Tendon-reinforced Ultralight Large Antenna Reflector

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Abstract

We have been investigating an ultralight large antenna reflector with an aperture diameter of more than 20 m and total mass of 130 kg including a boom structure and holding/release structures. This reflector is a geodesic cable network structure supported by a tendon-reinforced structure. Previous studies using a conceptual model showed that such large antenna reflectors seemed feasible. In this article, we clarify important design parameters, such as the catenary ratio and number of facets, to improve the manufacturability. Using detailed designs, we estimate the total weight and stowed size to clarify system compatibility.

1. Introduction

One direct way of enhancing the performance of satellite communication, broadcasting, interplanetary communication, and information gathering systems is to increase the size of the satellite antenna reflector because this improves the transmitting and receiving performances even if the satellite power system and transponder performance are not changed. Development programs for communications satellites have, over the last 20 years, yielded remarkably advanced reflector structures, and several structural concepts have been proposed by various organizations. These advances support the cellular phones and high-speed Internet connections being demanded for the next-generation of satellite communications by users on aircrafts and trains. Unfortunately, the capital costs of constructing advanced satellite systems using conventional technologies are excessive. Our solution is the combination of an ultralight large antenna reflector and a 100-beam-class multibeam feed system to construct a 1-Gbit/s, 1- or 1.5-ton-class satellite bus.

This article describes a design methodology for ultralight large antenna reflectors with aperture diameters larger than 20 m and an areal density of less than 0.25 kg/m^2. The target of the total mass is 130 kg including the boom structure and holding structure. Although, the Astro-Mesh [1], [2] is now providing large reflectors with a diameter of 13 m, and an enhanced version is being studied, the stowed size is too large to suit 1- or 1.5-ton-class satellite buses and the areal densities seem to be twice the required value.

To obtain an ultralight large antenna reflector, we propose a geodesic cable network structure supported by a tendon structure. First, we explain our target and the structural concept of the reflector. Experiments on a breadboard model were carried out to ensure feasibility. Next, we examine the relationship between the total mass and strength of the support structure so as to detail the structural design. We determined the cable-mesh structure that achieves the required design values given current manufacturing capabilities. To validate the proposed reflector, we clarified detailed candidates for hinges, linkage mechanisms, drive mechanisms, and stowed configurations of the basic structure. The total mass of the entire structure and the stowed configuration were examined to assess system compatibility.

2. Antenna reflector targets

Given the system frequency bandwidth of 35 MHz, meeting the 1-Gbit/s capacity requirement entails extensive frequency reuse. Our solution is a 3-beam cluster model with about 70 beams [3]. A satellite

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antenna with a gain of 43.5 dBi at EOL (end of life) can provide 70 beams; this is equivalent to a 20-m aperture. Making such a satellite based on conventional designs would yield a payload mass of more than 800 kg. To reduce the system cost, we aim to halve the payload mass [3], so the mass budget for the reflector is 130 kg, about half the weight of a conventional reflector [4]. An example of a satellite system configuration is shown in **Fig. 1**. A 20-m reflector is attached to a 1- or 1.5-ton-class satellite by a boom structure.

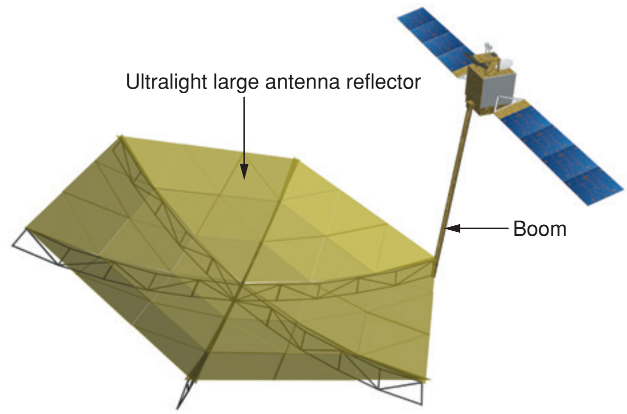

Fig. 1. System configuration.

3. Feasibility study of tendon-reinforced antenna reflector

3.1 Structural concept of an ultralight large antenna reflector

Our structural design approach has two aspects. The first is an extremely lightweight support structure in which the non-linearity of its structural behavior is taken into account. The other is a cable network structure that maintains the reflector's shape even if the support structures are severely deformed by in-orbit thermal and/or vibration disturbances. Our proposal is a geodesic cable network structure that is extended and supported by a tendon-reinforced deployable frame structure [5].

