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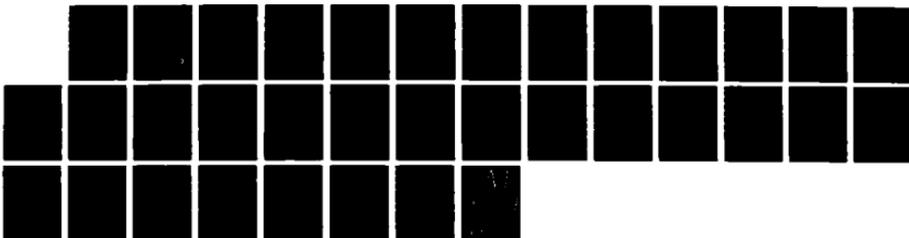
INVESTIGATION OF DESIGN CONCEPTS FOR LARGE SPACE
STRUCTURES TO SUPPORT MI. (U) CONSTRUCTION ENGINEERING
RESEARCH LAB (ARMY) CHAMPAIGN IL R A EUBANKS ET AL.
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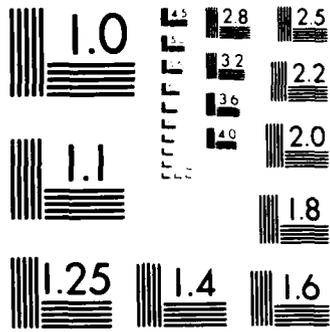
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USA-CERL TECHNICAL REPORT M-87/16

September 1987

Construction Technologies and Methodologies for Space

AD-A186 098

Investigation of Design Concepts for Large Space Structures to Support Military Applications

by
R. A. Eubanks
Alvin Smith

Future exploration and enterprise in low-Earth orbit will most likely require space stations for support. In addition, promotion of the Strategic Defense Initiative (SDI) is mandating research and development (R&D) into technologies for building structures to serve military objectives in space. However, an assessment of the state of the art for space construction technology has revealed that the field is immature, with little conceptual and experimental research completed.

The U.S. Army Construction Engineering Research Laboratory (USA-CERL) has collected information on existing technologies for possible application in designing large space structures (LSS) for military support. This work is part of an effort by the U.S. Army Corps of Engineers (USACE) to ensure mission-responsiveness in anticipation of a role in space construction. USA-CERL is USACE's designated lead laboratory for this program.

Military structures will require design criteria much different from those of experimental space stations. Proposed conceptual criteria for both types of structures are compared and differences are noted. Much R&D is needed before any of these structures can be deployed in space. To serve as background for future studies, a literature critique is included in this report.

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Military structures will require design criteria much different from those of experimental space stations. Proposed conceptual criteria for both types of structures are compared and differences are noted. Much R&D² is needed before any of these structures can be deployed in space. To serve as background for future studies, a literature critique is included in this report.

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FOREWORD

This research was conducted by the U.S. Army Construction Engineering Research Laboratory (USA-CERL) for the Office of the Chief of Engineers (OCE) under Project 4A162731AT41, "Military Facilities Engineering Technology"; Technical Area E, "Echelons Above Corps Support"; Work Unit 056, "Construction Technologies and Methodologies for Space." The work was initiated by a USA-CERL in-house sponsored effort, "Baseline Data for Large Space Structures." Supplemental funding was provided under Military Inter-Departmental Purchase Request (MIPR) Number W31RPD-7-D4099 from the U.S. Army Strategic Defense Command (USASDC). The OCE Technical Monitor was Mr. C. D. Smith, CERD-M; the USASDC Technical Monitor was Dr. L. Blakey, DASD-CD.

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INVESTIGATION OF DESIGN CONCEPTS FOR LARGE SPACE STRUCTURES TO SUPPORT MILITARY APPLICATIONS

1 INTRODUCTION

Background

Space shuttle flights are scheduled to resume as early as 1988, assuming the engineering and design problems that surfaced as a result of the Challenger disaster are corrected. Once the flight program is reestablished, a major objective of the National Aeronautics and Space Administration (NASA) is to construct a space station in low-Earth orbit. There is considerable pressure within NASA to complete such a structure by 1993, although a more realistic date now appears to be 1995.

At the same time, promotion of the Strategic Defense Initiative (SDI) is increasing the likelihood that future shuttle missions will involve military activities. Many of these missions, as well as some projected commercial enterprises, will require space stations for support.

The demand for permanent stations in low-Earth orbit has established the need for a construction technology serving this unique environment. To date, little research and development (R&D) has addressed this area because the focus has been on refining the shuttle technology and on prototype space station design.

The U.S. Army Corps of Engineers (USACE), anticipating a future role in the space construction effort, has initiated a program to ensure mission-responsiveness in this area. USACE is responsible for construction within the Army and Air Force and, on this basis, expects to become involved in the planning, design, and building of military structures in space.

A study by the U.S. Army Construction Engineering Research Laboratory (USA-CERL), USACE's designated lead laboratory for the space construction program, has revealed that the technology for designing and building structures in space is immature.¹ In particular, design concepts for large space structures (LSS) are lacking.

To better establish the state of the art in LSS technology, USA-CERL has singled out this specific topic for a follow-up investigation. By learning more about existing technologies, it should be possible to identify an approach to designing LSS for military applications.

Objective

The two-fold objective of this study is to (1) gather information on LSSs from the literature and other sources and prepare a quick reference guide as background for future

¹C. C. Lozar and L. D. Stephenson, *State-of-the-Art Technologies for Construction in Space: A Review*, Technical Report M-87/17 (U.S. Army Construction Engineering Research Laboratory [USA-CERL], September 1987).

investigations and (2) analyze this information for possible application in designing LSS to support military goals.

Approach

The literature was surveyed and the most applicable sources were documented (Appendix A). USA-CERL also sent representatives to conferences on this topic, and key personnel at NASA were interviewed. Concept design information was analyzed and compared with certain mission-critical elements of military structures. Based on this analysis, standard engineering principles were used to develop general criteria for designing LSS to serve military objectives.

Scope

This study is not intended to be an exhaustive literature review, but seeks only to develop a solid background in a specific area of space construction technology. Many references related to the overall subject are cited in the USA-CERL Technical Report *State-of-the-Art Technologies for Construction in Space: A Review*.

Mode of Technology Transfer

This information eventually will impact technical and operational documents produced as part of the Army Space Master Plan.²

²(S) *The Army Space Master Plan*. (U)

2 COMPARISON OF CONCEPTUAL DESIGN CRITERIA

The technology for LSS is underdeveloped with regard to both design and field testing. Only the simplest examples of LSS have been flown into space; at present, no truss-type LSS such as the space station is ready for deployment in space.* In addition, design procedures dedicated to construction in space have emerged to replace the standard iterative synthesis/analysis cycle outlined in Appendix B.

