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L. Bernard Garrett

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L. Bernard Garrett
Langley Research Center
Hampton, Virginia

National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

ABBREVIATIONS

ACS	attitude control system
ACTD	active damping
AMCD	Annular Momentum Control Device
ANALOG	Analogous Modeling (module)
AVID	Aerospace Vehicle Interactive Design (program)
CP	central processing
CRT	cathode ray tube
DYLO	Dynamic Loads (module)
GTS	General Truss Synthesizer (module)
I_{sp}	specific impulse
LASS	Large Advanced Space Systems
LASSDB	LASS data base
MRS	microwave radiometer spacecraft
POST	Postprocessor (module)
RCD	Rigid-body Control Dynamics (module)
RCS	reaction control system
RF	radio frequency
rms	root mean square
SA	Surface Accuracy (module)
SAP	Structural Analysis Program
S/C	Spacecraft
TA	Thermal Analysis (module)
TTSS	Tetrahedral Truss Structures Synthesizer

SUMMARY

An overview is presented of an interactive computer-aided design program used to perform systems-level design and analysis of large spacecraft concepts. The primary emphases are on rapid design and analysis of integrated spacecraft, including automatic spacecraft modeling for lattice (trusslike) structures. Capabilities and performance of the twenty-some multidiscipline applications modules, the executive and data management software, and graphics display features are reviewed. A single user at an interactive terminal can create, design, analyze, and conduct parametric studies of Earth-orbiting spacecraft with relative ease. The approach is particularly useful in the conceptual design phase of advanced space missions when a multiplicity of concepts must be evaluated in a cost-effective and timely manner.

Data generated in the design, analysis, and performance evaluation of an Earth-orbiting large-diameter (750-m) antenna satellite are used to illustrate current capabilities. Computer run time statistics for the individual modules quantify the speed at which modeling, analysis, and design evaluation of integrated spacecraft concepts can be accomplished in a user interactive computing environment.

INTRODUCTION

Large space systems on the order of hundreds of meters in size are projected to become operational in the future. The sizes will be determined by one or two principal considerations: economy of scale (e.g., antenna or sensor farms mounted on platforms with shared central utility supporting subsystems) or advanced systems which require large physical areas (e.g., high-power solar arrays or remote sensing microwave radiometer antenna systems). These future spacecraft, unlike today's spacecraft which are generally enclosed monocoque structures with a few appendages, will have large expanses of lattice (trusslike) structures with hundreds or thousands of individual connecting members. The lightweight, flexible structures will be subjected to on-orbit environmental loads (gravity gradient, thermal, low-frequency transient vibrations, etc.) which usually were ignored in past spacecraft designs. Unless efficient design and analysis capabilities are developed for these advanced structures, the engineers will be severely taxed by the modeling, design, and analysis effort.

The purpose of this paper is to describe an efficient computed-aided design and analysis capability which has been developed to relieve the engineer of much of the effort required in the past. Automated capabilities can be used to rapidly synthesize, evaluate, and determine performance characteristics and costs for future large spacecraft concepts. The Large Advanced Space Systems (LASS) computer-aided design and analysis program (ref. 1) is used to illustrate the power, efficiency, and versatility of the approach. Although the LASS capabilities are by no means complete, the program represents an initial effort to use interactive data-processing capabilities and spacecraft-systems-analysis-oriented software to guide the design of future large space systems.

The coupling of space environment modeling algorithms with simplified analysis and design modules in the LASS program permits rapid evaluation of competing spacecraft and mission designs. The approach is particularly useful in the conceptual design phase of advanced space missions when a multiplicity of concepts must be considered before a limited set can be selected for more detailed analysis. Integrated spacecraft systems-level data and data files are generated for subsystem and mission reexamination and/or refinement and for more rigorous analyses.

COMPUTER-AIDED DESIGN AND ANALYSIS CAPABILITIES

LASS Program Overview

The LASS program consists of twenty-some multidiscipline applications modules that include structural, thermal, and control system modeling; on-orbit static, dynamic, and thermal loading analyses; structural element design; surface accuracy analysis and cost approximations. The modules reside on both mainframe (Control Data CYBER 175 computer) and minicomputer (Prime 750 computer) systems. The modules are executable from remote interactive graphics terminals. Data files are transferable between the two computer systems. Processing and data control are accomplished via simple efficient executive and data-base programs and file management routines. User prompts for file names and unformatted data inputs are provided. CRT graphic displays of finite-element models and of summary information (temperature contours, element loading histograms, mode shapes, etc.) are presented to the user for immediate assessment and interactive modification of the spacecraft and/or mission as necessary.

Discussion of Capabilities

The primary LASS modules and basic functions of each module are shown in figure 1. The Aerospace Vehicle Interactive Design (AVID) program, developed by Wilhite (ref. 2), provides executive control and data-base management capabilities for LASS. Additional procedure files and data file management routines reside in the individual LASS modules.

LASS was developed for multidiscipline spacecraft systems analysts as opposed to single discipline specialists or computer systems experts. The executive, data-base/file management routines, and applications modules were selected to provide a rapid, cost effective computer-aided design and analysis capability for future large spacecraft systems concepts. The program is user friendly, prompting the analyst with queries or requests for information such as unformatted input data, file names, and processing paths. The applications modules have been integrated to pass compatible, properly formatted files and data-base information between single discipline programs. The creation, unbundling, and reformatting of data are transparent to the user.

LASS, operating in conjunction with AVID, keeps the user well informed on the status of data in the data base or in the permanent files. Data which were created external to an individual application program are displayed for user modification if desired. Variables missing from the data base are flagged with a nonfatal error message, permitting the user to input the desired values. New input variables not required by previous modules are input or modified by the user at the interactive terminal. Data that are more or less constant for each new case are defaulted in the modules with user override capabilities. Finally, data which are created from an individual application module and required by any subsequent module are written to a properly formatted file for immediate execution by the subsequent module or are reformatted by the later module in a manner which is transparent to the user. Data created on one computer system can be transferred to another computer system for execution of another applications module. For example, files created on the minicomputer can be automatically reformatted and transferred to the mainframe computer for a batch execution of the Structural Analysis Program (SAP). Upon completion of the run, the SAP output files can be accessed on the minicomputer for continuation of the interactive processing session.

Executive Program

The small AVID executive program (50 to 100 lines of coded instructions) allows the analyst to run the applications modules individually or in any desired sequence by menu selection. The menu of spacecraft programs currently available is shown in table I. All modules are set up to run in the interactive mode except for the ones prefaced with the word batch and the static and dynamic structural analysis modules. Note that all batch modules with the exception of the structural analyses modules have an interactive counterpart. Only the structural analyses modules have to be run in the batch mode because of the Langley Research Center 70 000-word memory interactive constraint for the mainframe computers. (Typical structural models analyzed to date require 150K to 200K memory for these modules.) The minicomputer system does not have this constraint.

The interactive design process begins with the user simply entering a string of single characters associated with the desired program sequence. The AVID system then automatically sets up all commands to the computer operating system such as calling sequences, data-base and file attachment, program run commands, and return of the system to user control. This use of executive program capabilities and internal procedure files frees the analyst from details of computer operation and system protocol and lets him concentrate exclusively on the spacecraft design tasks. These automated features also eliminate unnecessary repetitious effort each time the modules are run; thereby, input errors and throughput time are reduced.

Data-Base and File Management Systems

The AVID data-base manager program shown in figure 1 can be used for editing data either on a variable-by-variable basis or for specialized updates of larger quantities of data. In normal LASS operations, this program is not utilized since data base and files are automatically created and updated by the individual applications modules.

LASS uses a combination AVID data-base program and file management routine internal to the various applications modules to create, modify, store, and retrieve data and to transfer appropriately formatted data between the applications modules. Data are stored either in the AVID data base (which is used for single variables or small arrays, up to a total of 1024 variables) or in LASS user nameable permanent files. The LASS file structure showing the required input and output files associated with each applications module is shown in figure 2. LASSDB refers to the database file, all other acronyms refer to permanent file names. Default names are shown also; however, the user may uniquely name any file with a six-character alphanumeric designation. Each module is set up to prompt the user to specify the names of all required input and output files. Files or data-base parameters are updated at the completion of each module if the uder specifies the same name for the output files as for the corresponding input file. If the file names are different then each file is stored separately for later use, modification, or removal by the user.

Normally, it is easier to start a design process with previously created data base and files and simply modify the input variables as needed at the terminal than to start with all zero or default variables and create every input variable anew. This is an effective labor-saving approach particularly in parametric analyses from a given baseline (such as spacecraft size, orbital altitude, material perturbations, and change-out of a single subsystem).

LASS Applications Modules

The Tetrahedral Truss Structures Synthesizer (TTSS), ANALOG, and the General Truss Synthesizer (GTS) modules allow the user to create the finite-element model of the spacecraft structure, design the structural members and hardware components, add the supporting subsystems, and calculate the mass and inertia properties of the spacecraft.

TTSS.- The Tetrahedral Truss Structures Synthesizer module, developed by W. D. Honeycutt of the General Dynamics Corporation, Convair Division, is used to rapidly model flat or curved tetrahedral truss structures and to initially size the structural members. The module automatically generates the nodal geometry; the member connectivity, cross-sectional areas, and masses; and the resultant finite-element model of the structure for a specified dish diameter, shape, number of bays, and a diagonal angle which defines the truss depth. The tetrahedral truss configuraton definition and major hardware components are shown in figure 3(a).

The truss structural members are assumed to be circular tubes, isogrids, or triangular truss struts as shown in figure 3(b). The surface and diagonal members are sized separately for Euler buckling from input material properties and initial loading conditions. Upper and lower surface members are pinned; diagonal elements may be pinned or clamped at the user's option. Structural members can be constrained to minimum material thicknesses and tube diameters so that the column buckling equations will not design members too small for practical use. An option also permits the sizing of the member (diameter and thickness) from user-specified length over radius of gyration and a tube radius over thickness inputs.

The folding hinges, spiders, bearings, and end fittings masses are computed as functions of the structural member diameter. A mesh reflective surface and the support system may be optionally included in the calculations and is automatically distributed at each nodal point on one of the surfaces. The mesh control system, used to maintain contour is computed as a percentage of the mesh weight. A contingency mass is included which is defined as a percentage of the mass of all the structural components.

Forty-five input variables as shown in table II are needed to run TTSS. The module calculates and outputs the mass of the structural components, mesh system and total system; the center of gravity; and mass inertia properties. The displayed outputs also include structural member dimensions, hardware part counts, unit masses, total group masses, mesh area, and configuration packaging dimensions for inward and outward folded deployable surfaces. Uniquely nameable data base and files, including a complete finite-element model of the tetrahedral truss, are created in TTSS for later use in other modules.

In about 5 wall-clock min on the minicomputer, TTSS can detail all 6864 struts of a 32-bay tetrahedral dish of any diameter, curvature, and truss depth, size the structural members, incorporate all joints, pins, hinges, reflective mesh systems, display the output summary data and the structural finite-element model, and write the data-base/file information to LASS retrievable permanent disk storage. An eight-bay case (420 elements) can be completed in 1 to 2 wall-clock min on the minicomputer or in 6 wall-clock min using 27 sec of CP time on the mainframe computer. It should be noted that the use of the minicomputer reduces wall-clock times by factors of 5 to 10 because of the higher data transmission rates provided with this system (9600 baud on the minicomputer versus 1200 baud on the mainframe) and because the modules are not rolled in and out of core as they are in the Langley mainframe computer system during heavy usage periods.

