Design of Primary Feeds for 32m KDDI Antenna System IBA-4 in Cassegrain Configuration

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Abstract. *Physically large dimensional dish antennas in Cassegrain configuration have played an important role in satellite communications during the past several decades. Recently, however, emerging new technologies have begun to displace these elegant antennas in professional telecommunication service due to their lower operating costs. A beneficial aspect of this transitional situation is that it has created opportunities for amateur radio enthusiasts to use these soon-to-be-retired dish antenna systems for limited experimental testing. Adaptation of these professionally designed antennas to bands allocated for amateur radio service presents excellent educational opportunities in using antenna engineering skills and the use of modern electromagnetic simulation software provides a novel perspective for these antenna design and transformation tasks.*

Keywords

Cassegrain antenna, EME communication, Primary feed, Circular polarization, Dish antenna, Project Big Dish, KDDI antenna.

1. Introduction

A proposal for using the KDDI 32-meter Cassegrain reflecting dish antenna (see Fig.1) for amateur radio EME (Earth-Moon-Earth microwave communication utilizing the Moon as a passive reflector) was initiated in 2006 when a group of Japanese amateur radio enthusiasts met for their special meeting at KDDI-Ibaraki Satellite Communication Center in Takahagi City, Japan. This center, which is scheduled to be closed in the near future, was built as a communication node for INTELSAT services and has several immense parabolic dish antennas and associated infrastructure buildings for administrative, research, construction and maintenance purposes.

At the present time, not all KDDI antennas are in active service; some being in stand-by mode. This resulting availability of "antenna time" along with a favorable approval from KDDI fostered creation of amateur radio's "Project Big Dish", whose charter was to communicate on the 144 (2 m), 432 (70 cm), 1296 (23 cm) and 5760 (6 cm) MHz amateur radio bands. A special license and call sign, 8N1EME, was issued by the Japanese Telecommunication Authorities for this event. One of the requirements for its issue was to disclose the antenna's calculated radiation patterns. A special taskforce consisting of 40 Japanese radio amateurs was formed to solve the associated technical and logistic problems. Later, engineers from the Czech Technical University in Prague were invited into the team for consulting and designing the 2m, 70cm and 23cm primary feeds. Support from the Japan Amateur Radio League enabled the Project Big Dish to work on solving the many problems associated with launching its station onto the air within six months, before this center totally ceased operations.

Fig. 1. Overview of the 32m KDDI Antenna System IBA-4.

2. Electrical Requirements

Electrical requirements for the antenna system were determined based on antenna geometry, taking into account each band's specifications and operational requirements. The theoretical maximum directivity D for each band was calculated with the formula

$$D = 10\log\left[\frac{\pi^2}{\lambda^2}\left(D_m^2 - D_s^2\right)\right] \quad (1)$$

where D_m is the main reflector's diameter (32 meters), D_s is the subreflector's diameter (2.9 m), and λ is the wavelength. Consequently, the theoretical maximum directivity for the 2m band is 33.63 dBi. For 70cm it is 43.18 dBi and for 23cm 52.72 dBi. Band specifications were based on polarization characteristics: linear polarization for 2m and 70cm; circular polarization for the 23cm band. Summarized requirements for electrical parameters were:

I. High gain – good efficiency
II. Vertical polarization for 2m and 70cm bands
III. RH & LH circular polarization for the 23cm band
IV. Prompt band-switching without requiring tuning for multiband operation (not simultaneously)
V. Minimum possible reciprocal influence between feeds

From the available KDDI antenna geometry drawings it was apparent that both the subreflector and main reflector are "shaped," i.e. they are of custom geometries which are neither true parabolic nor hyperbolic. Unfortunately, accurate antenna system dimensions were not available and therefore, all computations for the feed design were made for a non-shaped Cassegrain antenna system with dimensions based on the main antenna's geometry (Fig.2; ICARA [1] software was used to compile the picture).

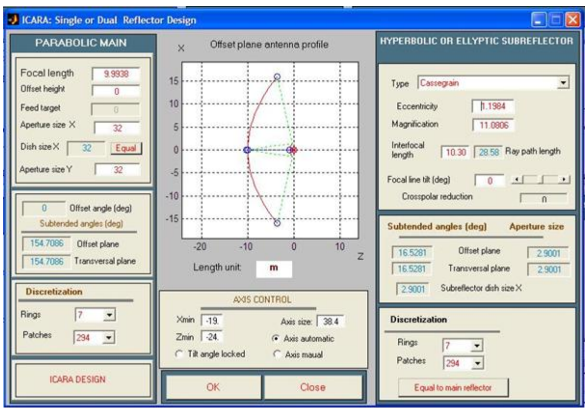

Fig. 2. Cassegrain antenna system in ICARA software.