It is extremely difficult to schedule space shuttle time for testing components. In addition, the Challenger accident triggered cancellation of flights for investigation and redesign. These factors, plus the anticipated military priority for shuttle flights after operations resume, have generated the need for redesign of experimental packages to permit them to be placed into orbit by large, unmanned rocket vehicles. Thus, many designs that were thought to be well advanced must now be reworked extensively. Moreover, increasing concern for astronaut safety has renewed the interest in deployable structures, which eliminate or reduce the demand for astronauts to work during extravehicular activity (EVA) and are better suited to unmanned launch than are erectable structures.

Design Philosophy for NASA Structures

The structures that NASA designs for its own applications--the space station, in particular--are based on requirements completely different from those which would be important for military space structures. NASA structures must facilitate and support scientific experimentation; for this reason, design flexibility is paramount. Also, NASA has assumed that all material and equipment will be transferred from Earth to the space station via the space shuttle, so that the payload must be designed to fit into the shuttle bay. Another assumption is that future experiments may require the space station to be extended in virtually every direction to accommodate any experiment that can be transported in the space shuttle bay. Other experiments may require that the overall configuration of the space station be changed. Hence, all sections of the space station structure should be capable of assembly and disassembly in space.

The nodal joint proposed by NASA's Langley team has some important characteristics: its nodes permit a spar to be attached from almost any desired direction and it is easy to connect/disconnect, which permits manipulation by astronauts wearing the clumsy pressurized gloves. The quick connect/disconnect feature permits nodal play, with consequent hysteretic vibrations of the structure. The joints have little moment resistance and almost no torsional resistance so that there is significant rotational freedom.

The Mobile Remote Manipulator System (MRMS) is essentially a self-propelled platform with an attached remote manipulator arm. NASA plans to use this device in building the space station as an aid in structural assembly, extension, and maintenance. Since NASA will want to use the MRMS on all parts of the structure, operating in all directions, the space station structure will have to provide tracks to support its

*It should be noted that the Hubble Space Telescope has been completed and is ready for placement in space. This structure is preconstructed on Earth and has deployable solar collector appendages. The telescope is 40 ft long with an elastic fundamental frequency of less than 1 Hz.

movement. This requirement is one of the reasons for selecting rectangular section trusses rather than the more structurally efficient triangular shape. More importantly, this is the basis for proposing a structural truss design that contains as many appendages located internally as possible so that the MRMS can traverse the structure unimpeded. The arm on the MRMS is 50 ft long and very flexible; since the remote control system is a "rigid-body" design, the arm must move very slowly to keep from intruding on its own arm's elastic frequencies.

Design Concepts for Military Structures

Structures for military applications will need to have characteristics suited to the specific mission. An important difference between these LSS and those for NASA deployment is that military structures will probably be designed for families of platforms/facilities, each built to meet specific operational requirements. It is therefore neither necessary nor desirable for these structures to be designed with the flexibility of NASA's space station. Furthermore, these structures need not be designed with an "erector set" or "pegboard" philosophy which provides for extensions and attachments at every position on the structure and in every direction.

In some cases, the orientation of military structures will be fixed, and the gravity-gradient stabilization that has been used in satellites and that will be used for NASA's space station is adequate and efficient. However, some military applications may require that the space structure orientation be changed upon command. A structure of this type would be more compact than a gradient-stabilized structure.

Many military structures will have to be capable of quick response and short settling time after a disturbance. In contrast, most civilian activities can be conducted at a much more leisurely pace; for example, the Hubble Space Telescope, which has been built by Marshall Space Flight Center and is awaiting deployment, contains no special provisions to damp vibrations (the fundamental frequency is less than 1 Hz). The telescope designers believe that the lowest frequencies can be controlled by the rigid body pointing control system and they will just wait for inherent structural damping to eliminate higher frequency vibrations. However, military structures will have to provide for fast pointing and immediate elimination of the vibrations resulting from disturbances. The anticipated low air resistance and little natural structural damping of these structures will require that artificial damping be introduced. Active control procedures would be the most effective for very low frequency vibrations, whereas artificially introduced passive damping would best control the higher frequencies. Since both types of amplitude control devices would add weight to the structure, only the level of damping absolutely necessary to function should be specified.

The configuration of military structures probably will be fixed. Therefore, it is not necessary that the structure be capable of disassembly in space, making it possible to rigidify the joints after the structure is assembled. This process of removing free motion from the joints could be combined with the installation of damping materials into the structure. Also, the introduction of a viscoelastic material into the joints to remove free play will increase the energy losses in the structure. (There are several possible approaches for designing these motion-reducing joints, but they are beyond the scope of this report.)

Another anticipated difference between military and civilian applications is in the degree to which structural designs will be duplicated. Most previous civilian space work has been performed on a single-item basis, that is, most structural designs have been

unique. The major exception is the shuttle spacecraft, where five have been produced with essentially the same capabilities, design, and construction. It is also probable that some satellites are duplicates of each other; however, the major duplication has occurred with the military satellites designed for surveillance and other intelligence-related assignments.

If the military protective plan is based on the establishment of a dense strategic protective screen or, more likely, a series of sequentially enclosing strategic protective envelopes, it can be expected that large numbers of very similar space structures will be deployed to serve as bases for antennas, mirrors, and destructive devices. Habitable space will be necessary to provide facilities for space control and space support functions; on-orbit servicing and maintenance; damage control and restoration, space vehicle recovery, and space debris management; and space research, development, test, and evaluation (RDT&E), resource exploitation, space manufacturing, and space port activities.

The concept of using a large number of identical structures implies a completely different set of tradeoffs than are considered in designing the single-item NASA missions. For example, if hundreds of identical antennas and antenna bases will be built, it will be important to spend more effort on optimizing structural design than has been typical of commercial projects. In addition, it will be cost-effective to field-test several successively improved structural designs in the space environment. These additional steps theoretically will reduce the structural loads in space, with a consequent reduction in cost and increased speed of deployment.

Since U.S. defense may depend on these LSS, the need for high levels of reliability and dependability will directly affect the structural design and the design process. Competent engineering and detailed analysis and testing will be critical. Structures can be designed for extreme reliability or for easy maintenance, or both; this issue will demand major tradeoff studies to ensure national security in the most cost-effective way.

Military structures will have to withstand the hostile space environment for very long periods of time. In addition, designers will need to consider hardening against hostile human attack at a systems level (e.g., the whole set of sensors, processors, communication links, and the supporting platform). Although some hardness may be incorporated into individual structures, it is possible that system hardness will depend instead on redundancy in the acquisition elements as well as in the weaponry. The approach chosen as the best solution will again strongly affect the engineering and structural design processes and, to varying degrees, construction support capabilities such as damage control and restoration.

