A Module Concept for a Cable-Mesh Deployable Antenna

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Abstract

This paper describes the design, manufacture, and deployment tests of a modular mesh deployable antenna. Reaction forces and moments created by a mesh and cable network are estimated using CASA. Deployment analysis is carried out using DADS. Three types of deployable antenna modules are developed and fabricated. Their design approach and deployment characteristics are also presented. Ground deployment tests are performed to verify design criteria.

INTRODUCTION

In recent years, the role of satellite communication has changed from being a supplemental system to being the main element of an advanced mobile communication system. An advance satellite communication experiment is being conducted using the engineering test satellite VI (ETS-VI) which is equipped with two deployable antennas 2.5 m and 3.5 m in diameter. While ETS-VI is expected to achieve its primary goal of advanced satellite communication, it may be insufficient for personal and anytime-anywhere satellite communication due to it's limited mission capabilities and relatively high cost. The future advanced satellite communication system, represented by the super compact hand-held telephone, will not be accomplished without carrying out further innovative research.

Large scale on-board antennas from 10 m to 100 m in diameter are desirable for future advanced mobile satellite communication systems. The current trend of recent reseach into large deployable space structures is the metamorphosis of a solid into a plane, a plane into a line and a line into a point. The weight per unit volume decreases rapidly with each of these metamorphoses. However, the ratio of deployment mechanism weight to the entire structure weight rapidly increases. Moreover, difficulties in ground testing would also increase. Figure 1 plots the estimated difficulty of deployment tests (DDT) in dimensionless units.[1] It indicates that antennas whose apertures exceed 10 m would be difficult to test on the ground. There is some influence from the diameter of the antenna's stowed configuration. Therefore, large antennas whose aperture is over 10 m would be best realized with a modular structure.

A 10-15 m diameter deployable mesh antenna is under development at NTT. The antenna reflector consists of a gold plated mesh surface, a spatially determined cable network, and deployable truss modules as the supporting structure. Seven standoffs connect each cable network to its truss structure. The cable network consists of surface, tie and back cables. Adjustment of tie cable length controls the

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displacement of the surface cable nodes. Seven deployable truss modules will be used to construct the 10 m diameter antenna reflector. The modules are independent of each other, so a larger reflector can be easily achieved by adding more modules. In addition, the modules can be independently fabricated and tested, and they are easy to handle and adjust.

MODULAR MESH DEPLOYABLE ANTENNA

System configuration

Figure 2 shows a system configuration candidate for the future advanced mobile communication satellite. Several deployable antenna modules will be used to construct antenna reflectors ranging from 10 m to 15 m in diameter. Each module is hexagonal and is from 2 m to 4 m in equivalent diameter. They are arranged annularly.

Structure of the basic module for large deployable antenna

Figure 3 shows the general composition of the basic deployable antenna module. Each module consists of a gold plated mesh surface, a spatially determined cable network, and a deployable truss module as the supporting structure. The cable network and deployable truss are connected to stand-offs. The cable network consists of three kinds of cables: surface, tie, and back cables. Surface cables link surface nodes that are distributed uniformly on the parabolic surface. Adjustment of tie cable length displaces the surface cable nodes. Nylon 6 was used for the surface cables and polyester coated Kevlar was used for the tie and back cables. They exhibit good mechanical performance in the cable network. However, they have not been proven suitable for long term space usage. Nylon 6 may not be suitable for the space environment.

Deployable truss structure

Figure 4 shows the basic deployment truss structure. The structure consists of longitudinal members, radial members, circumference members, folding members, diagonal members, revolving hinges, folding hinges, sliding hinges, and one driving motor. The basic concept of the deployable truss modules is a statically determined truss structure with a synchronized deployment motion. Truss joints are capable of either revolving or translating, and each truss module has only one degree of freedom. Thus only one driving motor is necessary for full deployment. Figure 5 shows the BBM (bread board model) of the central module of the 10m antenna that was fabricated to confirm the basic concept of the synchronized deployment truss structure.[2] It is 4m in equivalent diameter. Seven deployable antenna modules will be used to construct the 10 m diameter antenna reflector. A surface control experiment was performed, and after a few surface adjustments, surface accuracy of less than 1 mm RMS, was obtained.

As shown in figure 5, the synchronized deployment motion was confirmed by ground deployment tests. Moreover, the deployment characteristics were analyzed using the Dynamic Analysis and Design System (DADS). The synchronized deployment motion was also analytically evaluated. However, some problems due

to hinge mechanisms were found. Successful results have been obtained by a model that consists of rigid elements and tight hinges. In practice, the BBM suffered from joint slop, joint elasticity, and structural elasticity, so that the BBM actually had many degrees of freedom. This seriously degraded the deployment characteristics. For example, the peripheral sliding hinge did not reach its final position even though the driving motor hinge reached its final position. The points at issue can be summarized as (1) insufficient latch torque at folding hinges against cable network reaction forces, (2) insufficient transmission efficiency of the driving forces due to hinge slop or hinge elasticity.

Design of Integrated antenna modules

Although the previously described 4 m diameter BBM is symmetrical, the antenna reflector curvature required that peripheral modules should be slightly skewed. The reason for this is that standoff length would be excessive if the modules were symmetrical. In addition, considering the connectivity of each module, at least three types of deployable truss modules are necessary to assemble a structure of seven or more modules. The lacing pattern of the truss must be designed such that truss members can be synchronized to the adjacent modules. Because the design of the peripheral truss modules is complex, the hinge mechanisms of the 4 m diameter BBM were modified. Moreover, the driving mechanism and the latch mechanisms were also modified to improve deployment performance.

Figure 6 shows the upper view of the 4 m diameter BBM; the radial members and peripheral members are drawn as grid lines. As shown in this figure, grid lines of the 4 m diameter BBM cross at a 60 degree angle. In contrast to the 4 m diameter BBM, the integrated truss modules were designed to have square grids (90 degree crossing angle). The deployment truss modules with orthogonal grid lines have simple and superior deployment characteristics. The basic concept of the deployment and stowing motion of the deployment truss module is represented by the two dimensional shearing transformation of square links in the cross section of the deployment truss module. The initial shearing transformation of square links is accomplished by sliding one end of a diagonal member of the square links. Final shearing transformation, i.e., transformation from plane form to parabolic form, is accomplished by elongating or shortening the diagonal members of the square links. In this square grid concept, all deployment truss modules share common design criteria. The amount of elongation or shortening of the diagonal members and the length of folding members determines the final shape of the deployable truss module. In order to improve the deployment characteristics of the folding hinge mechanism, the square link hinge was employed. In addition, to offset the loss of transmission efficiency, two additional motors were set on each module.

