas have been

developed and elaborated by Ramnath through theoretical developments and a variety of aerospace applications^(14, 16, 18).



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16. Abstract This report presents the results of a study to identify potential real-time remote computational applications to support monitoring HRV flight test experiments and to define preliminary requirements. The study considered a major expansion of the support capability available at Ames-Dryden. The focus is on the use of extensive computation and data bases together with real-time flight data to generate and present high level information to those monitoring the flight. Six examples were considered: 1) boundary layer transition location; 2) shock wave position estimation; 3) performance estimation; 4) surface temperature estimation; 5) critical structural stress estimation; and 6) stability estimation.					
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