The concept of the resulting ultralight large antenna reflector is illustrated in **Fig. 2**. The key design advance is that the accuracy of the reflector's surface is determined by a geodesic cable network structure; the support structure simply tensions the geodesic cable network. To stiffen the deployable frame structures, we use tendon cables to restrain the post-buckling displacement between the deployable frame structures.

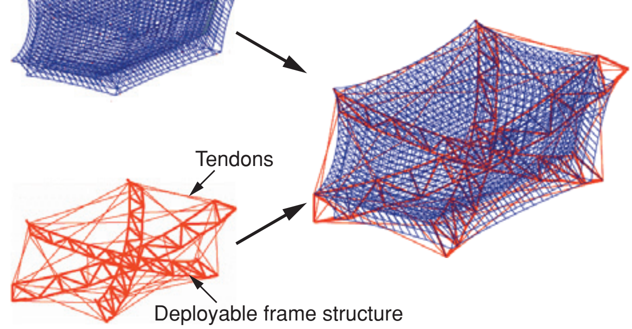

Fig. 2. Concept of our ultralight large antenna reflector.

3.2 Feasibility study of structural concept

The feasibility of this structure was evaluated by detailed analyses and tests conducted on a breadboard model. As shown in **Fig. 3**, we fabricated a breadboard model of the support structure; its diameter was 3.7 m. The support structure consists of six deployable frame structures arranged around a stiff post. The deployable frame structures were designed to form a spherical shell that best fits the desired parabolic surface. Some of the nodes on the deployable frame structures are connected by tendon cables. Although the geodesic cable network structure and the metallic mesh are not included in this model, their compressive forces are represented by dummy cables. Theoretical and measured results for bending stress are compared in **Fig. 4**.

The theoretical result matches the average of the measured results, which deviate significantly due to manufacturing tolerances and assembly errors. Therefore, the characteristics of the proposed structures can be estimated by the analysis method described herein. From our investigation, we reached the following conclusions [6].

(1) The tendons effectively suppress post-buckling deformation in the support structure. The use of tendon cables increases the compression rigidity of the long ribs of the support structure by around 10 times and their compression strength by 4 times.

(2) Assuming that the thermal distortion of the sup-

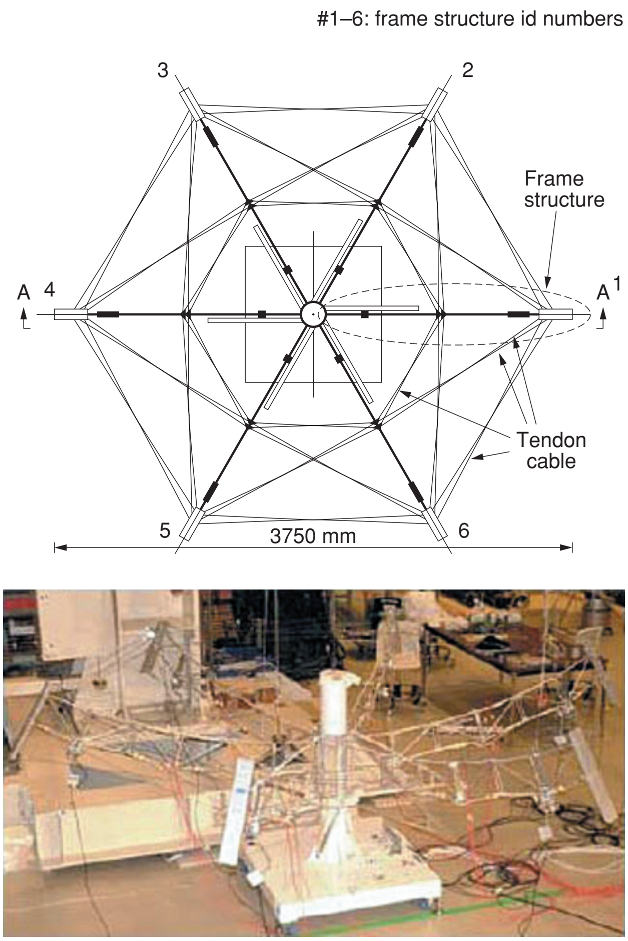

Fig. 3. Breadboard model of reflector.

