Mechanical Design and Development of a Deployable Space Antenna for Japanese VLBI Space Observatory Program

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Abstract. Mechanical design and development of a deployable mesh antenna with precise accuracy for a space VLBI mission are presented. Simple deployment scheme of an antenna structure is realized through the extension of six rib masts for a main reflector and the unfolding of support booms for a sub reflector. Mesh elements bounded by a cable network are pulled by the cables to form finer concave surfaces. Various aspects of the design and development are introduced in detail.

1. Introduction

Various types of antennas are classified according to (1) whether they are deployable or erectable; (2) what kind of surface is used (solid, mesh, or inflatable membrane surface); (3) whether a back-up structure is necessary or not, and if necessary what type of back-up structure is used (deployable truss, elastic rib, or cable structure). Many concepts are possible through appropriate combinations of these items. In the relatively near future, deployable reflector concepts (Freeland, 1983) are important in space development. For such a reflector structure, the surface accuracy and the packaging efficiency are of basic interest. A solid surface gives a very high accuracy under 1 mm rms (root mean square) error, but it shows a poor packaging efficiency. Since a fairing diameter of a launching vehicle is not large enough, flexible surfaces are much preferable for relatively large deployable reflectors whose diameter becomes over about 10 m. A mesh surface (Belvin \textit{et al.}, 1987; Lowe \textit{et al.}, 1993) which has good packaging properties needs an appropriate subdivision of the surface in order to get a better surface accuracy, because the positive curvatures in two directions can not be realized. A concept of a modularized inflatable reflector (Natori \textit{et al.}, 1990) seems to overcome some difficulties about both surface accuracy and packaging efficiency.

The Institute of Space and Astronautical Science (ISAS) is planning to launch
the engineering test satellite for antenna deployment in mid 1995, which is called MUSES-B (the second Mu Space Engineering Satellite), and its scientific object is to perform the VLBI Space Observatory Program (VSOP) (Hirabayashi et al., 1991). In 1992 the flight model development started. To keep the very high accuracy of about 0.5 mm rms (root mean square) error from base parabola is desired. After some initial studies for available antenna concepts, a tension truss antenna (Miura and Miyazaki, 1990) with improved mesh surface was selected for the mission. The tension truss network are deployed and supported by six extensible masts. In this paper, details of these antenna configurations are introduced. Theoretical calculations and test results to clarify various effects on deployment and surface accuracy are also shown.

2. Antenna Configuration and Surface Structure

Figure 1 shows both deployed and stowed configurations of the antenna. The diagonal line of a deployed hexagonal shape has 10 meter in length, and the equivalent aperture diameter is 8 meter. The total weight of antenna is requested to be 226 kg, and that of satellite is about 800 kg. Six extensible masts actuate both front and back cable networks, which give many hard points for mesh elements.

Figure 2 shows formation of the antenna network of the one sixth part of the antenna surface. The length of element cables of a surface tension truss is precisely adjusted to form many grid points to be on an exact base parabola. Thick Kevlar wire is selected as the material of tension truss cables whose property is relatively inextensional. Curved configuration of a back-up tension truss is not to interact with

![Diagram of Deployable Mesh Antenna](image-url)
a extensible mast. Each node of both surface and back-up tension truss cable networks is connected by a tie cable. Usually mesh surface directly attached to one triangle region of surface tension truss (triangle mesh element) is kept to be flat, but to get more precise surface accuracy the element is divided into nine smaller triangles shown in Fig. 2(c). One point inside of an element and six points at boundary are tied to the grid points of back-up cable network, and the mesh element could represent

Fig. 2. Formation of the antenna network.

Fig. 3. Antenna network.
more exact concave surface. The back cable network is also covered by mesh in order to avoid getting entangled during deployment. These tie and adjusting cables are shown in Fig. 3(a), and their total number of the entire surface is 930. Figure 3(b) is a top view of the antenna network. To get these network patterns whose major members are all in tension, some complicated numerical procedure was applied (Natori et al., 1993). Materials of mesh and network nodes are gold plated molybdenum and engineering thermoplastics (polyphenylene sulfide), respectively.

3. Deployment Scheme

The one fourth deployment model was developed in 1990 to get general aspects of deployment. In 1992, the deployment verification partial model was made, and tested to get various specifications for deployment, especially to check entanglement of cables during deployment. From the test results a deployment sequence shown in Fig. 4 is confirmed for the proto-flight model. Before deployment, all nodes except the outermost ones (on the line D in the figure) are constrained by stowage cables and are pulled closer to the central structure. Deployment of the antenna surface is performed as follows: Step 1: The outer nodes are extended by an extensible mast.

