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INTERACTIVE SYSTEMS DESIGN AND SYNTHESIS OF FUTURE SPACECRAFT CONCEPTS

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INTRODUCTION

During the conceptual design phase of advanced space missions, a large number of mission options and spacecraft concepts must be analyzed and evaluated in a timely and cost-effective manner. Computer-aided design, and especially color graphics and animation, can be a very powerful tool in the design selection process of a spaceflight project.

The Interactive Design and Evaluation of Advanced Spacecraft (IDEAS) system was developed to provide an integrated system of interactive computer-aided design and analysis software to evaluate the design, systems requirements, and technology needs of future spacecraft. These spacecraft concepts include manned Earth-orbiting space stations, large antenna systems for communications and Earth monitoring, space platforms (power or laser systems) and technologically advanced spacecraft. With the IDEAS system, the independent researcher or research team has the capability to rapidly and economically model, design, evaluate, refine and redesign spacecraft concepts.

The purpose of this paper is to describe the IDEAS system and its capabilities and to illustrate the design and synthesis process with results from current spacecraft conceptual design studies.

IDEAS SYSTEM OVERVIEW

The IDEAS system is described in detail in Refs. 1 and 2 and is summarized herein for completeness of the presentation.

IDEAS consists of about 40 technical modules (Refs. 2-9), an efficient executive, and data base/file management software (Ref. 10), and interactive graphics display capabilities. The modules reside on both mainframe and super minicomputer systems. Data files are transferable between the two computer systems. Data and graphical summary information are presented to the analyst on graphic display terminals for immediate assessment and interactive modification of the spacecraft or mission design, as appropriate.

Some examples of the capabilities of the IDEAS system are shown in Fig. 1. Technical modules include structural synthesizers and finite-element modelers; on-orbit static, dynamic, and thermal analyses; large area drag, gravity gradient, and solar-pressure environmental-loading algorithms; structural element design; subsystem design and data base; habitable module support systems; operational analysis; and performance, cost, and reliability algorithms.

Prior to the development of IDEAS, most existing computer codes for large advanced spacecraft analysis were either large, long-running, highly generalized, single-discipline codes, or did not have the breadth of capabilities needed to perform complete parametric tradeoffs of the total spacecraft, its supporting subsystems, and the on-orbit operational environment. Data generation, structural and thermal modeling, and the transfer of data between single-discipline programs were generally lengthy, time-consuming processes requiring several engineers and sometimes months to complete. IDEAS can be rapidly run in a few wall-clock hours by a single spacecraft analyst.

This process has been facilitated because of a number of developments in the IDEAS system which include automated finite-element modeling and structural synthesis. Also, data files created by any upstream technical module are automatically formatted for subsequent modules. User prompts for file names and unformatted inputs are provided. Further, much of the necessary computer command protocol has been directly coded into the executive, data base/file management software and the technical modules.

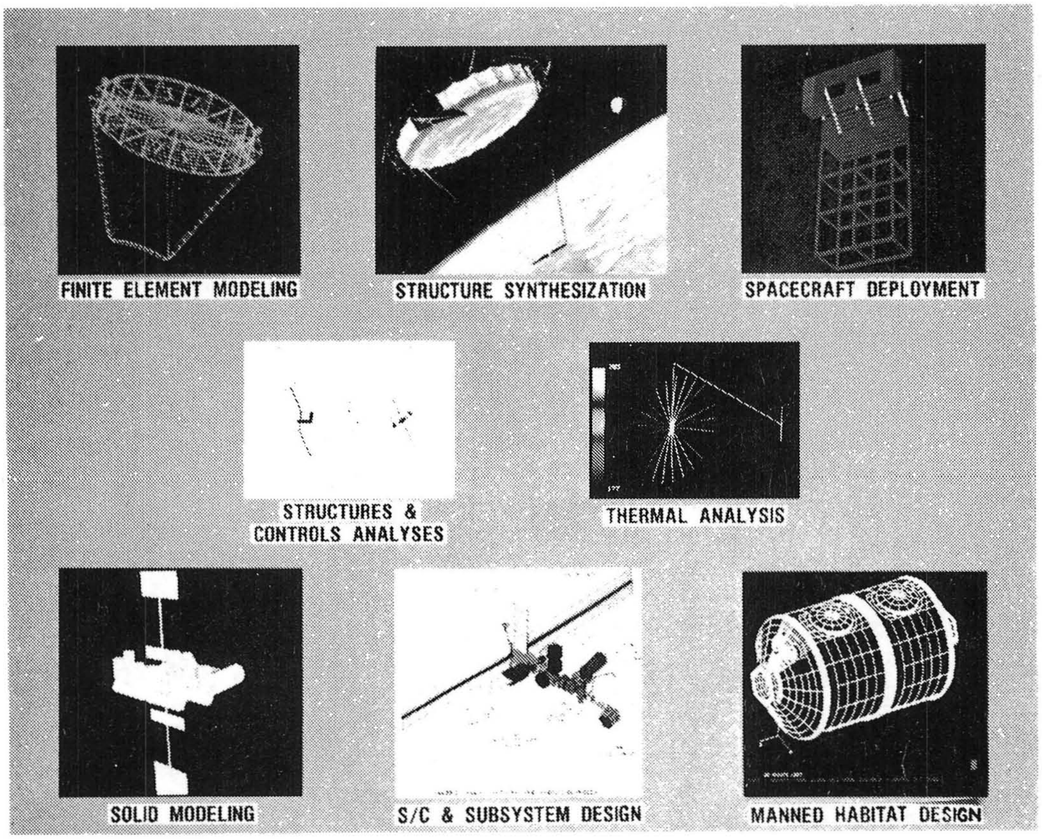


Figure 1. IDEAS Capabilities.

IDEAS SOFTWARE

The IDEAS technical programs are shown in Fig. 2. The IDEAS software currently includes all technical modules from the following software development efforts:

(1) Large Advanced Space Systems (LASS) computer program (Refs. 2-4) which emphasized structural, thermal and controls analysis/design, and cost for large structures (11 software modules).

(2) Spacecraft Design and Cost Module (SDCM) program (Ref. 5) which performs subsystem design and cost analyses through data base searches and iteration (six modules).

(3) Advanced Space Systems Analysis (ASSA) software (Ref. 6) which emphasizes structural synthesizers, environmental modeling, orbital transfer, and simplified radio frequency (RF) analyses (eight modules).

(4) Space Station Conceptual Design Model (SSCDM) program (Ref. 7) which sizes habitable modules and laboratory space, designs life support and related spacecraft subsystems, and computes logistic requirements (15 modules).

(5) Earth Observation Spacecraft (EOS) programs (Ref. 8) which emphasize structural deployment and expanded RF and orbital environmental analysis capabilities (five new and five upgraded modules).

(6) Environmental Control and Life Support System (ECLSS) Technology Assessment program (Ref. 9) which assesses technology options for life support systems (several modules under development).

Additional IDEAS capabilities include antenna packaging algorithms, plate and shell analysis modules for space station, rigid body control system expansions, and extensive augmentations to output graphic displays, including solid modeling and color. Programs are being developed to analyze the kinematics and kinetics of large structures during deployment and to accomplish space station design and operations analyses.

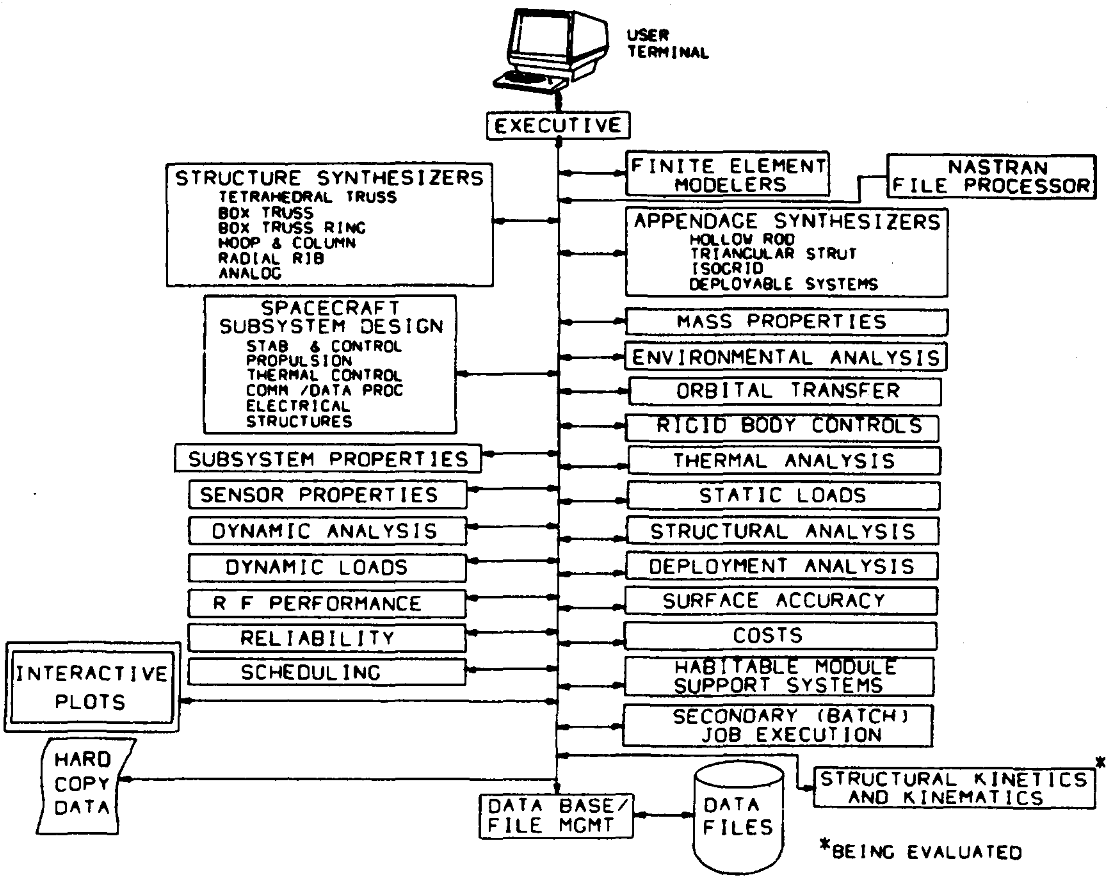


Figure 2. IDEAS Technical Program.

IDEAS FUNCTIONAL METHODOLOGY

The functional methodology of the Interactive Design and Evaluation of Advanced Spacecraft (IDEAS) computer-aided design and analysis system is shown in Fig. 3. The system methodology is divided into two distinct disciplines: interactive graphics and interactive computing. The interactive graphics provide graphical representations or visualization of the concept and data display on the interactive terminal, and the interactive computing consists of the actual multidisciplinary analysis programs that are available to the user. The design process begins with the creation of a three-dimensional geometry model (wire frame or solid) for concept visualization and verification. Analysis models are then created for input into the analysis programs. These models could be finite-element, finite-difference, or other mathematical representations of the concept. Mass properties are generated from the finite-element model for input into the analysis programs. The spacecraft subsystems are synthesized from an equipment data base for a total systems concept definition. A detailed analysis of the model is conducted using the multidisciplinary analytical tools within the IDEAS system.