As with its terrestrial structures, USACE will need to design military space structures for rapid, simple erection and deployment. The space surrounding Earth is inhospitable particularly at heights suitable for geosynchronous orbit.* If the structures will be deployed or erected by trained specialists during EVA, the bulkiness of the spacesuits and major effort required for ordinary tasks mandate that demands on the astronauts be simple. Also, the high levels of radiation and random ballistic hazard due to micrometeorites and space debris mean that EVA durations should be as short as possible or planned with proper shielding or protection. While construction by robots is a promising

*That is, an orbit in which the orbiting body's period of revolution is exactly the same as the period of rotation of the Earth.

alternative to EVA labor, this technology is still in the planning stages; teleoperated robots for space assembly will probably be available within the next 10 years. The unique military requirements for large numbers of identical space structures would justify the development of specialized robots dedicated to construction; nevertheless, robotic development will be hastened if the tasks to be performed are kept as simple as possible.

Robotic construction machines may be better suited than NASA's MRMS for both construction and maintenance of military structures. Maintenance on the military space installation could be conducted by a fleet of self-propelled robots that would carry specialized heads, actuators, and graspers specific to one or more structures. These maintenance machines could be teleoperated from the crew module on the space station, from the space shuttle, or, if control mechanisms could be modified to compensate for time lags, from land-based stations. The experience of both NASA and Soviet personnel in space shows that the human eye is more readily adaptable to situation-sensitive activities (such as robotic operations) than are electrooptic/television monitoring sight systems.

Impact of Special Constraints

To optimize the structural design of military LSS, constraints associated with the construction process in space will have to be considered. In many cases, these construction constraints will govern structural design of the system. The need for simple design and rapid construction has already been mentioned. Another consideration is that specific loadings may be greater during construction than at any other time. (This situation is in contrast to that of preconstructed, deployable structures, for which the design loading is expected to be greatest during launch.) Elements and substructures that will be well supported in the final design may be subjected to inertial loadings associated with slewing and positioning while they are in an unsupported state (i.e., as components are being added to the structure but before all are interconnected). In addition, since neither astronauts in EVA nor currently available robots have very sensitive feedback control, thin-walled tubing, sheeting, and other flimsy elements must be able to withstand insensitive handling as a major design criterion or they must be accommodated with the introduction of forming materials or stabilizing means such as scaffolding.

The erection of space structures requires a significant amount of time for an astronaut to don a space suit, connect the umbilicals, and enter the cargo compartment; a correspondingly long time period is involved in returning to the crew compartment and removing the EVA equipment. New, hard suit designs will shorten the egress/ingress times, but not the actual EVA period. Specific construction/assembly activities may be affected by the suit design, but no definitive data is available at this time. Therefore, it is assumed that, once astronauts have entered EVA, they will remain there until all required tasks are completed, even though several hours may elapse between these tasks. Sensible operational procedures can reduce the exposure and danger; however, an alternative would be to use deployable structures instead of erectable structures. Deployable structures can reduce the time required for astronauts to be in EVA. If astronauts must remain in EVA during periods when they have no task to perform except to be on hand to correct possible errors due to a miscue, the advantage of deployable structures is significantly reduced.

3 CONCLUSIONS

The technology for LSS design and construction is immature. Intensive R&D in this area is needed to ensure that the United States will be able to support future enterprises in space through deployment of structures. A special concern is for LSS that would be involved in national defense objectives such as SDI.

USA-CERL has surveyed the literature on LSS technology from the perspective of potential application to military construction in space (Appendix A). In addition, information from the literature and other sources has been analyzed from the standpoint of design requirements unique to the military mission.

Based on this analysis, it is clear that military structures would have design criteria different from those of NASA's conceptual space station. Military stations will most likely have a dedicated function, so that the flexibility designed into NASA's experimental structures would be unnecessary. However, military structures would need to be capable of rapid reorientation upon command.

Another difference is the redundancy projected for military construction in space. Previous missions have deployed structures such as antennas on a case-by-case basis; that is, each item has been through a separate design and construction process. Military systems probably will use large numbers of identical structures, thus making it cost-effective to concentrate resources on optimizing the design through field tests and evaluation.

As with all structures to be built in space, the design of military facilities must consider constraints inherent in the environment. Rather than depend on astronaut labor during EVA, it may be more cost-effective to develop robotic technology for construction and maintenance of military systems because of the expected repetition of identical structures. In addition, deployable structures may have advantages for military objectives that outweigh those of erectable systems.

APPENDIX A:

REVIEWS OF SELECTED DOCUMENTS

Large Space Antenna Systems Technology 1984, NASA Conference Publication 2368, Parts I and II, December 1984.

These two volumes are the proceedings of a conference held in Hampton, VA, during December 4-6, 1984. They are valuable because many of the 55 papers describe LSS concepts--both deployable and erectable. Some data on environment and performance criteria also are included. Titles and authors of the papers in these proceedings are as follows:

SESSION 1: MISSION APPLICATIONS FOR LARGE SPACE ANTENNA SYSTEMS

NASA Mobile Satellite Program

George Knouse and William Weber

Alternatives for Satellite Sound Broadcast Systems at HF and VHF

Bruce E. LeRoy

**Development Concerns for Satellite-Based Air Traffic Control
Surveillance Systems**

Keith D. McDonald

**Application of Pushbroom Altimetry From Space Using Large Space
Antennas**

C. L. Parsons, J. T. McGoogan, and F. B. Beck

**Orbiting Multi-Beam Microwave Radiometer for Soil Moisture Remote
Sensing**

J. C. Shiue and R. W. Lawrence

Low-Frequency Microwave Radiometer for N-Ross

J. P. Hollinger and R. C. Lo

**Large Space Antenna Technology Applied to Radar-Imaging, Rain-Rate
Measurements, and Ocean Wind Sensing**

R. K. Moore and S. P. Gogineni

**Advanced Two-Frequency Ocean Sensing Radar Using High Resolution
Antenna Beams**

D. E. Weissman and J. W. Johnson

**QUASAT - An Orbiting Very Long Baseline Interferometer Program Using
Large Space Antenna Systems**

J. F. Jordan, R. E. Freeland, G. S. Levy, and D. L. Potts

LDR System Concepts and Technology

Bruce Pittman

SESSION 2: LARGE SPACE ANTENNA STRUCTURAL SYSTEMS

Wrap-Rib Antenna Technology Development

R. E. Freeland, N. F. Garcia, and H. Iwamoto

Development of the 15-Meter Hoop/Column Antenna System

T. G. Campbell, D. H. Butler, K. Belvin, and B. B. Allen

Box Truss Development and Its Applications

J. V. Coyner

Synchronously Deployable Tetrahedral Truss Reflector

H. G. Bush, C. L. Herstrome, P. A. Stein, and R. R. Johnson

Antenna Technology for QUASAT Application

John S. Archer and William B. Palmer

Cable-Catenary Large Antenna Concept

W. Akle

Extreme Precision Antenna Reflector Study Results

G. R. Sharp, L. D. Gilger, and K. E. Ard

SESSION 3: MATERIALS AND STRUCTURES TECHNOLOGY

NASA Space Materials Research

Darrel R. Tenney, Stephen S. Tompkins, and George F. Sykes

New Concepts in Deployable Beam Structures

Marvin D. Rhodes

Precision Space Structures

Keto Soosaar

Precision Antenna Reflector Structures

John M. Hedgepath

Space Station Structures

W. Schneider

Verification for Large Space Structures

J. Chen and J. Garber

An Optimization Study to Minimize Surface Distortions of a Hoop/Column Antenna

G. A. Wrenn

Structural Dynamics Analysis

J. Housner, M. Anderson, W. Belvin, and G. Horner

AFWAL Space Control Technology Program

V. O. Hoehne

SESSION 4: STRUCTURAL DYNAMICS AND CONTROL TECHNOLOGY

On-Orbit Systems Identification of Flexible Spacecraft

Larry Taylor and Larry D. Pinson

An Eigensystem Realization Algorithm for Application to Modal Testing

Jern-Nan Juang

MSFC Data Analysis of the SAFE/DAE Experiment

R. W. Schock, T. E. Nesman, and D. K. Reed

Langley Research Center Photogrammic Measurements of Solar Array Dynamics: Preliminary Results

