NASA Technical Memorandum 87713

NASA-TM-87713 19860019512

INTEGRATED THERMAL-STRUCTURAL-ELECTROMAGNETIC DESIGN OPTIMIZATION OF LARGE SPACE ANTENNA REFLECTORS

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JUNE 1986

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Abstract

The requirements for low mass and high electromagnetic (EM) performance in large, flexible space antenna structures is motivating the development of a new systematic procedure for antenna design. In contrast to previous work which concentrated on reducing rms distortions of the reflector surface, thereby indirectly increasing antenna performance, the current work involves a direct approach to increasing electromagnetic performance using mathematical optimization. The present work also differs from past efforts in that the thermal, structural, and EM analyses are fully integrated in the context of an optimization procedure and, consequently, the interaction of the various responses is accounted for directly and automatically. Preliminary results are presented for sizing cross-sectional areas of a tetrahedral truss reflector. The results indicate potential for this integrated procedure from the standpoint of mass reduction, performance increase, and efficiency of the design process.

Introduction

In current analytical design practice for orbiting flexible space antennas, the calculation of disturbances such as temperatures in the structure, followed by the resulting surface distortions and finally the electromagnetic (EM) performance, are carried out in a sequential manner in which each disciplinary analysis is essentially decoupled from the others. The link between the structural deformation (as a single measure such as rms) and the loss of antenna performance is based on classical formulas such as that of Ruze (ref. 1). Antenna performance is indirectly maximized by minimizing rms surface distortions (refs. 2-5).

In reality, the antenna performance depends on details of the distortions throughout the reflector surface. Recently, some initial steps

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have been taken to integrate the thermal, structural, and EM analysis in order to produce a more efficient analysis procedure and to account for the relation between details of distortion and antenna performance (refs. 6,7). A next step would be to combine such an integrated analysis which accounts for the disciplinary interactions with an optimization procedure to produce antenna designs giving high performance and low mass. Such an extension is the subject of this paper.

The paper defines the disciplinary interactions applicable to space antennas; describes an integrated thermal-structural-EM analysis procedure;* and shows how the analyses are combined with a standard mathematical optimization program to produce a prototype system for antenna reflector design. The design variables presently used for the optimization are the cross-sectional areas of truss elements in support structures of antenna reflectors. Preliminary results are presented for optimization of a tetrahedral truss structure for a 55-meter reflector.

Interdisciplinary Design Considerations

This section defines the disciplinary interactions involved, the analyses needed, and the flow of data between disciplines in antenna design. The computer codes selected to fill analysis needs are identified and briefly described.

Figure 1 illustrates the interactions among the disciplines and shows the steps required in an antenna design. The thermal analysis calculates

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*The authors acknowledge Drs. M. C. Bailey and C. R. Cockrell of the Langley Research Center for assisting in the implementation and incorporation of the EM analysis.

the temperatures in the structure based on given heat loads and thermal properties of each element. The structural analysis uses the temperatures to calculate the elongation of elements and thus the displacements in the structure. The distorted shape of the reflector is then defined from displacement information. Presently, a two-dimensional spline fit of the displacements is used to represent what is in actuality a flexible mesh surface[4]. The electromagnetic performance analysis translates the distorted reflector shape into measures of EM signal power and quality. The optimizer calculates an improved design based on current values of mass and values of EM performance measures.

An analytical design method has been implemented based on figure 1. Computational costs associated with an antenna design can be high, so the procedure must be implemented efficiently. To minimize computational cost and effort, some "design-oriented" analysis techniques are used. For example, any quantities which are not functions of the design variables are calculated once, saved in a database, and never recalculated. Also, the optimizer is supplied with linear approximations to the objective and constraint functions, rather than the functions themselves, for some of the calculations.[8]

Figure 2 indicates the computer codes used. Thermal and structural analyses are performed by the Engineering Analysis Language (EAL) finite element code[9]. Electromagnetic performance is calculated by REFLCTR, an aperture integration method code written for NASA Langley by North Carolina State University and later modified[10]. Optimization is performed by CONMIN[11], a useable feasible directions code for constrained minimization. These last two programs are installed as integral parts of EAL so that sequences of EAL input commands called runstreams and EAL database facilities may be used to implement the transfer of data between analyses.