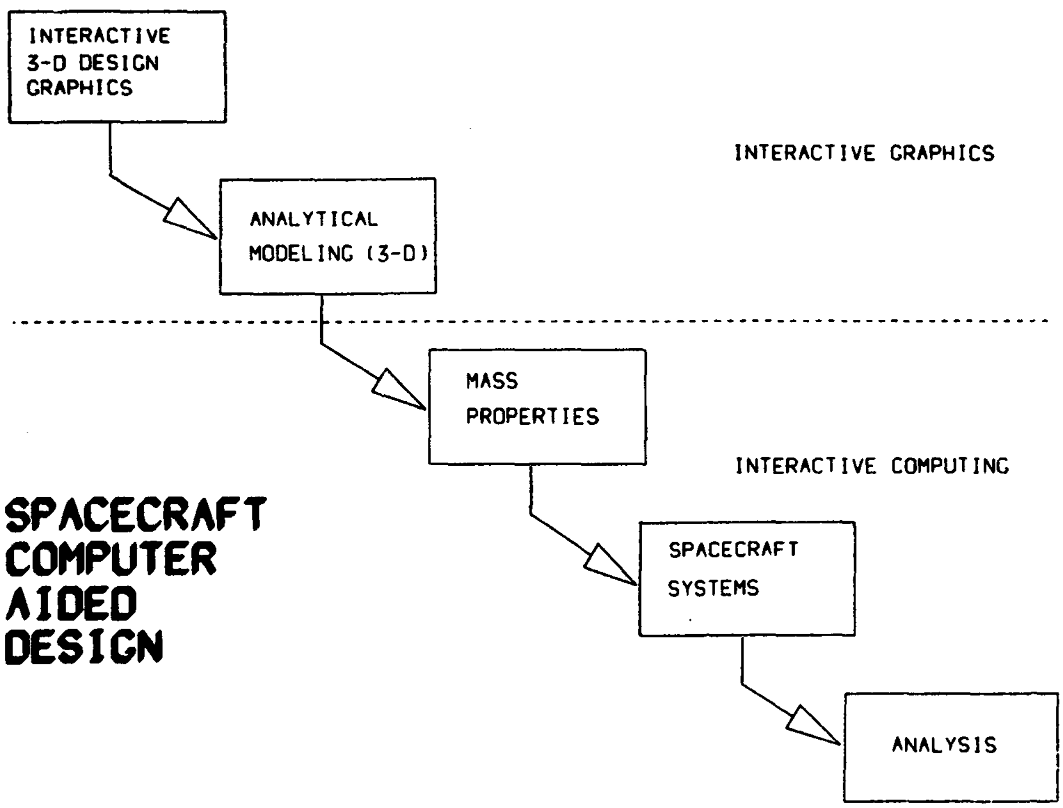


Figure 3. Functional Methodology.

INTERACTIVE 3-D DESIGN GRAPHICS

The first step in the initial modeling of a space system concept is the visualization of the proposed system to be analyzed. Depending on the concept, either solid or wire frame (stick) models are generated. For the case of enclosed structures, such as the space station, the geometry models are generated using a solid modeling geometry generator under development at NASA. Through the use of various primitive geometric entities such as cylinders, cones, rectangles, and volumes of revolution, combined with rotation, translation, and Boolean operations, an analyst can model a concept in order to determine form and fit criterion, concept feasibility, and functionality. For an open or lattice structure, such as a large antenna, stick models are generated by defining the structure's node points and connecting the nodes with straight lines. By refining the concept at the geometry level, one may save time and effort due to the fact that there are no analytical models created. Through the use of commercial geometry display software such as MOVIE-BYU (Ref. 11), the models can be observed in a time passage (dynamic) sequence.

SPACE STATION CONCEPTS

There are eight generic classes of space station under study. These are listed in Fig. 4(a) and described in Ref. 12.

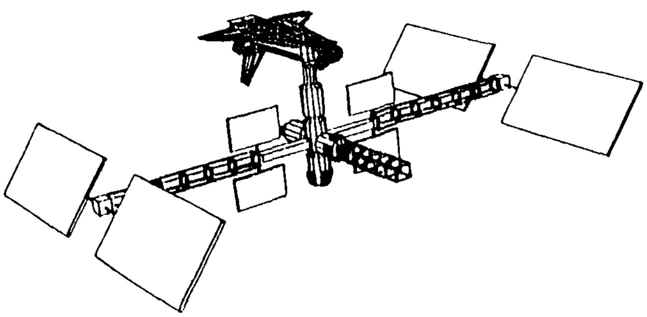
In the building block concept, the modules are mounted on one or more simple trusses. Concepts in this class are somewhat cheaper, and since the cg and cp locations can be easily determined, they are easier to control.

A number of concept designs utilize large space structures as a framework for supporting the space station modules. Consequently, these concepts are very rigid and have a large payload capability.

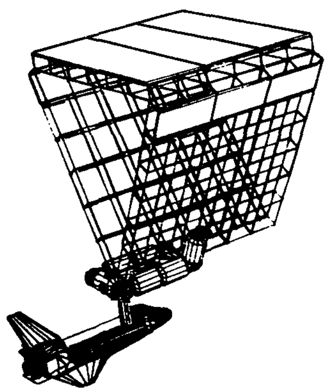
The planar and delta truss (Fig. 4(b)) will be used throughout the paper as examples of the closed structure. (Note: All of these concepts are currently under study and no selection of a preferred or best concept has been made.) Although these concepts vary greatly in appearance, they will utilize the same systems and subsystems to meet the prime objective of maintaining an eight-man crew in space for a specified period of time.

BUILDING BLOCK CONCEPTS	LARGE SPACE STRUCTURE CONCEPTS
Planar	Delta Truss
Axial Radial	Planar Truss (Bedspring)
Racetrack	Streamline "T"
	Gravity Gradient Tower (Power Tower)
	Dual Spin

a) Concept Classes.



Planar



Delta Truss

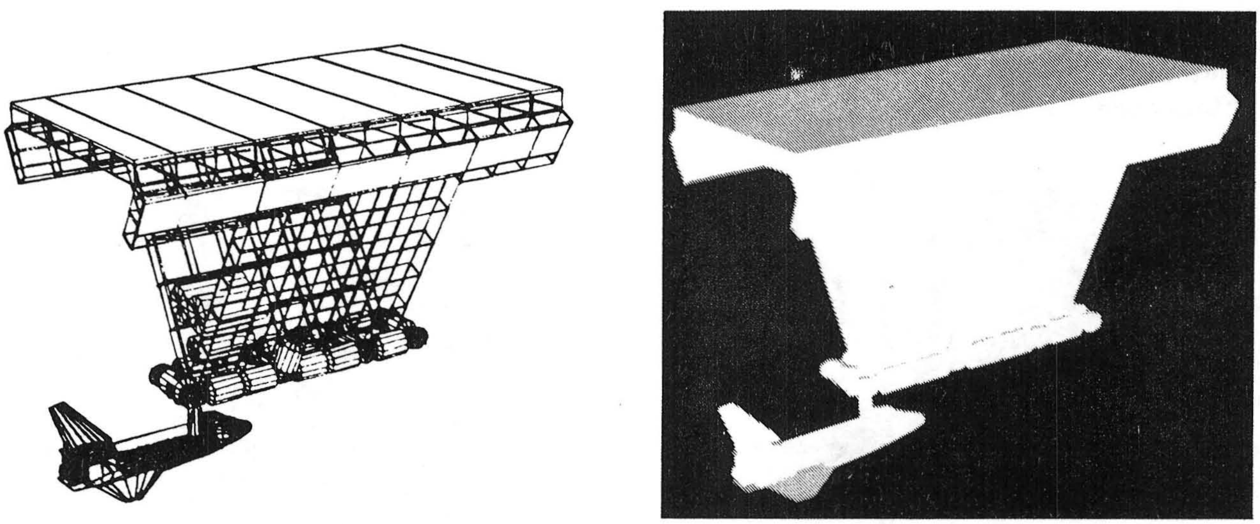
b) Examples of Closed Structures.

Figure 4. Space Station Generic Concepts.

SPACE STATION SOLID MODELS

The solid models are generated by placing various basic geometric shapes such as cylinders, cones, rectangles or other volumes of revolution at specified grid points. These shapes are rotated or translated to produce the desired configuration. The generated model will appear as a line drawing in the case of the antenna concepts. A hidden line algorithm can be applied to create a solid appearance, as in Fig. 5(a). Monochrome shading can be automatically applied to the model to render the more realistic, solid shaded figure of Fig. 5(b).

The solid models provide an easy technique for visual analysis of the configuration. Form and fit criteria, such as the dimensional relationships of parts, module connection pattern and payload accommodation areas, can be quickly evaluated. Orbiter approach path and docking clearances, and remote manipulator arm reach and clearances can be checked. The solid models also respond rapidly to configuration changes and provide a data base of geometry dimensions.



a) Using Hidden Line Algorithm. b) Using Monochrome Shading.

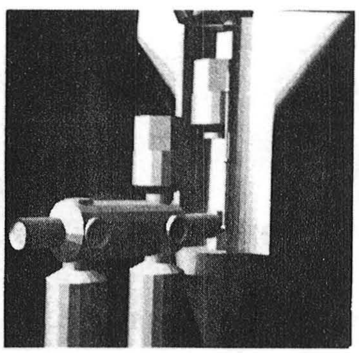
Figure 5. Solid Models.

TIME PASSAGE (DYNAMIC) MODELING

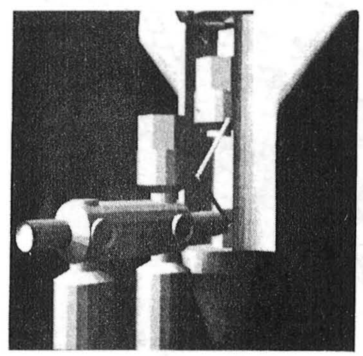
Once the three-dimensional solid model has been developed, commercial geometry display software, such as MOVIE BYU, can be incorporated to provide a time passage or dynamic sequence. MOVIE BYU also has the capability to rotate or translate the model and to zoom in or out during the dynamic sequence. These dynamic sequences are ideal for checking form and fit criteria, clearance between moving components, and interference problems that may exist. Time passage sequences can be used during the analysis steps in the methodology to illustrate the time passage of Sun-cast shadows over the model, deployment sequences, spacecraft thermal variations with time, and numerous space station operations.

Selected frames from a dynamic sequence of the shuttle orbiter/space station docking and logistics resupply operation are shown in Fig. 6. As the shuttle orbiter nears the space station, the cargo bay doors open prior to docking. After docking, the resupply cargo module is moved forward in the cargo bay. The spent logistics module is separated from the space station cargo port and placed in the shuttle bay. The resupply module is attached to the station and the spent module is repositioned to the center of gravity of the shuttle. The shuttle undocks and returns to the Earth.

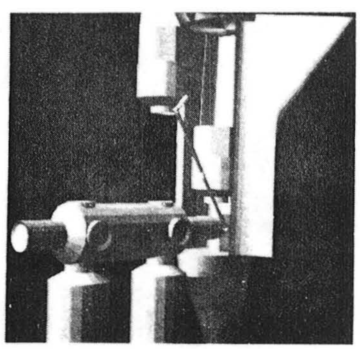
This sequence provides information on the form and fit criteria of the shuttle docking, movement and positioning of the logistics modules and clearance data for the remote manipulator arm during the canister transfers.



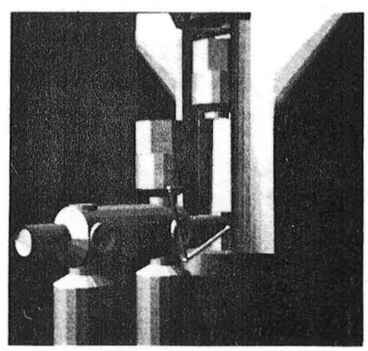
ORBITER/SPACE STATION DOCKING



REPLACEMENT MODULE TRANSFER IN CARGO BAY



SPENT MODULE REMOVAL FROM SPACE STATION



REPLACEMENT MODULE CONNECTED TO SPACE STATION

Figure 6. Docking and Resupply Sequence.

SPACECRAFT WIRE FRAME (STICK) MODELING

For an open or lattice structure, such as a large antenna, the truss structure is generated by defining the structure's grid points and connecting the grid with straight line elements. In many cases, these wire frame or stick models become the basis for the finite-element model in the analytical modeling step of the functional methodology (Fig. 3). By refining the concept at the geometry level, one may save time and effort due to the fact that no analytical models are created.

Typical lattice structures are the five deployable antenna concepts shown in Fig. 7 and described in Refs. 2 and 13-16. The five concepts are:

1) box truss
2) hoop and column
3) tetrahedral truss
4) box ring truss
5) radial rib

The box truss and hoop and column structures are typical of the linear-sequential and continuous deployment concepts, respectively, and will be used throughout the paper as examples of the open structure. (Note: All of the concepts are currently under study and no selection of a preferred or best concept has been made.)