ANALOG.- The ANALOG module is a preprocessor for TTSS and permits a large number of tetrahedral truss members in a flat platform or curved dish truss to be replaced for analysis by a smaller number of equivalent members, as illustrated in figure 4. The approach and transformation equations, developed by Leondis (ref. 3), are based on the use of a set of Constitutive Relations (stiffness characteristics) for repeating platelike lattice structures such as a tetrahedral truss. Member sizes and geometry, physical properties, and loads are transformed in such a manner as to retain the equivalent strength, stiffness, mass, inertia, and thermal characteristics of the original structure. The original dish diameter and truss depth are retained in the analogous model. The analogous modeling capability is particularly useful for rapid parametric analyses. For example, a single pass through all the LASS modules for a spacecraft with an eight-bay dish (121 nodes, 439 elements) required 5 min of CP time - including CP times of 62 and 159 sec, respectively, for the structural analysis program static and dynamic (15 modes) solutions. This case required 1 1/2 wall-clock hr of interactive processing time on the mainframe computer during a relatively busy period of the day. In contrast, the 16-bay case (421 nodes, 1723 elements) required 30 min of CP time (SAP static and dynamic CP times of 275 and 759 sec, respectively) and would require about 8 wall-clock hr. Yet, the spacecraft mass, inertias, center of gravity, and center of pressure agreed to within 1 percent for the two cases.

GTS.- The GTS module is used to complete the definition of the spacecraft structure, materials, and supporting subsystems. Required inputs include dish data files from TTSS; added structural members and connectivity, member design loads; subsystem locations, masses and areas; and mesh blockage factor. Outputs include the design of the added members, a finite-element model of the total spacecraft; an atmospheric drag approximation model; and updated mass, inertia, center-of-gravity, and center-of-pressure properties. The mass per unit area of all elements needed for the thermal analysis is also generated in this module. For 10 to 100 added elements, mainframe central processing times of 2 to 10 sec are typical for GTS. Nominal wall-clock times of 10 min are required for the addition of 10 to 20 elements and subsystems. However, throughput times can vary significantly depending on the number of elements and associated descriptors which the analyst must key in from the terminal. GTS can also be used to create spacecraft designs from keyboard input when no tetrahedral truss structure is desired. Alternatively, finite-element model data formatted by external structural analysis programs can be preprocessed and read directly into GTS to save labor and time.

RCD.- The Rigid-Body Control Dynamics (RCD) module calculates the on-orbit environment and maneuver forces and torques at user-specified circular orbital altitude and spacecraft orientation. It then determines the momentum storage and desaturation requirements, and iterates the masses of the control systems, propellent, and tankage to meet the orbit-keeping, attitude control, and maneuver requirements of the spacecraft. Principal features of RCD are shown in figure 5. The total torque and force time histories are analyzed to determine cyclic momentum for momentum exchange system sizing and accompanying momentum desaturation requirements. Momentum desaturation is accomplished by reaction control system (RCS) thrusters. RCS requirements for orbit keeping are also determined. Finally, RCS requirements are computed by assuming RCS control in lieu of the momentum exchange plus desaturation systems. Technical capabilities for this module were provided by Chiarappa and Eggleston (ref. 4). References 5 and 6 also provide supporting information on satellite drag and referenced atmospheric data.

Spacecraft mass, inertia, areas, and centers of gravity and pressure are input from GTS created files. Those parameters are updated in RCD in accordance with the momentum exchange and propulsion systems sizing and mass computations. A total of 34 addition input variables (shown in table III) plus a thruster force matrix are needed to run RCD. Input categories include orbital parameters; spacecraft orientation (inertial or Earth oriented), maneuver requirements, and pointing accuracy; control devices and thruster locations and characteristics; and propellant resupply periods. An arbitrary number of RCS thrusters may be located at multiple nodes. The thrust level and direction for each individual thruster is user specified. The program assumes that individual thrusters can fire in either a positive or negative direction along one of the principal axes. RCD executes in less than 1 min CP time and 15 min wall-clock time on the mainframe computer for three iterations on control system and propellant masses.

SAP static.- The static-load-carrying capabilities and internal stresses in the individual structural members are evaluated in the Structural Analysis Program (SAP) (ref. 7), which was originally the work of Edward L. Wilson of the University of California at Berkeley, and the Static Loads (STLO) module. SAP is a general purpose structural analysis program for static or dynamic linear analyses of three-dimensional structural systems. SAP static calculates nodal displacements and rotations and member forces and internal stresses. The calculations are performed for up to five separate load conditions and for the linear combination of all loads acting simultaneously. However, the program requires loading inputs to perform the analyses which are provided by the STLO module.

STLO.- The STLO module operates in two parts. STLO, part 1, collects all the appropriate static loads data in a properly formatted file, STAMOD (fig. 2), for SAP and generates environmental and spacecraft induced loads for five loading conditions: (1) pretension, (2) thermal, (3) gravity gradient, (4) atmospheric drag, and (5) static thrust. The structural finite-element model is included in the STAMOD file. Inputs to STLO, part 1, include a full description of the mass points for the gravity gradient computations from the DYML file, the projected area approximations for the atmospheric drag loads from GTS and RCD files, the isothermal member temperatures from the Thermal Analysis module and thrust and pretensioning forces. Following the SAP run, STLO, part 2, outputs summary data of the actual loads on the structural members, compares them to the design loads, and permits the user to redesign the members if the actual loads differ considerably from the design loads. If many members are poorly designed, the user can instruct the program to recycle through the appropriate TTSS and/or GTS modules with the updated design loads and revise the member sectional areas. If the spacecraft mass and inertia properties are significantly modified, the RCD module can redefine the control system requirements. Continuous iterations can be performed under user control until a satisfactory solution is obtained for the structural loads; member sizes; spacecraft mass, inertia, and drag properties; and the control system requirements. At any step in the design and analysis process, the user may decide that he has a poor design and may revise the design or change subsystems (which may be either current space-qualified hardware or advanced technology subsystems) and continue with the design process.

STLO executes in less than 10 sec CP time and 15 wall-clock min on the mainframe computer for 439 elements and 5 loading conditions. For 5 static loads, SAP static executes on the mainframe computer in 62 sec CP time for an 8-bay dish (420 members) and 275 sec CP time for a 16-bay dish (1704 members).

TA.- If thermal loads are to be included, the Thermal Analysis (TA) module is used to compute the radiation equilibrium temperature for each structural element at a given position in the spacecraft orbit. Technical capabilities for the module were developed by G. A. Howell of the General Dynamics Corporation, Convair Division, from the original work of Ballanger and Christensen (ref. 8). Heat sources are solar radiation, Earth albedo, and Earth radiation. The thermal response of each element is determined from the balance between absorption of energy from the three heat sources and reradiation of energy from the elements to deep space. The position of the elements relative to the Sun and the Earth are varied at 36 intervals in the orbit. Earth shadowing is included. The elements may be single or double shadowed by a translucent mesh. There is no radiation exchange or conduction between elements and no shadowing of elements by other elements. Inputs to TA include the thermal properties of the elements and mesh transmissivity constants; the finite-element geometry and unit area data files from GTS and/or RCD; and Sun-Earth-spacecraft geometry inputs from RCD. Outputs include the temperature of each element at a user-specified location in orbit, temperature contours of the dish upper and lower surface elements, and a temperature file TATMPS. Since one isothermal temperature is computed per element, the thermal model is completely compatible with the structural finite-element model. Temperatures for each element are read into STLO from the TATMPS file for use in conjunction with SAP for the generation of thermal loads and deflections. For 439 members, evaluated 12 min apart in the orbit, TA executes in 16 sec CP time and about 10 wall-clock min.

SA.- Performance must also be factored into the design evaluation process. For example, for large-aperture systems, surface distortions, boresight offset, and defocus are important parameters leading to the establishment of RF antenna or solar concentrator performance and figure control requirements. The LASS Surface Accuracy (SA) module establishes these first-order effects on performance. SA computes the overall surface roughness (rms displacement), lines of constant derivation from an ideal surface (distortions) and changes in focal length, boresight direction, and boresight displacement for reflective surfaces. The SAP static module files supply SA with the finite-element model data for all original and statically displaced node point locations. SA plots the local normal displacement and distortion contours for the mesh surface nodes. The shapes of surfaces available are parabolic, spherical, or flat.

It should be noted that most spacecraft are free-free structures which must have nonredundant translational constraints for purposes of static analysis. The STLO module has been coded to automatically provide nonredundant constraints at three node points on opposite corners of the dish structure (one node restrained in x, y, and z, one node clamped in x and z, and one node clamped in z only) to arrive at static loads. The calculated loads and stresses are valid for the real free-free spacecraft; however, resulting static deflections at individual node points are sensitive to the method of restraint and the nodes which are restrained. The Surface

Accuracy program is used to convert the artificially constrained nodal deflections into distortions that are independent of the constraints.

SAP dynamic.- In the LASS program the SAP Dynamic Analysis module is used to generate modal frequencies, normalized deflections, and associated generalized forces and stresses. The deflections are normalized to unit generalized mass. All appropriate dynamic analysis data accumulated from the structural synthesizer and other analysis modules are combined in a properly formatted input file (DYML) for the SAP Dynamic Analysis module. An automated eigenvalue shift procedure has been employed in LASS to overcome most numerical instability or singularity problems associated with rigid body modes (normally there are six of these zero roots for three-dimensional structures). SAP outputs data on the number of nodes requested by the user, including the first six rigid body modes which are nearly equal to zero. The remaining seven to N modes correspond to the flexible body modes for the linear system. A postprocessor has been added to the LaRC version of LASS to scale and plot flexible body mode shapes for the spacecraft structure. SAP Dynamic executes on the mainframe computer in 159 CP sec for an 8-bay case for 15 vibrational modes and 109 nodes with three degrees of freedom each. A corresponding 16-bay case with 409 nodes executes in 797 CP sec.

DYLO.- Other capabilities of LASS include the Dynamic Loads (DYLO) module developed by Leondis (ref. 1) to provide dynamic deflection data at node points and dynamic loads on each member. Inputs include the flexible body modes from SAP dynamic, the finite-element files (DYML), and user-specified transient force functions and structural damping characteristics. The use of active damping systems can be evaluated in this module.

POST.- The Postprocessor (POST) module converts data from the analogous model form used for internal program computations to equivalent real model form. POST outputs summary data of overall spacecraft mass, size, and inertia, and individual subsystem components (types, number required, dimensions, and masses). The number and masses of fittings, pins, bearings, and connectors; mesh system masses; and spacecraft mass contingency are also outputs. The module runs in less than 1 sec CP time and 2 min wall-clock time.

COST.- Developmental and first-unit costs are computed in the COST module principally from cost-estimating relationships. Subroutines calculate costs associated with large space structures comprised of many structural members of various types of materials and design complexity. Spacecraft subsystem costs are approximated from subsystem masses or performance. Shuttle launch costs are based on both spacecraft/subsystem mass and on packaging volumes. On-orbit construction costs may be estimated from user inputs on construction time and crew size. All costs estimating relationships are in 1976 dollars; however, total costs are updatable to any subsequent year with appropriate inflation factors.

Selected Mission and Spacecraft Design Details

The capabilities of the LASS program to deal with the multidiscipline aspects of spacecraft preliminary design are illustrated by examples in the design, analysis, and parametric evaluation of an advanced spacecraft - the passive microwave radiometer spacecraft (MRS) designed to perform soil moisture measurements from low Earth orbit.