Formulation of Optimization Problem

The purpose of an antenna reflector is to focus incoming electromagnetic waves to a single reception point or to redirect outgoing waves from the transmission point (feed) into a concentrated beam. Whether the antenna is a receiver or a transmitter or both, the reflector greatly increases the power of the signal. This power increase is measured as directive gain, or the ratio of signal power in a given direction to signal power from a standard antenna in the same direction. Normally, the maximum directive gain is determined and ten times the logarithm of this ratio is reported as the "peak gain" in decibels.

For an ideal paraboloidal reflector antenna with the feed at the focal point, the maximum directive gain occurs along the axis of symmetry and can be readily calculated. In the case of a distorted reflector surface, the gain will be modified (loss of gain), the maximum directive gain will occur in a different direction (pointing error), and some of the EM waves will oscillate at right angles to the others (cross-polarization). Excessive cross-polarization represents a loss of usable power and is a potential source of interference to other antennas.

To design an effective reflector antenna satellite, several steps are necessary. First, the characteristics of the feed and the size and shape of the reflector must be carefully matched. Next, the orbital track of the satellite and orientation of the reflector must be determined and the resulting thermal loads must be calculated. Finally, the structure must be designed for the thermal environment or else provided with active distortion control. Although there are many possible design variables, the current study varies only the cross-sectional areas of individual structural elements. As the areas of the elements are varied, the weight of the structure is changed, the thermal forces are changed, and the stiffness of the structure is varied.

Figure 3 contains a summary of the optimization problem to be solved. The object is to minimize structural mass of the antenna reflector truss while providing at least a specified level of gain and keeping the pointing error and cross-polarization below specified values. Accordingly, constraints are placed on directive gain, cross-polarization, and pointing accuracy.

Description of Test Problem

This section describes a problem used to test the optimization system. The test problem selected is a 55-meter tetrahedral truss similar to designs proposed for a microwave radiometer spacecraft[4,12,13]. The antenna is a center-fed parabolic reflector with operating frequency of 882 MHz (wavelength = 0.34 meters). The satellite will be in low earth orbit. Figure 4 illustrates the antenna configuration and the finite element model of the truss structure. The finite element model of the reflector support structure is an array of tetrahedral truss sections. All 420 truss elements are fabricated from graphite epoxy. For the optimization, all of the truss elements on the top or feed-facing surface of the antenna reflector, and all elements on the bottom will have the same cross-sectional areas. Also, all diagonal support members have the same cross-sectional area. In the present study, these two areas are the only design variables.

The finite element model and the thermal loading as a function of time were available from previous studies [5]. Figure 5 contains a plot of temperature versus time which is typical for most of the points on the antenna structure. There is a slight difference between the upper and lower surfaces due to self-shadowing. The present results represent an optimized design for a single orbital position indicated as the design point. Eventually, the procedure must be modified to calculate the "best" design over all orbital positions. The design requirements for electromagnetic performance, shown on figure 5, represent typical values of mission requirements for this class of antenna (e.g., refs. 10,12,13). Directive gain is calculated for points on the aperture plane. (This is a conceptual plane located just above the reflector surface and perpendicular to the axis of the reflector). The maximum directive gain, or peak gain is required to be no more than 0.50 decibels below the peak gain of a perfect (undistorted) reflector. Cross-polarization is required to be less than -40 dB. Finally, the pointing error is required to be less than 0.05 degrees. This means that the direction of peak gain should be within 0.05 degrees of the feed axis (axis of symmetry of the reflector).

Results and Discussion

The initial design, heat loads, and feed characteristics for the present study are based on results from preliminary design studies of this class of antenna (refs. 4, 5, 10). The initial mass is 1496 pounds and the gain loss is 0.33 dB. The rms distortion is about 0.4 inches. Table 1 contains a summary of optimization results including values of design variables, objective function (mass), and constraints for each cycle. The rms distortion is included for information, but is not used by the optimization procedure. After only three optimization cycles, the mass of the structure is reduced to 1,000 pounds and directive gain is increased to 0.03 dB below the perfect reflector value. Pointing direction and cross-polarization also improve to this point in the optimization. The final design, which appears as cycle 5 of the table, has electromagnetic characteristics similar to the initial design, but has a significantly smaller mass. Notice the pointing accuracy is at its allowable value in the final design. Any further decrease in mass causes unacceptable EM performance.