M. Larry Brumfield, Richard S. Pappa, James B. Miller, and Richard R. Adams

Large Antenna Control Methods: Current Status and Future Trends

G. Rodriguez, Y. H. Lin, and M. H. Milman

Experimental Development of a Failure Detection Scheme for Large Space Structures

Raymond C. Montgomery and Jeffrey P. Williams

Dynamic Verification of Large Space Structures

D. K. Tollison and H. B. Waites

Passive and Active Control of Space Structures (PACOSS)

G. Morosow, H. Harcrow, and L. Rogers

Application of the Maximum Entropy/Optimal Projection Control Design Approach for Large Space Structures

D. C. Hyland

SESSION 5: ELECTROMAGNETICS TECHNOLOGY

Electromagnetic Analysis for Surface Tolerance Effects on Large Space Antennas

C. R. Cockrell and R. C. Rudduck

Application of Modern Aperture Integration (AI) and Geometrical Theory of Diffraction (GTD) Techniques for Analysis of Large Reflector Antennas

Roger C. Rudduck

Feed System Design Considerations for Large Space Antenna Systems.

Part I - Multiple Apertures With Non-Overlapping Feeds

M. C. Bailey

Feed System Design Considerations for Large Space Antenna Systems.

Part II - Single Aperture With Overlapping Feeds

V. Jamnejad

Diffraction Analysis of Mesh Deployable Reflector Antennas
Y. Rahmat-Samii

**Determination of Electromagnetic Properties of Mesh Material Using
Advanced Radiometer Techniques**
R. F. Harrington and H-J C. Blume

SESSION 6: LARGE SPACE ANTENNA SYSTEMS AND THE SPACE STATION

The Space Station as a Construction Base for Large Space Structures
R. M. Gates

Utilization of Space Station by the Large Deployment Reflector
L. W. Bandermann and W. H. Alff

**Large Deployable Reflector (LDR) Requirements for Space Station
Accommodations**
David A. Crowe, Michael J. Clayton, and Fritz C. Runge

A Concept for Mobile Remote Manipulator System
Martin M. Mikulas, Jr., Harold G. Bush, Richard E. Wallsom, and
J. Kermit Jensen

**Space-Based Antenna Measurement System Concepts for Space Station
Operation**
C. Louis Cuccia, Thomas G. Campbell, W. L. Pritchard, and Jud Lyon

SESSION 7: FLIGHT TEST AND EVALUATION

Solar Array Experiment (SAE) Flight Experience
Henry C. Hill, Leighton E. Young, and Gary F. Turner

**Assembly Concept for Construction of Erectable Space Structure (ACCESS)
Neutral Buoyancy Testing Results**
Walter L. Heard, Jr.

**Space Technology Experimental Platform (STEP) Status - An In-Space Test
Facility**
Jack E. Harris

**Control of Flexible Structures (COFS) Flight Experiment Background and
Descriptions**
Brantley R. Hanks

Shuttle-Attached Antenna Flight Experiment Definition Study (FEDS)
G. J. Hannan

**Electro-Science Requirements for Shuttle-Attached Antenna Flight
Experiments**
William L. Grantham, Emedio M. Bracalente, and Lyle C. Schroeder

Session 2, Large Space Antenna Structural Systems, is particularly valuable because it presents much of the state-of-the-art in deployable structural systems as of 1984. Additional configurational data are included in Session 3; the articles by Rhodes and by

Soosaar are especially informative. Schneider's article updates many LSS construction ideas. Although most papers at this conference were conceptual, they do present a fairly comprehensive picture of current LSS thought.

Research on Large Highly Accurate Inflatable Reflectors, by R. Bradford, Spectro Research Systems, Huntsville AL, prepared for the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, CA, July 1984.

The abstract reads as follows:

Very large and accurate reflective surfaces are required for future space applications such as solar rocket propulsion, radar, laser power transmission and relay, solar energy collection, telescopes, and others. Present techniques used to construct highly accurate reflectors are limited in application to diameters of a few meters. Metalized thin film membranes have the potential to satisfy the requirements of most future applications with minimum weight systems. The objective of this research was to identify materials, construction and control techniques to improve the surface accuracy of inflatable reflectors. Film jointing and forming, support structure design options, surface accuracy measurement system options, and electrostatic surface configuration control techniques were investigated. Prototype models were designed, built, and tested to demonstrate film forming techniques, support structure deployment, and electrostatic membrane configuration control utilizing segmented charge plates and an electron gun. A laser ray-tracing technique was employed to measure surface accuracies. These demonstrations verified the feasibility of the concepts.

The report describes an investigation of the feasibility of attaining 0.1-mm RMS accuracy on an inflatable reflector for use in space. The text states:

Inflatable membrane double-paraboloid or cone-over-paraboloid reflectors typically incorporating a self-rigidized inflated peripheral support torus offer inherent simplicity structurally, in deployment, and in relative ease of obtaining a rather high precision of surface figure. The limitations include micrometeoroid penetration, inflatant leakage, membrane tensile nonuniformities, thermal expansion effects, micrometeoroid penetration tears, inherent membrane directional and thickness anisotropies, and a small inherent higher-order-term theoretical deviation from perfect paraboloid shape.

Although the document describes the feasibility of these concepts, the probability of achieving many of them is not established. This document also contains information on environment, material properties, and small-scale terrestrial tests, but there are crippling deficiencies. Especially notable is that virtually none of the formulas, procedures, or data-groups mentioned have a reference source cited. The reference list itself is quite short (15 sources) and incomplete. It is augmented by Appendix I--Illustrative Literature Survey Titles Listing--which contains 42 items with no indication of date, source, or even type of publication.

In-Space Research Technology and Engineering (RT&E) Workshop. Proceedings of a Conference at the National Conference Center, Williamsburg, VA, Oct 8-10, 1985; sponsored by NASA Langley Research Center and Office of Aeronautics and Space Technology (OAST).