Microwave Radiometry

Passive microwave radiometry technology can be applied in remote sensing soil moisture applications to support crop forecasting (ref. 9). It is preferable to monitor at microwave frequencies (<5 GHz) in order to penetrate clouds, haze, and ground cover. A large-aperture, smooth-surface antenna is required to capture and focus the low-signal-level Earth radiation on the sensors. The concept of passive microwave sensing (ref. 10) is depicted in figure 6. The resulting measurements are brightness temperatures which are functions of soil ambient temperatures and emissivity, where the emissivity is strongly dependent on the soil dielectric properties or the water content in the soil (to a depth of about 25 cm). The combination of antenna size and orbit altitude can be varied to meet the 1-km resolution requirements (i.e., the smaller the antenna size the lower the altitude but the higher the propellant mass requirements for long-duration missions). Missions and spacecraft systems requirements are summarized in table IV.

Spacecraft Details

The MRS structure and supporting systems are shown schematically in figure 7. The structure consists of a relatively stiff double-layered tetrahedral truss dish (graphite/epoxy composite structural members) with an RF reflective mesh (aluminized Du Pont Kapton with a unit mass of 0.03 kg/m^2) attached to offsets on the concave surface. Support beams (graphite/epoxy composite) and tension cables (Du Pont Kevlar) provide stabilization and boresight control for the feed horns mounted on a curved beam located at the focal arc of the reflector. The spacecraft dish points toward nadir with the feed beam oriented normal to the spacecraft velocity vector.

Attitude control is provided by a dual-ring Annular Momentum Control Device (AMCD) and eight 1-N liquid oxygen/liquid hydrogen thrusters. The AMCD rings are magnetically supported in races at the outer periphery of the convex surface of the dish to provide pitch, roll, and yaw control as illustrated in figure 8. Orbital velocity makeup is provided by four larger liquid oxygen/liquid hydrogen thrusters. Two are located on the dish structure to provide 1500 N thrust each and two are located at the extremities of the feed beam to provide 500 N thrust each. Three propellant tanks are located on the convex side of the dish in a triangular arrangement at thre three center-most nodes. Other subsystems included in the analysis are shown in figure 7.

Three-year propellant resupply periods are assumed in the analysis. AMCD tip speeds of 200 m/sec which are within the strength capabilities of applicable materials were used. The spacecraft is assumed to undergo one maneuver every five orbits with maneuver rates and accelerations of 10^{-4} rad/sec and 10^{-6} rad/sec^2, respectively. AMCD desaturation is once every orbit.

Microwave Radiometer Spacecraft Study Results

Parametric Analysis

Spacecraft size and mass are significant contributors to the overall cost and performance of large advanced spacecraft systems. The orbital attitude and antenna size of MRS can be varied over wide combinations of values and still meet the 1-km resolution requirements of the mission. For example, a 400-m-diameter spacecraft operating at an altitude of 400 km will provide the same resolution as a 1000-m-diameter spacecraft at an altitude of 1000 km. The smaller spacecraft will require significantly less structural mass but additional propellant for orbital velocity makeup because of higher atmospheric drag. A parametric analysis was conducted by using the LASS program to establish altitude and size combinations which would yield the minimum total spacecraft mass. The results are shown in figure 9. An optimum MRS antenna size around 750 m and an orbital altitude of 750 km is indicated. At the lower altitudes, the spacecraft mass is dominated by the propellant mass required to maintain orbital velocity. At the higher altitudes, the structure and the reflective antenna mesh masses become dominant.

Optimization studies of future spacecraft must include consideration of many advanced subsystems in the overall design if the potential performance, costs, and benefits of large systems are to be established. For example, additional control system options may be available to the MRS in the future. These include higher-specific-impulse electric-thruster systems which may be used in combination with, or in lieu of, the AMCD system. Results of such control-systems trade-offs are shown in figures 10 and 11.

These results and other data presented herein are used principally to reinforce the premise that rapid analysis and evaluation capabilities such as those provided by the LASS program are needed prior to the initiation of the expensive, time-consuming preliminary and final design processes.

Another labor-saving feature incorporated into the LASS program is the automated computation of effective drag areas for lattice structures with porous reflective antenna mesh. This process is generally lengthy and time-consuming. However, it is mandatory that this be an input for computation of orbital propellant requirements. In single discipline analyses, the structural analyst may have no need for these areas and the aerodynamicist is sometimes faced with the formidable task of generating these data for various structural elements and orientations from design drawings. Drag areas can range from a low percent of the solid spacecraft area in the direction of the velocity vector up to multiples of solid area depending on such factors as the spacecraft size and orientation and the type and quantity of structural members. Leondis (ref. 1) has provided a capability in the LASS program to rapidly accumulate these areas from the model data created in ANALOG, TTSS, GTS, and RCD. The atmospheric drag area approximation approach is illustrated in figure 12. Each node, which consists of the intersection of several structural members at various orientations, is reduced from the finite-element model to an equivalent solid structural area normal to the spacecraft velocity vector. The blockage effects of upstream areas on downstream areas are factored into the solution. In addition, the program will incorporate the drag effects of the variable transmissibility mesh into the solution from user-specified inputs on the porosity of the reflective mesh and the orientation angle at which mesh appears solid to the incident molecules. Solid areas of supporting subsystems (such as solar arrays) are included. The resulting outputs are effective drag areas of the spacecraft in the x-, y-, and z-directions. These areas plus center-of-gravity and center-of-pressure offsets required for the control system solution are automatically read into the RCD module from the GTS module. The solution is integrated over 60 points in the circular orbit. (Note: the effective drag areas are continuously changed for inertial-oriented spacecraft whereas for the nadir pointing spacecraft, the X-, Y-, and Z-areas remain constant throughout the orbit.) For the MRS baseline case, the effective drag area was approximately 55 percent of that for the solid area of the spacecraft in the orbital velocity direction.

Static Loads Analysis and Structural Member Design

All MRS structural members were analyzed and designed in LASS to accommodate the on-orbit environmental loading conditions and the self-imposed loads created by the tension cables and static thrusters. The dish structural members were hollow tubes, tension cables were solid rods, and feed/feed support beams were triangular truss struts. All members, except the tension cables, were sized to accommodate combined Euler buckling axial loads and bending-moment loads. Loads created by bending moments were reduced to stress equivalent axial forces in the analysis. Histograms of the combined static loads (atmospheric drag, gravity gradient, static thrust, thermal, and pretensioning) on the various structural members are given in figure 13 for the 750-m-diameter MRS baseline case. The internal load levels and the number of structural members have been converted back into the 16-bay real model in accordance with the transformations developed in reference 3. These real-to-analogous model transformations approximate the general distribution of internal loads in the real structure.

The surface members and the diagonal members were designed to carry the maximum load experienced by any individual member in that class. However, it is apparent from the load histogram distribution in figure 13 that use of a design load for the lighter loaded members would significantly reduce spacecraft structural mass and control system requirements. If the members are selectively designed as per the load histogram distribution, the masses of the dish structure and the control system could be reduced by 50 percent or more.

Additional spacecraft mass savings could be realized if alternative concepts from tension cables are developed to boresight the dish and feed beam. The results of the loads analysis revealed that the structure is loading itself via the tension cables and all environmental loads are relatively small in comparison (about 1 to 10 orders of magnitude lower). In descending order of importance, the net load on the structural elements for the MRS baseline case were contributed by

(1) Pretensioning

(2) Static thrust for orbital velocity

(3) Thermal

(4) Gravity gradient

(5) Atmospheric drag

The contributions of various load conditions are illustrated in figures 14 and 15 for the three-load case (thermal, gravity gradient, and atmospheric drag) and for thermal load only. Note that there is little change in the loads levels or distribution from the thermal-only case to the three-load case. Changes in orbit altitude, spacecraft orientation, and orbit location (for thermal) would change the relative ranking of these loads.

Thermal Analysis

Thermal loads on the individual elements will vary throughout the orbit and it is not generally known a priori where in the orbit the loads reach the maximum. However, some insight on maximum thermal loading can be gained by calculating element temperatures and temperature differentials at selected orbital points. In this study, heating rates and temperatures of each MRS structural element were calculated in the LASS Thermal Analysis (TA) module at four points in the orbit:

Point a: Orbit anomaly angle = 1.5 rad
Time = 0.40 hr (just prior to S/C entry into Earth shadow)

Point b: Orbit anomaly angle = 3.7 rad
Time = 0.98 hr (just prior to S/C exit from Earth shadow)

Point c: Orbit anomaly angle = 3.9 rad
Time = 1.03 hr (just after S/C exit from Earth shadow)

Point d: Orbit anomaly angle = 5.8 rad
Time = 1.53 hr (midway in Sunlight portion of orbit)

Start and end of Earth shadow were at anomaly angles of 1.6 and 3.8 rad (time of 0.4239 hr and 1.005 hr), respectively. The orbit period was 1.667 hr at the 750-km altitude. Summary results in the thermal computations for each point are given in table V where the maximum and minimum temperatures of the various elements are shown.

Element temperatures for point c (just after exit of the spacecraft from Earth shadow) were selected for use in the static loads analysis. This point was selected on the combined basis of near maximum temperature difference between elements and relatively low temperatures for all the elements. Thermal loads for some of the individual elements were more than an order of magnitude below the pretensioning loads and were not significant enough to warrant a more detailed examination. However, for other spacecraft which are not self-loading, the thermal loads could become a significant design consideration. Selected thermal contours for dish members oriented in the same direction are shown in figure 16. The solid lines denote the structural members for which the temperature contours are applicable. Similar contours are also plotted for both concave and convex surface members oriented in the other directions. The contours aid the analyst in rapidly visualizing approximate temperature ranges and distributions for the entire structure and is preferable in the interactive analysis to review of temperature printouts for hundreds of members.

Surface Accuracy

Contours of the MRS surface distortions of the structural nodes on the mesh side of the dish are shown in figure 17. The deviation from a perfect spherical segment are caused principally by the structural loadings from the tension cables. MRS surface roughness of 6.6 cm exceeds the 6-mm accuracy requirements by an order of magnitude. However, these distortions are principally affected by the cable tensioning (note the near symmetry of contour patterns about the X- and Z-axes). Thus, it is expected that predesign of the surface (i.e., tailored mesh offsets) to yield a spherical mesh surface which, when under tension, will reduce the effective large-scale distortion error to acceptable millimeter levels.

Defocus and boresight offset data for the dish are also presented in figure 17. The surface is drawn inward (toward the feed) an average of 1.1 cm. More significant, the tension cables draw the feed toward the dish by 22 cm for an overall defocus distance of 23 cm. The boresight offset between the dish and feed is about 25 cm. This translates into a ground-track pointing-location error for the dish of about 300 m which is within the 1-km resolution accuracy band. Proper predesign of the preloaded antenna structural members should significantly reduce the defocus and boresight errors for the MRS spacecraft.

If the tension cables are eliminated, the structural surface distortions caused by environmental effects (thermal, gravity gradient, and atmospheric drag) are reduced more than an order of magnitude and meet the 6-mm surface accuracy requirements as shown in figure 18. Defocus and boresight errors are reduced commensurately.

Dynamic Analysis

The lowest natural vibration frequencies for each of three MRS spacecraft sizes range from 0.04 to 0.09 Hz and are listed in table VI. These frequencies are far below the design capabilities of space-qualified controllers/actuators and will require innovative control concepts and much more detailed analysis. Also shown is the fundamental frequency of a 725-m-diameter dish which is an order of magnitude higher than the spacecraft with the attached feed system. Selected mode shapes for the MRS baseline are shown in figure 19. These figures were generated in the Interactive Plotting module from SAP dynamic solutions. Although this study did not address minimum vibrational frequency or flexible-body control system requirements for the MRS, it should be noted that the triangular truss beams could be replaced with somewhat stiffer structural elements to provide moderate increases (possibly a factor of 2 or 3) in the lower order frequencies. However, even with technology advances in stiff, lightweight materials and structural design concepts, it is likely that these low frequencies and possibly high-amplitude vibrations will be typical of large future systems.