![Step 1, Step 2, Step 3, Step 4](image)

**Fig. 4.** Deployment sequence.

![Network support mechanism](image)

**Fig. 5.** Network support mechanism.
Tension forces are given to the connected cables, and they are released from stowage cables. Step 2 and Step 3: Nodes located halfway between outer and inner peripheral (on the lines B, C) are extended, and constraint of these nodes are released. Step 4: The innermost nodes (on the line A) are extended and released. Figure 5 shows a network support mechanism.

In the entire antenna system, extensible masts are used as deployment actuators and a support structure after deployment. Figure 6 shows components of an extensible mast (Kitamura et al., 1990), which has articulated longerons and moderate stiffness property. It also has a retractable function; a DC motor at canister base operates mast deployment, and another motor at tip can stretch antenna network.

Mast alignment is affected by structural performance of both pointing at mast tip and the angle of end plate. Main source of undesired alignment is joint looseness. The increase in looseness of joint holes degenerates mast alignment, and the adjustment to increase initial tension of diagonal rods can put looseness to one side. The manufacturing tolerance of mast members are carefully controlled, and mast repeatability is estimated to be 1.1 mm through the tests of a functional mast model, which is converted to the surface accuracy of 0.096 mm rms shown in Table 1.

Sub-reflector structure is also deployable, and Fig. 7 illustrates its deployment sequence. It is deployed by one motor, and at the upper part of subreflector the

Fig. 6. Extendible mast (HIMAT).
synchronous mechanism is installed to achieve smooth deployment. The repeatability of the sub reflector position is within 0.6 mm, and this high repeatability gives sufficient allowance for positions of feeders.

4. Surface Accuracy Analysis

There are various surface error sources, and the following items are checked in detail: (1) surface adjustment error, (2.1) repeatability error of mast deployment, (2.2) repeatability error of mesh surface deployment, (3.1) material property error due to hygroscopic condition on ground, (3.2) material property error due to radiation in space, (3.3) creep effect, (4.1) adjustment error due to gravity, (4.2) manufacturing and assembly error due to limitation of adjustment, and (5) thermal deformation. They are summarized in Table 1. Active adjustment functions of these errors in orbit are not considered in this program, since the various resources are limited. A passive way to adjust the above errors at assembly on ground is planned, and exact estimation of the error is very important.

An antenna surface segment bounded by three tension truss cables is shown in Fig. 8. Component members’ characteristics are shown in Table 2. By using the
Table 2. Properties of antenna surface components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Materials</th>
<th>Stiffness</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesh</td>
<td>Gold plated molybdenum wire</td>
<td>20kgf/m (knitting direction)</td>
<td>500grf/m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6kgf/m (normal)</td>
<td></td>
</tr>
<tr>
<td>Cable net</td>
<td>Kevlar 149 (core)</td>
<td>EA: 120kgf</td>
<td>140 - 180grf</td>
</tr>
<tr>
<td>Adjust cable</td>
<td>+ Cornex</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tie cable</td>
<td>(envelope)</td>
<td>16 - 30grf</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>250 - 300grf</td>
<td></td>
</tr>
<tr>
<td>Tension Truss</td>
<td>Kevlar 149</td>
<td>EA: 1,800kgf</td>
<td>0.8 - 2.6kgf</td>
</tr>
<tr>
<td></td>
<td>+ Cornex</td>
<td></td>
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</table>

Fig. 8. Antenna surface.

Fig. 9. Pillow effect.

values listed in Table 2, pillow effect is calculated, and the result is shown in Fig. 9. Based on this result the tension of cable net is controlled between 140 and 180 grf shown in Table 2, and the corresponding surface accuracy is under 0.3 mm rms.

For cable materials, Kevlar (Kevlar 149, 49, 29), α-quartz, T-glass, and carbon fibers (Toray T300, T400, T900) were checked, and Kevlar was selected because of easy handling. Some combinations of Kevlar (core) and Cornex (envelope), and of Technora (core) and Cornex (envelope) were also checked for hybrid cables. The combination of Kevlar 149 and Cornex and that of Kevlar 49 and Cornex (both impregnated by Teflon) were selected for tension truss cables and cable nets,
respectively. Test items for those materials are as follows: stiffness and strength, hysteresis, coefficient of thermal expansion, radio active rays (proton beam, electron beam and ultra violet ray), creep deformation, outgas, ultra-red emittance, and solar absorption.