3. Mechanical Requirements

Mechanical design and construction was to conform to the agreement made between the EME group and KDDI Company. That was, any permanent changes to KDDI antennas such as drilling, milling, edging, etc. were not allowed. Another constraint, to not remove or move the hyperbolic subreflector, was the most limiting, as we later discovered.

Logistic requirements necessitated quick and easy installation and removal of the antenna feeds on/from the antenna structure and mechanical construction should allow for the positional movement of the 144 and 432 MHz feeds for initial impedance matching alignment.

4. Design of the 23cm Feed

Detailed examination of the KDDI Cassegrain antenna system's geometry enables us to determine computer modeling parameters for the hyperbolic subreflector and parabolic dish reflector. See Fig. 3.

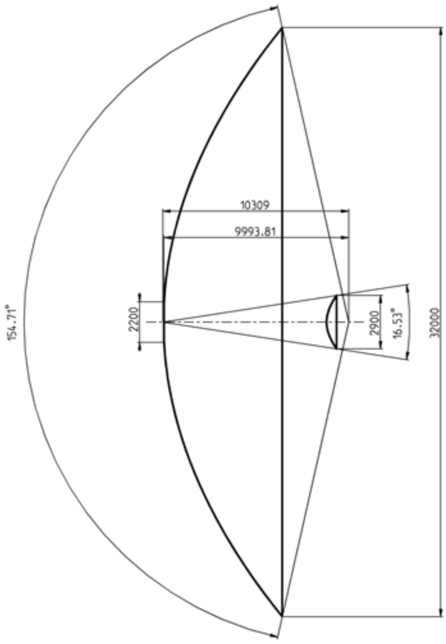

Fig. 3. Schematic view of the KDDI Cassegrain antenna system.

From [2], equations for the hyperbolic subreflector are:

$$\frac{x^2}{a^2} - \frac{y^2}{b^2} = 1 \quad (2)$$

where $b^2 = c^2 - a^2$, (3)
focal length: $f_{hyp}=2c$, (4)
eccentricity: $e = c/a$, (5)
magnification: $M = \frac{e+1}{e-1}$. (6)

From these equations, values for the hyperbolic subreflector constants are determined:

a = 4301.2,
b = 2840.1,
c = 5154.5,
e = 1.1984 ,
M = 11.0806.

Equations for the parabolic reflector are:

$$y^2 = 4 \cdot f \cdot x, \quad (7)$$

focal length: $f_{par} = f$, (8)

eccentricity: $e = 1$. (9)

Based on these equations and the antenna's dimensions, a model of the KDDI Cassegrain antenna system was created using ICARA software. Antenna models for FEKO [3] and CST MW Studio [4] were also determined for additional computations and optimization of the antenna system.

From Fig. 2 and 3, we can see that the focus of the KDDI Casegrain antenna is located behind the vertex of the main parabolic reflector. To facilitate placing the primary feed in this location, a 2.2 m diameter aperture is incorporated in the main parabolic reflector design. This technically elegant configuration eliminates problems associated with the primary feed blocking the main parabolic reflector.

For proper operation and to avoid substantial degradation in efficiency caused by diffractive effects, the antenna's subreflector diameter should exceed 10 wavelengths. As a result, the KDDI Cassegrain antenna's operating frequency is forced to be greater than about 1 GHz.

To determine the optimum edge taper for the subreflector, ICARA software was used. This software utilizes a radiation pattern modeled by the function

$$U(\theta) = \cos^{2N}(\theta) \quad \text{for} \quad \theta \le \pi/2, \quad (10)$$

which very closely approximates the primary feed's actual radiation pattern. The results are compiled in Fig. 4 and show that, apparently, an 11 dB edge taper is the best. The feed's taper must take into account space attenuation, so it is calculated to be the sum of the subreflector edge taper plus space attenuation. To calculate edge space attenuation, the antenna geometry and equations (2) and (3) were used.

We calculated a value of -0.6 dB for space attenuation, so the required taper for the feed is 10.4 dB.