This report is published in eight volumes:

1. Executive Summary
2. Space Structures (dynamics and control)
3. Fluid Management
4. Space Environmental Effects
5. Energy Systems and Thermal Management
6. Information Systems
7. Automation and Robotics
8. In-Space Operations.

The papers comprising these documents were generated primarily by NASA in-house activity. Almost all papers describe a possible experiment to be conducted in space to answer one or more questions involving the space environment or operations in space. The conference was called by NASA and OAST to provide a forum for critical evaluation of NASA's plans by industrial and university representatives.

Each volume is meant to stand alone; Volume 1, the executive summary, is very useful because it summarizes all work and cites the conclusions for each of the seven theme sections. Volume 2, space structures dynamics and control, is particularly applicable to USA-CERL's mission. Although 31 different experiments are described, they are the work of a much smaller number of contributors. Notable among the engineers who had multiple presentations are Woo and Marzwell of the Jet Propulsion Laboratory (JPL), Gates of Boeing, and Crawley of Massachusetts Institute of Technology (MIT). The following articles are presented on this theme:

Control of Flexible Structures (COFS)

Herman L. Bohon (Langley Research Center [LaRC])

Space Station System Performance Technology Experiment

Uriel M. Lovelace (LaRC)

Flight Dynamics Identification

Raymond Woo and Neville Marzwell (JPL)

Advanced Controls

Claude R. Keckler (LaRC)

Advanced Experiment Pointing and Isolation Device

Claude R. Keckler (LaRC)

Large Space Structures Disturbance Suppression

Raymond Woo and Neville Marzwell (JPL)

Distributed Control

Raymond Woo and Neville Marzwell (JPL)

Advanced Adaptive Control
Raymond Woo and Neville Marzwell (JPL)

Attitude Control and Energy Experiment
Eric Rodriguez (Goddard Space Flight Center [GSFC])

Large Space Reflectors Flight Experiment on the Space Station
Robert E. Freeland and John C. Mankins (JPL)

Large Space Structures
Richard M. Gates (Boeing/MSFC)

Space Station Modifications
Richard M. Gates (Boeing) and James K. Harrison (MSFC)

Fiber Optic Sensors in Space Applications
Wilfred Otaguro, E. Udd, and R. Cahill (McDonnell-Douglas Aircraft Company [MDAC])

EVA Large Structures Assembly
Robert J. Dellacamera (MDAC)

Advanced Antenna Assembly and Performance
Richard M. Gates (Boeing/MSFC)

On-Orbit Spacecraft Assembly/Test
Richard M. Gates (Boeing/MSFC)

Precision Optical System Assembly
Richard M. Gates (Boeing)

Inflatable/Rigidizable Structural Element
Gordon Bakken (Wyle/MSFC)

In-Space Actively Controlled Structure
Philip Studer (GSFC)

Space Station Strain and Acoustic Sensors
Joseph Heyman (LaRC)

Thermal Shape Control
Howard M. Adelman (LaRC)

Advanced Control Device Technology
Nelson J. Groom (LaRC)

Ion Beam Cold Welding
Bernard L. Sater (LaRC)

Large Deployable Reflector Space Station Impact
William Alff (Lockheed Missiles and Space Company/Ames Research Center [LMSC/ARC])

Technology Development Mission for Large Deployable Reflector
Donald L. Agnew (Kodak/ARC)

Structural Concepts Research Facility
Edward Crawley (MIT)

Micro-Meteorite Protection
Edward Crawley (MIT)

Environmental Influence on Structural Dynamics
Edward Crawley (MIT)

Polymeric Materials for Space Mechanisms
Stuart Lowenthal (Lewis Research Center [LeRC])

Berthing and Docking Sensor
Wilfred Otaguro (MDAC) and Harry Erwin (JSC)

Assembly Concept for Construction of Erectable Space Structure
Doug Heard (LeRC)

The summaries are of great interest because they evaluate and report technologies and critical elements that need to be developed. Noteworthy comments are included:

The committee felt that validation of proposed space station initial operational capability (IOC) structure including construction techniques, utility integration, and long-term integrity, was not adequately addressed. The use of passive damping to solve station vibration problems was lacking. No experiments involved with in-space loads characterization for the station were proposed. Consideration of cost-effective hardware was not apparent in proposed experiments. Finally, efforts on structurally embedded sensors/actuators, vibration shape/control devices, and low-frequency isolators were inadequate.

The committee felt that there was a lack of advanced structural concepts for space construction. More effort is needed on design and ground tests of advanced concepts for making structural surfaces elements and joints, for providing protection from debris and for developing advanced large antennas. Once the station is operational it was anticipated that numerous opportunities for making structures in-space might be conceived.

It is apparent that there is incohesiveness in the proposed experiments. Most of them propose using the space station as a base for experimentation; on the other hand, actual construction of the space station requires the knowledge that several experiments are supposed to impart. Some central authority should apply judicious thought to eliminating this dilemma.

This proceedings is important because it presents NASA's understanding of the state of the art as of October 1985. Since the Challenger accident in January 1986 has been a major setback to development, it can be assumed that this series is close to reporting the current (September 1986) state of the art.

Measurement of the Inertial Constants of a Rigid or Flexible Structure of Arbitrary Shape Through a Vibration Test, by D. Engrand and J. Cortial, Leo Kanner Associates, Redwood City, CA, NASA TM-77557, March 1983 (Microfilm).

This article is translated from a July 1970 French version. It presents a series of vibration tests with known auxiliary springs, in known directions. Analytical juggling of the test results can, in theory, deliver the components of the rigid-body mass and inertial matrices. If the item under investigation has significant flexibility, the auxiliary springs must be quite soft and additional tests must be run to eliminate the effects of the structural flexibility.

This method requires several tests that may be difficult to establish for a large or ungainly piece of equipment. Errors can be introduced from many sources, including the finite impedances of the test bed, deviations in the test setups, and inaccurate readings. Manipulations required for the test results can amplify errors to the point at which statistical deviations are much greater than the values to be determined. This procedure is not useful for LSS.

"Parameter Estimation for Large Space Structures," by T.K. Hasselman and Jon D. Chrostowski, in *Optimization Issues in the Design and Control of Large Space Structures*, American Society of Civil Engineers (ASCE), May 1985.

This paper discusses mathematical modeling of structures and the effect of using different parameters in fitting the mathematical model response to experimentally observed responses. Model modification to reflect differences in gravity effects is one possible application of this approach, but the current evaluation of a complex structure is not very probable.

"Structural Approximation of Control Performance, by Brantley R. Hanks, in *Optimization Issues in the Design and Control of Large Space Structures*, ASCE, May 1985.

The author shows a method by which linear optimal control system theory can be used as a guide to determining mass and stiffness distributions; these distributed values permit a driven passive beam to approximate an optimal response. However, it would appear that similar results can be achieved directly without requiring an extraneous theory. From a practical standpoint, it is not clear that the need for a tailored response will arise. Thus, this paper may represent an approximate solution to a nonexistent problem.