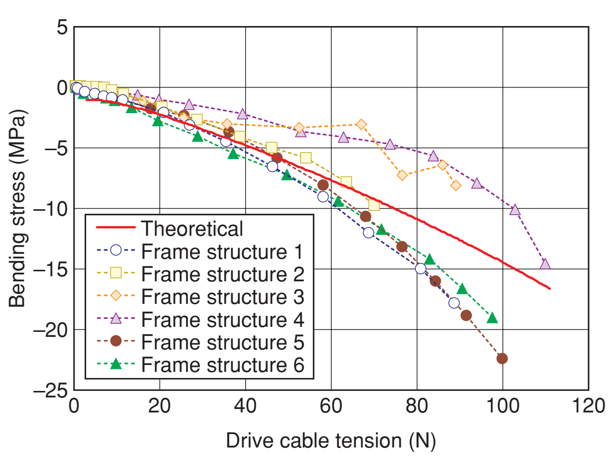

Fig. 4. Static load response (bending of the upper side) versus cable tension. The red line shows the result of theoretical analysis and the symbols show measured data for individual frames.

port structure is 2 mm, the reflector structure has sufficient margin (surface accuracy) against disturbances while in orbit (confirmed by a sensitivity analysis for cable networks).

Therefore, the characteristics of the deployable reflector can be estimated by analysis, and this reflector can offer a lower weight.

3.3 Issues for detailed design

In order to advance the design status to the level needed for engineering and/or pre-flight modeling, the following issues must be carefully considered.

(1) Confirmation of the detailed structural design of the support structure
(2) Manufacturability of the geodesic cable network structure
(3) Detailed design of mechanisms
(4) System compatibilities

There are also other important issues that we must consider to improve system reliability. These include test and verification methods for deployment reliability, structural stiffness/strength, and surface accuracy. These issues are not covered in this article.

4. Detailed design consideration and manufacturability

4.1 Detailed design of deployable support structure

As described above, the target mass of the antenna reflector (20 m in diameter) is 130 kg, including the boom structure. While reducing the mass of the antenna reflector, we had to maintain a sufficient margin of safety against applied compressive force. To minimize the structural mass, we examined three design parameters: representative tube diameter, tube thickness, and height of the frame structure.

When designing a structure of this type, we need to take into account the large deformation and structure buckling expected. To deal with the large deformation, a co-rotational formulated finite element method with direct coordinate partitioning [7] was implemented on the analysis tool SPADE (simple partitioning algorithm based dynamics of finite element). We enhanced the previous version of SPADE by adding a new computational method that can find a bifurcation point and estimate the buckling mode: its validity was confirmed by comparing the analytical result to the theoretical solution for a simple beam structure. We used the new design tool to analyze the equilibrium shape and deployment motion of the proposed structure. The analysis model for a 20-m-diameter antenna reflector is shown in **Fig. 5**. Tendons are treated as cables and each frame structure is composed of beam elements connected by hinge elements.

We evaluated two compressive force limits: 1) the limit load, which is the limit indicated by the linear stress response, and 2) the ultimate load, which is the load at which the stress in the most critical member reaches a margin of safety of 0.5. We also calculated the total mass of the reflector including the boom based on the structural mass obtained using the analysis model. For simplicity, the compressive forces created by the geodesic cable network structure and the mesh were represented by dummy cables. The mass ratios of hinges, deployment mechanisms, and other non-structural assemblies to the structural mass were determined using previously developed models.

As one analytical result, **Fig. 6** shows the effect of tube thickness on both acceptable load and total mass. The limit load is not linear against wall thickness due to the load created by post-buckling displacement. Assuming that the maximum applied compressive force is 100 N, we should choose a representative tube diameter of 18 mm and thickness of 0.7 mm. In this case, we can reach the total mass of 149 kg with a margin of safety value of 0.5.

4.2 Geodesic cable network structure design optimization considering manufacturability

The design parameters for the geodesic cable network structure are elasticity, initial length, and strength of cable elements. We must determine these parameters considering current manufacturing capabilities. For example, the elasticity of a cable element can be reduced by reducing the cable diameter. However, this lowers cable strength.

Since the geodesic cable network structure determines the accuracy of the reflector, it must be manufactured using well-proven techniques. From this point of view, the most important issue is to decrease the ratio of maximum to minimum cable tension. The ease of manufacturing the cable elements is restricted by both the maximum and the minimum tension. The maximum tension is limited by cable strength for a given diameter and also by fastener strength (cable to terminal). Meanwhile, the minimum tension is determined by the achievable accuracy in cable tension. Moreover, the tension ratio is large when the geodesic cable network structure consists of many cables.