CONCLUDING REMARKS

Capabilities, performance, and advantages of a systems-oriented interactive computer-aided design and analysis system have been presented. A single user at an interactive terminal can create, design, analyze, and conduct parametric studies of Earth-orbiting spacecraft with relative ease. The approach is shown to be particularly useful in the conceptual design phase where various missions and spacecraft options are to be evaluated in a cost-effective, timely manner.

The Large Advanced Space Systems (LASS) computer-aided design and analysis program was developed specifically to provide spacecraft system analysts with the interactive capabilities to rapidly analyze and evaluate spacecraft performance across several disciplines. The primary technical emphases are on structures, thermal analyses, and controls. Simple and efficient executive, data-base, and file management systems relieve the analyst of much of the tedium associated with computer system command protocol and formatted data inputs, reduce possibilities for input errors, and greatly increase throughput capabilities. Extensive graphical displays let the analyst rapidly evaluate the results, make timely design changes, and continue in the interactive processing mode.

An example problem of a large microwave radiometer spacecraft in low-Earth orbit has been used to illustrate current capabilities of the interactive LASS program. Output results of the MRS study include optimized spacecraft mass, establishment of propulsion and control system sensitivities to current and advanced subsystems, optimized structural design, quantification of spacecraft loads and environmental effects on antenna performance (surface accuracy), and definiton of structural dynamics.

The interactive design and analysis capabilities for advanced spacecraft systems are by no means complete; however, the LASS program represents a substantial start in that direction. The program demonstrates that rapid modeling, analysis, and design of integrated spacecraft can be accomplished with user interactive computer-aided design software. Spacecraft redesign is easily accomplished and baseline designs can be altered in an orderly manner for subsystem and mission design trades. Top-level systems data are available to discipline analysts for subsystem reexamination and/or refinement and for more rigorous analysis.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
November 12, 1981

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TABLE I.- LASS MENU

[Input letter(s) of program(s) to be executed]

```
A - AVID DATA MANAGEMENT PROGRAM - AVID DMP
B - LASS PREPROCESSOR - ANALOG
C - TETRAHEDRAL TRUSS STRUCTURE SYNTHESIZER - TTSS
D - GENERAL TRUSS SYNTHESIZER - GTS
E - RIGID-BODY CONTROL DYNAMICS - RCD
F - THERMAL ANALYSIS - TA
G - STATIC LOADS - SL
H - STRUCTURAL ANALYSIS PROGRAM (STATIC,DYNAMIC) - SAP
I - SURFACE ACCURACY -SA
J - ACTIVE DAMPING - ACTD
K - DYNAMIC LOADS - DL
L - LASS POST PROCESSOR - POST
M - LASS COST PROGRAM - COST
N - EXIT LASS PROGRAM
O - BATCH TTSS
P - BATCH RCD
Q - SYSTEM DESIGN AND COST MODULE - SDCM
R - BATCH GTS
S - GENERAL TRUSS SYNTHESIZER (NON-DISH)
T - BATCH TA
U - INTERACTIVE MODE PLOTTING MODULE
V - BOX RING AND POST PROCESSOR
```

TABLE II.- LASS INPUT VARIABLES

```
 1  RFDM   -RADIO FREQUENCY DIAMETER (METERS)
 2  SHAPE  -SHAPE FLAG  1-PARABOLA, 2-SPHERE, 3-FLAT
 3  FOVERD -FOCAL LENGTH TO RF DIAMETER RATIO
 4  NBAYS  -NUMBER OF BAYS IN REAL DISH STRUCTURE
 5  ANBAYS -ANALYSIS NUMBER OF BAYS
 6  THETA  -DIAGONAL ANGLE TO SURFACE (RADIANS)
 7  SODM   -MESH STAND-OFF DISTANCE (METERS)
 8  MOUNTF -DISH MOUNTING FLAG: 0-APEX, 1-EDGE, 3-FREE
 9  REMOVF -STRUT REMOVE FLAG: 0-NO, 1-NEW SET, 9-REPEAT
10  NMODE  -NUMBER OF MODE SHAPES (0-NO SAP MODELS)
11  XANACM -X COORDINATE FOR ANGULAR ACCELERATION (METERS)
12  YANACM -Y COORDINATE FOR ANGULAR ACCELERATION (METERS)
13  ZANACM -Z COORDINATE FOR ANGULAR ACCELERATION (METERS)
14  TUBTYP -STRUT TYPE  0-L/R, 1-EULER, 2-ISOG, 3-TRUSS
15  SLOR   -SURFACE STRUT LENGTH OVER RADIUS OF GYR RATIO
16  SDOT   -SURFACE STRUT DIAMETER OVER THICKNESS RATIO
17  SSYMM  -SURFACE STRUT YOUNGS MODULUS (NEWTONS/SQUARE METER)
18  SMINDM -SURFACE STRUT MINIMUM DIAMETER (METERS)
19  SMINTM -SURFACE STRUT MINIMUM THICKNESS (METERS
20  SPCRM  -SURFACE STRUT EULER LOAD FOR DESIGN (NEWTONS)
21  SHAR   -SURFACE STRUT HINGE AREA RATIO
22  SHLR   -SURFACE STRUT HINGE LENGTH RATIO
23  SHMOD  -SURFACE STRUT HINGE MODULUS OR TRUSS LACE MODULUS
24  DLOR   -DIAGONAL STRUT LENGTH OVER RADIUS OF GYR RATIO
25  DDOT   -DIAGONAL STRUT DIAMETER OVER THICKNESS RATIO
26  DSYMM  -DIAGONAL STRUT YOUNGS MODULUS (NEWTONS/SQUARE METER)
27  DMINDM -DIAGONAL STRUT MINIMUM DIAMETER (METERS)
28  DMINTM -DIAGONAL STRUT MINIMUM THICKNESS (METERS)
29  DPCRM  -DIAGONAL STRUT EULER LOAD FOR DESIGN (NEWTONS)
30  DIFROD -DIAGONAL STRUT PIN-ENDED (ROD) FLAG: 0-BEAM, 1-ROD
31  DSSM   -DIAGONAL STRUT SHEAR MODULUS (N/M**2)  USED IF DIFROD-0.
32  SRHO   -SURFACE STRUT DENSITY (KILOGRAMS/CUBIC METER)
33  SSBRW  -SURFACE STRUT BEARING REFERENCE WEIGHT (KILOGRAMS)
34  SEFRW  -SURFACE STRUT END FITTING REFERENCE WEIGHT (KILOGRAMS)
35  SHLACE -SURFACE STRUT HINGE OR LACE DENSITY (KILOGRAMS/METER**3)
36  DRHOM  -DIAGONAL STRUT DENSITY (KILOGRAMS/CUBIC METER)
37  DSBRW  -DIAGONAL STRUT BEARING REFERENCE WEIGHT (KILOGRAMS)
38  DEFRW  -DIAGONAL STRUT END FITTING REFERENCE WEIGHT (KILOGRAMS)
39  DLACE  -DIAGONAL STRUT TRUSS LACING DENSITY (KILOGRAMS/METER**3)
40  UWSTOM -UNIT WEIGHT OF STAND-OFF ( 1 METERS LONG) (KILOGRAMS)
41  SRWM   -SPIDER REFERENCE WEIGHT (KILOGRAMS)
42  UWMESH -UNIT WEIGHT OF MESH (KILOGRAMS/SQUARE METER)
43  UWMCSR -MESH SYSTEM TO MESH ONLY WEIGHT RATIO
44  WTCONT -WEIGHT CONTINGENCY (ALL WEIGHT*(1+WTCONT))
45  MESHBK -MESH ON BACK FLAG  (-1, ONLY IF FLAT) 0-FRONT
```

TABLE III.- RIGID-BODY CONTROL DYNAMICS INPUT

```
 1  H       - ORBIT ALTITUDE (METERS)
 2  INCLIN  - ORBIT INCLINATION (RADIANS)
 3  PSIN    - ORBIT ASCENDING NODE (RADIANS)
 4  TFUEL   - TIME BETWEEN REFUELING (YEARS)
 5  ISP     - SPECIFIC IMPULSE (NEWTON-SECONDS PER KILOGRAM)
 6  CD      - AERODYNAMIC DRAG COEFFICIENT
 7  IE      - ORIENTATION FLAG (= 1. FOR INERTIAL OR = 2. FOR EARTH)
 8  OPSI    - EULER ANGLES (3) DEFINING ORIENTATION OF SPACECRAFT FOR BOTH
 9  OTHETA      INERTIAL AND EARTH.  OPSI IS ROTATION ABOUT THE Z AXIS,
10  OPHI        OTHETA ABOUT THE NEW Y AXIS, OPHI ABOUT X.  (RADIANS)
11  WM3(1)  - SPACECRAFT MANEUVER RATE REQUIREMENT X, Y, Z COMPONENTS
12  WM3(2)      RESPECTIVELY (RADIANS PER SECOND)
13  WM3(3)
14  ALFAM3  - SPACECRAFT MANEUVER ACCELERATION REQUIREMENT X, Y, Z
15     (2)      COMPONENTS RESPECTIVELY (RADIANS PER SECOND SQUARED)
16     (3)
17  NM      - NUMBER OF MANEUVERS PER ORBIT
18  E3(1)   - INERTIAL ATTITUDE ACCURACY REQUIREMENT X, Y, Z COMPONENTS
19  E3(2)       RESPECTIVELY (RADIANS)
20  E3(3)
21  UAS3(1)- UNIT VECTOR ALONG AMCD SPIN AXIS X, Y, Z COMPONENTS
22  UAS3(2)     RESPECTIVELY
23  UAS3(3)
24  GAMMA   - AMCD PIVOT AXIS ANGULAR RANGE (RADIANS)
25  RO      - AMCD UNIT WHEEL RADIUS (METERS)
26  EMA     - RATIO OF TOTAL TO DOUBLE WHEEL MASS
27  KU      - AMCD MASS SIZING PROPORTIONALITY FACTOR (METERS PER SECOND)
28  NORDES  - NUMBER OF ORBITS BETWEEN DESATURATIONS
29  MACS    - MASS OF ACS EXCLUDING AMCD ACTUATION ASSEMBLY (KILOGRAMS)
30  PACS    - POWER REQUIREMENT OF ACS EXCLUDING AMCD SPIN AXIS (WATTS)
31  LM(1)   - MINIMUM LINEAR IMPULSE BIT WHEN CONTROLLING TORQUE,
32  LM(2)       X, Y, Z AXES RESPECTIVELY (NEWTON-SECONDS)
33  LM(3)
34  NRCSGP  - NUMBER OF THRUSTER GRIDPOINTS (= NUMBER OF ROWS IN RCSMAT)
```

TABLE IV.- MRS SYSTEM DESIGN REQUIREMENTS

Frequency, GHz	1.08, 2.03, and 4.95
Resolution, km	1
Antenna aperture, m/beam	300 (nominal)
Total antenna aperture, m	750 (nominal)
Focal length, m	575 (nominal)
Gain, dB	70
Surface accuracy, mm	6
Orbit altitude range, km	400 to 1000
Nominal orbit altitude, km	750
Orbit inclination	60° and Sun synchronous
Lifetime, yr	15 with 3 resupply
Pointing accuracy, deg	0.01
Slew rate, deg/sec	0.060
Data rate, bps	$\approx 30 \times 10^6$
Power, kW	10
Launch system	Shuttle transportation system