BREAD BOARD MODELS OF INTEGRATED DEPLOYABLE ANTENNA MODULES

Figure 7 shows a photograph of the three integrated antenna modules. The modules were designed to have the same F/D (Focus divided by Diameter) value as the 4 m diameter BBM. They are 1m in equivalent diameter.

Structural basis

The deployable truss structure consists of longitudinal members, radial members, circumference members, diagonal member, folding members, revolving hinges, sliding hinges, folding hinges, and driving motors. Longitudinal, radial and circumference members are made of CFRP (Carbon Fiber Reinforced Plastic). Diagonal members consist of an aluminum tube, a steel stem, a coil spring, and a lock/release mechanism. Figure 8 shows the cross section of both a collapsing and a extending diagonal member. The folding hinge mechanism consists of a revolving hinge axis, two linkage arms and a spiral spring set on a linkage node. Sliding hinges move along the motor axes and are driven by motors.

Three functionally independent antenna modules were fabricated and integrated. They were named type 1, type 2, and type 3. Their locations on the parabolic surface are shown in figure 9. Figure 10 explains the deployment direction of the truss nodes. In this figure, filled triangles denote in-plane motions, double circles denote upward motions and crosses denote downward motions. In order to synchronize a module to the two adjacent modules, one of the three modules must be designed to turn the truss topology upside down. The type 3 module was designed to achieve this. Structural features of each antenna module are described as follows.
(1) The type 1 antenna module is placed on the center of the parabolic surface, so it is symmetrical.
(2) Diagonal members of each antenna module have different combinations of collapsing and extending elements.
(3) The final shape of each antenna module is determined by the length of the folding and diagonal members.

Design and analysis of deployment mechanism

The sliding hinge mechanisms and the latch mechanisms of the folding members must driven with sufficient force and moment to overcome the resistant forces of the cable network and surface mesh. These resistant forces were estimated by calculating the reaction forces against the cable network at each standoff point using CAble Structure Analyzer (CASA)[3]. Figure 11 shows the transition in standoff force during deployment as a function of the rotation angle of the truss member. These forces rapidly increase as the fully deployed position is approached.

Excessive torque of folding members results in anomalous deployment. Figure 12 shows the motor reaction force transition during deployment motion. The instant that the truss module is released, rapid deployment motion is induced independently of the three driving motors. The reason for this is that elastic deformations arise at hinge mechanisms due to folding members. Soon, these deployed members rebound to their original position. When this happens,

unexpected reaction forces arise at the driving motors which then failed to hold their predetermined positions.

GROUND DEPLOYMENT TEST

The object of ground deployment tests is to confirm design criteria for the integrated antenna modules under the 1G environment and to get meaningful data for the estimation of deployment characteristics. These data will be compared to the actual deployment characteristics under micro-gravity environment to improve the accuracy of analytical models.

Test equipment
Ground deployment tests must be carried out to verify the deployability of the antenna modules and improve the analytical model. However, the antenna module has insufficient structural strength to overcome gravity, especially the integrated modules. In addition, deployment characteristics are seriously altered by gravity. Therefore, a gravity compensation technique was developed around a simple suspension method. Figure 13 shows the ground deployment apparatus for both the unit module and the integrated modules. The suspension equipment consists of nine movements set on nine linear bearings, pulleys, suspending wires and counter weights. The linear bearings are aligned along the projected motion tracks of the deployment truss nodes. Suspension wires are fixed to truss nodes and the wires are tensioned by counter weights through pulleys. The nine bearings are not driven by any actuators, but follow the truss nodes passively. The antenna module is fixed to the ground plate at lower end of the central motor axis for single deployment while the antenna modules are fixed at lower end of the central motor axis of the central modules for integrated deployment.

Measurement and Data handling method
Deployment characteristics were quantitatively measured by several strain gauges and qualitatively observed by a video recording system. Several LEDs were set on truss nodes to indicate instantaneous position in the video records. The video tracking system will be used to deal with these data. The operations of the diagonal members and latch mechanisms were confirmed by this visual observation. Figure 14 indicates the locations selected for the strain gauges. These locations were selected considering the following evaluation items.
(1) Reaction force transitions due to the cable network during deployment.
(2) The influence of diagonal members on the deployment motion.
(3) Twisting mode shapes due to excessive torque of folding members or inadequate gravity compensation.
(4) The influence of module integration on the deployment motion.
A pair of strain gages was fastened to the center of each member to be tested. Strain data were amplified by a strain amplifier and quantized by a micro computer. These data were then converted into axial forces and bending moments using the following equations,

$$F = EA\frac{(\varepsilon_1 + \varepsilon_2)}{2} \text{ (N)}$$

$$.....(1)$$

$$M = EI\frac{(\varepsilon_1 - \varepsilon_2)}{d} \ (Nm),$$

$$.....(2)$$

where ε_1 and ε_2 are the pair of strain data, E is Young's ratio (N/m²), A is the cross-sectional area of the member (m²), d is the diameter of the member (m), I is the moment of inertia (m⁴), F is the axial force, and M is the bending moment.

Experimental results

Figure 15 shows the deployment motion of the integrated antenna modules. The deployment of each antenna module and the integrated antenna modules were successfully completed and latch up was achieved. However, unexpected stresses arose at hinge mechanisms during deployment. Figure 16 shows bending moment transition in a radial upper member of the type 1 module. This figure indicates that bending moments arise when the diagonal members are released but disappear at full deployment. The reason for this is the unexpected deformations that arose at the hinge mechanisms. Figure 17 shows bending moment transition in a standoff during deployment. The reaction forces against the cable network(the bending moment divided by standoff length) increase gently as compared to analytical results(figure 11). The most undesirable result was that the cable network frequently clung to the hinge mechanisms. To prevent cable entanglement, the cable network must be arranged carefully before deployment.