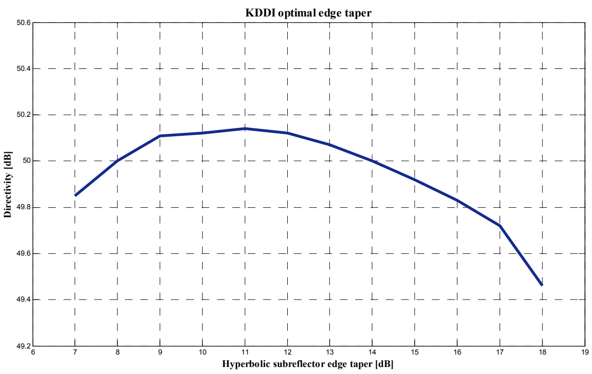

Fig. 4. Subreflector edge taper characteristics.

Based on the $\cos^{2N}(\theta)$ function we determined the primary feed directivity as follows:

$$BW = 2\cos^{-1}\left(10^{-Lvl/20N}\right), \quad (11)$$

$$N = \frac{-Lvl}{20\log[\cos(BW/2)]}, \quad (12)$$

$$D = 10\log[2(2N+1)]. \quad (13)$$

Inserting actual KDDI antenna values (Lvl =10.4 dB, $BW_{-10.4\mathrm{dB}}$ = 16.5°) into equation (12), we get N = 114.7. Subsequently, from equation (13), calculated directivity of the primary feed for this antenna system should be 26.6 dBi, basis an ideal lossless feed. As mentioned in the previous section, the KDDI reflectors are shaped for optimum efficiency. For shaped Cassegrain antenna systems, some authors [5], [6] recommend the use of edge tapers between 13 and 16 dB to lower diffraction losses and to better-fit field distribution characteristics to the shaped hyperbolic subreflector.

For our purposes, we specified a subreflector edge taper of 11 dB or higher, which meant utilizing a primary feed gain of greater than 26.6 dB. To achieve this value of gain, the primary feed should have an effective area (considering the circular aperture) of

$$A = \pi\left(D_{ap}/2\right)^2, \quad (14)$$

$$D = \frac{4\pi A}{\lambda^2}, \quad (15)$$

$$G = \eta_{ap} D \quad (16)$$

where A is the effective area, D_{ap} is the aperture diameter, D is the directivity and G is the gain.

Consider an aperture efficiency of 63 %. To compensate for aperture losses it is necessary to achieve a primary feed directivity of 28.6 dB (ratio 726 in linear measure). By combining equations (14) and (15) we get:

$$D_{ap} = \sqrt{\left[\left(D\lambda^2\right)/\pi^2\right]}. \quad (17)$$

Inserting KDDI antenna values ($Directivity_{ratio}$ = 726, λ = 0.231 m) into equation (17), we get D_{ap} = 1.98 m for the minimum diameter of the primary feed aperture. The primary feed can be realized using a horn or dish antenna of at least 1.98 m diameter placed at the focus of the KDDI antenna. Since a horn configuration was impractical due to the required length, a 2.32 m diameter, f/D_{ratio} = 0.43 dish antenna fitted with a circularly polarized feed (Fig. 5) developed by Galuscak and Hazdra [7] was chosen. The larger-than-required diameter ensures some reserve gain and the operational features of the circularly polarized feed enables utilization of both RH and LH circular polarization with good impedance matching and without the need for additional mechanical or electrical adjustments.

Due to physical limitations in the mechanical construction of the primary feed, consisting of a 2.32m dish and the Galuscak-Hazdra feed [7], it was not possible to place its phase center at the exact focus of the KDDI antenna system. The phase center was placed slightly forward relative to the hyperbolic subreflector which can cause a slight reduction of overall system efficiency.

Fig. 5. Primary feed for 23cm band.