TABLE V.- MEMBER TEMPERATURES

Point	Maximum/minimum temperature, K, for -					
	Concave surface (mesh side)	Convex surface	Diagonal	Feed beam	Feed support beam	Tension cables
A	312/232	312/237	312/236	313	312/308	310/286
B	191/183	184/183	179/176	191	179/179	180/180
C	251/201	264/196	255/214	267	261/256	262/229
D	332/324	328/324	325/300	321	298/271	301/275

TABLE VI.- LASS DYNAMIC ANALYSIS FOR FIRST NATURAL VIBRATIONAL FREQUENCY

MRS antenna diameter, m	First elastic frequency, Hz
400	0.09019
750	.0560
1000	.04191
Dish only (725 diam.)	.6255

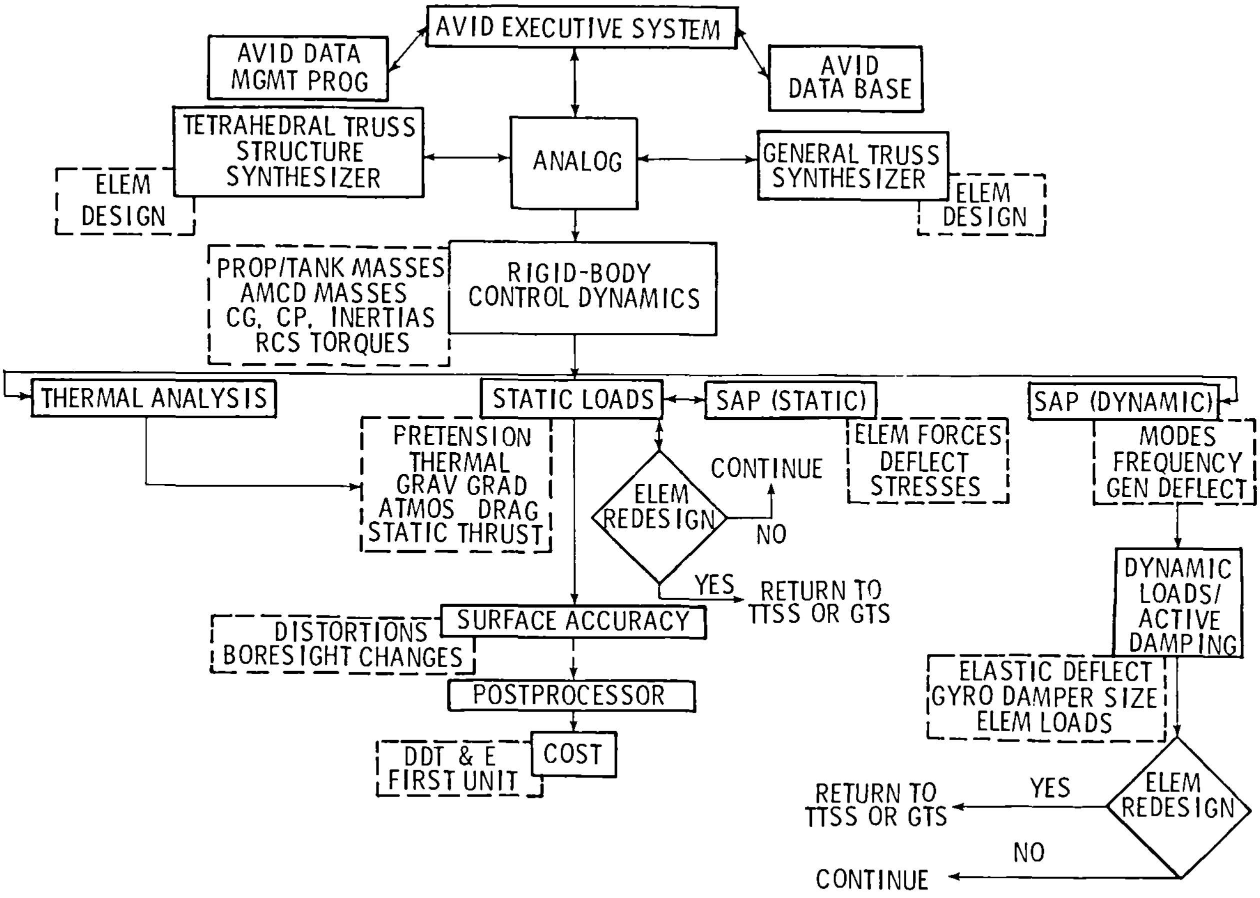


Figure 1.- LASS computer program flowchart.

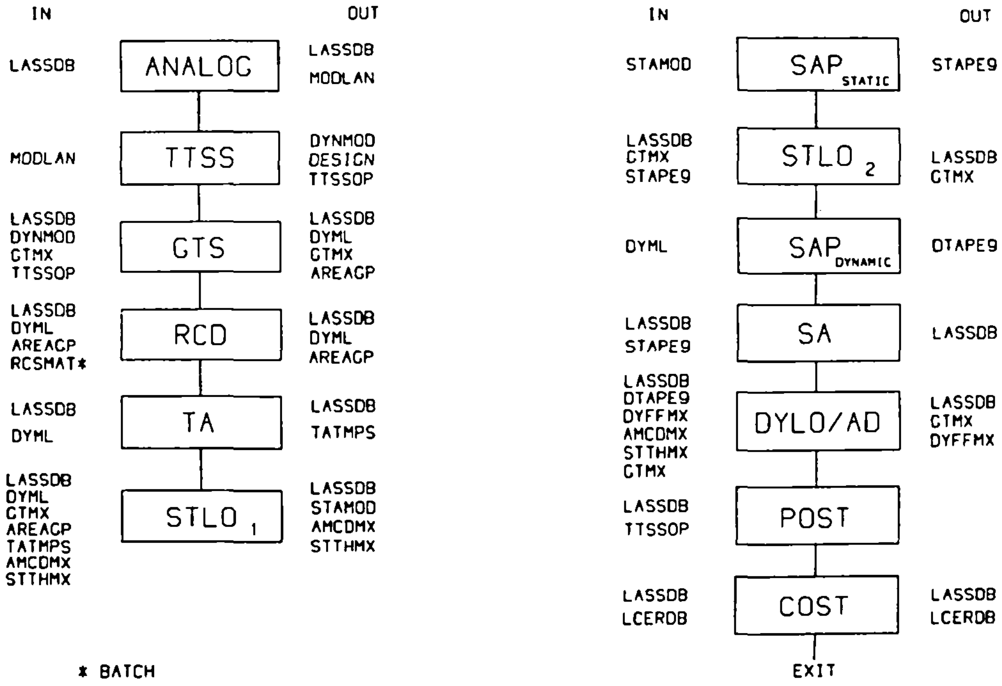
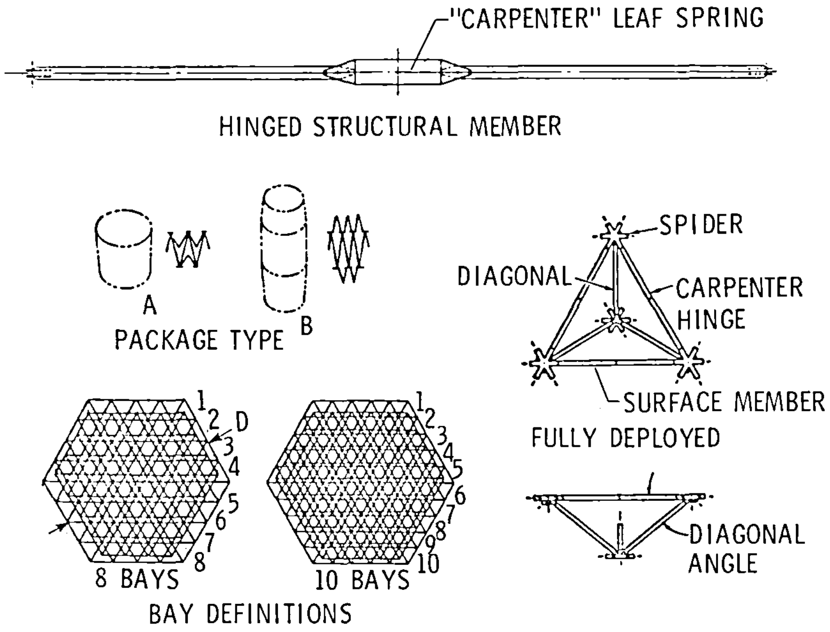
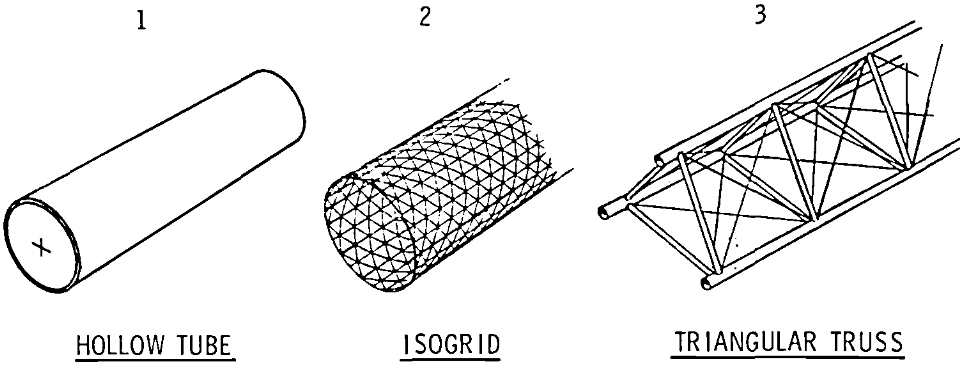


Figure 2.- File structure of LASS.



(a) Configuration definition.



(b) Structural member types.

Figure 3.- Principal features in TTSS module.

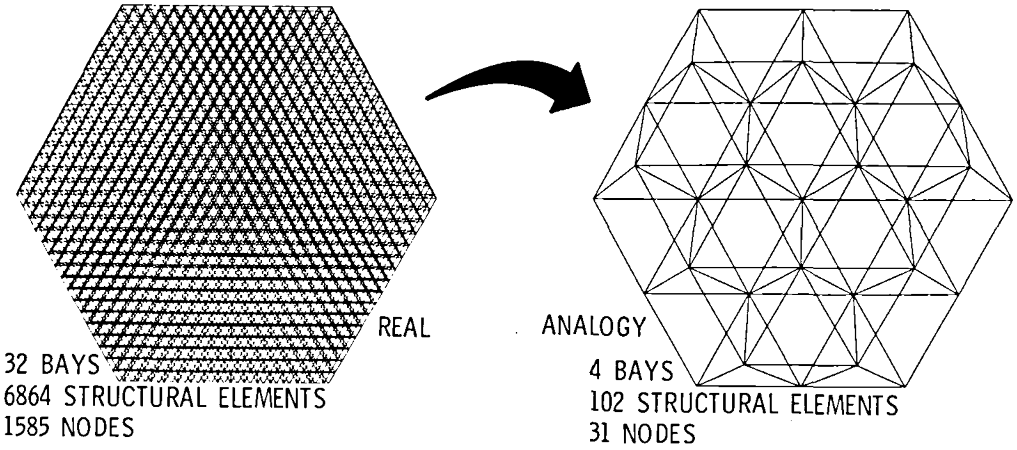


Figure 4.- Analogous modeling concept.