DEPLOYMENT ANALYSIS FOR SQUARE GRID DEPLOYABLE TRUSS

As described previously, transformation from a plane form to a parabolic form, is accomplished by elongating or shortening the diagonal members of the square links. The transformation must be smoothly accomplished without any elastic deformation. According to experimental results, however, some elastic deformations were created when the diagonal members were released. These elastic deformations vanished at full deployment. The reason for this is that the antenna modules were not designed for transient deployment but only for stowed and deployed configurations. In order to clarify the transient deployment motions, a simple geometric model and a actual dynamic model were considered. Elastic deformations at hinge mechanisms in a dynamic model were calculated using DADS (Dynamic Analysis and Design System).

Deployment to a plane form

Figure 18 shows a simple geometric model of the integrated antenna modules. In this figure, P_{ij} denotes a grid point located at the i-th coordinate in the x direction and the j-th coordinate in the y direction. α_{ij} and β_{ij} denote inclination angles of members which are connected to P_{ij} from x direction and y direction, respectively. α_{ij} and β_{ij} are defined as ,

$$\alpha_{ij} = \beta_{ij} = (-1)^{i+j-1}\theta$$

$$.....(3)$$

where θ is the stowing angle from full deployment position. The coordinates of grid point P_{ij} are expressed as follows.

$$x_{ij} = \sum_{m=1}^{i} \left(l\cos \alpha_{mj}\right) = l\cos \theta \cdot i$$

$$.....(4)$$

$$y_{ij} = \sum_{m=1}^{j} \left(l\cos \beta_{im}\right) = l\cos \theta \cdot j$$

$$.....(5)$$

$$z_{ij} = \sum_{m=1}^{i} \left(l\sin\alpha_{m0}\right) + \sum_{m=1}^{j} \left(l\sin\beta_{im}\right) = \frac{l\sin\theta\left\{1 - (-1)^{i+j}\right\}}{2}$$

$$.....(6)$$

These equations indicate that x_{ij} and y_{ij} are independent of j and i, respectively. Thus grid lines that consist of truss members cross at an orthogonal angle during deployment to a plane.

Shearing deformation from a plane form

In this analytical case, the shearing deformation to a parabolic surface is assumed to begin at the fully deployed plane form. Assuming the surface to be the central part of a parabolic surface, the coordinates on the surface are related through focal length f where $z_{ij} = \dfrac{x_{ij}^2 + y_{ij}^2}{4f}$. Thus shearing angles in the line parallel to the x axis or y axis, have the same value. α_{ij} and β_{ij} are defined as

$$\alpha_{ij} = \varphi_i^x$$

$$.....(7)$$

$$\beta_{ij} = \varphi_j^y,$$

$$.....(8)$$

where φ_i^x, φ_j^y are the shearing angles in x direction, and y direction respectively. φ_i^x, φ_j^y are arbitrary values during deployment . The final values are determined as

$$\cos^2\varphi_1 = \frac{8f^2}{l^2}\left[\sqrt{\left(1 + \frac{l^2}{4f^2}\right)} - 1\right]$$

$$.....(9)$$

$$\tan \varphi_{m+1} = \frac{1}{4f}\left(2\sum_{k=1}^{m} \cos \varphi_k + \cos \varphi_{m+1}\right)$$

$$.....(10)$$

Considering $\varphi_m^x = \varphi_m^y = \varphi_m$, the coordinates of grid points are expressed as

$$x_{ij} = \sum_{m=1}^{i} \left(l\cos \varphi_m\right) = x_{ij}(i)$$

$$.....(11)$$

$$y_{ij} = \sum_{m=1}^{j} (lcos\ \varphi_m) = y_{ij}(j)$$

.....(12)

These equations also indicate that x_{ij} and y_{ij} are independent of j and i, respectively. Thus grid lines that consist of truss members cross orthogonally during shearing deformation.

Composite deployment motion

During composite deployment motion, inclination angles of truss members and coordinates of grid points can be written as follows.

$$\alpha_{ij} = \varphi_i + (-1)^{i+j-1}\theta$$

.....(13)

$$\beta_{ij} = \varphi_j + (-1)^{i+j-1}\theta$$

.....(14)

$$x_{ij} = \sum_{m=1}^{i} lcos\ \alpha_{mj} = \sum_{m=1}^{i} cos\ \varphi_m cos\ \theta - \sum_{m=1}^{i} (-1)^{m+j-1} sin\ \varphi_m sin\ \theta$$

.....(15)

$$y_{ij} = x_{ij}$$

.....(16)

$$z_{ij} = \sum_{m=1}^{i} sin\ \alpha_{mj} + \sum_{m=1}^{j} sin\ \beta_{im}$$

$$= \left(\sum_{m=1}^{i} cos\ \varphi_m + \sum_{m=1}^{j} cos\ \varphi_m \right) cos\ \theta$$

$$+ \left(\sum_{m=1}^{i} (-1)^{m+j-1} cos\ \varphi_m + \sum_{m=1}^{j} (-1)^{m+i-1} cos\ \varphi_m \right) sin\ \theta$$

.....(17)

Above equations indicate that x_{ij} and y_{ij} are functions of i and j. This means that the grid points x_{in} (n=1,2,3,...) or x_{nj} (n=1,2,3,...) are not in line, and the crossing angles of grid lines vary with their position. Thus some elastic deformation arises when the diagonal members are released.

Dynamic deployment analysis using DADS

According to the above simple model, hinge stress is inevitable. However, elasticity and hinge mechanism slop would ease geometric distortion in actual deployment modules. Forces and moments at a hinge mechanism can be calculated using DADS. Truss members are assumed to be rigid bodies. Their degrees of freedom are connected to each other by elastic elements (except for the rotation around the hinge axes). Deployment motion is divided into three portions: deployment to a plane form, composite deployment, and deployment to a parabolic form. Extending or shortening of diagonal members can be modeled by three discontinuous constraint conditions. These conditions are fixed initial length, a constant elongation or shortening rate and fixed final length. Joint slop is not

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considered in this case. Figure 19 shows schematic deployment motions of a portion of the deployment antenna module. In this figure, a gap between two portions of a diagonal member indicates elongation of the diagonal member. Figure 20 shows axial force transition at a hinge mechanism during deployment. Elastic deformation arises when the diagonal members are released, and vanishes at full deployment.

