ULTRA LIGHTWEIGHT SATELLITE ANTENNA WITH STRETCHED SURFACE

Shigenori KABASHIMA[1], Tsuyoshi OZAKI[1]
Toru TAKAHASHI[2], Yoshihiko KONISHI[2]

[1] *Advanced Technology R & D Center, Mitsubishi Electric Corporation*
1-1-57, Miyashimo, Sagamihara, Kanagawa, 229-1195, Japan
[2] *Information Technology R & D Center, Mitsubishi Electric Corporation*
5-1-1, Ofuna, Kamakura, Kanagawa, 247-8501,Japan

SUMMARY: A new telecommunication system based on inclined geosynchronous earth orbit (GEO) satellites was proposed. The system employs several inclined GEO satellites mounted with deployable phased array antennas of which apertures are 44.8m. The antennas communicate with compact mobile terminals realizing 100,000 digital voice channels. Since conventional honeycomb sandwich structures are too heavy to build the antennas required for this system, a new composite structure that has composite frames and stretched mesh sheets has been developed. CFRP (Carbon fiber reinforced plastic) and triaxially woven Kevlar fabric were used for the frame and the mesh sheets, respectively. A phased array antenna with the new structure was fabricated and its electrical performance was evaluated.

KEYWORDS: phased array antenna, satellite communication system, inclined GEO satellite, lightweight structure.

1. INTRODUCTION

With rapid growth of the telecommunication market, various space-based communication systems have been proposed [1]. In this context, the use of orbiting satellites in either low-altitude earth orbit (LEO) or medium-altitude earth orbit (MEO) has attracted a great deal of attention for global satellite communication systems that use mobile terminals [2][3][4]. However, for countries with a limited land such as Japan, orbiting satellites are not necessarily a good choice. We propose a telecommunication system that effectively covers the service area by placing satellites in an inclined GEO. The system uses compact, lightweight communication terminals such as cellular phones. Because inclined GEOs enable satellites to stay in position directly above the service area, high-quality signal transmission is expected. In order to communicate with compact mobile terminals, the satellites require large antennas. The initial studies pointed out that the aperture of the antennas should be extremely large•[5] and conventional antenna structures and deploying mechanisms are not applicable. Thus, a large area active phased array antenna with a two-dimensional deploying mechanism was designed. Then, a totally new structure with a composite frame and stretched surfaces was

developed to satisfy the requirement on weight and stowability. In the present paper, overview of the new telecommunication system and the newly developed antenna structure are reported.

2. OVERVIEW OF THE SYSTEM

2.1 System concept

The concept of the proposed system is shown in Fig. 1. In the system, the satellite illuminates multiple beams and communicates with 5 million mobile terminals realizing 100,000 digital voice channels. The service area is supposed to cover the mainland of Japan. Fig. 2 shows the relationship between the number of the channels and the aperture of the satellite antenna. Here, 5.6 kbps digital voice service with 12.5 kHz carrier signal frequency bandwidth is supposed. The carrier frequency and the frequency bandwidth of one of the multiple beams are 2.5 GHz and 7.5 MHz, respectively. According to Fig. 2, the aperture of the satellite antenna needs to be 45m, in order to attain the desired communication capacity.

The satellites are placed in an inclined GEO. Fig. 3 shows an example of the path of an inclined GEO satellite on the surface of the earth. One can see that the satellite travels directly above the service area, the mainland of Japan. Therefore, the system is expected to be less influential from the shadowing effect, due to steep lookangles.

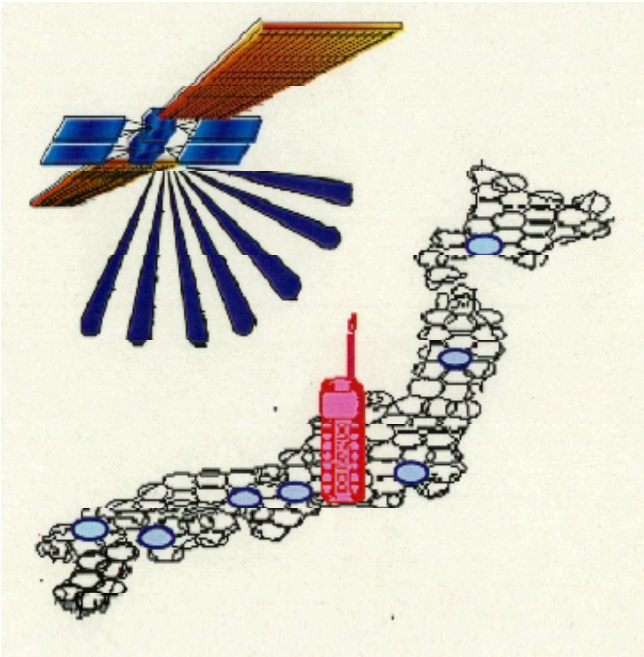


Fig. 1: Concept of the proposed system.