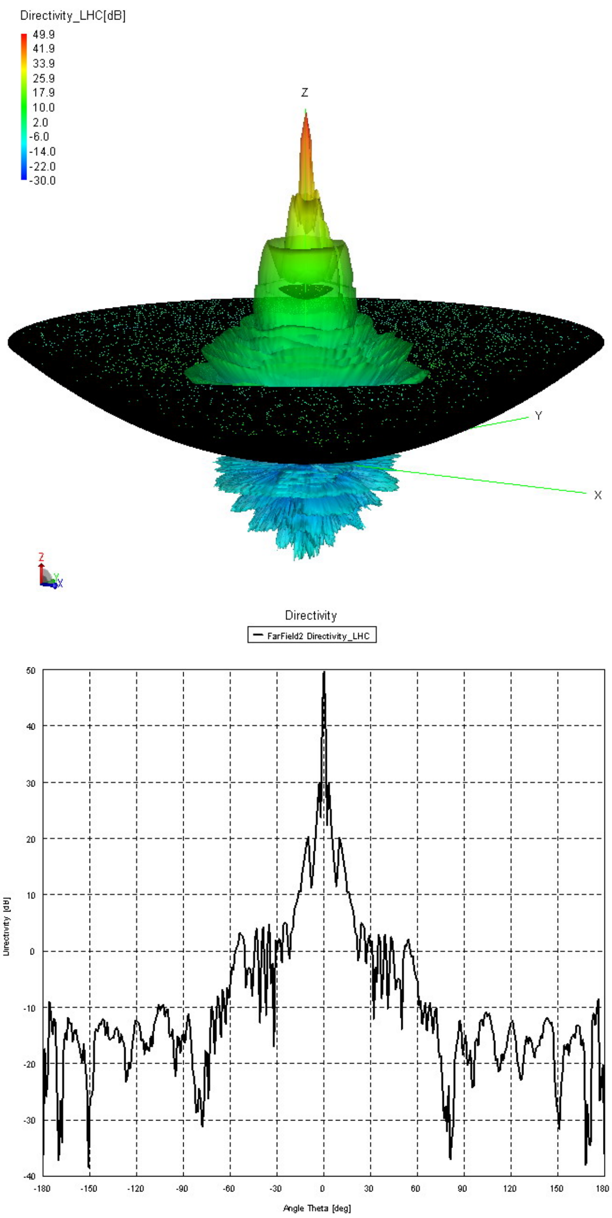

Fig. 6. Copolarization Radiation Pattern (3D) - above and 2D – below, at plane φ = 90 °

Note that the phase center of a dish antenna assembly is not focused to a compact localized "point," but is distributed in 3-D space in the form of a torus located between the parabolic reflector and its focus [8].

Since a single full-wave analytical computer computation of the entire modeled KDDI antenna system consisting of main parabolic dish, hyperbolic subreflector, and primary feed consisting of a dish and its associated circularly polarized feed was impractical due to its size and complexity, the calculations were divided into two steps. First, the primary feed was modeled with the FIT method using CST MW Studio [4] software. The radiation pattern output from this computation expressed in electric field in ASCII format was then imported to FEKO [3] software as a point input driving source for the KDDI Cassegrain antenna model. The calculated copolarization radiation pattern (using the MLFMM method) is shown in Fig.6. An overall antenna system design efficiency of 52% was achieved.

5. Design of Feeds for 70m and 2m Bands

With the subreflector's electrical specifications from the previous section in mind, we tried to configure the KDDI Cassegrain antenna for at least the 70cm band, finding a reasonable compromise between simple mechanical construction and useable system efficiency. To accomplish this, we modeled the antenna's driving source as a 9-element Yagi antenna located between the Cassegrain configuration's focus and the subreflector so as to achieve both E and H plane edge tapers of 11 dB for the hyperbolic subreflector. The simulation of this configuration yielded an overall antenna system efficiency of about 36 %. Apparently, the subreflector's small electrical diameter prevented us from achieving a higher efficiency. Also, this design did not comply with the requirements for mechanical construction and therefore was not considered for further use.

Due to time constraints for studying various other possibilities for 2m and 70cm feeds, a design using two one-wavelength loop antennas placed in front of the hyperbolic subreflector was used. This configuration was a tradeoff between mechanical construction complexity and efficiency degradation, mainly on the 70cm band. This feed's geometry is shown in Fig. 7. As we can see, the combination of a loop antenna with the hyperbolic subreflector creates a virtual prime-focus feed for the main parabolic reflector, but with relatively high axial deviation (axial defocusing) from it's properly positioned, in-focus, main parabolic reflector. To study the radiation pattern and to adjust the impedance match, a parametric model of the feed was designed using CST MW Studio software. The variables were the loops' diameters and their distance from the subreflector, see Fig 7. The phase center of this structure is located between the loops and vertex of the hyperbolic subreflector. The deviation between the feed's phase center and parabolic reflector focus was 0.46 λ for the 2m band and 1.29 λ for the 70cm band. This axial defocusing introduces a phase error loss, whose magnitude can be calculated using maximum phase deviation and quadratic phase error loss calculations [2]. Additional details are available in the reference.