CONCLUSION

The modular concept for the construction of cable-mesh deployable antennas was proposed. In order to extend the unit antenna module to the integrated antenna modules, square grid deployable trusses were designed, fabricated, and tested. The integrated antenna modules were successfully deployed and latched up in both 1 G and micro gravity environment. However, unexpected loads arose in the hinge mechanisms. These loads could be analytically estimated by a simple model and DADS. More consideration has to be paid to the difference in the deployment characteristics between the 1 G and micro gravity environments.

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3. Jin Mitsugi and Tetsuo Yasaka, Nonlinear Static and Dynamic Analysis Method of Cable Structures, AIAA Journal, Technical Note, vol. 29, No., 1991, pp. 150-152.

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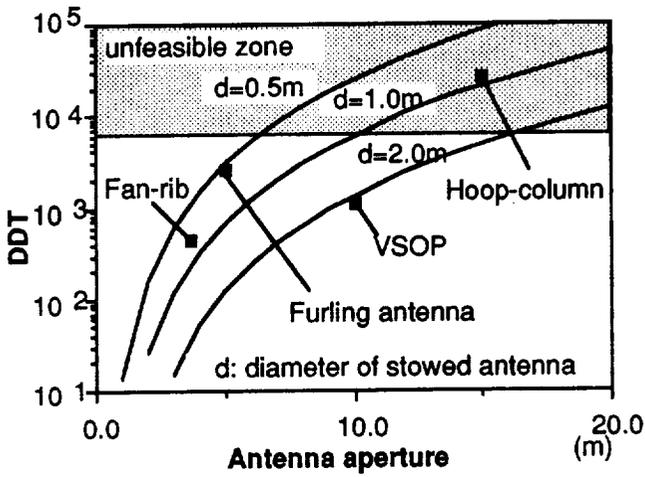
Figure 1 Ground test feasibility
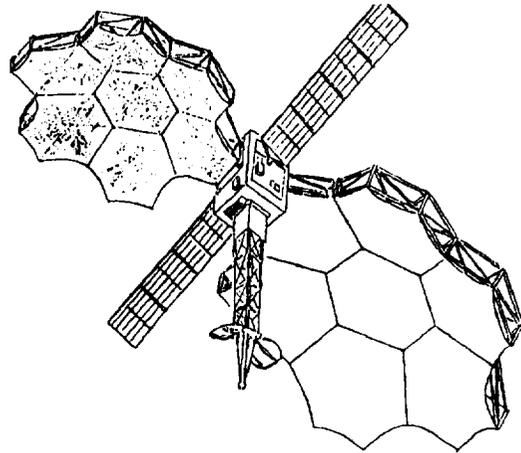
Figure 2 The future advanced mobile communication satellite.
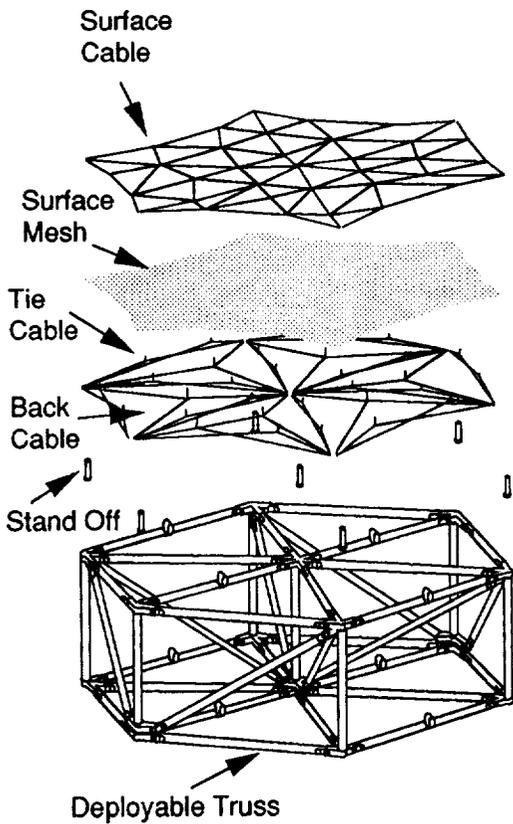
Figure 3 Basic Module Structure
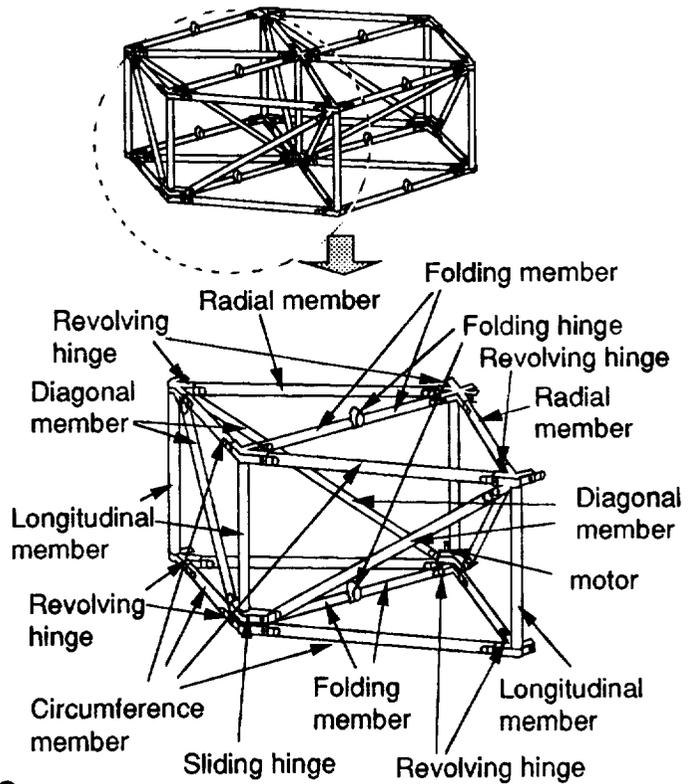
Figure 4 Deployable Truss Structure
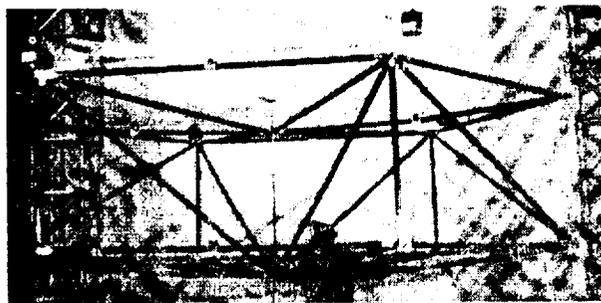
**Deployed**