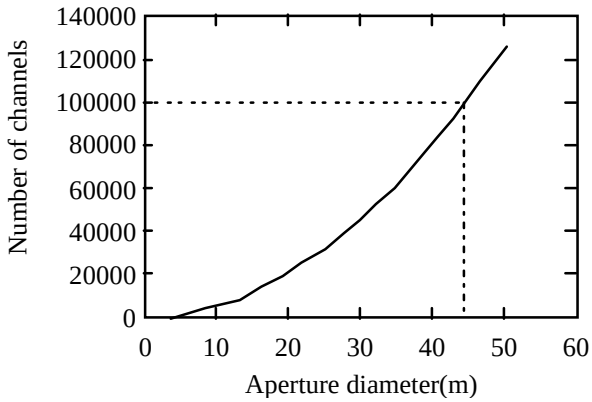


Fig. 2: Relationship between number of the channels and the aperture diameter.

Fig. 3: Path of an inclined GEO satellite on the surface of the earth.

2.2 The inclined GEO

In the first step of the system design, the lookangle of the inclined GEO satellite was calculated. Fig. 4 shows the earth centered coordinate. The position of the satellite in terms of the earth-centered coordinate (r_{xe}, r_{ye}, r_{ze}) can be calculated from Eqn. 1. Here, ϕ is the earth rotation angle and r is the distance of the satellite from the coordinate origin.

$$\begin{bmatrix} r_{xe} \\ r_{ye} \\ r_{ze} \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\Omega & -\sin\Omega & 0 \\ \sin\Omega & \cos\Omega & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$\times \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{bmatrix} \begin{bmatrix} \cos\omega & -\sin\omega & 0 \\ \sin\omega & \cos\omega & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r\cos\theta \\ r\sin\theta \\ 0 \end{bmatrix} \qquad (1)$$

The orbit of the satellite is inclined with the inclination of i against the celestial equator and is elliptical with the eccentricity of e. In Fig. 4, P is the perigee, A is the apogee, Ω is the right ascension of the ascending node and ω is the angle of perigee from the ascending node of the orbit. Eventually, the latitude α_E and longitude α_k of the satellite can be calculated from the equations below.

$$\sin\alpha_E = \frac{r_{xe}}{\sqrt{r_{xe}^2 + r_{ye}^2 + r_{ze}^2}} \qquad (2)$$

$$\cos\alpha_k = \frac{r_{xe}}{\sqrt{r_{xe}^2 + r_{ye}^2}} \qquad (3)$$

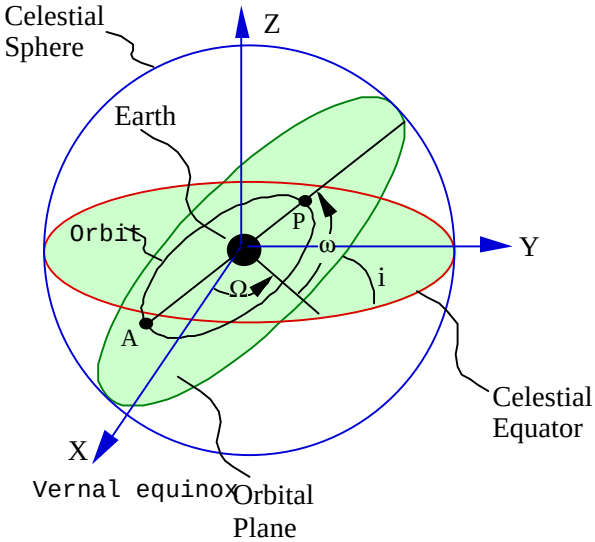


Fig. 4: The earth centered coordinate.