Figure 6 contains contour plots of the reflector surface at each cycle. The contour lines measure the difference between the distorted reflector surface and the perfect paraboloidal surface. Dashed lines indicate negative deflections (i.e., the surface is farther from the feed than it should be) and solid lines indicate positive deflections. Note that thermal distortions of the initial design result in a depression in the center. After one cycle of thermal, structural, and electromagnetic analysis and one set of optimization calculations, the reflector surface is dramatically improved. Subsequent cycles indicate that the mass of the structure can be further reduced without affecting the reflector smoothness. These promising results suggest that an interdisciplinary approach to antenna reflector optimization can significantly reduce the mass of the antenna while improving performance.

Figure 7 outlines the most likely near-term extensions of the present work. The first would be to supplement the design variables. For example, thermal coatings on the elements can change the absorptivity and emissivity of the structure in a desirable way so that these properties may be treated as design variables[14]. Also, active controls which alter the lengths of truss elements (e.g., corrective heaters or force actuators) offer a means of adjusting the antenna shape in orbit and are very effective design variables[5]. Another extension of the work involves improving the structural model by modeling not only the reflector back-up structure, but also the also the feed support and the flexible reflector surface. Finally, methods to determine the best design applicable to all orbital positions need to be developed

Concluding Remarks

This paper described the status of development of an integrated analysis and optimization procedure to design orbiting space antenna reflectors for minimum mass and maximum performance while accounting for the interactions among thermal, structural, and electromagnetic behavior. A prototype system combines a finite element thermal analysis and structural deformation analysis program with a NASA developed electromagnetic radiation program and a standard optimization program. The procedure was tested for a 55-meter tetrahedral truss antenna reflector with a thermal loading for a representative orbital position in low earth orbit. The results indicate that structural mass can be significantly reduced and electromagnetic performance enhanced using this interdisciplinary optimization procedure.

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TABLE 1. OPTIMIZATION RESULTS

CYCLE NO.	DESIGN VARIABLES			OBJECTIVE	CONSTRAINTS			SURFACE DISTORTION
	A_1* SQ. IN.	A_2* SQ. IN.	A_3* SQ. IN.	MASS LBS.	GAIN dB	CROSS POL. dB	POINTING DEG.	RMS IN.
0	.253	.174	.253	1496	-.33	-64	.05	.398
1	.177	.155	.177	1097	-.02	-81	.01	.042
2	.179	.108	.179	1038	-.02	-75	.01	.049
3	.181	.076	.181	1000	-.03	-76	.01	.061
4	.100	.075	.100	600	-.17	-61	.06	.512
5	.109	.078	.109	648	-.19	-63	.05	.435