"The Effects of Structural Optimization on the Design of Controls in Large Space Structures," by N. S. Khot and V. B. Venkayya, in *Optimization Issues in the Design and Control of Large Space Structures*, ASCE, May 1985.

A static optimal design approach is presented in which the weighted sum of the squares of the displacements of a finite number of points in a structure is minimized, subject to a constant-weight type assumption. The article then hypothesizes that an active control system which is applied to a structure will be able to generate a higher effective damping if the structure has been statically optimized. As with most structural optimization approaches, the procedures developed in this paper would rapidly become unwieldy as the number of structural degrees of freedom increases. In addition, the usefulness of this paper is questioned because of the well known fact that the optimal solution to the static structural problem will always be statically determinate. In most

practical designs, redundancy has so many desirable effects in terms of safety (such as the early warning of failure) that it is nearly always required.

In their structural optimization scheme, the authors neglect to indicate the role of the applied forces. Since minimizing these forces would lead to a trivial result, it must be assumed that the forces in their optimization are prescribed and constant.

"Active Control of Structures and Non-Linear Response," by Manohar P. Kamat, in *Optimization Issues in the Design and Control of Large Space Structures*, ASCE, May 1985.

The author has developed a control design approach for active control of nonlinear structures. The nonlinearities considered are associated with extremely large deflections; these large deflections would not be included in the design envelope of any currently established design process. This paper might be of theoretical interest to control systems researchers, but it does not seem to contribute much to the state of the art in pragmatic structural design. However, this paper does consider the special characteristics of extremely large structures and proposes a computational algorithm that takes advantage of the relative lack of stiffness matrices associated with such large structures.

Optimization Issues in the Design and Control of Large Space Structures, ASCE, May 1985.

A general statement about this collection of four papers on active control of structures is that it is mistitled. In fact, only one of the four papers, that by Dr. Kamat, contains information on the special nature of LSS. In two other cases, the authors are actually concerned with shaping the structure's time-response behavior. This problem is very important in electronics engineering design and has some application in designing mechanical controls. However, there is no apparent rationale for applying this technology to structural analysis.

Structural Stiffness, Strength and Dynamic Characteristics of Large Tetrahedral Space Truss Structures, by Martin M. Mikulas, Jr., Harold G. Bush, and Michael F. Card, NASA Technical Memorandum TM X-74001, March 1977.

The abstract is as follows:

Physical characteristics of large skeletal frameworks for space applications are investigated by analyzing one concept: the tetrahedral truss, which is idealized as a sandwich plate with isotropic faces. Appropriate analytical relations are presented in terms of the truss column element properties which for calculations were taken as slender graphite/epoxy tubes. Column loads, resulting from gravity gradient control and orbital transfer, are found to be small for the class structure investigated. Fundamental frequencies of large truss structures are shown to be an order of magnitude lower than large earth base structures. Permissible loads are shown to result in small lateral deflections of the truss due to low-strain at Euler buckling of the slender graphite/epoxy truss column elements. Lateral thermal deflections are found to be a fraction of the truss depth using graphite/epoxy columns.

The truss structure described in this report is apparently best suited for large planar trusses. Several formulas are presented without references.

Recent Advances in Structural Technology for Large Deployable and Erectable Spacecraft, by H. G. Bush and W. L. Heard, Jr., NASA Technical Memorandum 81905, October 1980.

This report summarizes information generated previously and reported in other papers, primarily NASA Technical Memorandum 81904 (see next entry). Technical Memorandum 81905 contains figures and graphs showing design considerations, but no derivation for these results is included.

Deployable and Erectable Concepts for Large Spacecraft, by H. G. Bush, W. L. Heard, Jr., J. E. Walz, and J. J. Rehder, NASA Technical Memorandum 81904, October 1980.

This report compares a packaging and transportation scheme for a deployable tetrahedral space truss with that of an erectable tetrahedral space truss. Some equations are presented without derivation, and most material shown in the graphs of results is unreferenced. In some cases, this material has resulted from application of a FORTRAN optimization computer program. The deployable concept requires that the structure be folded and placed inside the space shuttle cargo bay. On the other hand, the erectable concept is said to be more efficient for larger structures because the struts are conical tubes which are packed in such a way that they nest inside each other; this packaging efficiency would minimize shuttle flights required to build very large space structures. Since both deployable and erectable structures have been mass-optimized, the restrictions on space shuttle payload weight apply only in the case of smaller structures and very-low-frequency platforms.

General Description of Nestable Column Structure and Assembly Technology, by Harold G. Bush and Walter L. Heard, Jr., NASA Technical Memorandum 83255, December 1981.

Investigations on the nestable column structural concept are described. This erectable structure requires two astronauts in EVA with the help of a work platform. A large tetrahedral truss segment was manufactured in a 1-G environment; this test article contained 36 struts, each 5.3 m long. A second structure that contained 38 struts was also assembled. At the time of this report, some work had been done in the Neutral Buoyancy Facility at Marshall Space Flight Center, but only a scale model of this Langley Research Center structure had been tested underwater.

A Mobile Work Station Concept for Mechanically Aided Astronaut Assembly of Large Space Trusses, by Walter L. Heard, Jr., Harold G. Bush, Richard E. Wallsom, and J. Kermit Jensen, NASA Technical Paper 2108, March 1983.

The tetrahedral truss just discussed is analyzed for assembly of the erectable truss form. The primary tool to be developed is a mobile workstation. This station would help astronauts assemble the structure, but EVA would still be necessary for the entire process. A workstation model was constructed and tested in an underwater tank. The assembly procedure was considered to be satisfactory.

"Design, Development and Mechanization of Precision Deployable Truss With Optimized Structural Efficiency for Space Borne Applications," by N. D. Craighead, T. D. Hult, and R. J. Preliasco, in *Proceedings of the 16th Aerospace Mechanism Symposium*, NASA Publication 2221, May 1982.

A 122-meter-long, 40-bay mast composed of tapered graphite-epoxy tubes slightly greater than 3 m long is described. This beam structure has folding longerons and is

deployable through automation. It is part of an antenna system that fits inside the shuttle cargo bay. Joint details are given and the automated deployment procedure is described.

"Flexible Vibration of Gravity-Stabilized, Structurally Damped, Large Flexible Satellites," by Shashi K. Shrivastava and Prashanta K. Maharana, in *Journal of Guidance*, Vol 8, No. 2, March-April 1985.

This condensed paper is directed toward specialists of guidance and control. In many cases, the symbols are poorly defined and the reasoning is somewhat hard to follow. However, some of the results are intriguing--particularly those of stability plots for flexural vibration in elliptic orbits, for which several unstable ranges are shown to exist.

Fabrication of Slender Struts for Deployable Antennas, by R. Bluck and R. R. Johnson, Lockheed Missiles and Space Company, NASA Contractor Report 172164, April 1983.