The orbital elements were chosen as follows.

i	: 45 [degree]
e	: 0.139
ω	: 270 [degree]
Ω	: 238.8 [degree]

Using these parameters and assuming that there are three satellites travelling in an interval of 8 hours, the lookangles of the satellites observed from Tokyo within 24 hours were calculated as shown in Fig. 5. This figure shows that at least one satellite of the three can be seen in angles higher than 79.2 degrees all the time. Hence, high quality signal transmission, virtually free from interference by man-

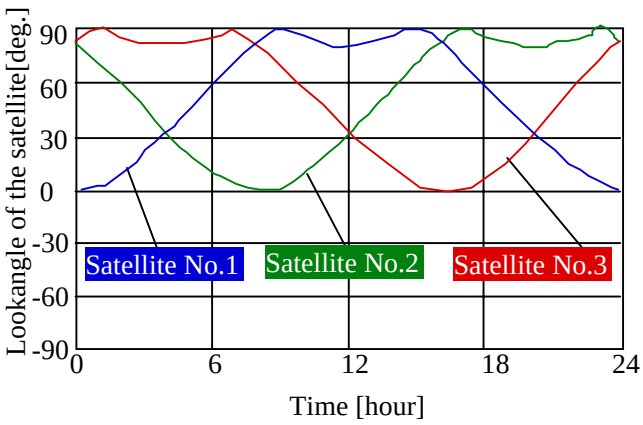


Fig. 5: The lookangles of the satellites observed from Tokyo.

made structures, mountains, and other topographical features, is expected.

2.3 Deployable phased array antenna

As shown in 2.1, the system requires huge satellite antennas of which apertures are 45 m. Hence, lightweight and stowability became a severe and essential requirement. When stowability is concerned, phased array antennas are advantageous compared with reflector type antennas. Though there are some work on deployment mechanism for large antennas [6], they are focused on reflector type antennas, and size of the antennas is coming to a limit. Because a new deployment mechanism for phased array antennas should be developed, in order to stow the large antenna required here in the existing rockets, a two-dimensional deployment mechanism was designed. Fig. 6 shows the concept of the deployment mechanism. The mechanism uses flexible hinges that work as lock mechanism after deployment. Utilizing the two-dimensional deployment mechanism, a deployable active phased array antenna was designed. Fig. 7 (a), (b) and (c) show the whole view, the deploying unit structure and the electrical unit panel, respectively. The electrical unit panel, of which dimension is 700 mm $\times$ 700 mm, is a microstrip antenna with sixteen patch radiators. The patch radiators are connected together and fed by microstrip lines. As shown in Fig. 7 (b), sixteen electrical unit panels constitute the deploying unit structure of which dimension is 2800 mm $\times$ 2800 mm. As one can see in Fig. 7 (a), 256 deploying unit structures are assembled in sixteen by sixteen rows forming the whole antenna. The antenna, of which size is 44.8 m $\times$ 44.8 m, can be stowed into the size of 2800 mm $\times$ 2800 mm, the size of the deploying unit structure.

Since the designed antenna is so large as shown above, its structure should be lightweight and thin. The weight of the antenna should be less than 2×10^3 kg when the launching abilities of the existing rockets are concerned. Approximate calculation showed that, if this antenna is built with a conventional honeycomb sandwich structure, the weight will be as much as 6×10^3 kg. These values include the weight of the antenna structure, the deploying mechanism, the electrical fibers, the back structures and so on. A study on the weight budget pointed out that the weight of the antenna structure should be less than 300 g/m^2 in areal weight, which is one third of that of the conventional structure. Realizing this severe request of weight reduction is the goal of the present research.