*A_1 = A_3 = CROSS-SECTIONAL AREA OF ELEMENTS IN UPPER AND LOWER SURFACE

A_2 = CROSS-SECTIONAL AREA OF DIAGONAL ELEMENTS

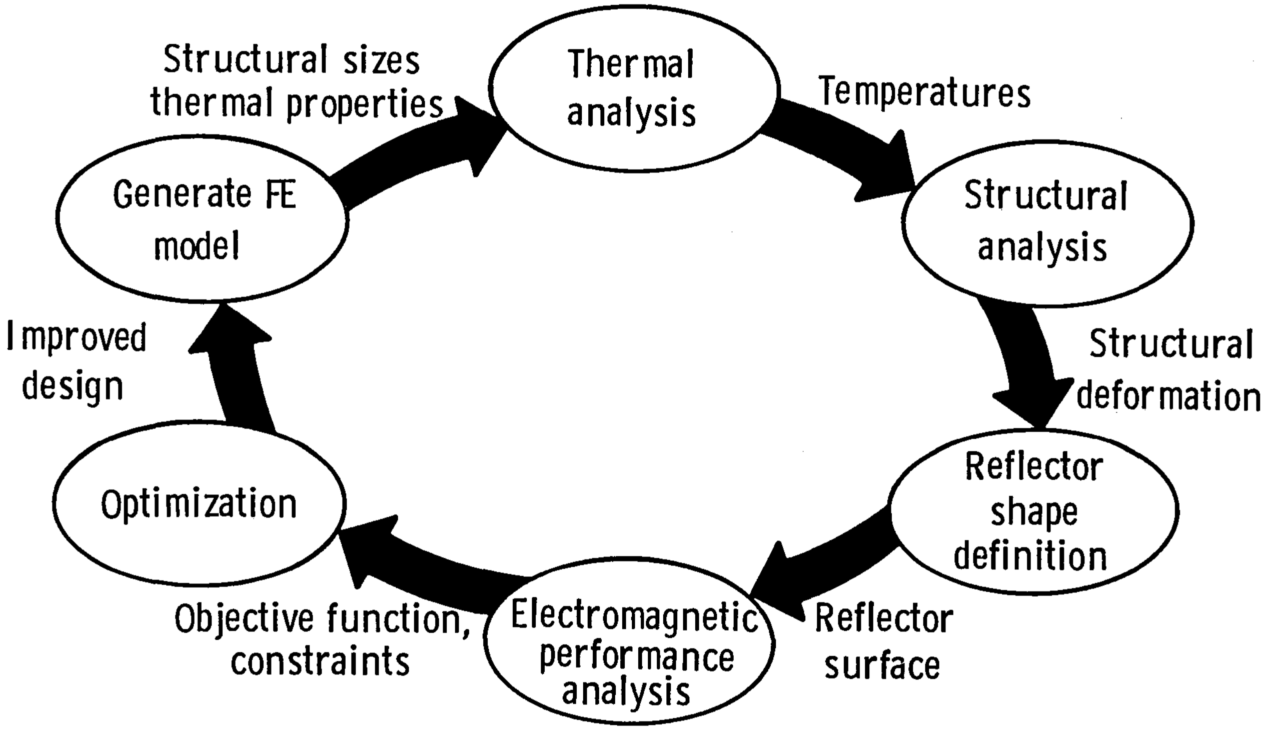


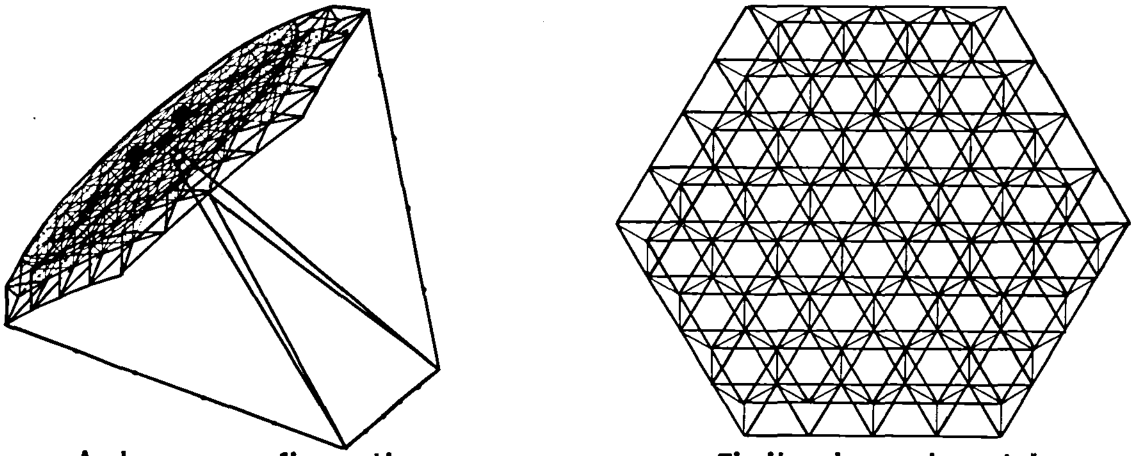
Figure 1.- Interdisciplinary aspects of space antenna optimization.

Thermal analysis	EAL Finite Element Program
Structural analysis	
Electromagnetic performance analysis	REFLCTR Aperture Integration Program
Optimizer	CONMIN Constrained Minimization Program

Figure 2.- Computer codes used in interdisciplinary antenna design procedure.

- Objective function: Structural mass
- Design variables: Cross-sectional areas of truss members
- Constraints:
  - Directive gain ≧ power required
  - Cross polarization ≦ interference limit
  - Pointing error ≦ specified tolerance

Figure 3.- Formulation of the optimization problem.