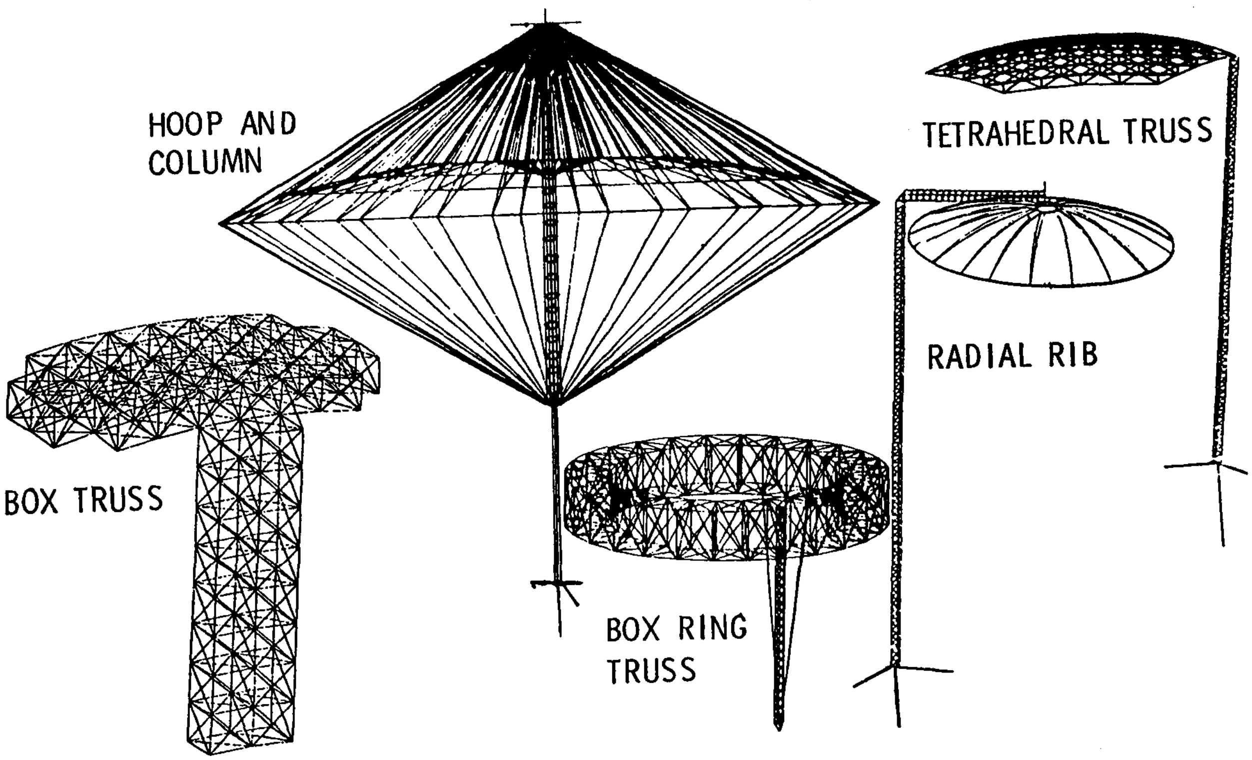


Figure 7. Deployable Antenna Concepts.

BOX TRUSS CONFIGURATION

The box truss configuration, shown in Fig. 8, consists of a series of cubes joined together to form the lattice structure of the spacecraft. The individual cubes are 15-m on each side and designed such that the horizontal tubes are hinged and fold against the nonfolding vertical tubes for packaging. After deployment, pretensioned telescoping tapes extend from each corner (both in the place of the faces and across the cube diagonals) to stabilize the deployed cube. Both the tubular members and the telescoping tapes are constructed of graphite. The deployed spacecraft consists of a 120-m by 60-m spherical/parabolic reflector, a 120-m long feed support mast, and a 30-m feed beam on the focal axis. The antenna surface is spherical in the 120-m direction (with a radius of 232-m) and parabolic in the 60-m direction with a focal length of 116.1 m.

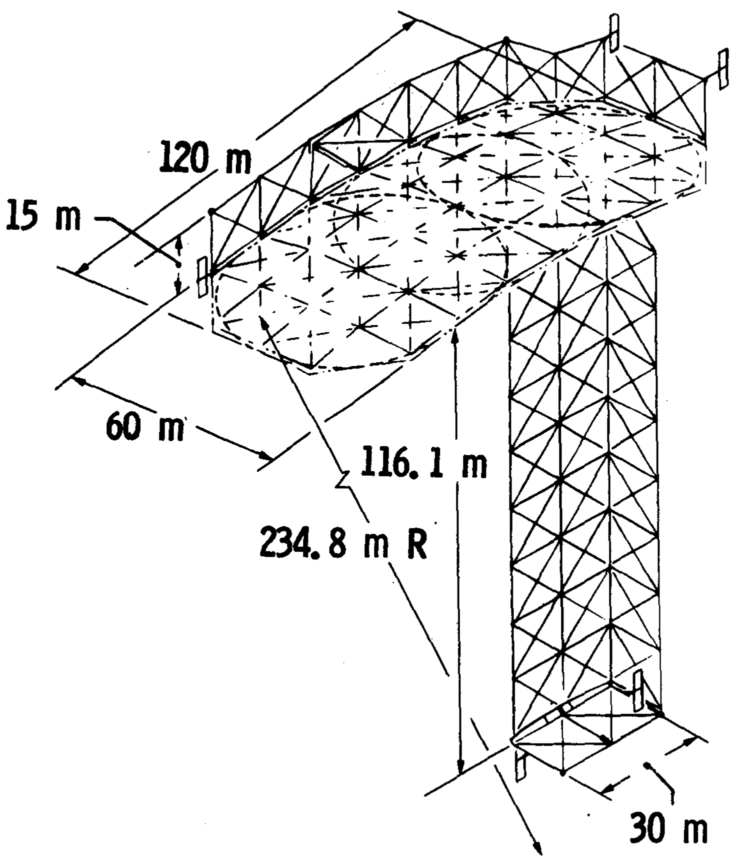


Figure 8. Box Truss Configuration.

HOOP AND COLUMN CONFIGURATION

The hoop and column structural configuration of Fig. 9 consists of a long column with a hoop supporting the antenna. Pretensioned cables connect the hoop to the column and serve to stabilize the deployed spacecraft. The column or feed mast is 120-m long and supports the antenna feed system at the focal point of the antenna. After deployment, the diameter of the hoop is 120-m. The antenna utilizes a quad-aperture system of 55-m with a focal radius of 82-m. The components of the hoop and mast are graphite. The tension cables on the reflector side of the spacecraft are quartz to reduce reception losses.

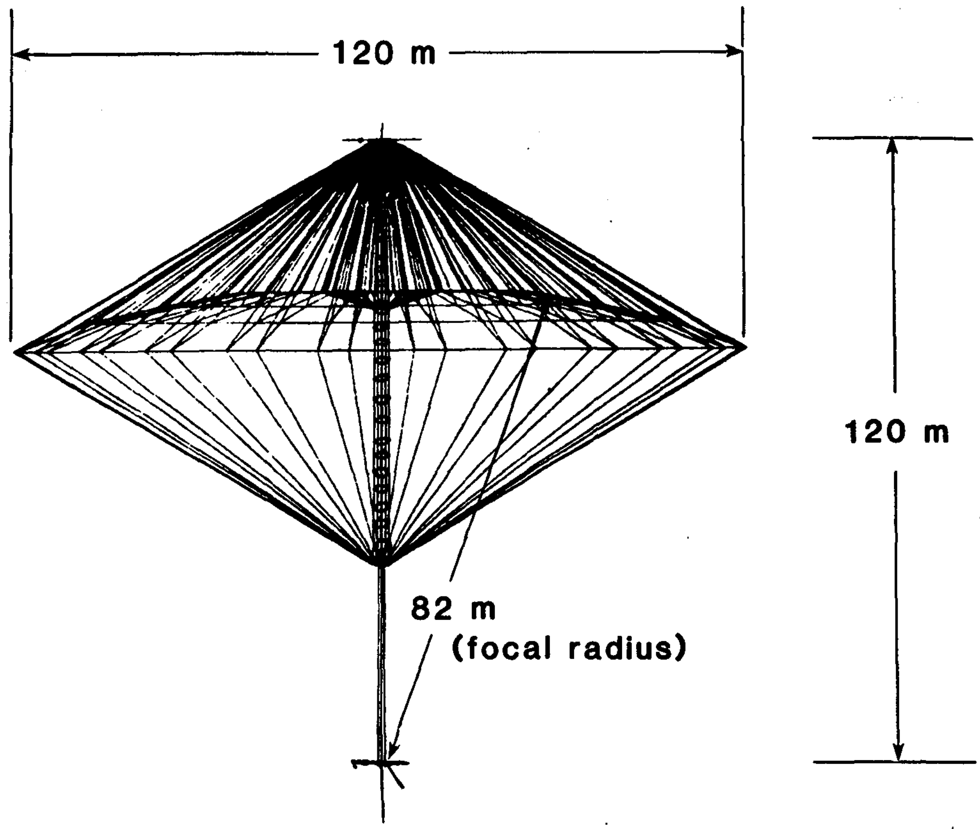


Figure 9. Hoop and Column Configuration.

ANALYTICAL MODELING

Once the three-dimensional geometry model of the spacecraft configuration is defined, the concept is analytically modeled. Finite-element models are generated for structural analysis, finite-difference models are developed for thermal calculations and area models are generated for aerodynamic drag calculations.

The IDEAS approach to analytical modeling is to use strict mathematical relations (synthesis) to automatically generate a finite-element model of the repeating structural members in complex truss-like structures of any user-specified size, shape, and structural density. Structural synthesizers have been developed for the five structural classes shown in Fig. 7: tetrahedral, box and box ring trusses; hoop and column; and radial rib. User inputs into the structural synthesizers are antenna dish or platform diameter; number of bays; ribs or cable/mesh segments; focal length to diameter ratio; platform structural depth; material and section properties; and hinge and mesh masses. From these inputs, the synthesizers rapidly create the mass and inertia properties of the finite-element model in formats compatible with subsequent design and analysis programs in the IDEAS systems. The automated modeling and synthesis computations typically can be completed in 5 to 10 wall-clock minutes and with several minutes CP time.

The IDEAS system allows the user to design and add structural appendages to the dish or platform and to locate spacecraft subsystems on the structure. This process results in an updated finite-element model and mass/inertia properties for the entire spacecraft. Standard structural elements are shown in Fig. 10 and include the hollow rod, a mass-efficient isogrid, a relatively stiff triangular strut, and tension cables. These members are automatically designed to user-specified Euler buckling loads (or tensile loads for the pretensioned cables).

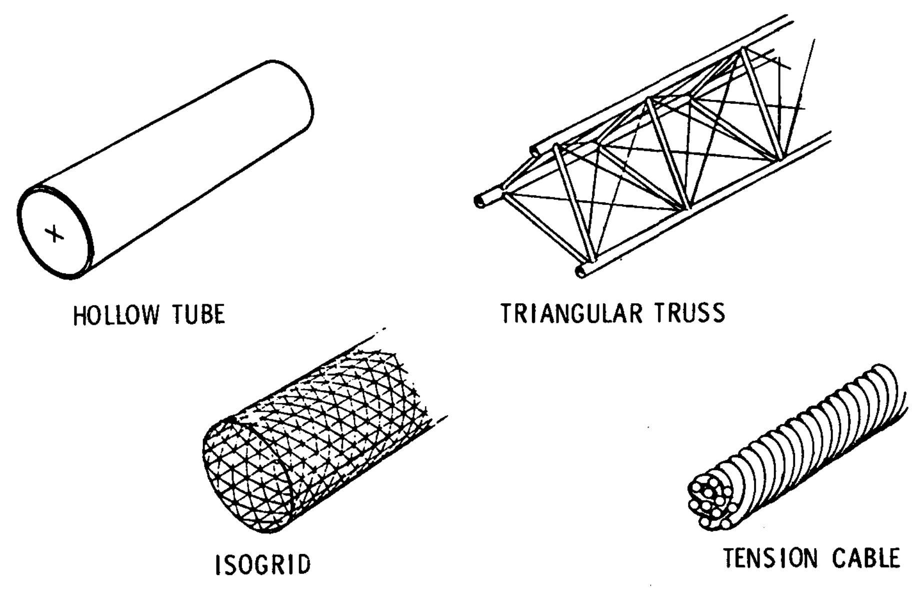


Figure 10. Standard Structural Elements.

MASS PROPERTIES

Mass property data are generated as an outgrowth of the data from the analytical modeling (finite-element modeling) function.

The interconnecting truss hardware masses and sizes are computed as a function of the structural member diameter and these masses are distributed at appropriate nodal points in the truss finite-element model. In general, the synthesizers create and output the masses of the structural components, the masses of the reflective mesh systems (in the case of antenna design), and the mass of the total system. The center-of-gravity and mass-moment-of-inertia tensors are computed. Appendage synthesizers are used to design and add structural appendages to a repeating structural system. The process results in an updated structural model and updated mass/inertia properties for the entire spacecraft.