Stowed

**Figure 5 The BBM of the central module of the 10 m antenna**

60 deg
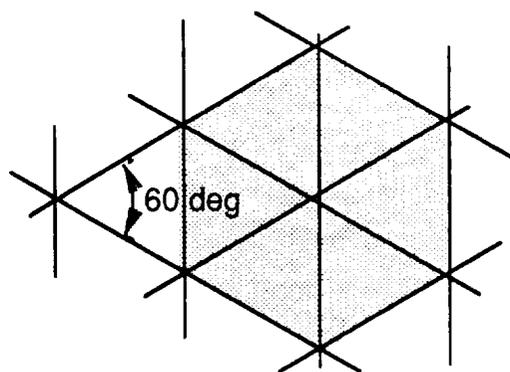
Figure 6 The upper view of the 4 m diameter BBM
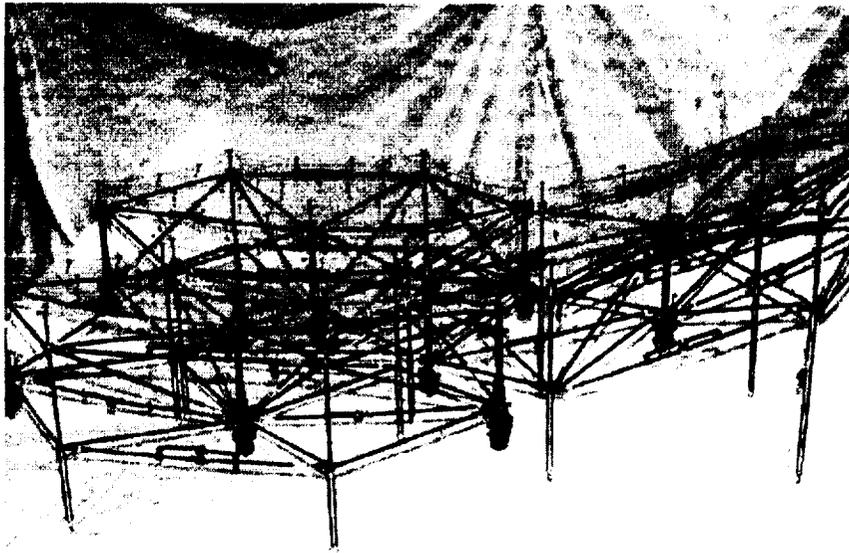
**Figure 7 The integrated antenna modules**

Spring   Elongation member

Release pin
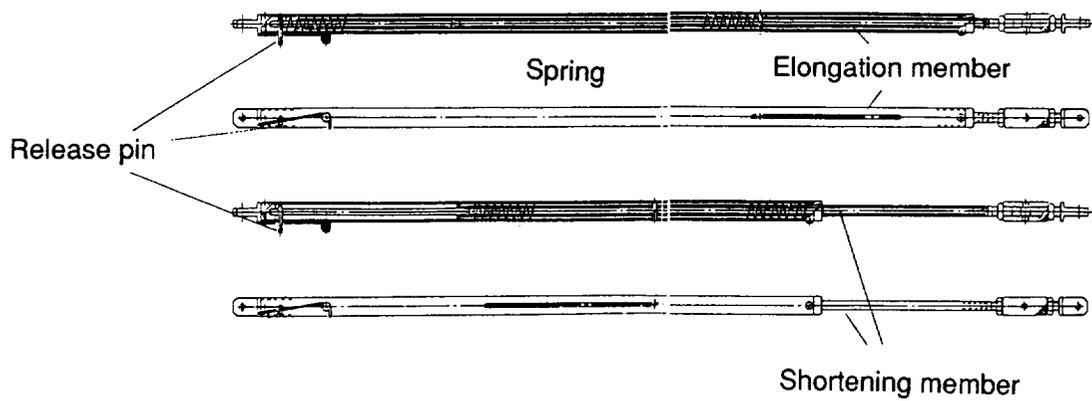
Shortening member

Figure 8 Shortening and elongation diagonal members
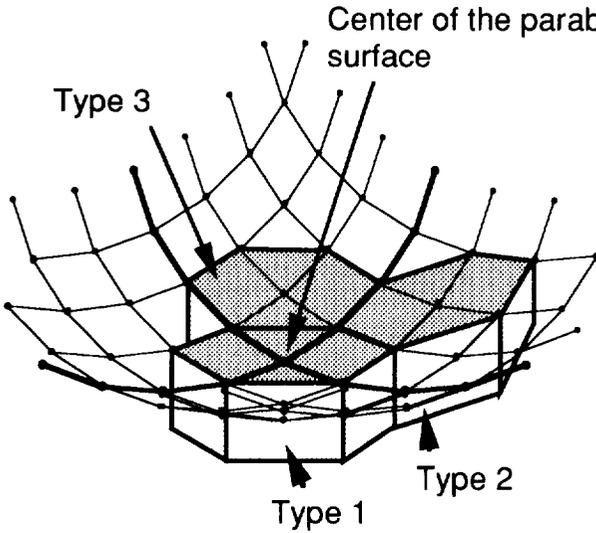
Figure 9 Locations of antenna modules on the parabolic surface
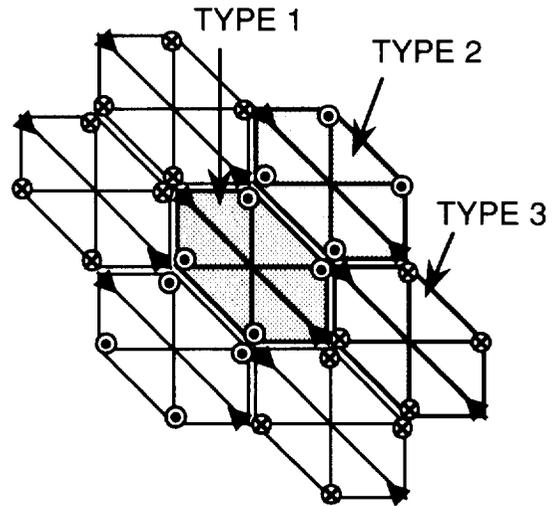
Figure 10 Deployment direction of truss nodes.
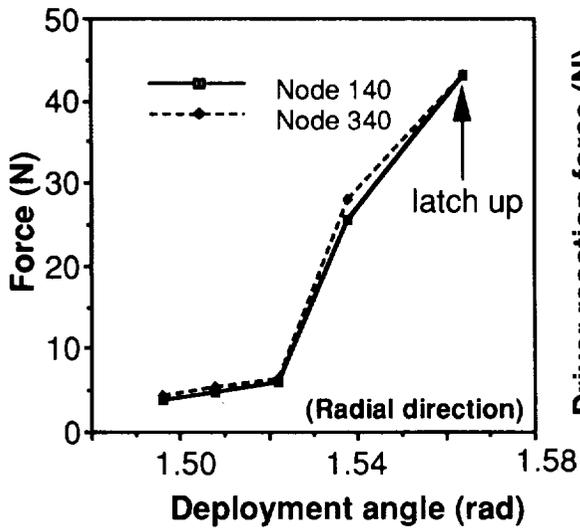