A procedure is described for manufacturing long, slender, graphite tubing. Also, a procedure for fabricating graphite-epoxy tubing with aluminum foil inner and outer wraps is proposed.

Considerations in the Design of Large Space Structures, by John M. Hedgepeth, Richard H. MacNeal, Karl Knapp, and Charles S. MacGillivray, NASA Contractor Report 165744, August 1981.

This document is a collection of four unrelated presentations, all of which are concerned with various aspects of LSS design. Primary issues addressed are with large antennas and reflectors. The following four articles are contained in the document:

Disturbing Torques, and Pointing Errors--Large Earth-Oriented Microwave Reflectors
Richard H. MacNeal

Effect of Phase Errors on Antenna Performance
J. M. Hedgepeth and Karl Knapp

Deployment of Folded Foil Surfaces
Karl Knapp and Charles S. MacGillivray

Meteoroid Damage to Rod-Type Structural Elements
John M. Hedgepeth

The articles are written clearly and are well documented. The first one includes much data of interest and importance to LSS design. Particularly valuable are the comparisons of various environmental effects at varying attitude and of stabilizing forces generated by physical effects such as gyro stabilizers, gravity gradient, and magnetic field.

Design Concepts for Large Reflector Antenna Structures, by John M. Hedgepeth and Louis R. Adams, NASA Contractor Report 3663, January 1983.

This paper is a fairly complete first study of deployable tetrahedral trusses. Trusses discussed include the quasiplanar type that support hexagonal mirror arrays and the beam-column tetrahedral type. The report is well documented and is particularly

valuable because of the clear demonstrations of deployability, structural construction stages, hinge position, and consequent concerns and joint design requirements.

Modelling an Identification of the Structural Properties of an Astromast, by Y. Soucy and F. Vigneron, CRC Report 1374, Communications Research Center, Ottawa (Ontario), Canada, November 1983.

An Astromast is a fiberglass, triangular, deployable truss manufactured by the Astro Research Corporation, Carpinteria, CA. The study presents results of extensive mathematical calculations and experimental testing of a purchased Astromast. The mast is highly flexible and fragile; as a result, experimental results did not compare well with finite element model calculations. The structure was found to behave nonlinearly for frequencies higher than 30 Hz. The authors made no conclusions about this structure's applicability to actual space use.

Development of Deployable Structures for Large Space Platform Systems, Design Development, Volume 2, by H. S. Greenberg, NASA CR 170689, October 1983.

Development of Deployable Structures for Large Space Platform Systems, Volume 2, Technical Final Report, by R. L. Cox and R. A. Nelson, NASA CR 170690, May 1983.

These reports represent two different approaches to a competitive Marshall Space Flight Center contract which was let in 1982. (The first proposal won the bid and a model of the design was built.) Deployable structural systems (primarily beam trusses) are discussed in both documents. Report 170689 offers a much more detailed analysis of the truss systems than does Report 170690. On the other hand, both reports discuss manned living module and laboratory module designs to some extent. All structural packaging designs are established with the space shuttle cargo bay as the intended cargo recipient. Conversely, most of the deployable systems are developed based on automatic or semiautomatic deployment and, as a result, many of the systems could apply to orbit insertion as the cargo of an Atlas or similar rocket. These two documents deserve careful study.

Conceptual Design and Evaluation of Selected Space Station Concepts. Executive Summary, Volumes 1 and 2, NASA JSC 19521, December 1983.

This massive report compares three different concepts for space station design: the Building Block concept, in which pressurized work and living modules form the structural basis; the Delta concept, consisting of a large wedge of three planar truss arrays to which the pressurized modules are attached; and the Big T concept that involves two joined planar arrays to which the other equipment is attached.

The report concludes that all three concepts are feasible and that the total costs are quite similar--less than 10 percent variation between the high cost (in 1984 dollars) of \$8 billion for the Delta arrangement versus \$8.7 billion for the Big T arrangement. The report also points out that, in all programs, most of the cost is for overhead, such as system and program level tasks. About 75 percent of the design and engineering costs are in overhead for systems and program level administration. Roughly 40 percent of the production costs fall under administrative overhead as well.

Many parts of this report are quite detailed and, since the investigators clearly state many of their criteria and compare the three concepts for satisfaction of these criteria, this study could be used to evaluate the three concepts in terms of the different criteria that would be associated with military structures.

Thermo-Visco-Elastic Analysis of Dimensionally Stable Fiber Composite Space Structures, by Zvi Hashin, E. A. Humphreys, and Jonathan Goering, AFOSR TR 84-1124, August 1984.

A theory is developed for the thermo-viscoelastic response of a polymeric matrix. The fibers are assumed to be linear, elastic temperature-independent, transversely isotropic materials, whereas the matrix is modeled as a linear, thermo-visco-elastic isotropic material which is thermorheologically complex. The theory is very complicated and requires numerical analysis for very simple problems. It does not appear to have been compared with any experimental results.

"Continuum Modeling of Damping in Large Space Structures," by S. Abrate and C. T. Sun, in *Proceedings of the Second International Conference on Recent Advances in Structural Dynamics*, University of Southampton Institute of Sound and Vibration Research, Southampton, England, April 1984.

This paper claims to show how damping coefficients for an LSS can be obtained by considering the damping coefficients for the individual beam-column elements. The approach is straightforward and most of the information presented is either a part of the classic literature or is a repeat of that which is in the references. The major problem is that a large-truss structure has damping contributions from the joints as well as internal damping of the individual elements, and this approach considers only the latter damping.

The authors mention the general lack of experimental data at the low stress levels and low frequencies of interest for low-speed structures. They also point out the difficulties in obtaining these data.

"Applications of Space Tethers," by Ivan Bekey, in *Proceedings of the 35th Congress of the International Aeronautical Federation*, Lausanne, Switzerland, October 1984.

This qualitative paper presents some tether concepts and several possible space applications for tethers, including low-power orbit changing and electrical power generation. These applications are claimed to offer very positive results at low cost. Unfortunately, the paper contains no references to more detailed engineering studies for the tethers, which in this case are long Kevlar strings.

Support Structures for Large Infrared Telescopes, by John M. Hedgepeth, NASA CR-3800, July 1984.

The abstract reads as follows:

An infrared telescope requires an accuracy of its reflecting surfaces of less than a micrometer. Future missions may require such accuracy from telescopes that are 20 meters or larger in diameter. The structure for supporting such a telescope will probably take the form of a deep truss. Various approaches for constructing the primary mirror in space are illustrated. One that employs automated deployment of interconnected reflector-structure modules is described in detail. Estimates are made of the precision obtainable with properly configured truss structures and the required ability of active control systems for achieving the desired accuracy.

Although this is an initial, exploratory study, the results appear to be promising. Any future reports by Hedgepeth on this topic should be studied carefully.

Conceptual Design of a Mobile Remote Manipulator System, by Harold G. Bush, Martin Mikulas, Jr., Richard E. Wallsom, and J. Kermit Jenson, NASA Technical Memorandum 86262, July 1984.