SPACECRAFT SYSTEMS SYNTHESIS

In addition to performing candidate system tradeoffs, the basic program architecture has been developed for modeling the bulk properties (mass, volume and performance capabilities) of subsystems, components and sensors of the five major systems: electical power, propulsion, communications, data management, and stability and control. The subsystems are synthesized by selecting individual subsystem component parts from an equipment data base which consists of approximately 1500 component parts. Structural and thermal subsystems are not created through the use of data base entries because the shape, size, volume, and power requirements of the total system are unknown until the other subsystems are defined. In the case of manned spacecraft, environmental control and life support systems (ECLSS) are also modeled. Although a limited set of models are currently available, efforts are underway to extend these capabilities.

SPACECRAFT DESIGN AND COST MODULE (SDCM)

The Spacecraft Design and Cost Module (SDCM) performs subsystem design and cost analyses through data base searches and iterations of spacecraft components that meet or exceed user-specified requirements. This data base consists of components such as CMG's, IRU's, thrusters, tanks, batteries, transponders, and antennas. An overview of the program with the major subsystems included in the design is shown in Fig. 11. The SDCM matches subsystem capabilities in the data base file with the mission requirements (subsystem selection factors) and payload support criteria to provide the most reliable subsystem for the mission. The program iterates several times to produce the optimum spacecraft design. If a needed item is not readily available in the data base, that item is flagged as a subsystem for future technology development.

Although the principal use of the SDCM to date has been in the design and costing of small Earth-orbiting satellites, some of the components and subsystems have been modeled and integrated into larger spacecraft designs. A wide range of space-qualified and state-of-the-art components are included in the data base. Output is in the form of total system and subsystem performance data, and an assembly listing of all components selected from the data base. Efforts are continuing to expand the data base to include additional state-of-the-art and technologically advanced components and subsystems.

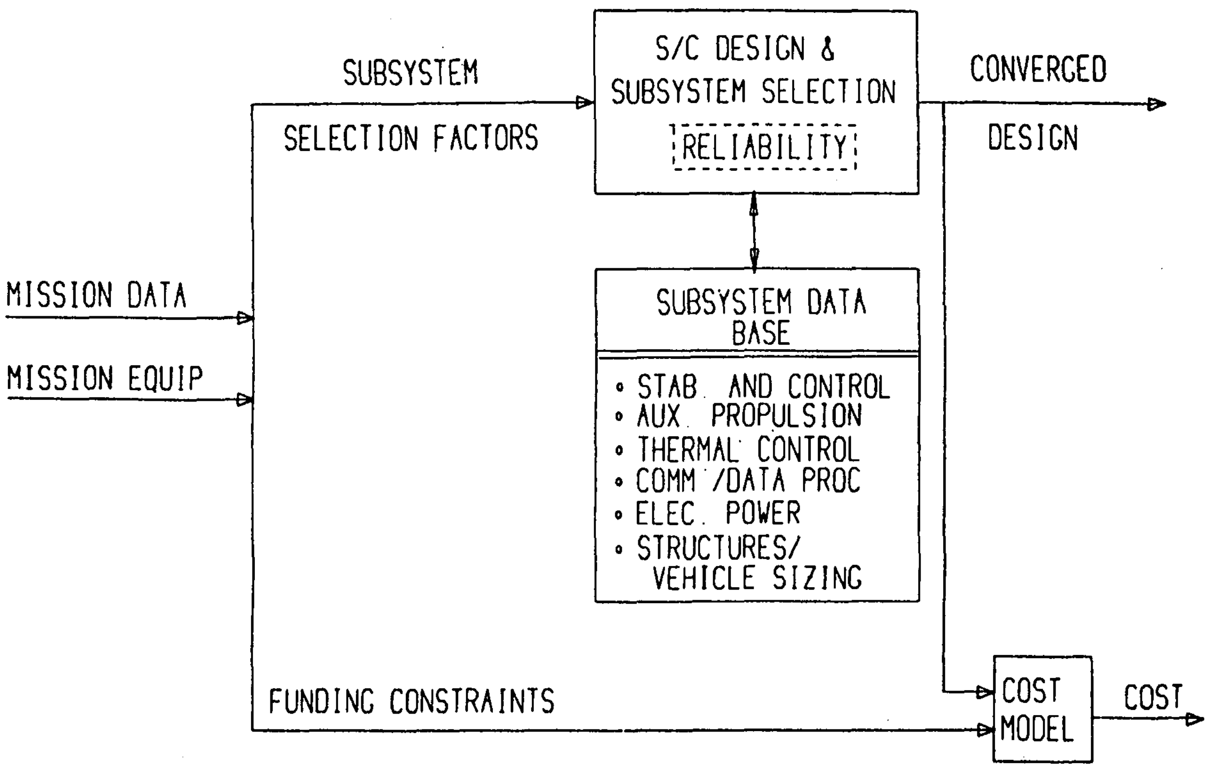


Figure 11. SDCM Program Overview.

ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEM (ECLSS) TECHNOLOGY ASSESSMENT PROGRAM

In the case of manned space flight, an Environmental Control and Life Support System (ECLSS) technology assessment program has been developed at NASA Langley Research Center (Ref. 9). The ECLSS program consists of the data base and methodology to rapidly assess technology options for life-support systems such as water reclamation and air revitalization based on mission options that include crew size, mission duration, resupply interval, etc. Basically, the program incorporates a data base for each technology option, metabolic design loads associated with crew activity, mission model variables to accommodate evolving mission requirements, and algorithms to produce data for comparison with specific assessment criteria. These data, including life cycle costs, are used to provide recommendations relative to candidate technology selection and development. The ECLSS Technology Assessment Program (Fig. 12) receives three forms of inputs: mission requirements and consumption rates, the candidate subsystems to be evaluated, and the criterion to which the evaluation is to be based. Mission inputs include mission duration, resupply interval, and crew size. Consumption rates include metabolic rates, water usage rates, and waste production rates. Various options are available in each of the ECLSS subsystems. For instance, air revitalization can be either achieved through stored gas or water electrolysis. Other methods of air revitalization could be used. Any of the subsystem options can be used in conjunction with other subsystem options in order to determine overall ECLSS system performance. The output yields three results. First, the resupply and consumables requirements are determined. Second, overall ECLSS system performance is quantified and finally, the life cycle costs for all candidate systems are computed.

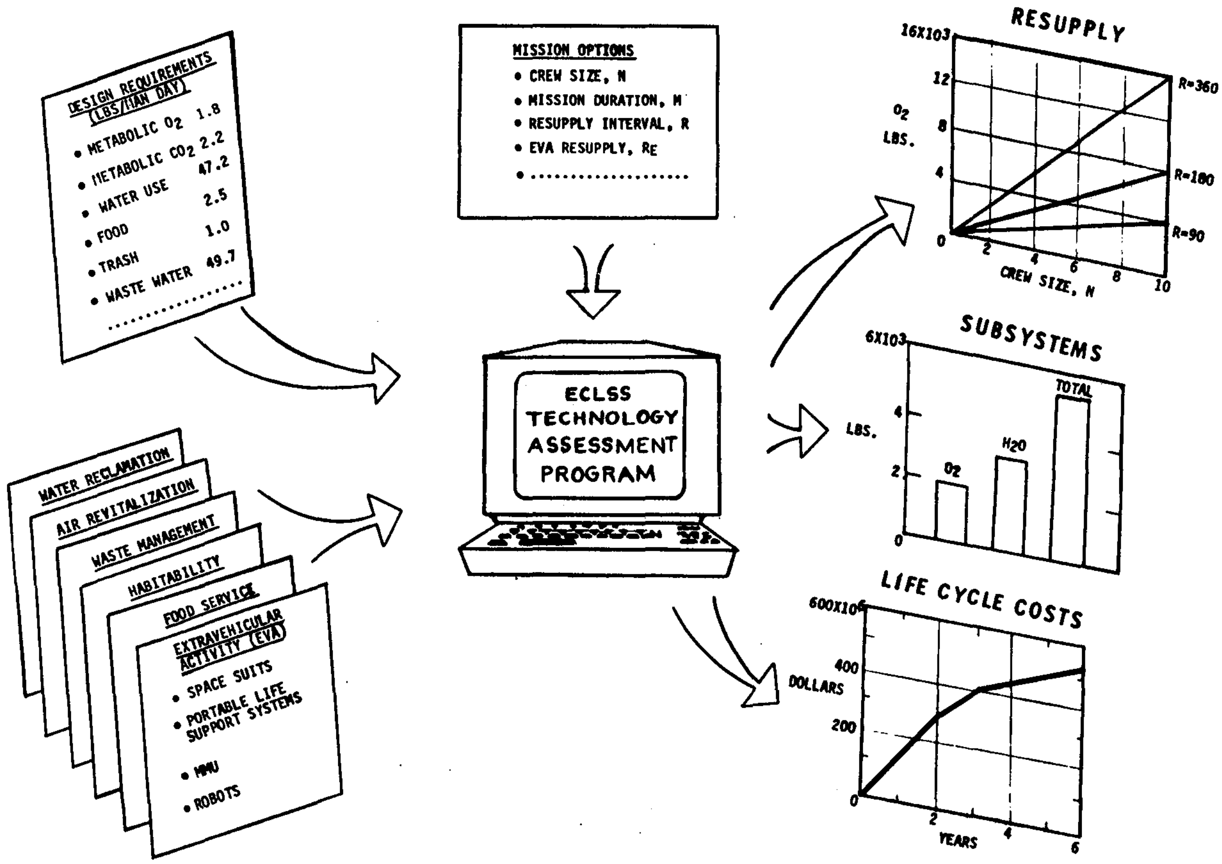


Figure 12. ECLSS Technology Assessment Program.

ANALYSIS

With the completion of the analytical models and the generation of structural (mass) properties and subsystems, the final step in the functional methodology is the detailed analysis of the spacecraft concept using the multidisciplinary analytical tools within the IDEAS system. The evaluation of the spacecraft concept incorporates the following disciplinary analyses:

1) deployment
2) rigid-body and on-orbit controllability
3) drag area
4) static structural
5) dynamic structural
6) surface accuracy
7) thermal

DEPLOYMENT ANALYSIS

During deployment, a spacecraft undergoes large changes in inertia and movement in the center-of-gravity location that may affect its stability and influence the design of the rigid-body control system. The large changes in inertia along the column centerline of the hoop-and-column spacecraft during deployment are shown in Fig. 13. The capability to generate finite-element models of these structures as deployment occurs is a prerequisite to conducting stability and stress analyses. The application of the mathematical synthesis techniques of IDEAS to describe the deploying structure provides a rapid, effective means for generating the needed finite-element models at any stage of deployment (Ref. 17). Once the finite-element models are developed, the MOVIE BYU software is incorporated to provide a time-passage deployment sequence. Selected frames from a dynamic sequence of the continuous deployment of the hoop-and-column spacecraft and the linear, sequential deployment of the box truss are shown in Figs. 14(a) and 14(b), respectively.

Such dynamic sequences provide information on the kinetics and kinematics of the deployment maneuver which are essential to the understanding of the dynamics of the deploying spacecraft and the controllability of the resulting instabilities. Deployment times can range from less than a minute up to an hour in duration for the various antenna concepts. For the fast deploying structures (such as the tetrahedral truss), the kinetic behavior must be fully understood. High stress buildup in the structural members at latchup can be the major structural design driver. Deployment-induced vibrations may also lead to undesirable dynamic behavior of the spacecraft.