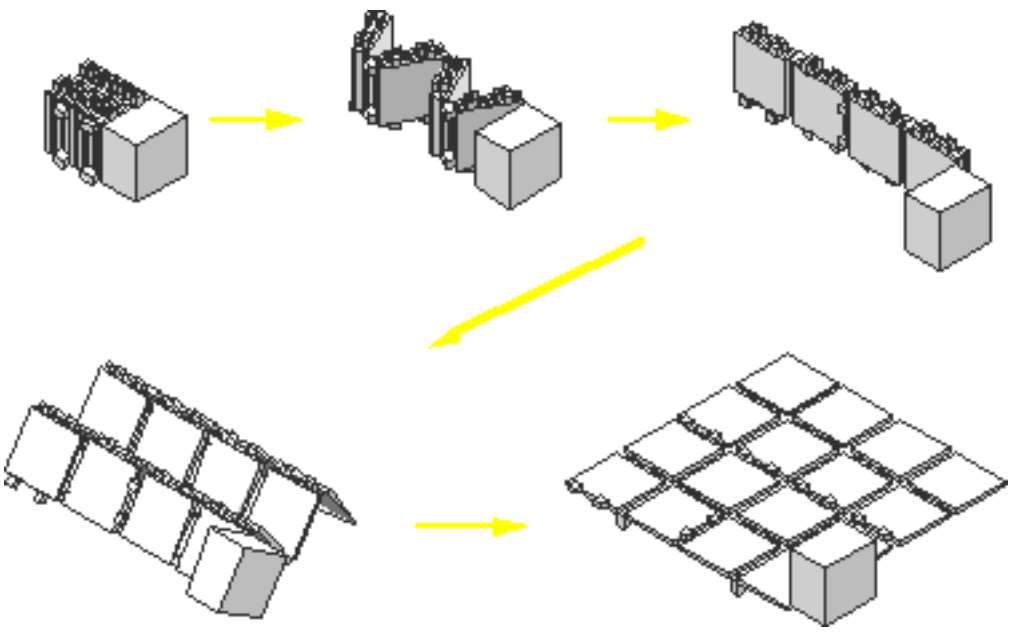
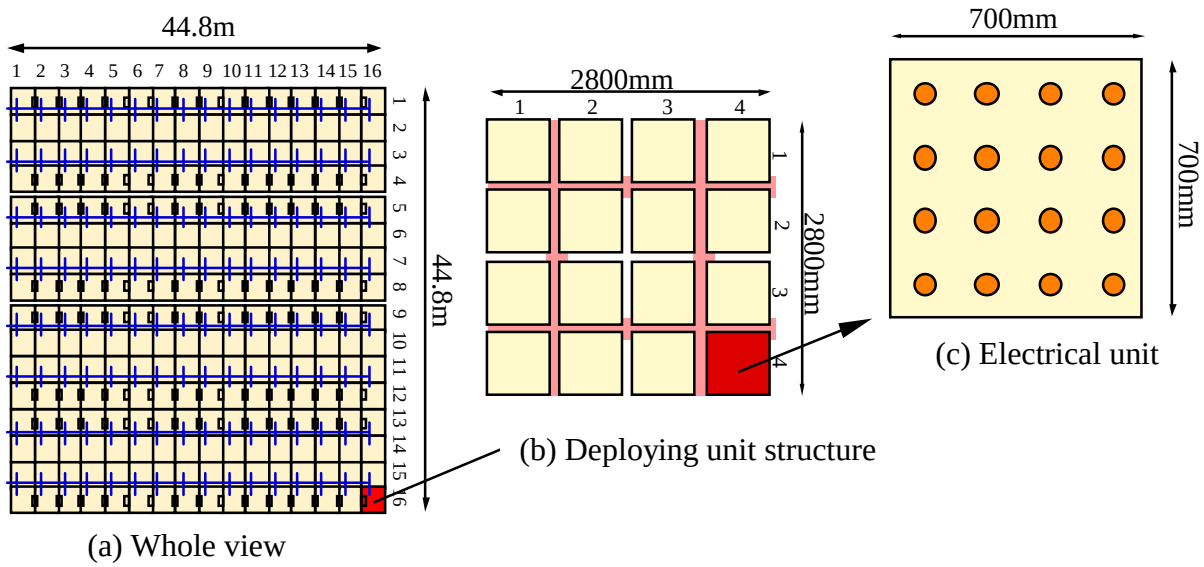


Fig. 6: Concept of two-dimensional deployment.



(a) Whole view

(b) Deploying unit structure

(c) Electrical unit

Fig. 7: Deployable active phased array antenna.

3. NEW MATERIAL AND STRUCTURE

3.1 Strategy of weight reduction

For drastic weight reduction of the antenna structure, two approaches were employed; one is to utilize a new material, and the other is to develop a totally new structure. Fig. 8 shows the conventional phased array antenna with a honeycomb sandwich structure. In this structure, electrically essential constituents are the patch radiators and the earth conductor. Thus we had the basic idea of reducing or removing the mass of the other constituent like dielectric sheets and honeycomb core employing the two approaches mentioned above. The newly utilized material is triaxially woven fabric (TWF) and the developed structure is one with a composite frame and stretched surfaces.