Two design parameters were found to be effective at reducing the tension ratio: the number of cables and the depth of the edge catenary, as shown in **Fig. 7**. The

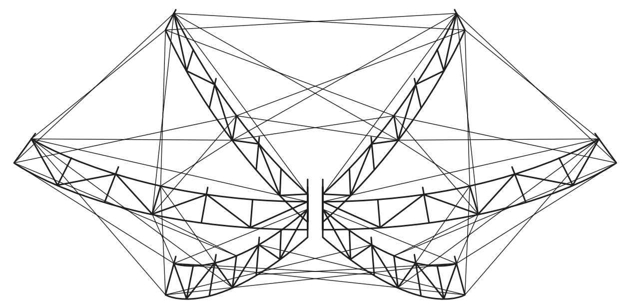

Fig. 5. Analysis model.

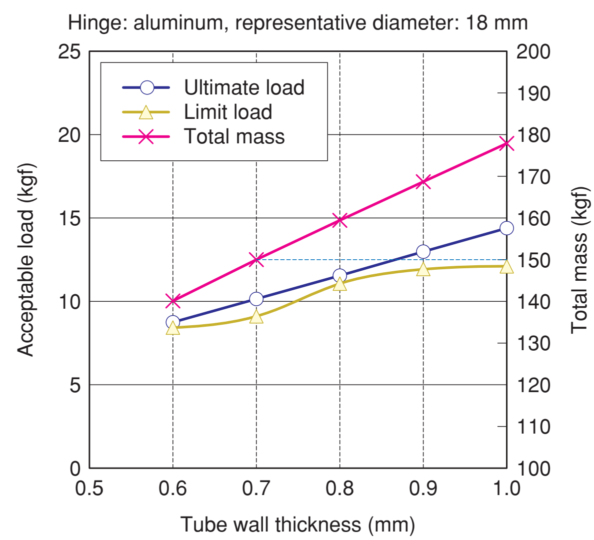

Fig. 6. Effect of tube thickness on acceptable load and total mass.

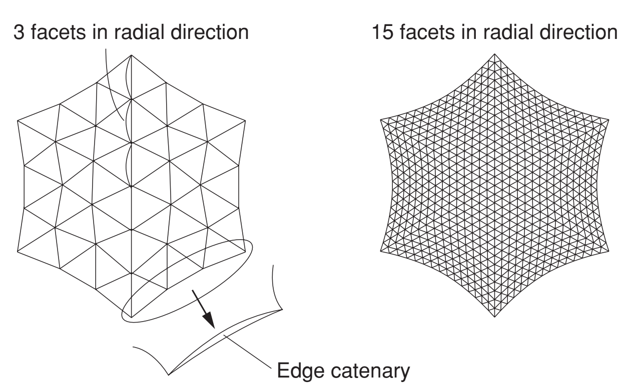

Fig. 7. Effective parameters for tension ratio.

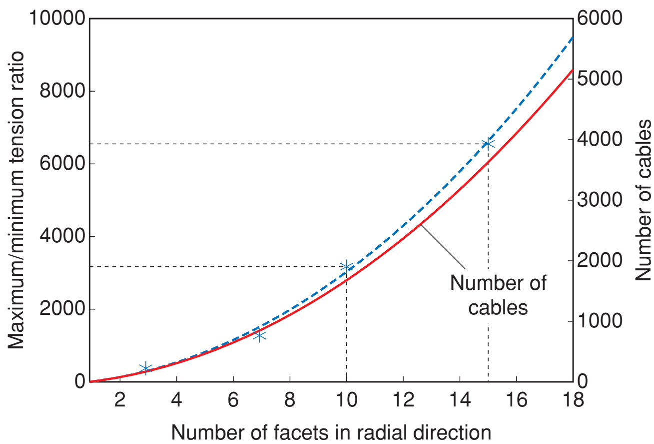

Fig. 8. Tension ratio versus the number of facets.