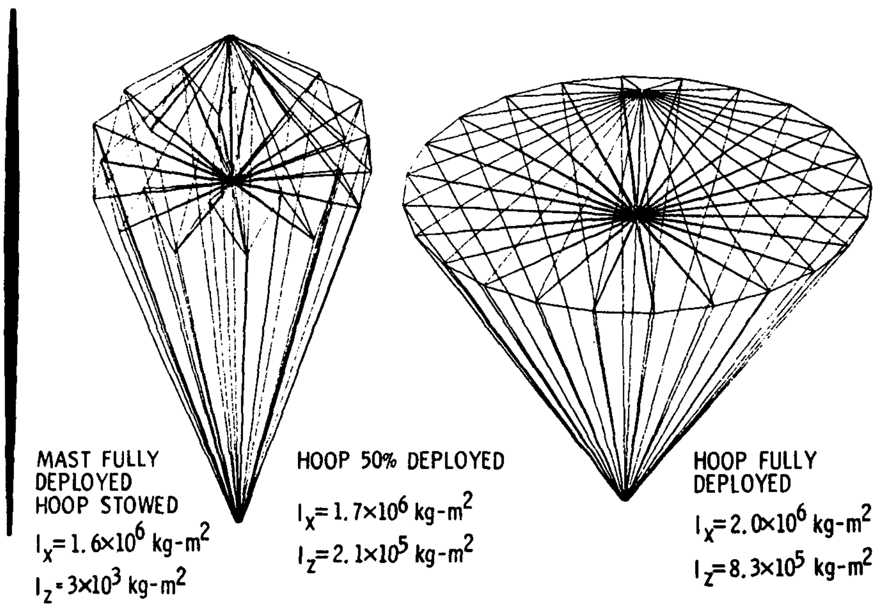
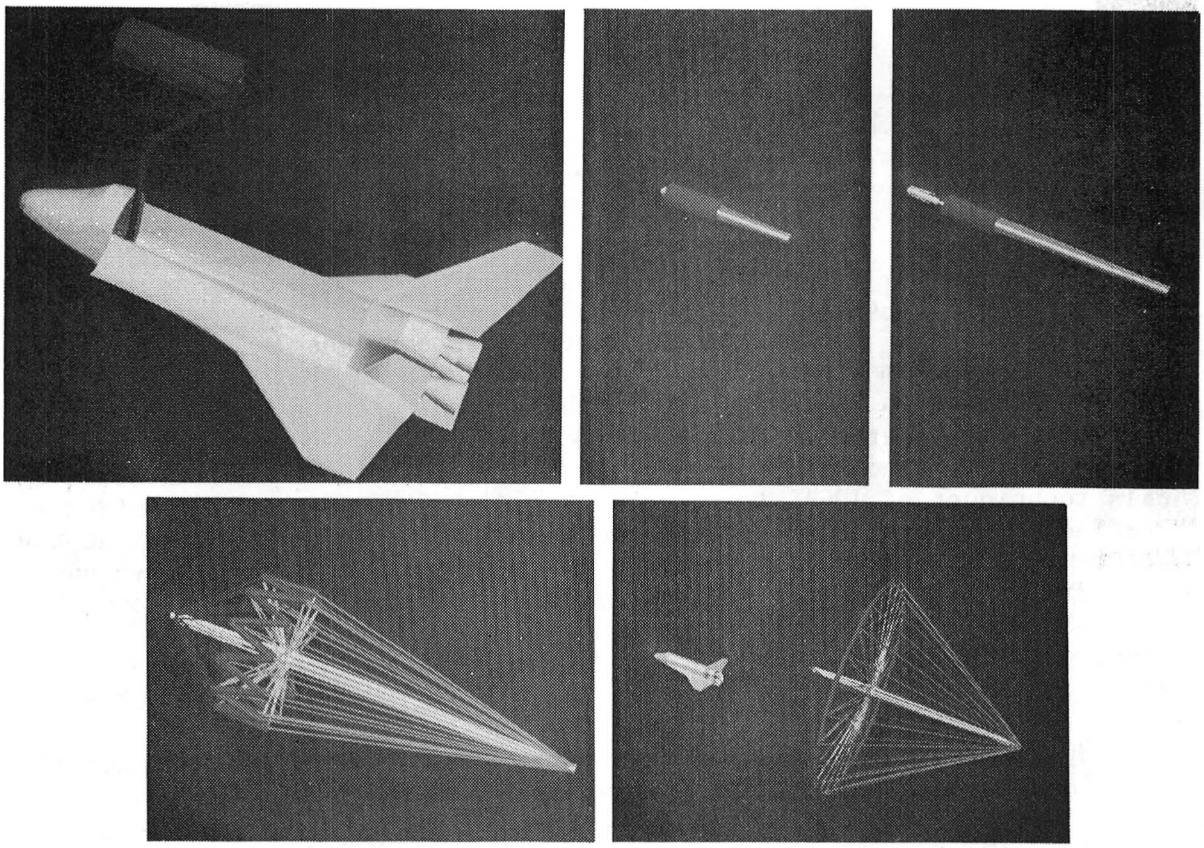
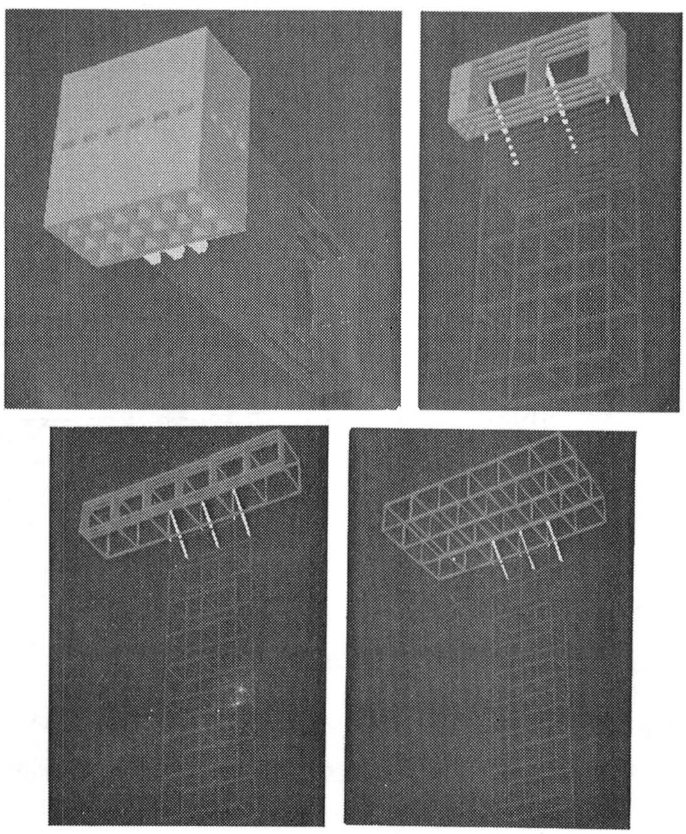


Figure 13. Hoop and Column Deployment Changes in Inertia.



a) Hoop and Column.



b) Box Truss.

Figure 14. Deployment Sequence.

RIGID-BODY CONTROLLABILITY ANALYSIS

A rigid-body controllability analysis is conducted to determine the on-orbit environmental forces and maneuver forces and their resulting torques on the spacecraft at user-specified circular orbital altitudes, spacecraft orientations, and mission durations. In addition to these parameters, the IDEAS Rigid-Body Control Dynamics (RCD) module also determines momentum storage and desaturation requirements, control-system sizing criterion, and propellant required for station keeping, attitude control, and user-specified maneuvers. The flow diagram for RCD is shown in Fig. 15. Total torque and force time histories are analyzed to determine cyclic momentum for momentum-exchange-system sizing and desaturation requirements. Momentum desaturation and orbit/station-keeping requirements define the requirements (size, power) of the reaction control system (RCS) thrusters.

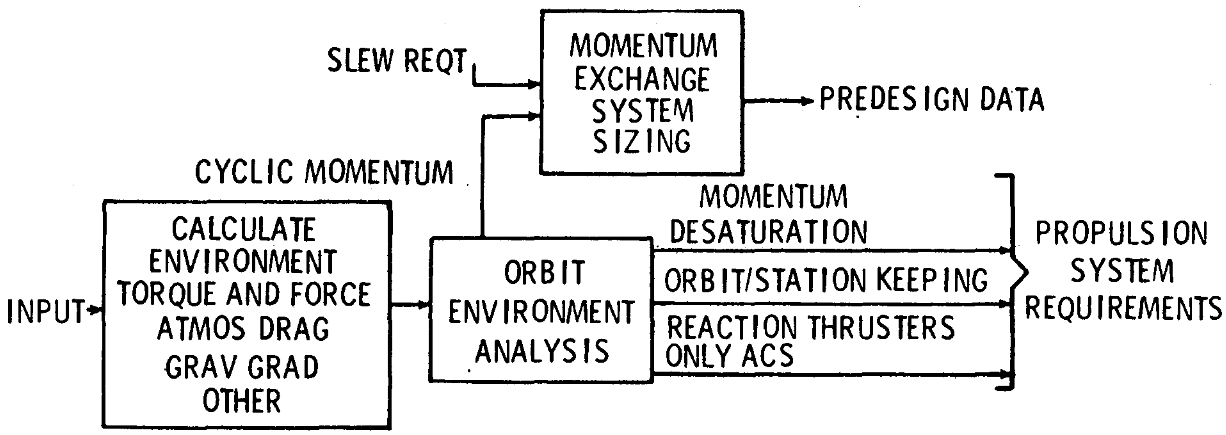


Figure 15. RCD Flow Diagram.

SPACE STATION ON-ORBIT CONTROLLABILITY ANALYSIS

A primary criterion for evaluating space station concepts is the on-orbit controllability of the space station. Since all of the space station concepts utilize the modular design concept, the controllability of each space station will vary during its evolutionary build-up phase. The center of pressure, center of mass, moments and products of inertia, and aerodynamic drag areas change continuously with the addition of each new module. Forces, torques, and controller torques are being determined for the generic configurations of Fig. 4. These forces are caused by mass changes, aerodynamic drag, gravity gradient and solar pressure. Time histories of angular momentum requirements such as shown in Fig. 16 are used to size control-moment gyroscopes and propellant storage facilities on the space station. These histories are also used to determine the relative merits of various orientations for the different configurations.

As a matter of fact, when the shuttle docks with the space station (either during buildup or when completed), the mass, center of pressure, moments and products of inertia, and aerodynamic drag areas of the new configuration will change. A new set of forces and torques will be imparted to the space station that must be determined and subsequently controlled. An assessment of the controllability of the generic space station concepts is given in Ref. 12.

In the dynamic sequence of Fig. 17, the space station is shown in its preferred orientation for minimum momentum storage and maximum solar efficiency. After the shuttle docks, the added mass of the shuttle creates a new space station/shuttle preferred orientation. This orientation may require regimballing the solar panels to full sun orientation. For the case of the delta truss with fixed solar panels, vehicle maneuvers may be required.