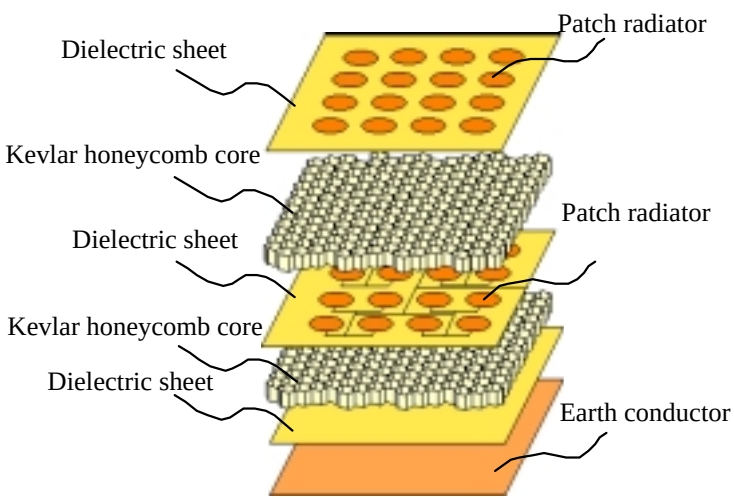


Fig. 8: Conventional antenna structure.

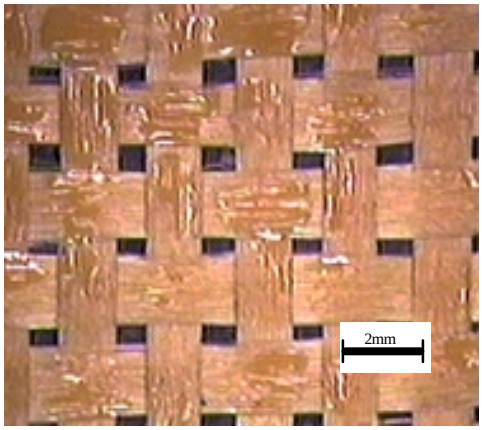
3.2 Triaxially woven fabric

In the conventional antenna structure shown in Fig. 8, KFRP (Kevlar fiber reinforced plastic) sheets were utilized as the dielectric sheets that support the patch radiators and the earth conductor. Kevlar is commonly supplied in the form of biaxially woven fabric (BWF, Fig. 9(a)) for this kind of application. BWF should be stacked in symmetrical sequences so that

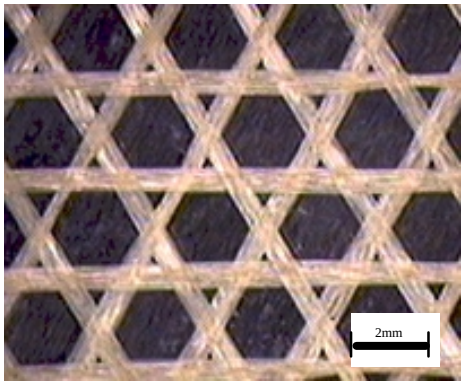
the anisotropy of each lamina can be cancelled. Therefore each dielectric sheet cannot help being multi-layered, and the weight of the dielectric sheets multiplies.

TWF is a kind of fabric that has three threads crossing each other with the angle of 120 degrees as shown in Fig. 9 (b). TWF has a remarkable feature of being mechanically isotropic on its own [7]. Therefore it doesn't require the symmetrical lamination as BWF does for the cancellation of the anisotropy. Thus the dielectric sheet can be single layer of TWF and drastic weight reduction is possible. Besides, TWF, in general, is coarser compared with BWF. This feature contributes for further weight reduction.

The unit weight of TWF used here is 40g/m^2. On the other hand, conventionally used BWF has the unit weight of 97g/m^2. If BWF is symmetrically laminated in the sequence of [(0°/90°)/(_45°)/(0°/90°)], the weight will be 291g/m^2. This is more than seven times heavier than that of the TWF in single ply.



(a) Biaxailly woven fabric (97g/m^2)



(b) Triaxailly woven fabric (40g/m^2)

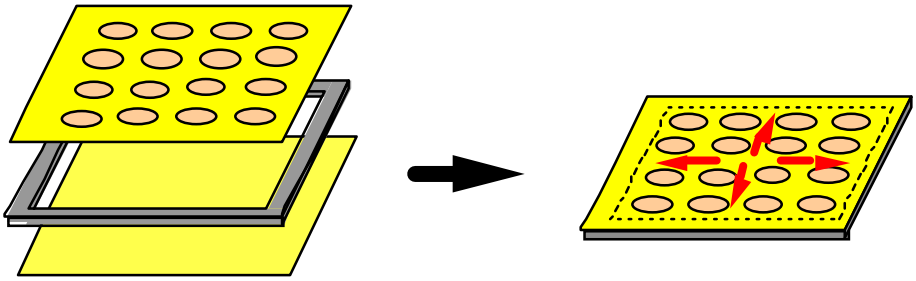
Fig. 9: Two kinds of Kevlar fabrics.