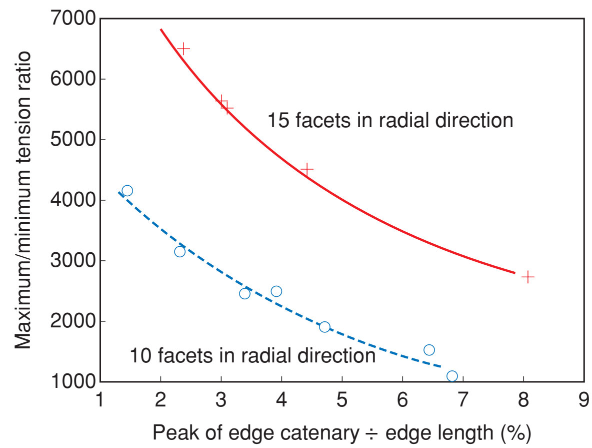

Fig. 9. Tension ratio versus catenary.

number of cables is represented by the number of facets along the reflector's radius, and the catenary depth is represented by the ratio of the peak of the catenary edge to the edge length.

As shown in **Fig. 8**, increasing the number of facets rapidly increases the tension ratio. On the other hand, the number of facets strongly affects the surface random error from the ideal parabolic surface. The allotted random error for the facet approximation should be less than 0.5 mm (rms), so the number of facets should be more than 10.

The effect of catenary depth on the tension ratio is shown in **Fig. 9**. The tension ratio decreases rapidly as the ratio of the catenary peak to the edge length increases. The catenary also affects the peak electrical gain of the antenna reflector, so it should be limited to around 10%. The tension ratio is expected to decrease to a value of several hundred when the catenary ratio is 10%. Considering that the maximum cable tension is estimated to be 100 N, the minimum cable tension will be more than 0.1 N, which eases manufacturing concerns. In addition, decreasing the maximum cable tension reduces the mass of the deployment support structure.

These results show that with 10 facets the catenary ratio is around 8% to 10% and the cable tension is acceptable.

4.3 Detailed mechanism design

Since the composition of the mechanism is customized for each structure, it is difficult to decide the mass of mechanisms, such as deployment drive mechanisms, control mechanisms, and hold/release mechanisms, by estimation based on the analytical model. As described previously, the total mass of our reflector should be 149 kg; however, the accuracy of estimating the mass budget for mechanisms (non-structural mass) is problematic because these masses are assumed to be proportional to the structural mass using the relationships developed for traditional designs. Therefore, detailed design of the mechanisms for the real scale is required to clarify the mass and the potential problems with installation on a satellite. We examined these mechanisms for a real 20-m-scale reflector in detail. Structural and mechanism design drawings were created based on the design heritage of Engineering Test Satellite VIII.

The aperture and catenary (top view) are shown in **Fig. 10**. The structural design parameters, such as tube diameter and thickness, were taken from the results in section 4.1.

A side view of the structure in the fully deployed configuration is shown in **Fig. 11**, and the basic cell structure is shown in **Fig. 12**. Frame structures are composed of several basic cell structures, each consisting of several beam members connected to each other via revolute hinges to permit stowage and deployment. They form two quadrangular frames. To each frame, we added diagonal members that can be folded at an intermediate position. The main driving force is provided by coil-spring-driven four-bar linkage arms attached to the central axis. The linkage arm mechanism is set at a geometrically singular position when the basic cell structure is completely stowed. Therefore, we installed an ancillary coil-spring at the connection hinge between the central lateral member and the lower radial member. Some details of the drive linkage arms and the ancillary coil-spring are

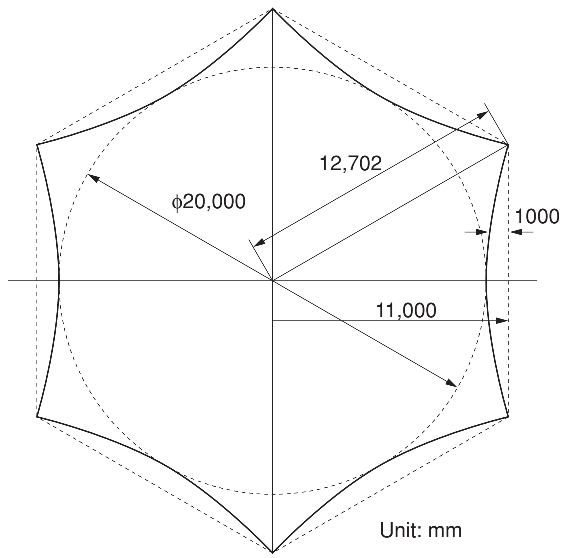

Fig. 10. Aperture and edge catenary.