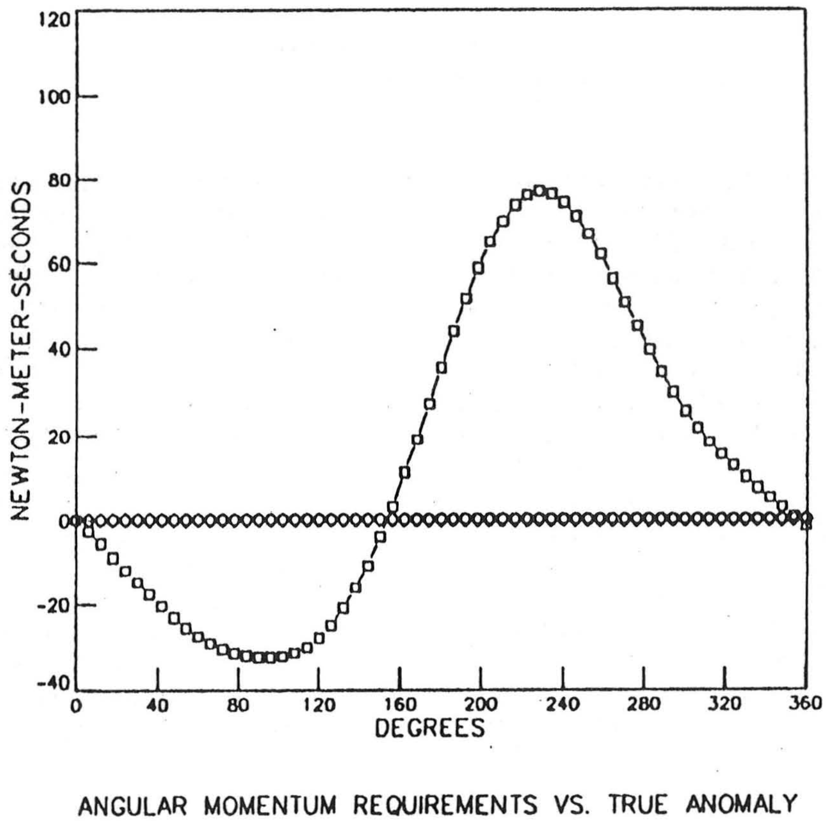
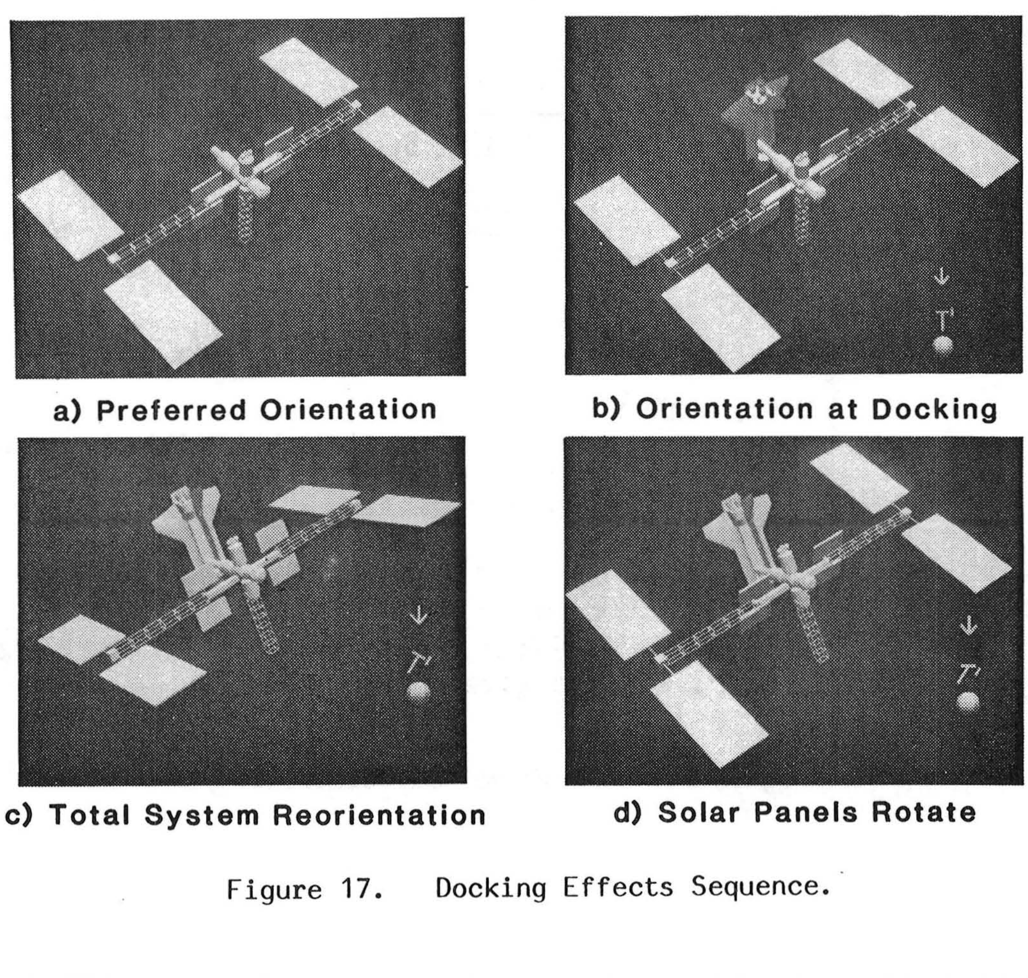


Figure 16. Time Histories of Angular Momentum Requirements.



a) Preferred Orientation

b) Orientation at Docking

c) Total System Reorientation

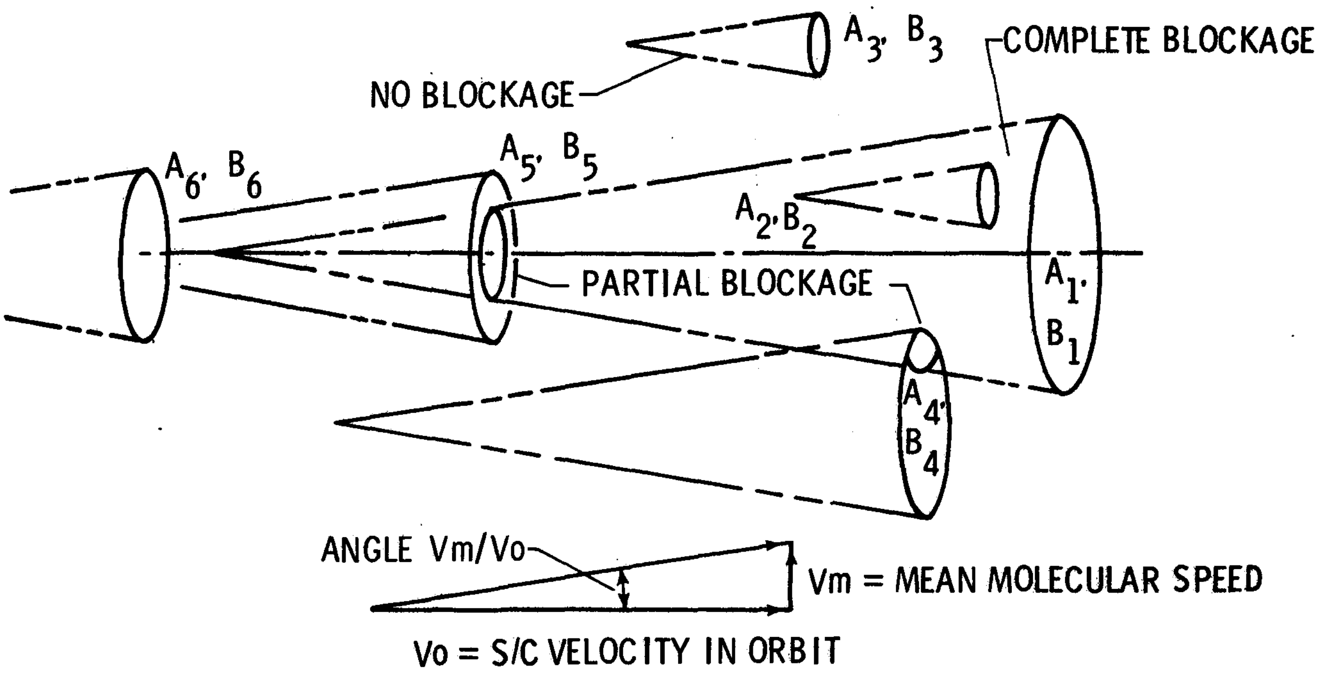
d) Solar Panels Rotate

Figure 17. Docking Effects Sequence.

DRAG AREA CALCULATIONS

Effective drag areas for lattice structures (both with or without a porous mesh) must be determined to generate an aerodynamic drag model for rigid-body controllability analysis and orbital propellant requirements. Drag areas can range from a low percentage of the solid spacecraft area up to the total solid area depending on such factors as the spacecraft size, and the orientation, type, and quantity of structural members. The IDEAS program rapidly accumulates these areas for the rigid-body controls analysis from the data base and finite-element model data created in the synthesizer program

The approach for approximating aerodynamic drag areas is illustrated in Fig. 18. Each node consists of the intersection of several structural elements at various orientations and 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 considered in the calculations. Also, in the case of a porous mesh, the drag effects of the variable transmissability (dependent on the porosity of the mesh and the orientation angle at which the mesh appears solid to the incident molecules) are determined. Solid areas of external suporting subsystems (solar arrays, communication, and control systems) are included.



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 18. Drag Area Calculations.

STATIC STRUCTURAL ANALYSIS

A static structural loading analysis is conducted on the structural elements of the spacecraft concepts that were created in the synthesizer program. These elements are individually designed to support initial estimates of Euler buckling loads. The Static Loads (STLO) program computes on-orbit environmental and spacecraft-induced static loads (thermal, gravity gradient, drag, static thrust, and pretension in the case of tension/compression structures). These loads and the structural element temperatures are input into the Structural Analysis Program (SAP), a general purpose program for linear static or dynamic analyses of three-dimensional structures. The actual static loads, nodal deflections, and internal stresses are determined and compared to the design loads. If the actual and design loads differ greatly, the structural elements can be redesigned. If the redesign significantly modifies the mass and inertia of the spacecraft, the control system requirements can be redefined by the RCD module. Continuous iterations can be performed until a satisfactory solution is obtained for the structural loads, element sizes, spacecraft mass, inertia and drag properties, and control system requirements. At any step in the design and analysis process, the analyst can interactively redesign specific elements that are identified as having potential stress problems and subsystems (which may be either current space-qualified hardware or advanced technology subsystems) can be changed.

DYNAMIC STRUCTURAL ANALYSIS

Mode shapes and natural frequencies of the spacecraft must be defined to determine flexible body controllability requirements. A linear dynamic analysis is provided by the Structural Analysis Program (SAP) dynamic module using inputs from the finite-element model. The first three flexible body frequencies and mode shapes for the contiguous box truss structure used for Earth science and resources missions are shown in Fig. 19. These shapes and frequencies are used in the dynamic response analysis of this class of structure (Ref. 18).

The actual distortions are small, on the order of cm, but are greatly exaggerated here for easy visualization.

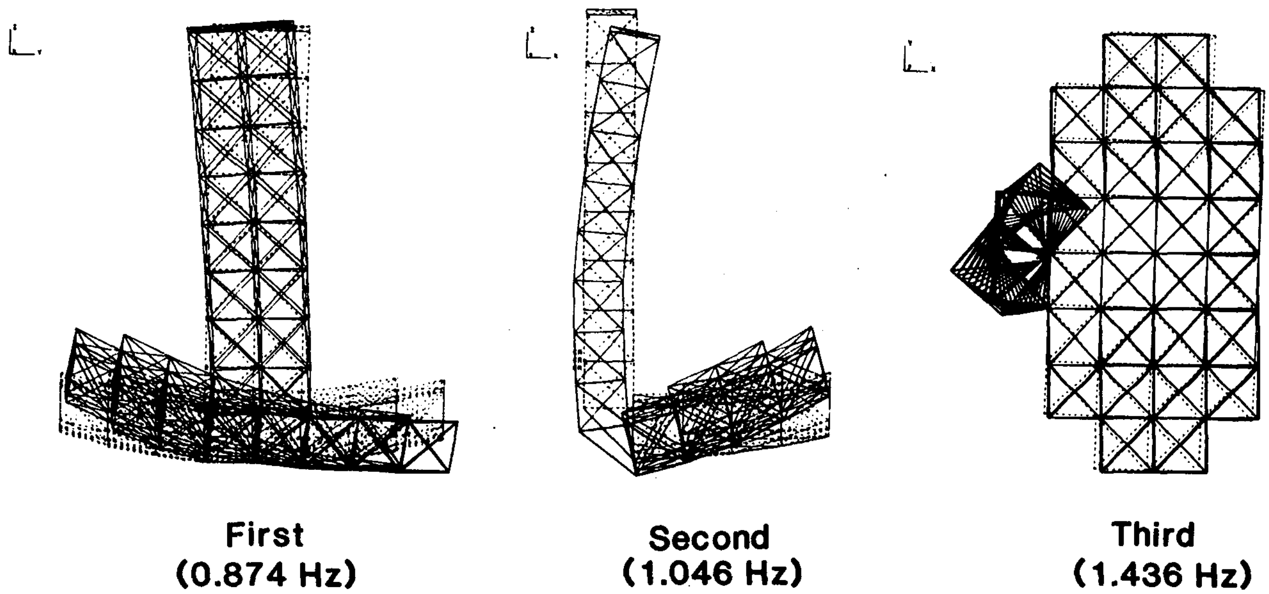
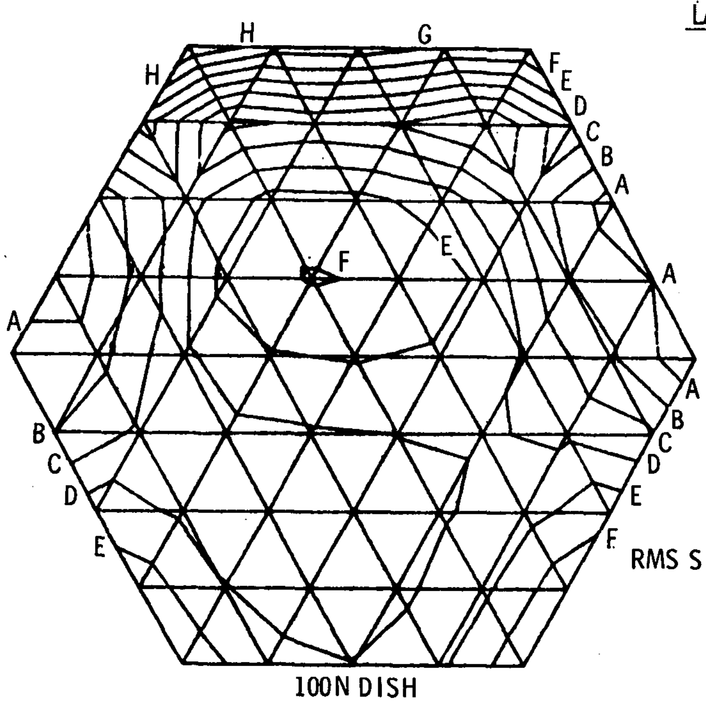


Figure 19. Natural Frequencies and Mode Shapes.