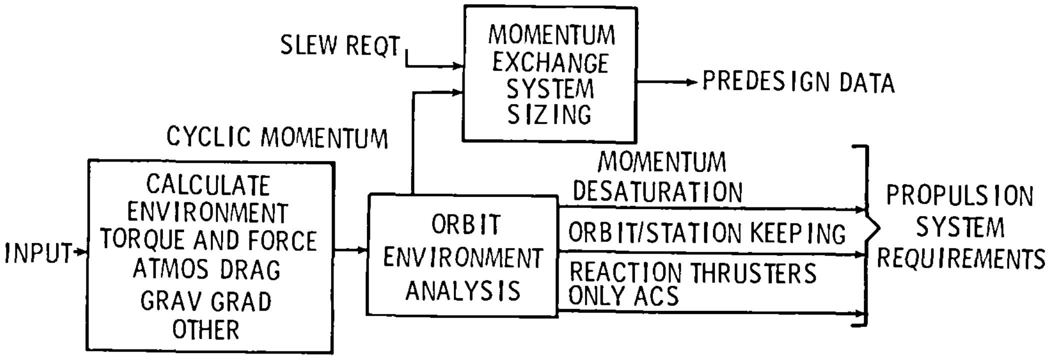


Figure 5.- Rigid-body control dynamics module.

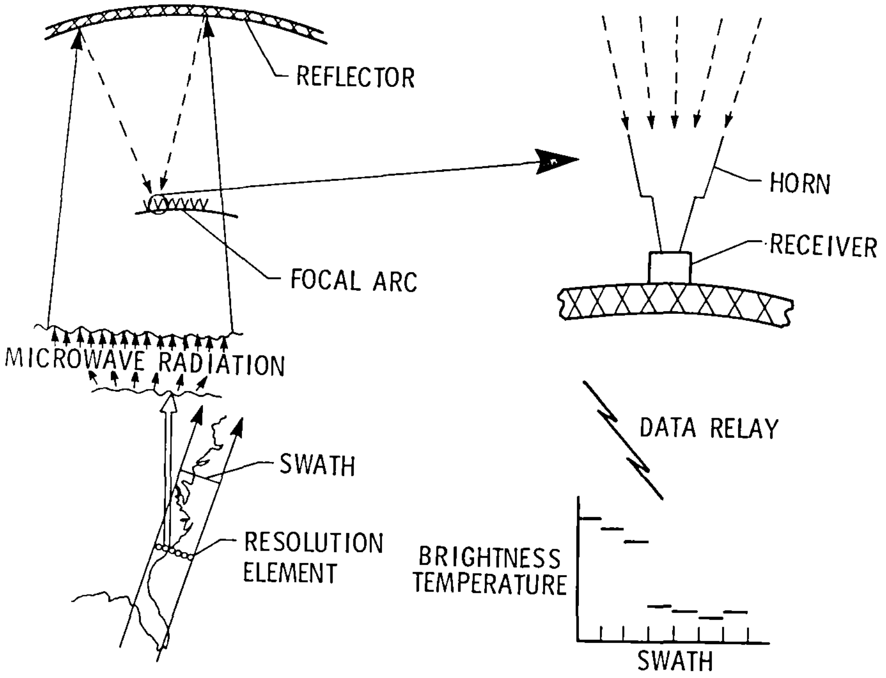


Figure 6.- Microwave sensing concept.

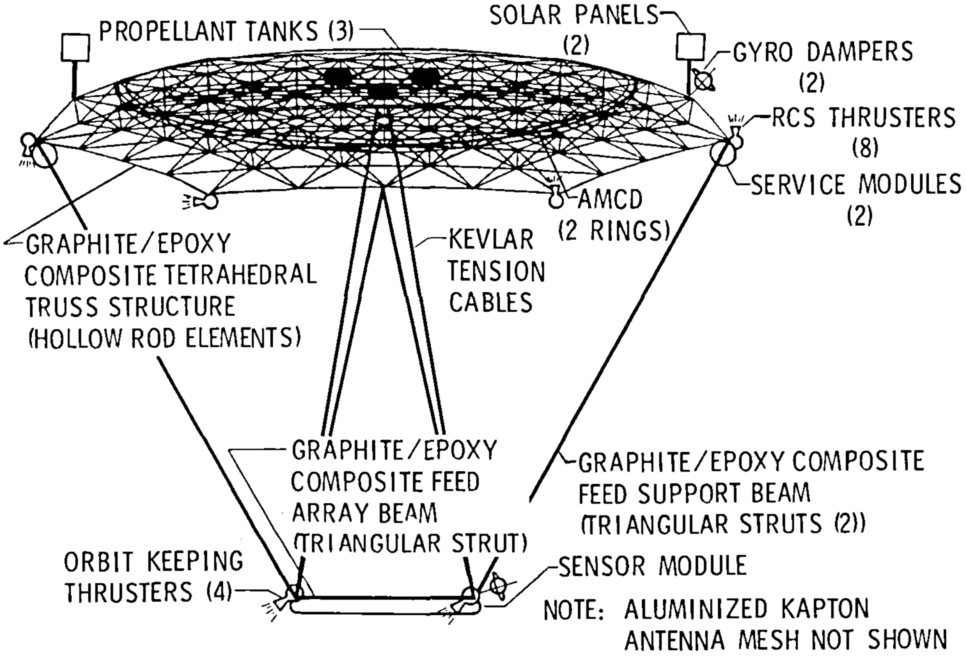


Figure 7.- Microwave radiation spacecraft.

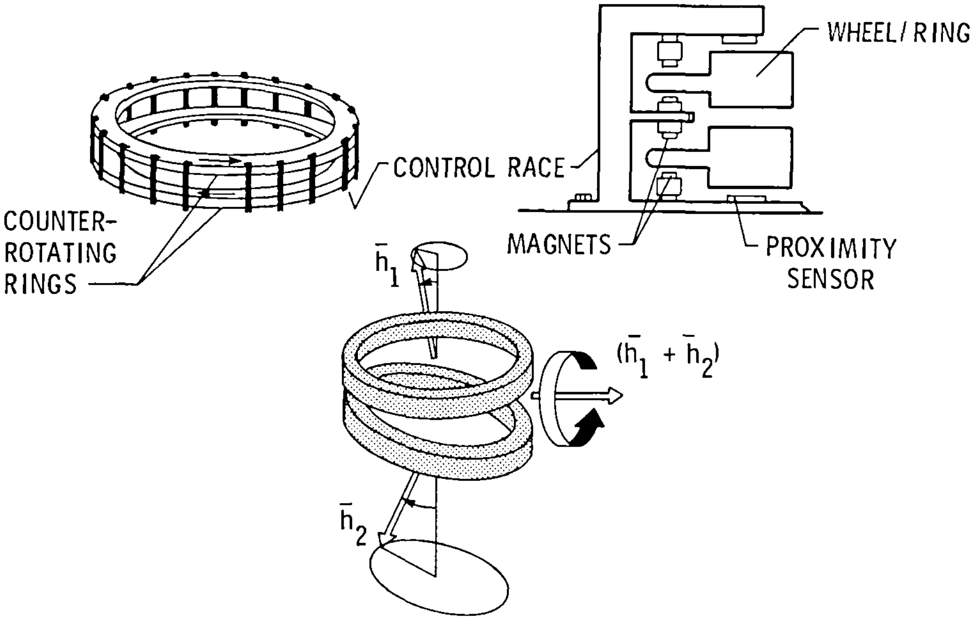


Figure 8.- Dual-momentum vector control concept.

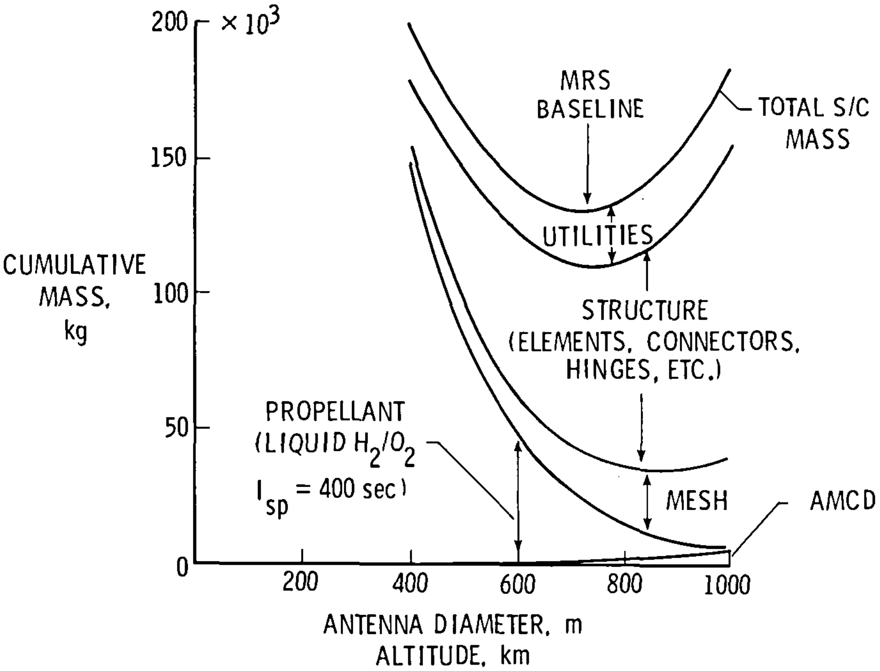


Figure 9.- MRS mass optimization.

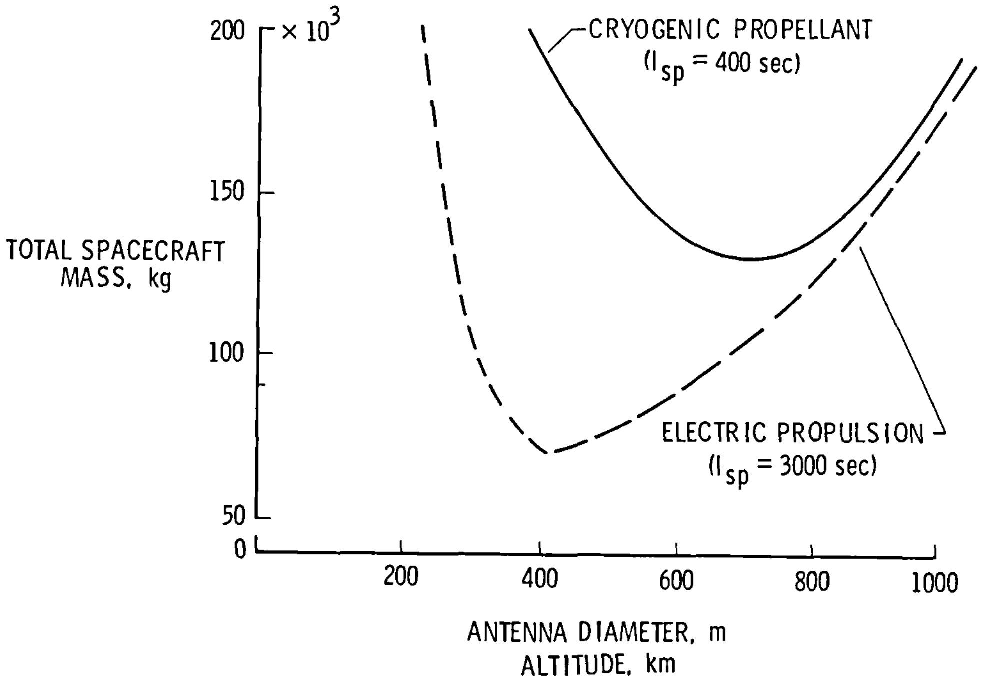


Figure 10.- Cryogenic versus electric propulsion options.