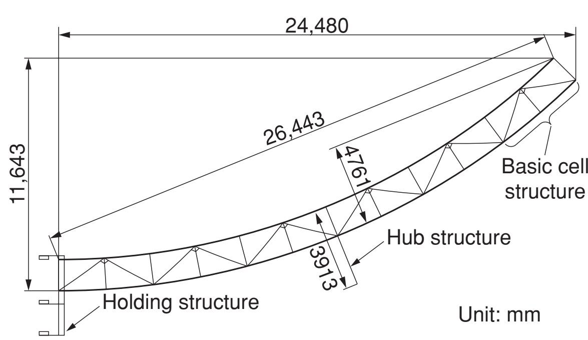

Fig. 11. Deployed configuration of rib structure.

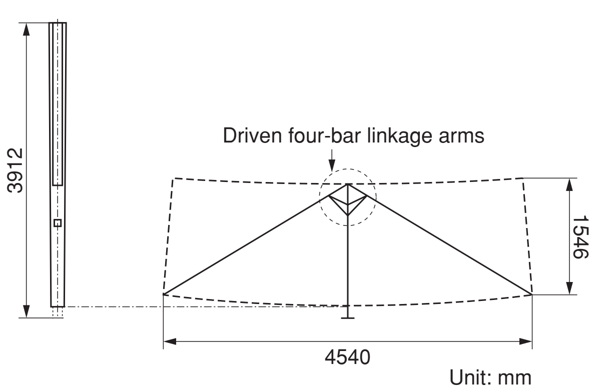

Fig. 12. Basic cell structure.

shown in **Fig. 13**. In addition, to avoid tendon cable entanglement and to enhance the synchronization of the deployment behavior, the tendon cables are wound on drums and released passively as the reflector deploys. The drums are installed at the connection points of tendon cables.

4.4 System compatibility

To clarify the problem of achieving the target mass budget, we estimated the total mass of our reflector structure from the above-mentioned design drawings. In addition, we also considered antenna dimensions in the stowed configuration to clarify the installation feasibility for launch vehicles.

4.4.1 Mass budget of antenna reflector

Details of the support structure masses are shown in **Table 1**. The masses of the holding structure, driving and control mechanism, ancillary spring, and tendon

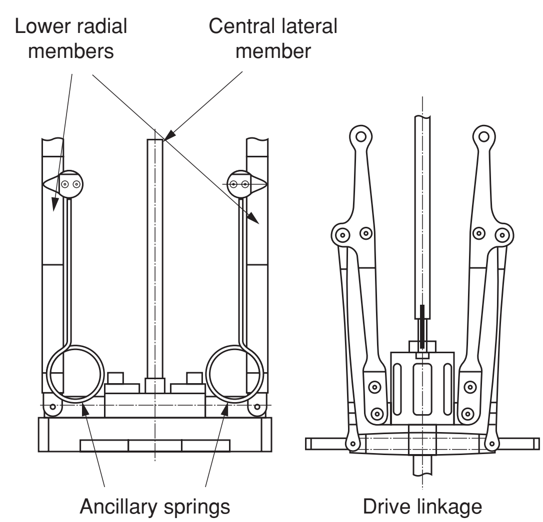

Fig. 13. Details of mechanism design.

Table 1. Detailed mass budget in support structure.

	Analysis	Design drawing
Structural member	38	37
Deployment mechanism	11	8
Holding structure	4	10
Drive/control mechanism	11	39
Ancillary spring	0	14
Tendon structure	0	14
Total	64	122

Unit: kg

structure (including drums) exceed the estimated values used in the analysis. The main reason for this discrepancy is that the design drawings of the mechanisms were based on a two-dimensional deployment structure with the conventional mechanism design methodology.

The mass budget of the antenna reflector in comparison with the results of the analytical estimation are shown in **Table 2**. This table shows that the mass estimated from the design drawings of the deployment support structure is twice that yielded by the analytical estimation. As mentioned above, this difference is caused by the non-structural members of the support structure. Consequently, the first detailed design trial for these mechanisms shows that a new design methodology is needed to reduce the mass of the deployment drive and control mechanisms for one-dimensional deployable structures.