SURFACE ACCURACY OF ANTENNA CONCEPTS

The performance of an antenna's reflective surface is directly related to the smoothness of the surface. Random distortions or surface roughness in a reflector antenna surface can produce secondary radiation patterns that can differ significantly from those of perfectly smooth reflectors (Ref. 19). The reflective surface of large aperture antennas will be constructed of metallic mesh material for weightsaving. Such mesh reflectors are very susceptible to structural deflections in the antenna support structure. The Surface Accuracy (SA) module computes the overall surface roughness (rms displacement), lines of constant deviation from an ideal surface (distortions), changes in focal length, boresight direction and boresight displacement, and plots the local normal displacement and distortion contours for the mesh surface nodes. Structural surface distortions on a tetrahedral truss antenna due to environmental effects (thermal, gravity gradient, and atmospheric drag) only are shown in Fig. 20. The effects of pretensioning of cables are not included. The tetrahedral truss is shown as an example of the surface accuracy analysis since no surface accuracy results are available for the box truss and the hoop and column configurations.



CONTOUR LEVELS

LABEL	VALUE, cm
A	-.0038
B	-.0025
C	-.0013
D	0.0
E	.0013
F	.0025
G	.0038
H	.0051

RMS SURFACE ACCURACY, cm
.0023

Figure 20. Surface Distortion Caused by Environmental Effects.

INTERACTIVE THERMAL ANALYSIS

The finite-element model files can be transferred automatically to the Thermal Analyzer Program in order to calculate the transient temperature response for each structural member at a given position in the spacecraft orbit. Heat sources are solar radiation, Earth albedo, and Earth thermal radiation. The balance between absorption of energy from the three heat sources and reradiation of energy from the elements into deep space is used to determine the transient thermal response. Earth shadowing is included. Three major assumptions are made in this type of analysis. First, each element is considered to be an isothermal element. Secondly, the radiation exchanges between structural members are neglected due to the small radiation view factors. Finally, structural member-to-member shadowing is neglected. Input into this module consists of the model geometry, thermal characteristics of all materials used in the structure, and the position in the orbit where the thermal analysis begins and ends. Output yields elemental temperatures and heating-rate time histories in Fig. 21 and 22 for the box truss configuration of Refs. 16 and 18.

Temperature data on each member can be displayed in a time-passage (dynamic) simulation using the MOVIE BYU software. The temperatures are converted to colors using a color bar ranging from deep blue (160° K) to white (340° K) such that the spacecraft is displayed as a multicolor structure. Selected frames from a dynamic sequence of the spacecraft orbiting the Earth (Ref. 20) are shown in Fig. 23. The figure shows a visualization of the spacecraft structural temperatures at six points in the orbit:

a) On Earth-Sun line, $\eta=0°$,
b) Just prior to entry into Earth's shadow, $\eta=112.5°$,
c) Just after entry into Earth's shadow, $\eta=123.75°$,
d) At mispoint of Earth's shadow, $\eta=180°$,
e) Just prior to exit from Earth's shadow, $\eta=247.5°$ and,
f) Five minutes after exit from Earth's shadow, $\eta=258.75°$.

where η is the angle between the Earth-Sun line and orbital location with respect to the Earth.

To eliminate the motion variable, the spacecraft was held stationary in each figure and the Earth and Sun were allowed to rotate about the spacecraft. A sketch of the orbital plane with the location of the spacecraft at the time of the measurements is shown in the upper-right corner. Since the orbit altitude is extremely small (≈720 km) relative to the Earth's radius, the orbital track is exaggerated to simplify visualization.

At the hottest point in the orbit (Fig. 23(a)), the maximum number of members are aligned perpendicular or near perpendicular to the Sun-Earth line, and the member temperatures range from 266° to 337° K. Just prior to entry into the Earth's shadow (η = 112.50°), the vertical members have changed orientation from parallel to perpendicular to the Earth-Sun line, and have increased temperature to slightly over 300° K and the horizontal members are cooling (Fig. 23(b)). During transit of the Earth's shadow (Figs. 23(c) through 23(e)), the entire spacecraft cools by radiation to 183° to 195° K at the point of exit. Note that the model depicts the gradual cooling in the shadow, instead of producing a step-function decrease after the entry into the shadow. Figure 23(f) shows the rapid rise in temperature that occurred during the first 5 minutes after shadow exit.

The sudden temperature rise in the spacecraft members during the 5 minutes following the Earth's shadow was observed to be approximately 100° K for the hot members and 35° K for the colder members. To provide a more detailed look at this situation, 10 additional data points were taken 1/2-minute intervals during the first 5 minutes after exit from the shadow, the coldest point in the orbit, and are shown in Fig. 24. All members have cooled to between 183° and 195° K (Fig. 24(a)). In the first minute after exit (Fig. 24(b)), the horizontal and vertical members experience a temperature rise of about 50° K to a temperature of 247° K while the diagonal tapes increase less than 5° K.

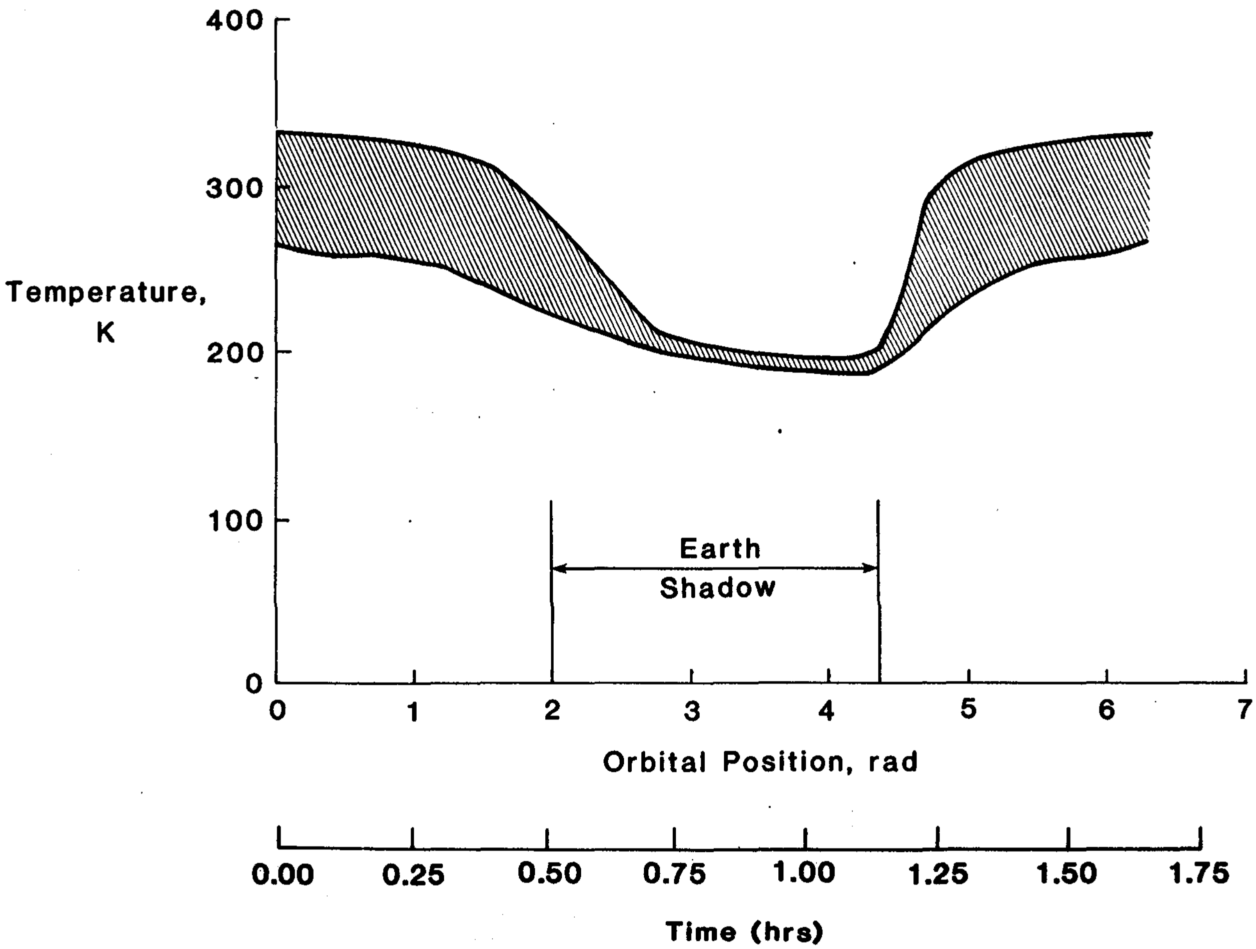
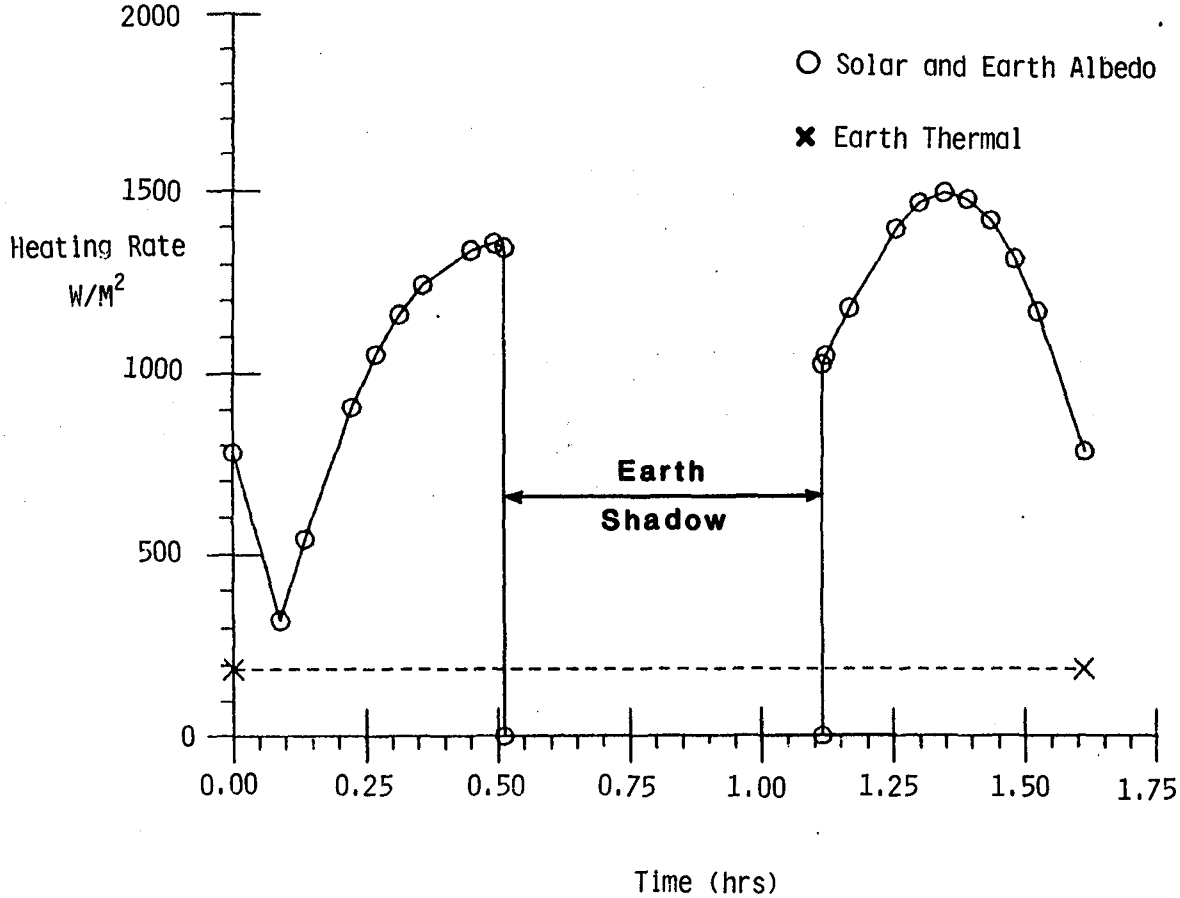
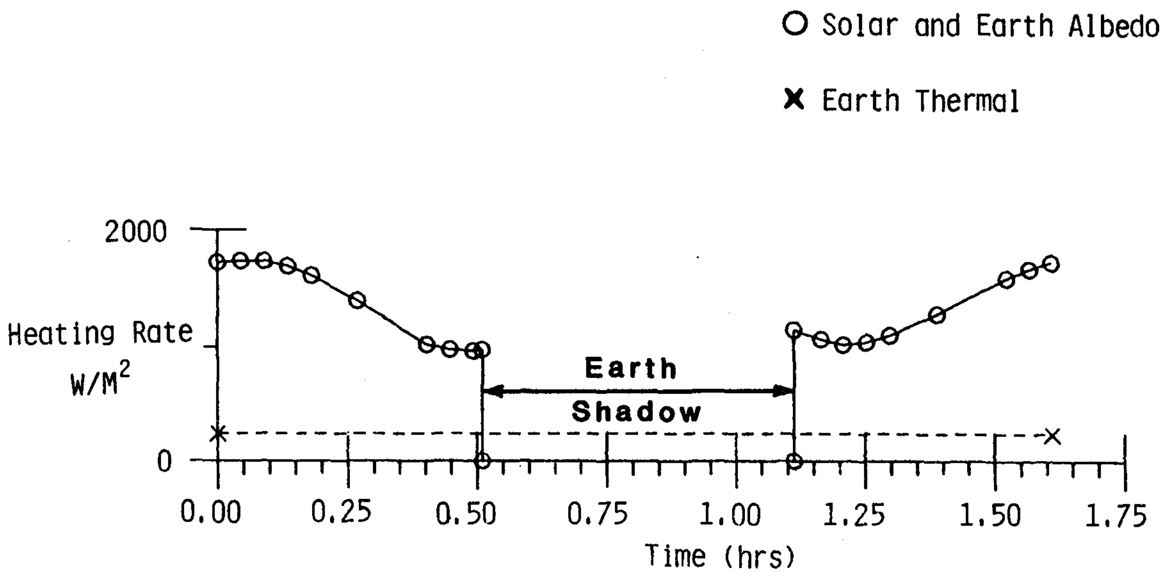