Figure 10 shows hygroscopic property of Kevlar 149, and it is very much affected by moisture. Assuming the moisture condition on ground is 60%, the strain of cables in space due to moisture desorption is $2.1 \times 10^{-4}$, and assuming also all cables are subjected to this strain change for worst case, distortion of surface accuracy becomes 1 mm rms shown in Table 1. The effect of moisture absorption measured from the antenna network partial model is shown in Fig. 11. The surface accuracy distortion corresponding to the absolute moisture variation of $4 \times 10^{-3}$ kg/mm$^3$ is 0.3 mm rms, which leads to the distortion of 0.9 mm rms in space assuming that the absolute moisture on ground is $12 \times 10^{-3}$ kg/mm$^3$.

Creep tests of Kevlar were carried out by applying the tensile load of 33.3 kgf. Test results show very stable characteristics, and assuming actual applied load is under 2.6 kgf, we can conclude that the change of surface accuracy due to creep is very small.

Effect of radio active rays on material property was checked for the radiation equivalent to 2.5 years, and the reduction of Young's modulus was within 15%. Due to this change the surface accuracy decreases by 0.3 mm rms.

Kevlar cables are affected by initial stretch and hysteresis, and a typical data of hysteresis test is shown in Fig. 12. Thirty times loadings and unloadings are shown there, and the result of latter five times shown in the same figure shows rather stable behavior. Cable members must be used under this stable condition.

Complete compensation of gravity effect on ground for relatively large scale space structures is difficult. Improvement by using both mathematical and hardware models are tried. Figure 13 shows procedure for the antenna network, and Fig. 14 is for the entire antenna system. After fixing mast tip positions at ideal ones in space, we first adjust the antenna surface, and the procedure shown in Fig. 13 consists of four phases. The first phase is to adjust the mathematical model L0 to the hardware model L1. Under 1G condition, from measurements of node points cable length is determined, and the measurements of natural frequency of each cable member give the value of cable tension. Cable stiffness is identified by using nonlinear relation measured such as in Fig. 12, and by measuring displacements. After some modification of L0, the approximate model L2 is obtained. By using L2, 0G analysis is done to obtain the ideal surface in space, and this is the second phase. In the third phase, the object surface on ground is made. To adjust the hardware model to this surface is the forth phase, and these phases are repeated to obtain the same tension values in both hardware and mathematical models. The procedure for antenna network shown in Fig. 13 just corresponds to the second parenthesis shown in Fig. 14. After deflection analysis for different tip loads the mathematical models of masts are improved to coincide the tip deflections of both mathematical and hardware models (Fig. 14). Changing the root angle of mast due to shim leads to complete the gravity compensation of the entire antenna system.

To approve the procedure to compensate the gravity effect on the antenna
network, the antenna network partial model was made. It corresponds to the outer triangles of one sixth of the entire antenna surface. Various trials were carried out; the effectiveness of the procedure was roughly approved, but some difficulty to simulate the nonlinear behavior of cables still remains. The limit of cable assembly
Fig. 13. Procedure to compensate the gravity effect on the antenna network.

Fig. 14. Procedure to compensate the gravity effect on the entire antenna system.

Fig. 15. Limit of cable assembly and adjustment.
and adjustment is shown in Fig. 15. This is the result of repeated trials by using the partial model at the fourth phase to adjust the hardware model to an object surface. Test were conducted under the condition that the temperature variation was under 2°C, and the moisture variation was controlled under 10%. Good convergent property was obtained, and the effectiveness of adjustment procedure shown in Fig. 13 was approved for the cable assembly and adjustment.

Thermal analysis was performed in order to obtain the order of thermal deformation and to predict the temperatures of tension trusses and extensible masts. By checking the thermal deformation of the antenna, it is roughly concluded that the surface accuracy degrades at the low temperature case, and that the half sun configuration shows the worst accuracy (1.03 mm rms). More precise thermal analysis is planned, and some offset adjustment at the cable assembly will be decided through the operational requirements for scientific observation.

5. Conclusion

Various aspects of design and development of a deployable mesh antenna with high accuracy are presented. Through the investigation of surface error sources a reliable high performance deployable antenna has become possible.

The successful deployment and high precision surface formation are expected for this program.

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