Figure 11 Stand-off force during deployment
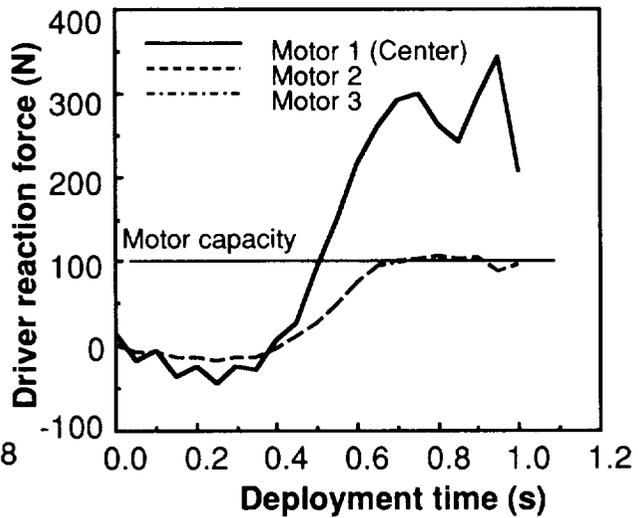
**Figure 12 Motor reaction force during deployment**

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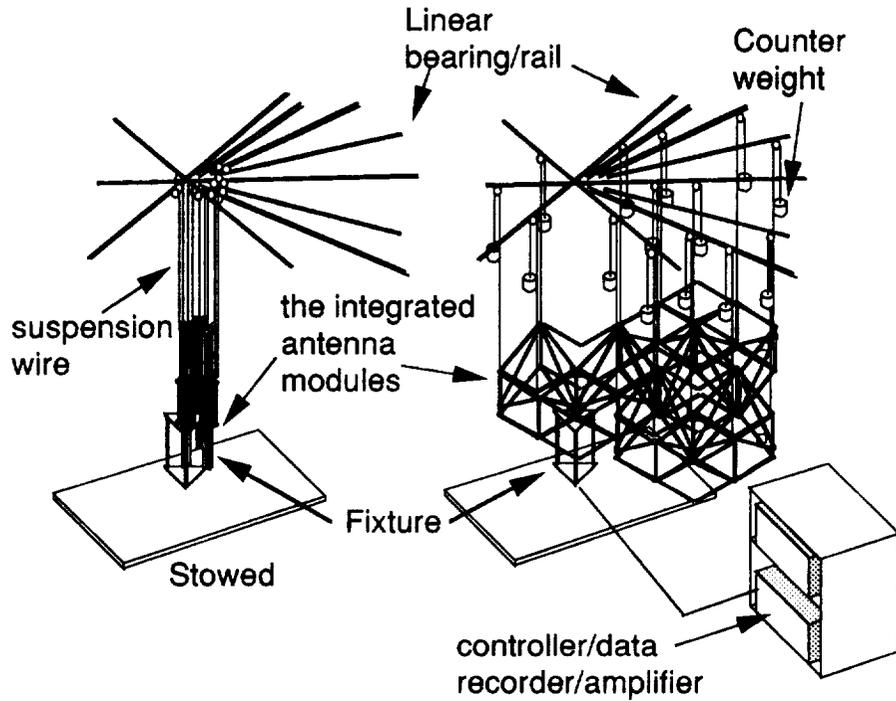
Figure 13 Ground test apparatus
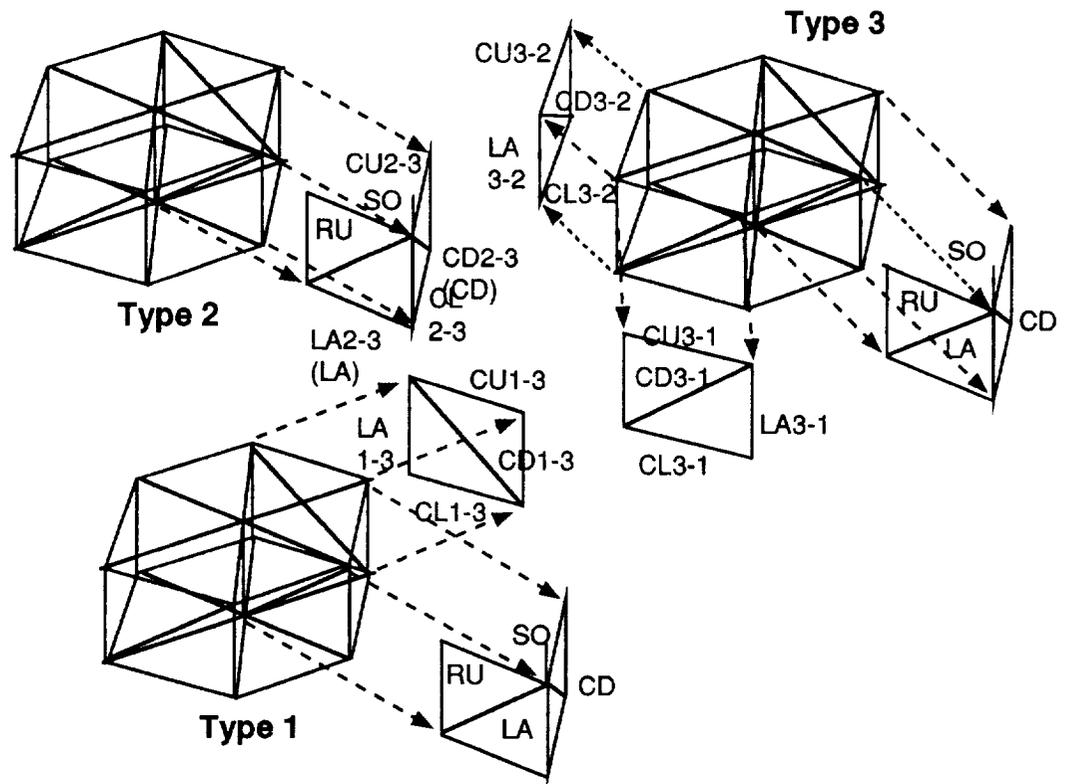
Figure 14 Selected locations of strain gages