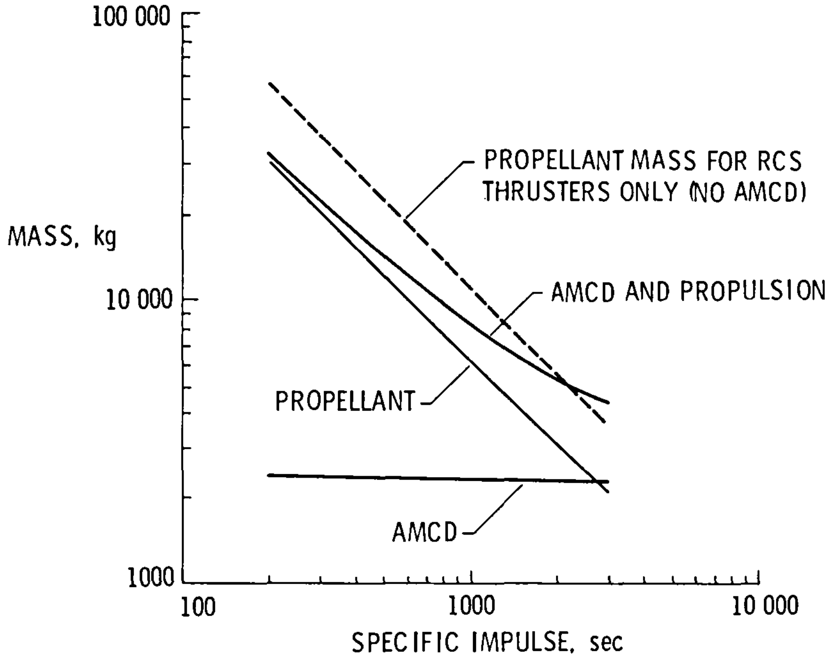
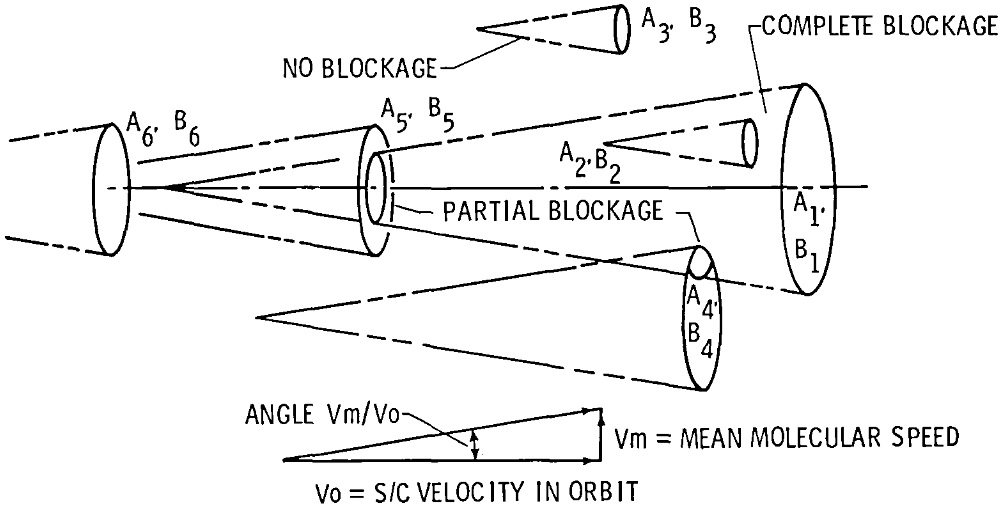


Figure 11.- MRS control subsystems trade-off. 750-m diameter; 750-km altitude; 3-yr propellant resupply.



EACH NODE POINT REDUCED TO EQUIVALENT CIRCULAR AREA
EACH AREA HAS A BLOCKAGE FACTOR, B (= 1 IF SOLID)
MASKING AREAS REDUCED IN PROPORTION TO DOWNSTREAM DISTANCE
DRAG IS FUNCTION OF MASKED AREA TIMES BLOCKAGE FACTOR

Figure 12.- Atmospheric drag approximation.

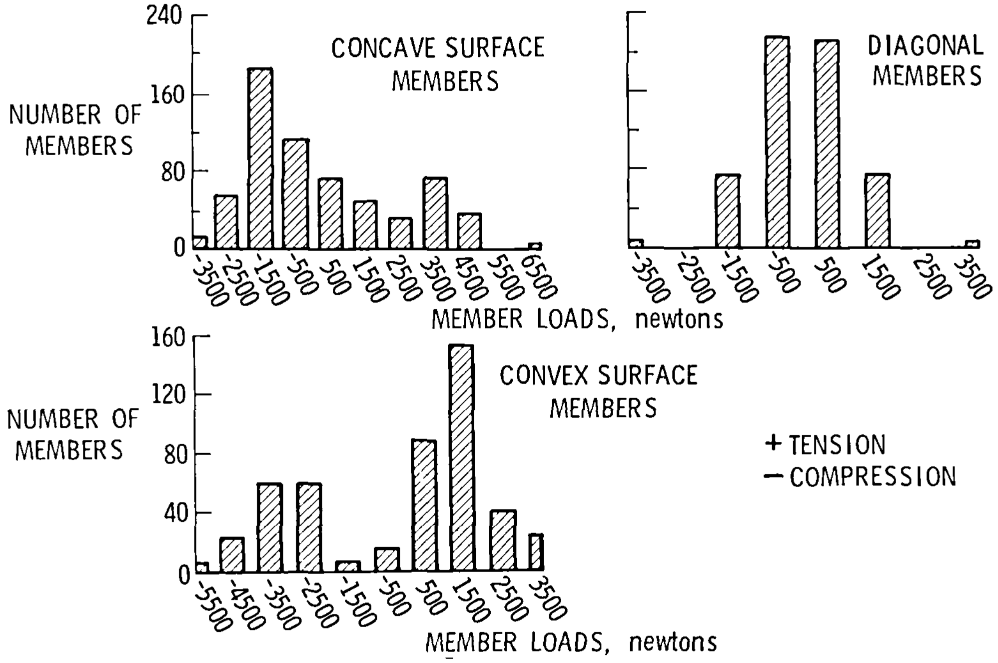


Figure 13.- MRS member loads for five-load condition (atmospheric drag, gravity gradient, static thrust, thermal, and pretensioning).

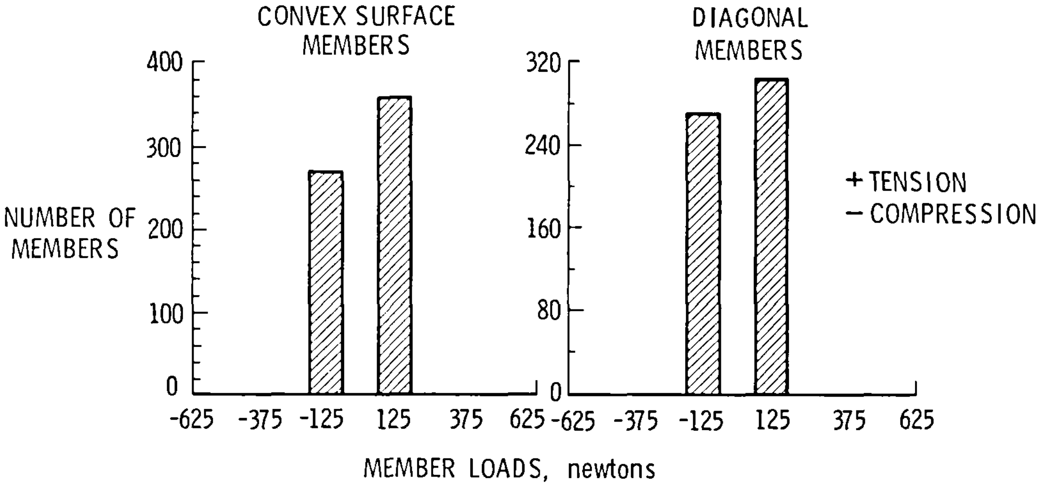


Figure 14.- MRS member loads for three environmental loads (thermal, gravity gradient, and atmospheric drag).

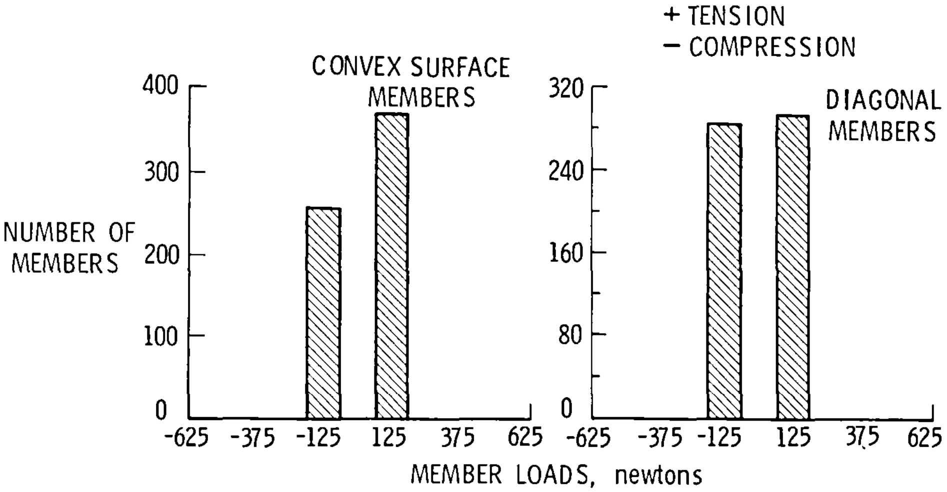
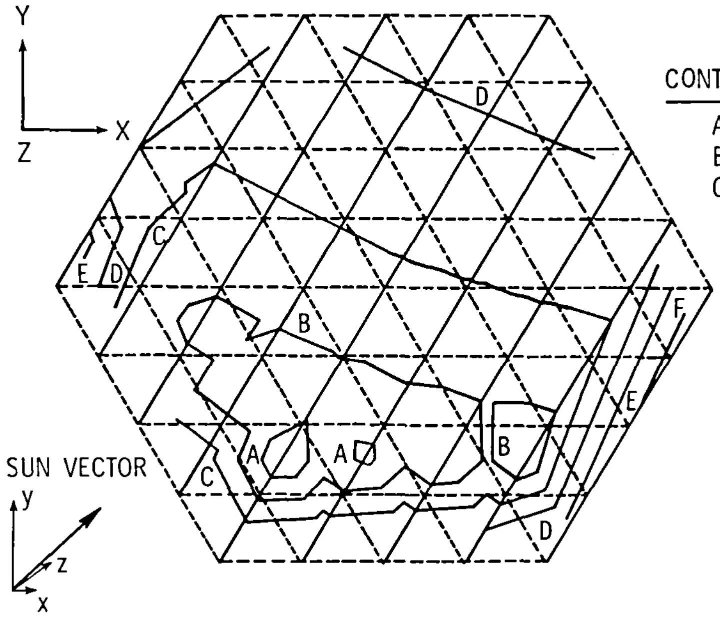


Figure 15.- MRS member loads for thermal load only.



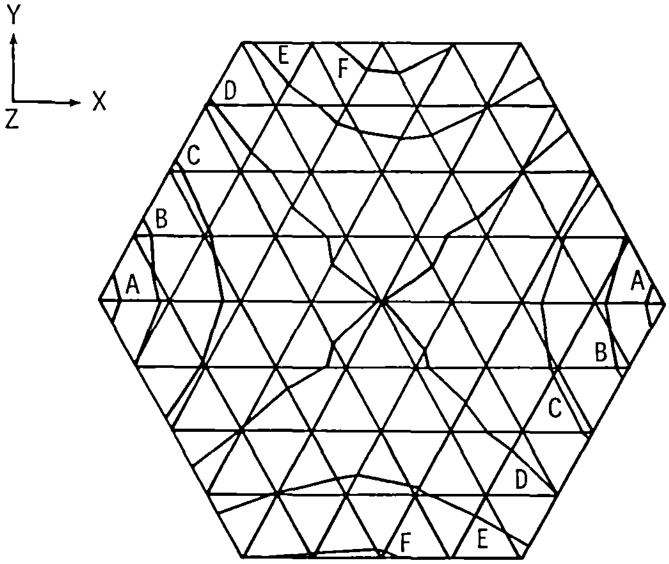
CONTOUR LEVELS, K

A	205	D	220
B	210	E	225
C	215	F	230

S/C IN SUNLIGHT FOR 1.5 MINUTES AFTER 35 MINUTES COLD SOAK IN SHADOW

CONTOUR LINES ARE FOR SOLID ELEMENTS ORIENTED IN SAME DIRECTIONS RELATIVE TO SUN AND TO EARTH

Figure 16.- Temperature contours for MRS structural member. Baseline case.