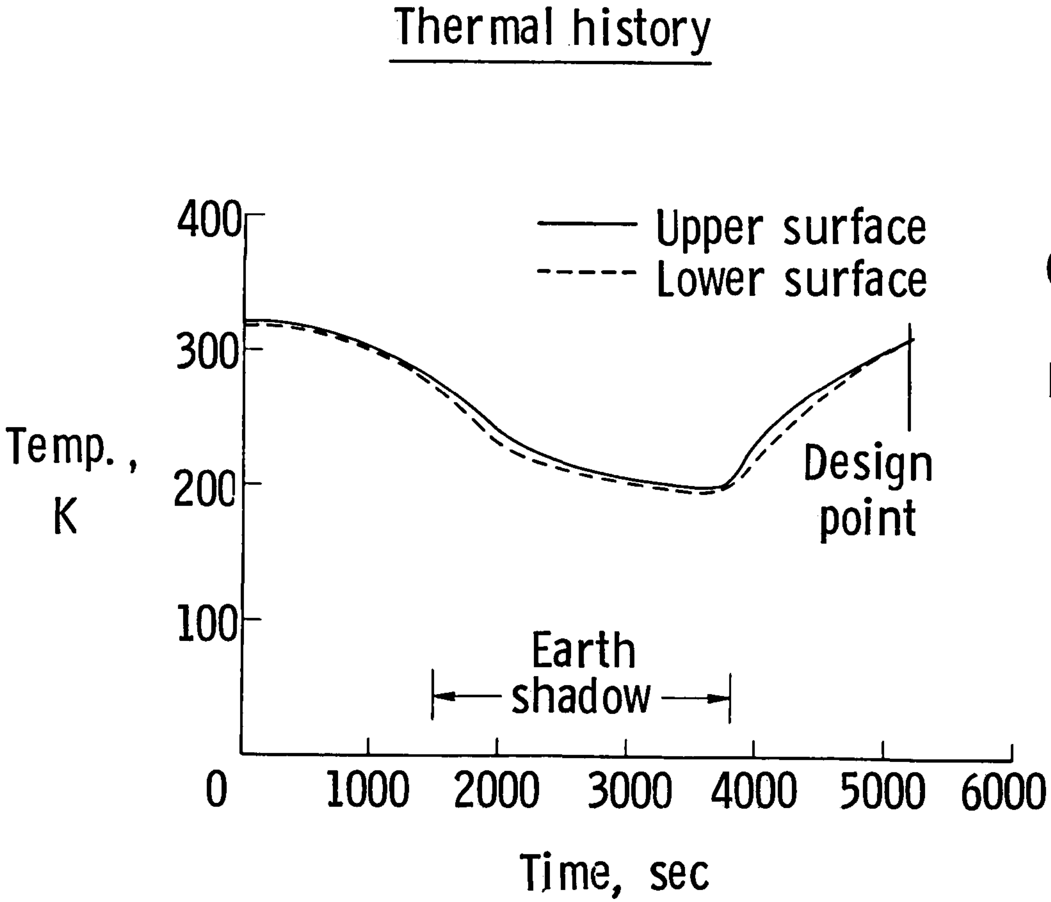
Antenna configuration

- 55 m tetrahedral truss
- Low earth orbit mission
- Wavelength ~ 0.3 m

Finite element model

- 109 grid points
- 420 truss elements
- Three design variables
- Graphite epoxy

Figure 4.- Model description for test problem.