Stowed · Deployment to a plane surface

Elongation of the diagonal member

Deployment to a parabolic surface
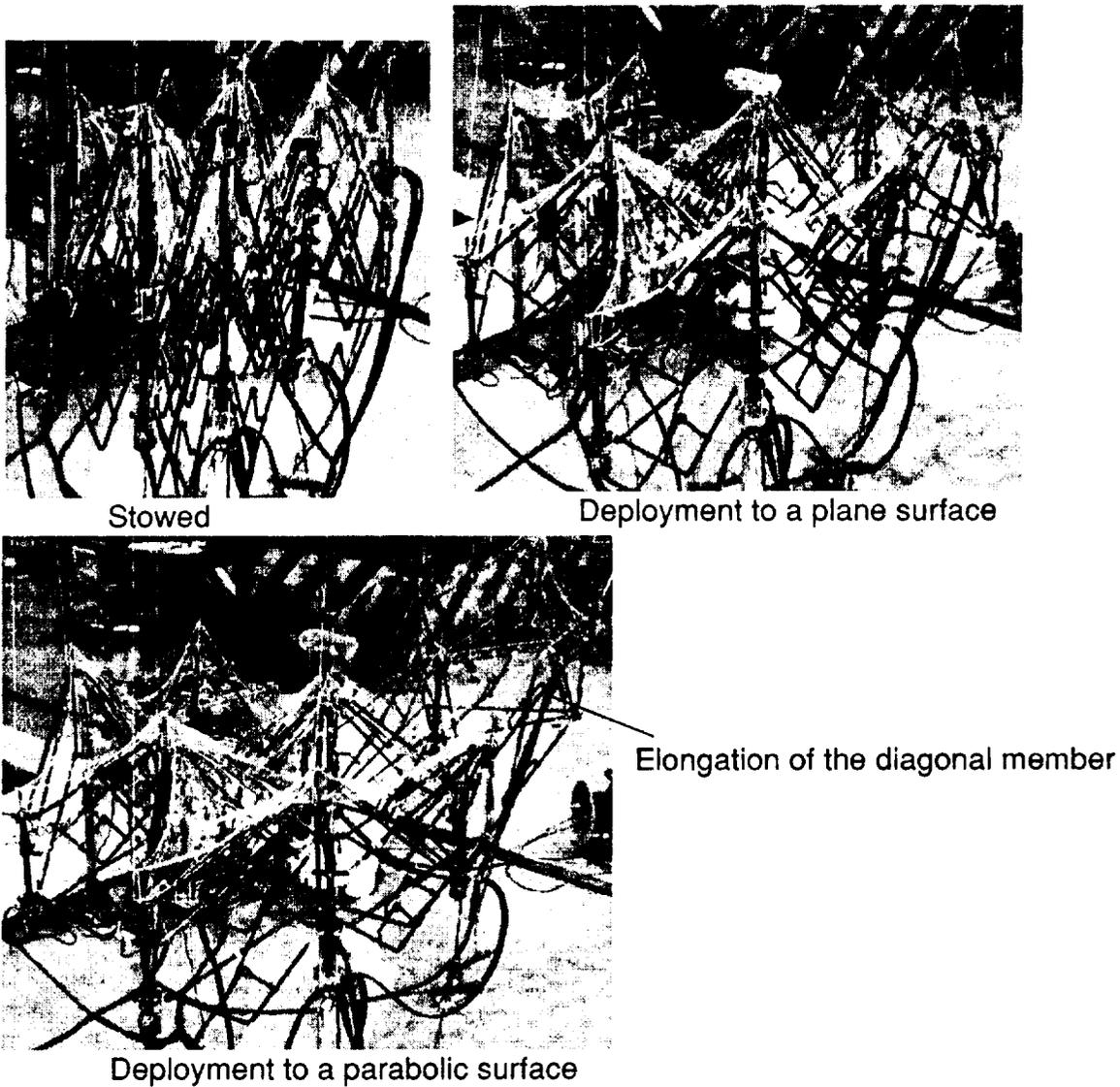
Figure 15 Deployment motion of the integrated modules
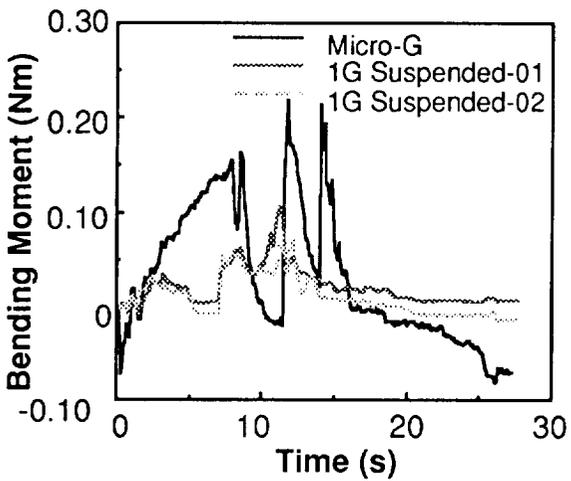