3.3 Frame structure with stretched surface

Honeycomb sandwich structures are widely used for satellites because they are lightweight and highly stiff [8][9]. However, further weight reduction is required in the ongoing project. Another point is that the use of honeycomb cores imposes restrictions on the electrical design of antennas; the distance between the patch radiators and the earth conductor cannot be smaller than 2 - 3mm. This is because honeycomb cores made of dielectric materials such as KFRP and Aramid paper can not be sliced thinner than this value with enough accuracy. In the antenna designed here, the distance between the electrical elements should be as small as 0.5 mm. Besides, honeycomb core inserted between the patch radiators and the earth conductor causes dielectric loss and degrades the electric performance of the antenna. Hence, we focused on developing a new structure without honeycomb core.

A phased array antennas requires a flat surface. The new structure provides flat surfaces by stretching KFRP mesh sheets on a CFRP frame. Fig. 10 shows the concept of the structure. KFRP mesh sheets, on which patch radiators are installed, are glued on a CFRP frame at the temperature of 170 degrees Celsius. The KFRP mesh sheet used here consists of triaxially woven Kevlar 49 and cyanate ester resin (EX1515, Bryte technologies). The frame is made of unidirectional CFRP composed of cyanate ester resin (EX1515) and PAN based carbon fiber (T800, Toray). At operation temperatures, that are lower than 100 degrees

Celsius, the CFRP frame automatically stretches the KFRP mesh sheets. This happens due to the difference of the values of CTE (coefficient of thermal expansion) between the materials; the CTE values of the KFRP and the CFRP are 0.3×10^{-6}/K and -1.0×10^{-6}/K, respectively. In



this structure, less dielectric loss is expected compared with honeycomb sandwich structure because no dielectric material is inserted between the patch radiators and the earth conductor

Glued at 170 degree C Operation temperature ~ 100 degree C

Fig. 10: Composite frame structure with stretched surfaces.

other than the coarse KFRP mesh.

3.4 Earth conductor

Satellite antennas are often exposed to severe temperature change. This can lead to a fatal thermal deformation of a structure. When the structure of the microstrip antenna is taken into account, it is possible that the earth conductor causes a severe thermal deformation. This is because the earth conductor has been conventionally copper foil, and metals often generate high thermal stress. Therefore, it is desirable to use as small amount of metal as possible in the earth conductor and distribute it in a discrete way. For this reason, mesh type earth conductor was studied. In order to provide mesh type earth conductor, KFRP mesh sheet consists of triaxially woven Kevlar 49 and cyanate ester resin was plated with copper. Experimental study clarified that the plating need to be thicker than 20 μm in order to achieve the necessary electrical performance. When this earth conductor is applicable, the unit weight of metal used in the earth conductor will be 40 g/m^2, which is one forth of that of conventional earth conductor. This contributes to not only weight reduction but also the relaxation of thermal stress.

Using the mesh type earth conductor, an antenna with a patch radiator was fabricated. It consists of KFRP mesh, a CFRP frame and earth conductor. KFRP mesh, which supports the patch radiator, and earth conductor are stretched on the CFRP frame (Fig. 11). Small amount of GFRP (glass reinforced plastic) spacers that fix the layer to layer distance were inserted between the patch radiator and the earth conductor. Fig. 12 shows the calculated and measured input impedance. The calculation was carried out by electricmotive force method. Fig. 13 shows the calculated and measured radiation pattern. The calculation was carried out by cavity model analysis. In both figures, one can see that the measured and calculated values correspond well. Hence, it was proved that the newly developed mesh type earth conductor has good electrical performance, and is applicable for microstrip antennas.

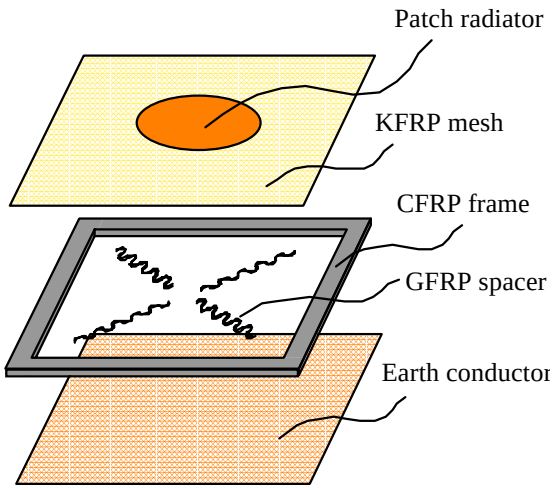


Fig. 11: One patch radiator antenna.