Like all of the recent Langley Research Center space structure concepts, this paper assumes that construction and maintenance will be aided by a Mobile Remote Manipulator System (MRMS). A conceptual design is presented on MRMS that would require only guide points at structural joints and would be only one bay. Clearly, much more specific design and testing will be required before this concept can be considered operational.

Variable Geometry Truss Concept, by Koryo Miura, Institute of Space and Aeronautical Science Report Number 614, September 1984.

This paper describes a truss concept that has unconfirmed practical application. The truss is one-dimensional (as compared with, e.g., planar) and is based on repetition of an octahedral truss module. However, even for a truss with a linear centerline, the truss longerons are at an angle to the centerline. The structural efficiency of this truss is thus questionable. The truss does have two advantages: first, it is readily deployable because it has telescoping cross members; second, the truss can be deployed with a curvilinear centerline which might be useful for some applications.

Shear Deformation Plate Continua of Large Double Layered Space Structures, by Mohamed Samir Heszy and Adnan H. Nayfeh, NASA Conference Publication 2335, October 1984.

This is a theoretical paper in which the authors attempt to take a large planar truss structure and replace its analysis with analysis for a continuous plate structure that follows couple-stress constitutive relations. This approach leads to a relatively complex set of governing differential equations that are based on a match of the strain energies for the two corresponding structures. Actual solution of these problems would require that there be correspondence of boundary conditions between the two candidate structures. This correspondence (which probably should be established on the basis of virtual work expressions) is not presented in this document. Also, the correspondence that was made does not hold for detailed deflections, but instead generates comparison between what are loosely called "global" deformations. In dealing with a truss structure, the information produced will probably not be accurate for the relative deflection of surface points which are closer together than the nodal distance. If this theory is extended to a dynamic theory, the expected outcome is poor correspondence for solution frequencies that are less than 10 times the natural frequency of an individual truss element in the original structure.

APPENDIX B:

PROPOSED SEQUENCE FOR DESIGNING SPACE STRUCTURES

The structural design process described in this appendix could apply to any structure to be designed for any environment. This sequence normally would be followed by the construction of models and extensive experimental loading and analysis--especially when many of these structures will ultimately be constructed.

Outer space is difficult to reach and inhospitable to travelers; therefore, it is critical to exercise extreme care with the mathematical analyses and make every effort to conduct as many experiments as possible on Earth. Nevertheless, it is essential to erect and test a complete, full-size model in space before the design process can be considered complete. If conscientious efforts have been applied to the synthesis, analysis, and experimentation on Earth, the design modifications generated as a result of the space shakedown flight should be minimal.

1. A space structure consists of a foundation plus one or more pieces of equipment. These elements are complementary and must be designed concurrently.

2. A primary concern is the stabilization procedure to be used. Stabilization can be based on gravity gradients, inertial systems, or active control. The overall structural configuration will depend heavily on this design criterion. On the other hand, equipment characteristics may have a major role in determining the basic structural configuration. For example, if the equipment includes a nuclear-powered generator and a crew capsule, the need for a large spatial separation of these two elements may require a structure that is very long in one dimension and eminently suitable for gravity-gradient stabilization.

3. Once a general stabilized design is acquired, a more detailed design is established. The "first guess" design must be based on criteria of strength, stiffness, transportability, and ease of erection. Attachment points for the equipment must be designed in conference with the equipment designers.

4. The next step is analysis. Simplified computer models of the design are subjected to the static and dynamic loadings that will be generated during launch, erection, and operation. Basic geometric and dynamic information regarding the equipment must be acquired so that pointing errors, slew factors, and settling times can be computed correctly.

5. At the end of the first set of analyses, the equipment and structure designers must confer to discuss any errors and operational difficulties exposed in the first analyses. They should also agree upon the ways in which these problems can be resolved. In all cases, a redesign of the structure will be mandated. On the other hand, it is quite possible that some equipment redesign can facilitate the structural design while having little or no effect on the operational goals. At this point, it will also be pertinent for investigators to reexamine the overall system specifications to determine if a loosening or recasting of the specifications would ease the equipment and structural designs or would lead to more efficient redesigns.

6. The structure is now resynthesized to better satisfy the new and revised criteria, and the initial dynamic model is reanalyzed. This cycle is repeated until the simplified model yields results close to or exceeding specifications.

7. Once the simplified model yields good results, a more complex model, which is closer to reality, is constructed. Several examples can point to possible differences between the original and refined computer models.

- The original model may have represented the structure as a pin-jointed truss, whereas the refined model will represent the structure as a semirigid frame.
- The original model may have ignored all interactions between axial loadings and bending; in contrast, the refined model will include the P-delta effect.
- The original model may have assumed instantaneous actuator response in active damping systems, whereas the refined model will include important lags and phase shifts.

8. In the study of the refined model, attention will be paid to possible web bucklings, initial structural distortions, and other potential imperfections that might affect final performance.

9. Results of the initial analysis of the refined model are used to correct and modify the model. The new model is analyzed again and performance is compared with specifications. This design-analysis-correlation sequence is repeated until specifications are met or exceeded.

10. Some structural characteristics and requirements cannot be included in the synthesis-analysis sequence. These criteria must be examined qualitatively and/or experimentally. Examples of these concerns are ease and speed of construction, identification and application of coatings, determination of correct packaging and shipping procedures, and many others.

11. Fabrication, transportation, and erection follow completion of the basic design. The responsibility for planning and executing these tasks is assumed by new groups of specialists (e.g., manufacturing engineers, construction engineers) as when conventional Earth-based structures are developed. Good engineering management does, however, require that liaison be maintained with the structural designers; this association should be much more extensive for LSS than for Earth structures.

12. Detailed drawings and plans must be generated for the structure. The detailer must work closely with the designer to ensure that the hardware design will duplicate the mathematical model. A simple error, such as the substitution of a hinge for a ball joint, could be disastrous. At this point, the construction methodology should be finalized. Will constructed modules or deployable modules be jointed in space? Or will only basic elements (e.g., beams, shells) be transported to space with the structure completely erected in space?

13. The structure has been designed to do its job after it is fully erected. Additional design considerations must be given to the substructures, modules, and elements to be shipped and joined. Launch loads, loads generated by positioning in space, and loads associated with joining must be considered. In most cases, these construction loads can be accommodated through temporary bracing to retain appropriate component positioning. Occasionally, the basic design must be changed to provide necessary resistance to stresses introduced in the assembly or deployment process. If this change is not trivial, the entire design analysis should be rechecked.

14. The final step in any structural design venture is a thorough check (and test, if possible) of the completed structure. For an LSS, these tests will include the usual visual examinations for continuity, alignment, and connectivity. Errors of omission (e.g., loose joints) or of commissions (e.g., damaged elements) should be found if present. Further desirable checks include the comparison of free vibrational frequencies and damping decrements with those predicted by the mathematical model.

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