4.4.2 Stowed configuration

If the target stowed size is to be compatible with the fairing of Sea Launch (diameter: 3.75 m) or Speltra of ARIANE5 (diameter: 4.57 m, height: 5 m), then the maximum stowed size should be a diameter of 1.6 m and height of 3.5 m. The stowed dimensions obtained from the detailed design are a maximum diameter of 1.6 m and height of about 4 m, as shown in **Fig. 14**. Therefore, to meet the target height of 3.5 m, the aperture must be reduced to 19 m, which still yields acceptable electrical performance. In addition to the mass budget, we need to refine the dimensions to achieve a sufficient margin.

5. Conclusion

To make an ultralight large antenna reflector, we have proposed a new structural concept and confirmed its basic feasibility. Detailed structural and mechanism designs were carefully considered, as well as manufacturability and system compatibility. The following conclusions were reached.

(1) Assuming that the maximum applied compressive force is 100 N, our design has a representative tube diameter of 18 mm and thickness of 0.7 mm. In this case, we can hold the total mass down to 149 kg with a margin-of-safety value of 0.5.

(2) The ratio of maximum to minimum cable tension in the geodesic cable network structure is expected to decrease to several hundred when the catenary depth is 10%. Considering that the maximum cable tension is estimated to be 100 N, the minimum cable tension will be more than 0.1 N, which simplifies manufacture.

(3) Mechanism design drawings were generated based on the conventional mechanism design methodology. The first detailed design trial for the reflector mechanisms clarified that a new design methodology is needed to reduce the mass of the deployment drive and control mechanisms.

To achieve our goals, we will continue to study the remaining issues associated with the mechanisms and also refine the overall dimensions considering system requirements.

Table 2. Mass of antenna reflector.

Component	Analysis		Design drawing
	Primary	Present	
Cable-mesh reflector	20	(20)	(20)
Support structure	66	64	122
Holding/release structure	34	33	37
Boom	32	(32)	(32)
Total	152	149	211

Unit: kg ( ) not designed at this time

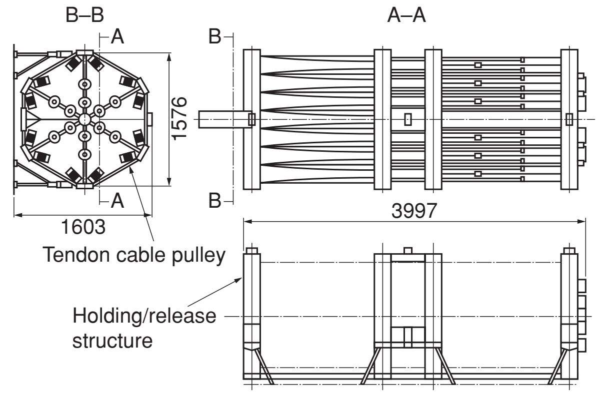

Fig. 14. Stowed configuration.

References

[1] M. W. Thomson, "ASTROMESH Deployable Reflectors for Ku and Ka Band Commercial Satellites," Proc. ICSSC, AIAA-2002-2032, 2002.

[2] T. Smith, B. Lee, D. Semler, and D. Chae, "A Large S-band Antenna for a Mobile Satellite," Space 2004 Conference and Exposition, San Diego, CA, Sep. 28-30, AIAA-2004-6120, 2004.

[3] M. Ueba, K. Ohata, J. Mitsugi, and M. Umehira, "Broadband and scalable mobile satellite communication system for future access networks," Proc. of 22nd ICSSC, Monterey, AIAA-2004-3154, 2004.

[4] Y. Suzuki, A. Meguro, K. Kobayashi, and M. Ueba, "Multibeam

Phased Array Feed System Using Beam Group Concept ," NTT Technical Review, Vol. 5, No. 1, pp. 61-69, 2007.

[5] S. Harada, A. Meguro, and M. Watanabe, "New Tendon Reinforced Reflector for Large-Scale and Ultra-Lightweight Antenna onboard the Satellite," 45th Structures Structural Dynamics and Materials Conference, Palm Springs, AIAA-2004, 2004.

[6] A. Meguro, S. Harada, and M. Ueba, "A Feasibility Study of an Ultra-Light Large Antenna Reflector for Future Mobile Communications Satellites," 56th International Astronautical Congress, Fukuoka, IAF-05-C2.1.B. 02, 2005.

[7] J. Mitsugi, Direct Coordinate "Partitioning for Multibody Dynamics Based on Finite Element Method," 36th Structures Structural Dynamics and Materials Conference, AIAA-95-1442-CP, 1995.

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