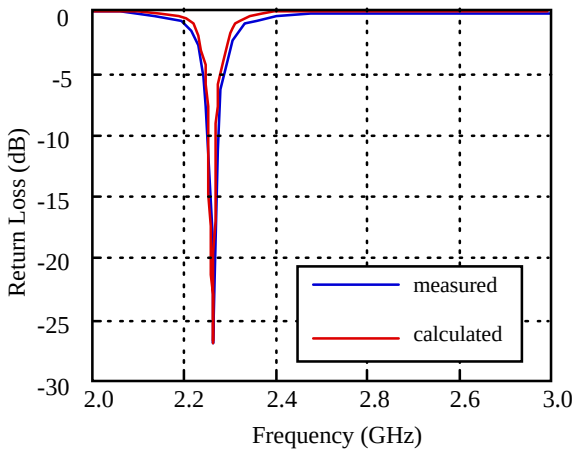


Fig. 12: Input impedance of one patch radiator antenna.

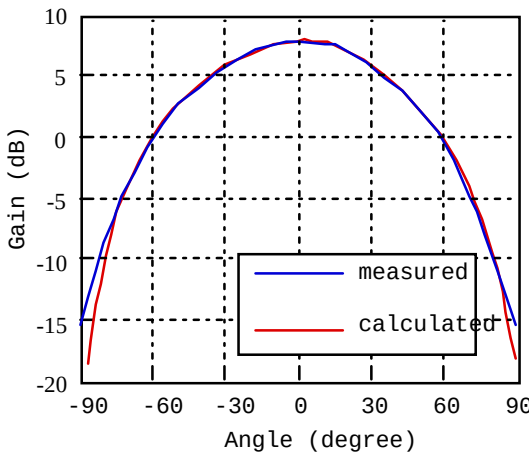


Fig. 13: Radiation pattern of one patch radiator antenna.

4. PERFORMANCE OF THE DEVELOPED ANTENNA

By integrating the new materials and the new structure explained in the previous chapter, the electrical unit panel was fabricated. Fig. 14 shows the configuration of the electrical unit panel. It consists of CFRP frames, KFRP mesh sheets installed with sixteen patch radiators and earth conductor. GFRP spacers are inserted between the layers. Fig. 15 shows the measured and calculated radiation pattern of the electrical unit panel. The two patterns agree well. This result shows that the desired pattern can be formed in the developed antenna. Further, the fabricated panel was found to be slightly lighter than 300 g/m^2 in areal weight, which value satisfies the design requirement.

Finally, a 5/7 scale model of the deploying unit structure was fabricated (Fig. 16). It consists of sixteen electrical unit panels, of which size is 500 mm $\times$ 500 mm, installed on a CFRP pipe structure. Desired beam pattern was successfully formed in the model using a digital beam former.

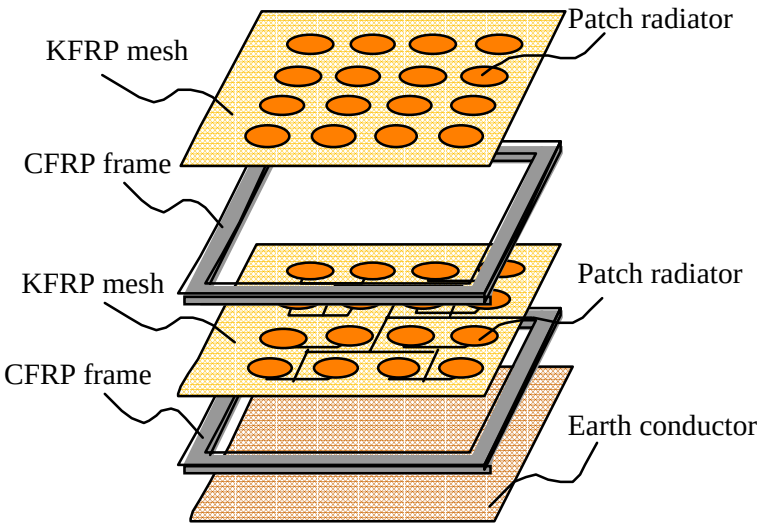


Fig. 14: Configuration of the electrical unit panel.