CONTOUR LEVELS, cm

A	-15	D	0
B	-10	E	+5
C	-5	F	+10

rms ROUGHNESS

6.6 cm

Z-AXIS DISPLACEMENT

1.1 cm

ROTATION ABOUT X-AXIS

6.9×10^{-5} rad

ROTATION ABOUT Y-AXIS

-3.7×10^{-4} rad

Figure 17.- MRS surface accuracy results. Baseline case.

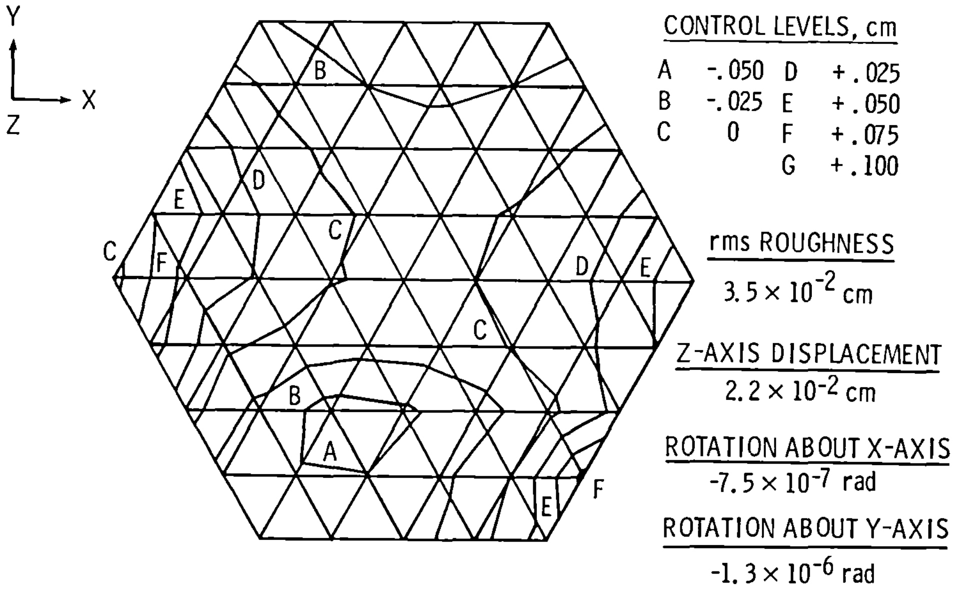
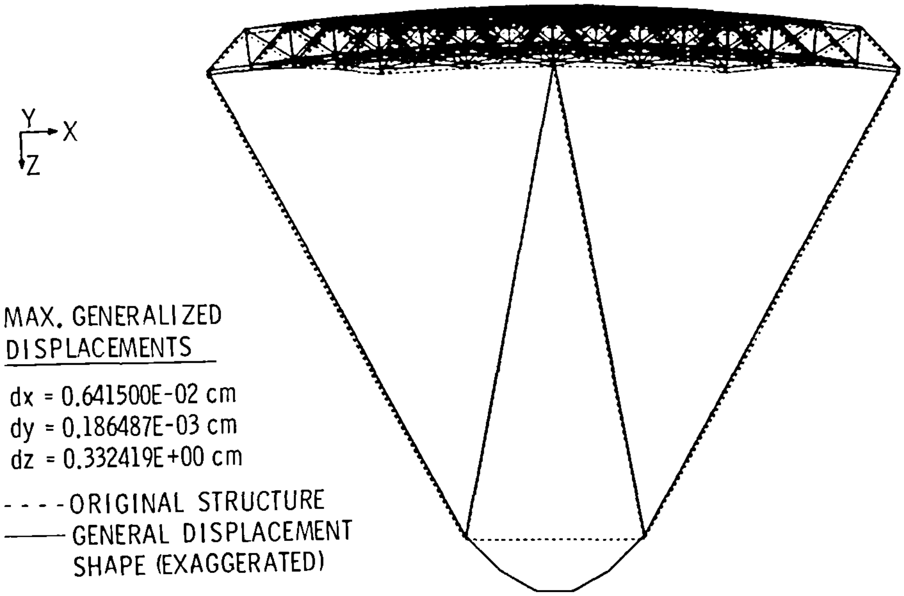
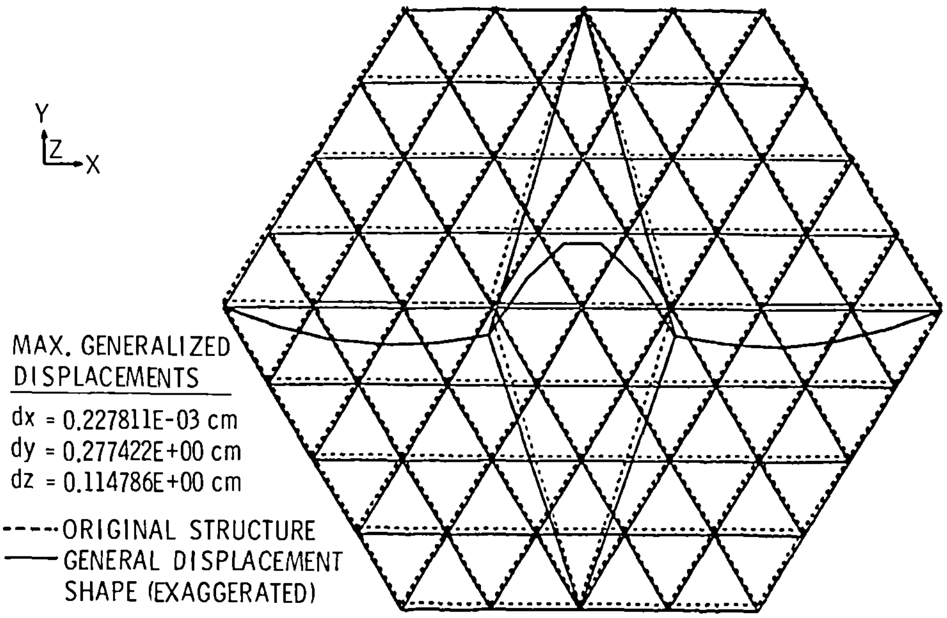


Figure 18.- MRS distortions from environmental loads.

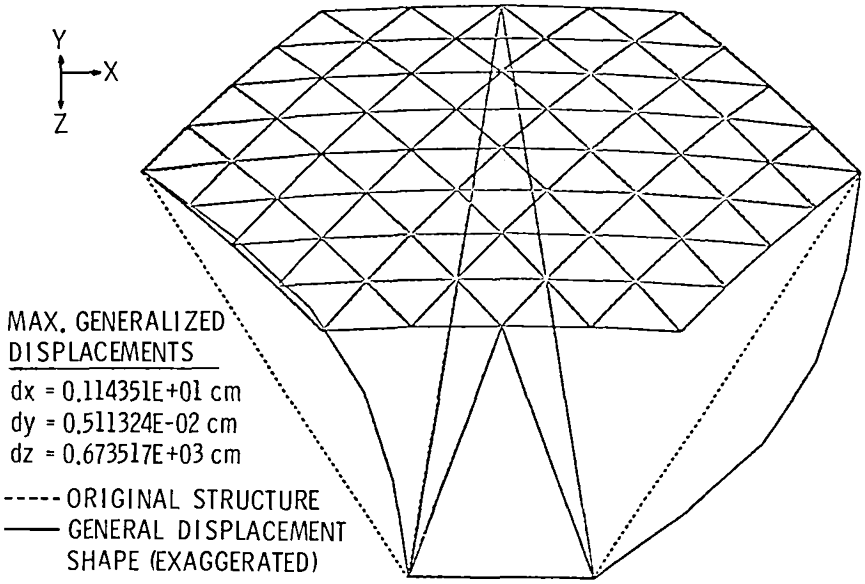


(a) Mode 1; $f_1 = 0.05601$ Hz.

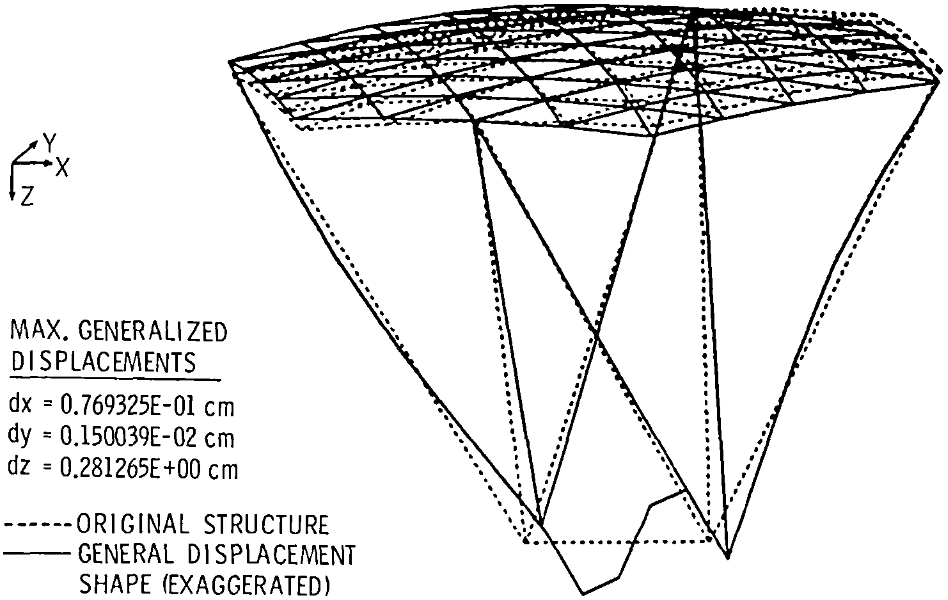


(b) Mode 2; $f_2 = 0.06935$ Hz.

Figure 19.- Generalized displacements from LASS dynamic analysis for MRS baseline case.



(c) Mode 4; $f_4 = 0.1000$ Hz.



(d) Mode 9; $f_9 = 0.2264$ Hz.

Figure 19.- Concluded.

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16. Abstract

An overview is presented of an interactive computer-aided design program used to perform systems-level design and analysis of large spacecraft concepts. The primary emphases are on rapid design and analysis of integrated spacecraft, including automatic spacecraft modeling for lattice (trusslike) structures. Capabilities and performance of the twenty-some multidiscipline applications modules, the executive and data management software, and graphics display features are reviewed. A single user at an interactive terminal can create, design, analyze, and conduct parametric studies of Earth-orbiting spacecraft with relative ease. The approach is particularly useful in the conceptual design phase of advanced space missions when a multiplicity of concepts must be evaluated in a cost-effective and timely manner. Data generated in the design, analysis, and performance evaluation of an Earth-orbiting large-diameter (750-m) antenna satellite are used to illustrate current capabilities. Computer run time statistics for the individual modules quantify the speed at which modeling, analysis, and design evaluation of integrated spacecraft concepts can be accomplished in a user interactive computing environment.

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