Figure 21. Elemental Temperatures.

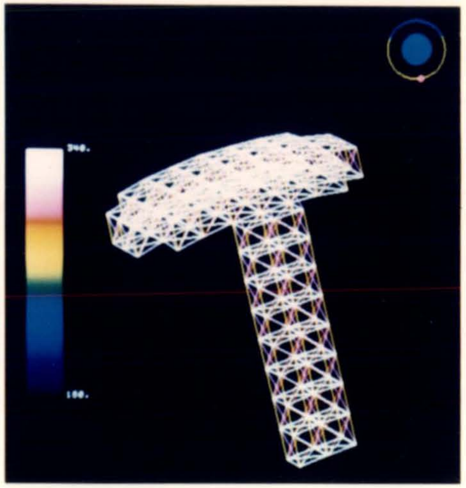


a) Vertical Tube in Feed Mast.

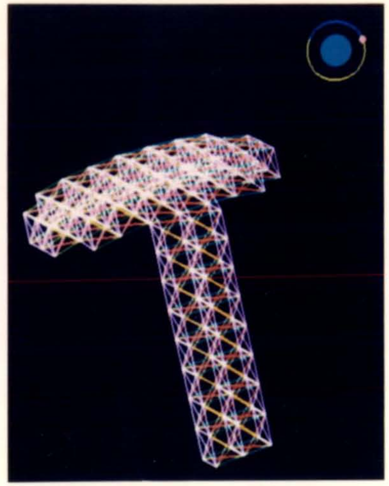


b) Vertical Cable.

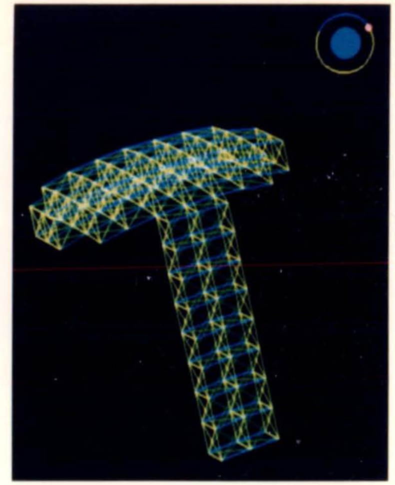
Figure 22. Elemental Heating Rates.



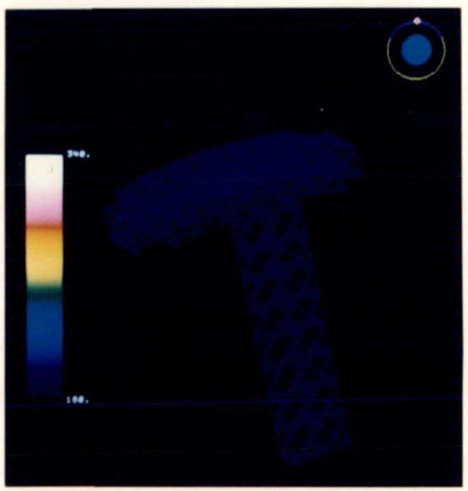
(a) At the hottest point, $\Phi \approx 19°$.



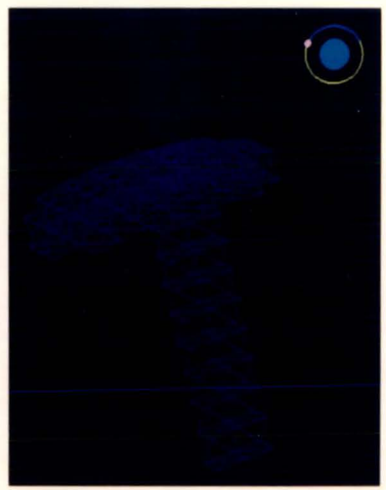
(b) Just prior to entry into Earth's shadow, $\Phi = 112.5°$.



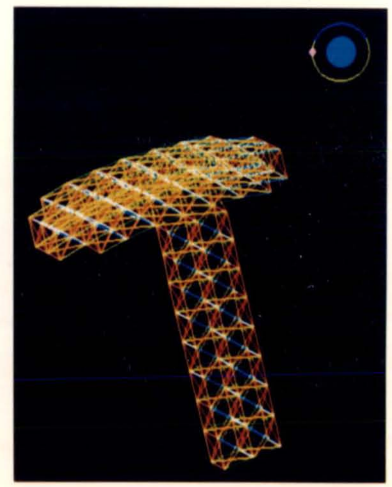
(c) Just after entry into Earth's shadow, $\Phi = 123.75°$.



(d) At midpoint of Earth's shadow, $\Phi = 180°$.

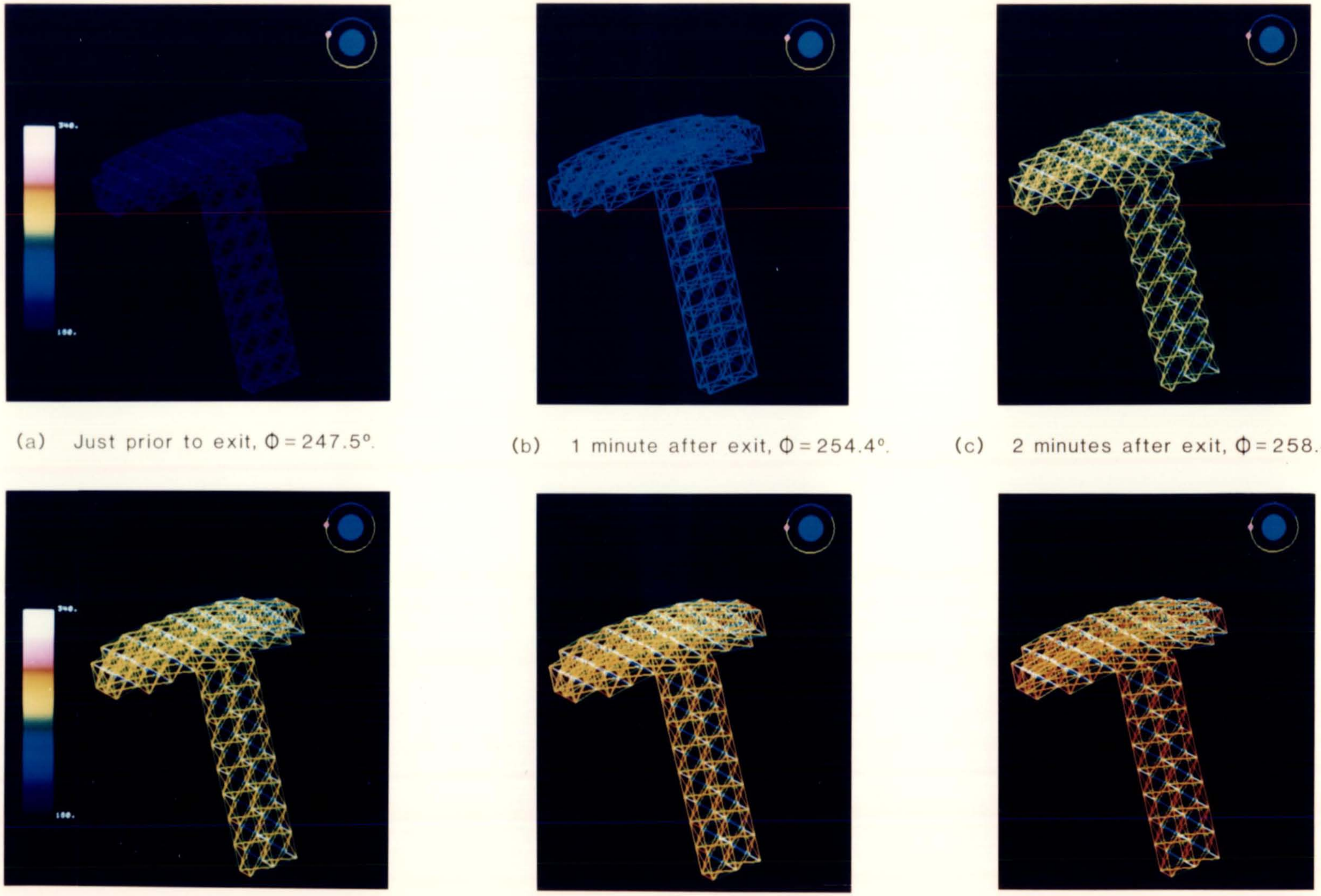


(e) Just prior to exit from Earth's shadow, $\Phi = 247.5°$.



(f) 5 minutes after exit from Earth's shadow, $\Phi = 270.4°$.

Figure 23. Color graphic display of temperature data.



(a) Just prior to exit, $\Phi = 247.5°$.

(b) 1 minute after exit, $\Phi = 254.4°$.

(c) 2 minutes after exit, $\Phi = 258.4°$.

(d) 3 minutes after exit, $\Phi = 262.4°$.

(e) 4 minutes after exit, $\Phi = 268.4°$.

(f) 5 minutes after exit, $\Phi = 270.4°$.

Figure 24. Temperature data at exit from Earth's shadow.

CONCLUDING REMARKS

An interactive systems design and synthesis system for evaluating future spacecraft concepts has been described. The capabilities of the system in synthesizing both large antenna and space station concepts, and space station evolutionary growth designs has been demonstrated. The IDEAS system provides the user with both an interactive graphics and interactive computing capability consisting of over 40 multidisciplinary modules. Using the IDEAS system, a single user can create, analyze, and conduct parametric studies and modify Earth-orbiting spacecraft design at an interactive terminal with relative ease. The IDEAS approach is useful during the conceptual design phase of advanced space missions to the analyst responsible for analyzing and evaluating a multidisciplinary of parameters and concepts in a cost-effective and timely manner.

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16. Abstract

An interactive systems design and synthesis is performed on future spacecraft concepts using the Interactive Design and Evaluation of Advanced spacecraft (IDEAS) computer-aided design and analysis system. The capabilities and advantages of the systems-oriented interactive computer-aided design and analysis system are described. The synthesis of both large antenna and space station concepts, and space station evolutionary growth is demonstrated. The IDEAS program provides the user with both an interactive graphics and an interactive computing capability which consists of over 40 multidisciplinary synthesis and analysis modules. Thus, the user can create, analyze, and conduct parametric studies and modify Earth-orbiting spacecraft designs (space stations, large antennas or platforms, and technologically advanced spacecraft) at an interactive terminal with relative ease. The IDEAS approach is useful during the conceptual design phase of advanced space missions when a multiplicity of parameters and concepts must be analyzed and evaluated in a cost-effective and timely manner.

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