Thermal history

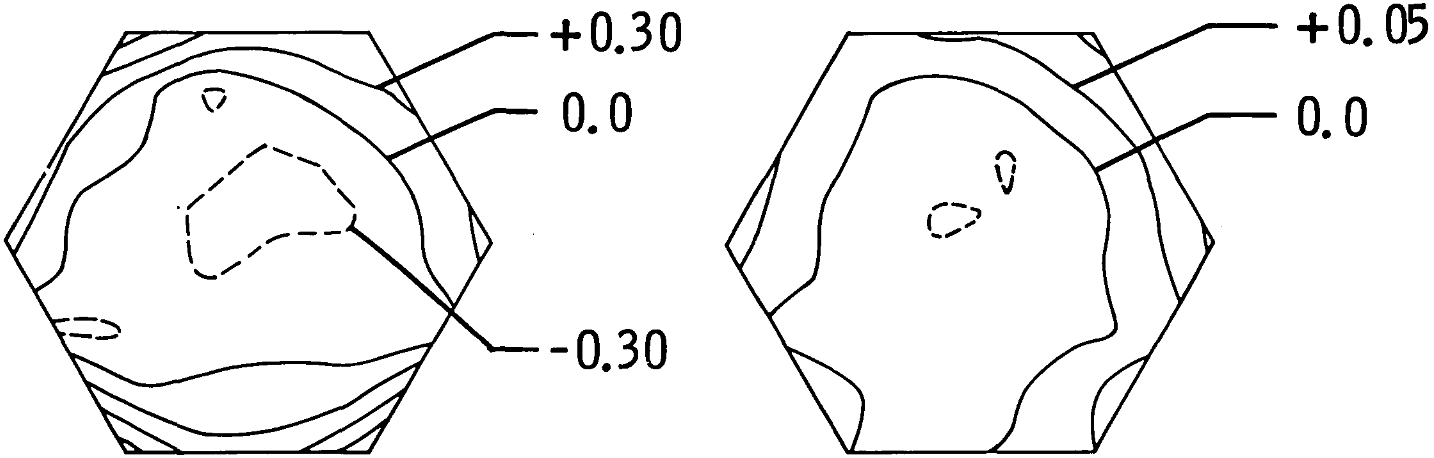
Design requirements

Peak gain ≥ Ideal - 0.5 dB

Cross polarization ≤ -40 dB

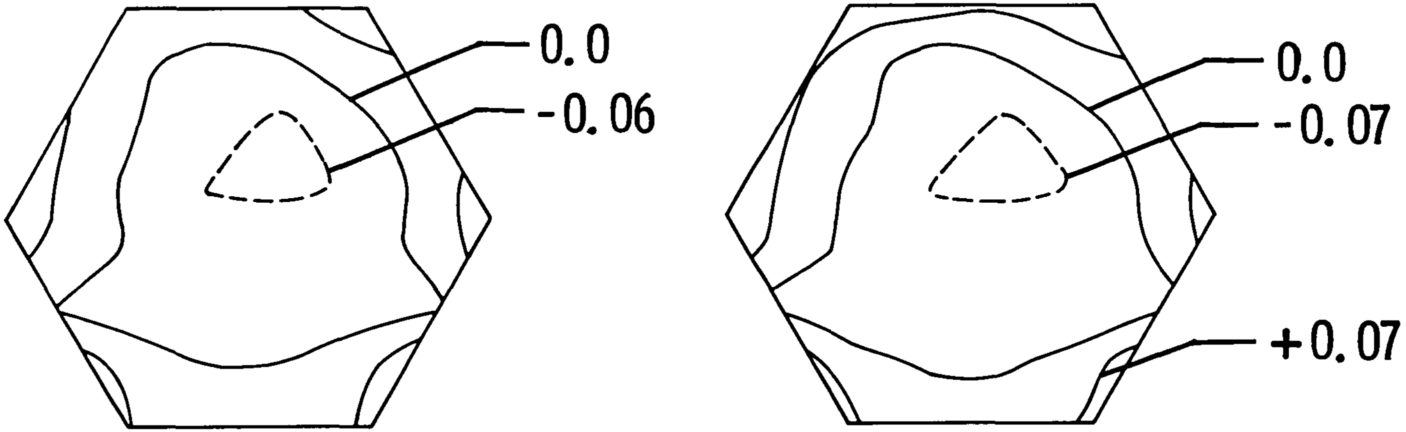
Pointing error ≤ 0.05 deg

Figure 5.- Mission requirements for test problem.



Initial design

Cycle 1



Cycle 2

Cycle 3

Figure 6.- Contour plots of surface distortions of antenna. Values are deflections in inches. Positive deflections are toward the feed.

- Add design variables
    - Thermal properties α, ε
    - Corrective heaters at selected joints
- Improve model
    - Add feed mast
    - Improve mesh model
- Determine best design for all orbital positions

Figure 7.- Future work.

1. Report No. NASA TM-87713	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Integrated Thermal-Structural-Electromagnetic Design Optimization of Large Space Antenna Reflectors		5. Report Date June 1986
		6. Performing Organization Code 506-43-41-01
7. Author(s) Howard M. Adelman and Sharon L. Padula		8. Performing Organization Report No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665		10. Work Unit No.
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics & Space Administration Washington, DC 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Presented as work-in-progress paper at 27th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, San Antonio, TX, May 19-21, 1986.

16. Abstract

The requirements for low mass and high electromagnetic (EM) performance in large, flexible space antenna structures is motivating the development of a new systematic procedure for antenna design. In contrast to previous work which concentrated on reducing rms distortions of the reflector surface, thereby indirectly increasing antenna performance, the current work involves a direct approach to increasing electromagnetic performance using mathematical optimization. The present work also differs from past efforts in that the thermal, structural, and EM analyses are fully integrated in the context of an optimization procedure and, consequently, the interaction of the various responses is accounted for directly and automatically. Preliminary results are presented for sizing cross-sectional areas of a tetrahedral truss reflector. The results indicate potential for this integrated procedure from the standpoint of mass reduction, performance increase, and efficiency of the design process.

17 Key Words (Suggested by Author(s)) Large space structures Space antenna Optimization methods	18. Distribution Statement Unclassified - Unlimited Star Category 18

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 17	22. Price A02

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