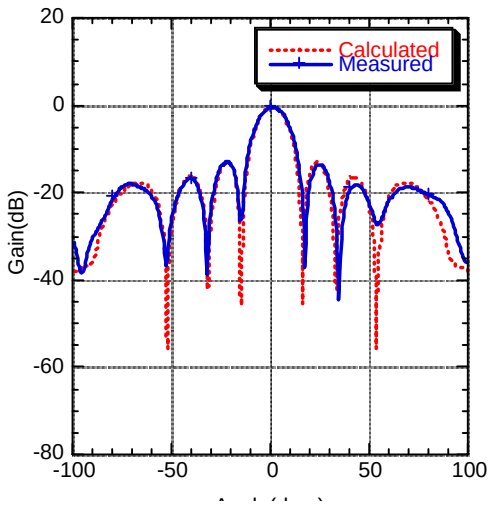


Fig. 15: Radiation pattern of the electrical unit panel.

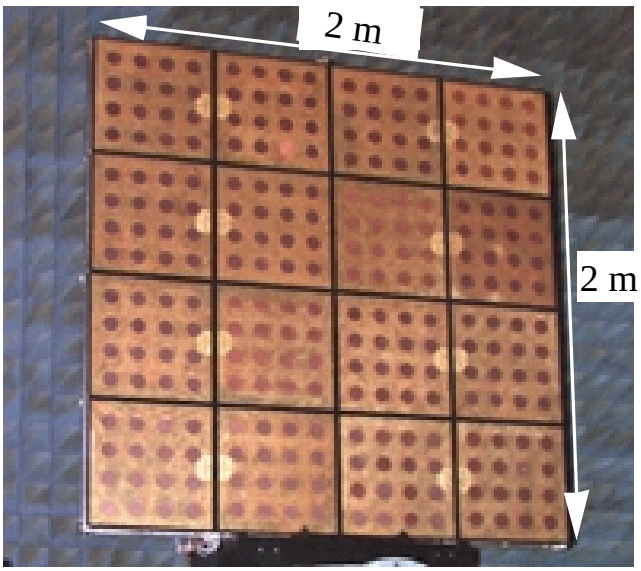


Fig. 16 : A 5/7 scale model of the deployment unit structure.

5. CONCLUSION

A new telecommunication system that employs inclined GEO satellites and compact mobile terminals was purposed. The system provides a communication capacity of 100,000 digital voice channels, and is virtually free from interference by obstacles like buildings and mountains. In order to provide the high communication capacity, a large area active phased array antenna was designed. It is two-dimensionally deployable and its size is 44.8 m $\times$ 44.8 m.

In order to attain drastic weight reduction, a new composite structure with a CFRP frame and stretched surfaces was developed. For further weight reduction, triaxially woven Kevlar fabric and mesh type earth conductor were applied. A partial model of the antenna was fabricated and found to be less than 300 g/m^2 in areal weight and have electrical performance as designed.

REFERENCES

1. Evans, J.V., "New Satellites for Personal Communication", *Scientific American*, April 1998, pp. 60-67.

2. Dietrich, F. J., "The Globalstar Satellite Cellular Communication System: Design and Status", *17th International Communications Satellite Systems Conference and Exhibit*, 1998, pp. 47-56.

3. Makita, F., Smith, K., "Design and Implementation of ICO System", *17th International Communications Satellite Systems Conference and Exhibit*, 1998, pp. 57-65.

4. Schuss, J. J., Upton, J., Myers, **B.,** Sikina, T., Rohwer, A., Makridakas, P., Francois, R., Wardle, L., Kreutel, W., Smith, R., "The IRIDIUM Main Mission Antenna Concept", *IEEE AES System Magazine*, December, 1997, pp. 3-12.

5. Chiba, I., Urasaki, S., Konishi, Y. and Yonezawa, R., "Inclined GEO Satellite Communication System with Deployable Phased Array Antennas", *17th International Communications Satellite Systems Conference and Exhibit*, 1998, pp. 243-249.

6. Nakamura, K., Tsutsumi Y., Uchimaru, K., "Large Deployable Reflector on ETS-VIII", *17th International Communications Satellite Systems Conference and Exhibit*, 1998

7. D'Amato, E., Durante, F., Fedele, G., "Numerical and Experimental Analyses of the Structural Behavior of Braided Composite Materials", *Key Engineering Materials*, 1998, vol. 144, pp. 293-300.

8. Ozaki, T., Miyahara, N., Kabashima, S., "Thermal Stability and Electrical Loss Performance of Sandwich Panels for Space Antenna", *40th International SAMPE Symposium*, 1995, pp. 1637-1652.

9. Peterson, P., "Development of Extremely Accurate Space Reflectors", *41st International SAMPE Symposium*, 1998, pp. 851-860.