Figure 16 Bending moment in a radial upper member
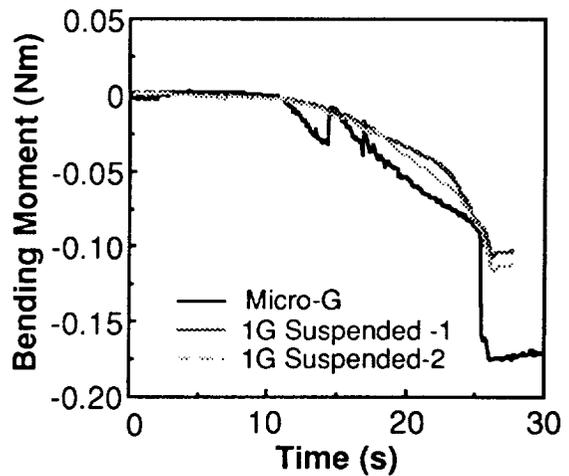
**Figure 17 Standoff bending moment transition**

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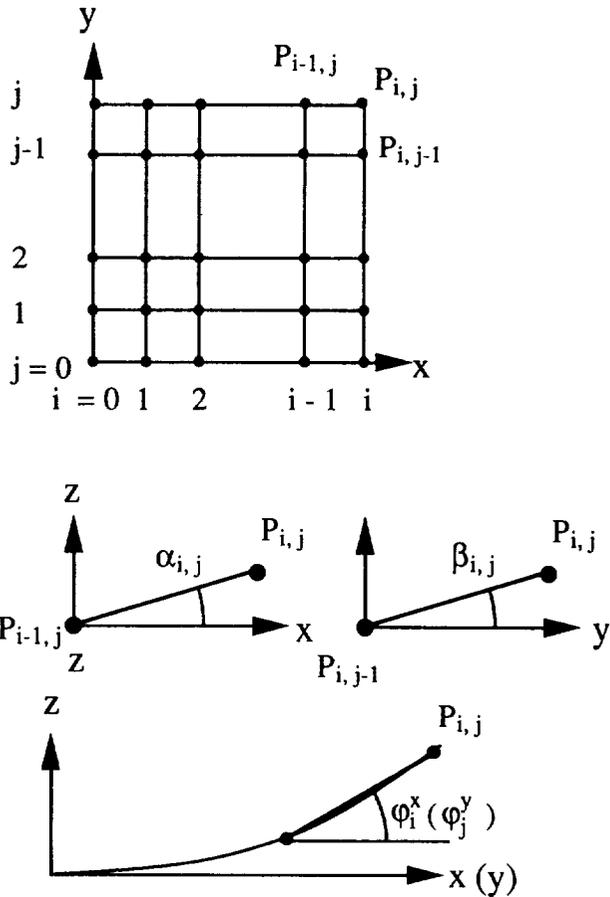
Figure 18 A simple geometric model of the integrated antenna modules

Stowed

Deployment to a plane surface

Elongation

Deployment to a parabolic surface
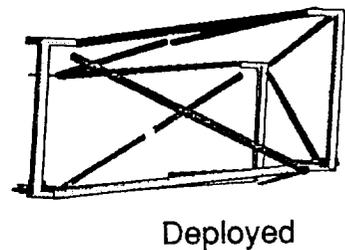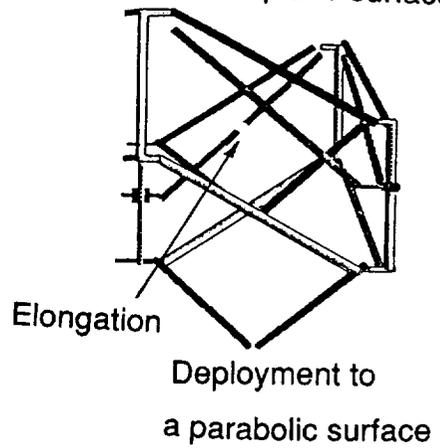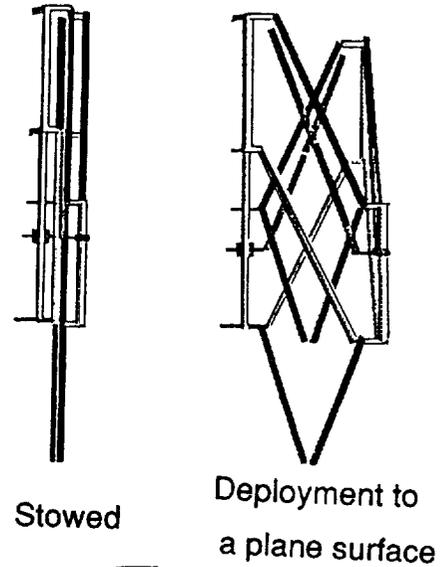
Deployed

Figure 19 Deployment motion of a portion of the deployment antenna module

X direction
Y direction
Z direction
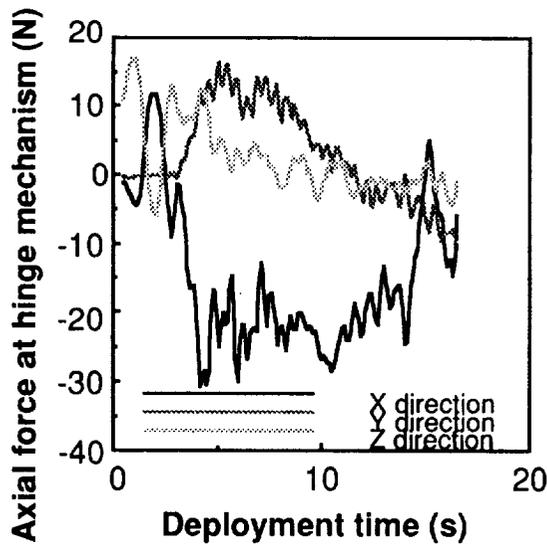
Figure 20 Axial force transition at a hinge mechanism