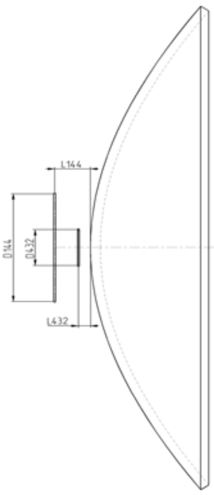

Fig. 7. 2m and 70cm loops geometry.

Impedance matching was adjusted by varying the distance between the loop antennas and hyperbolic subreflector and also by the loop's lengths. Good impedance matches were attained on both bands. See Fig. 8.

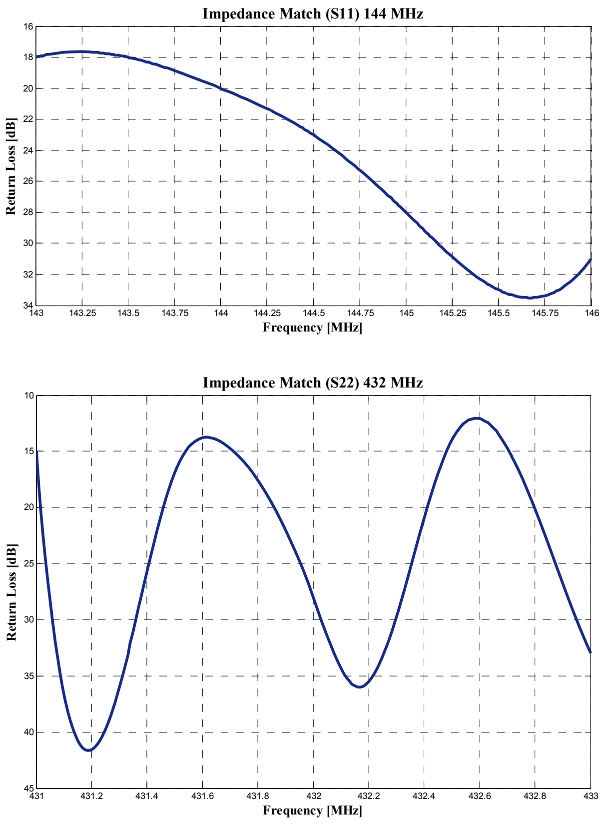

Fig. 8. Measured return loss of the loops, 2m (above), 70cm (below).

Changes in the radiation pattern due to varying the loop's positions relative to the subreflector were negligible. The calculated radiation pattern expressed in ASCII electric field format was again imported into FEKO software to calculate the final antenna system's radiation pattern. Patterns for 2m and 70cm are shown in Fig. 9 and Fig. 10. From the figures, it is apparent that efficiency degradation (31% on 2m {28.5dBi}, 13% on 70cm {34.3dBi}) caused by the improper primary feed position is substantial. By comparison, the same feed placed at a parabolic reflector focus should operate at 53% efficiency. Unfortunately, it was not possible to change the position of the hyperbolic subreflector with the objective of improving the efficiency. S_{21} isolation between loops, which does not have an influence on practical operation, is shown in Fig.11.

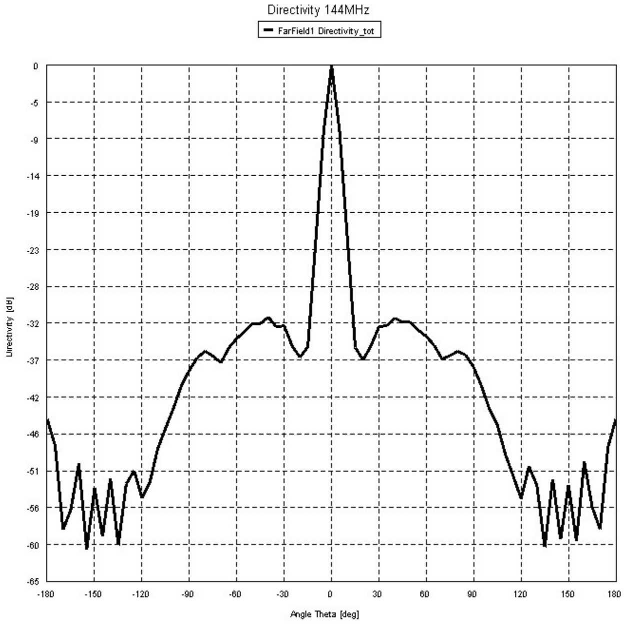

Fig. 9. 2 D Normalized Radiation Pattern 144 MHz, φ = 90 °.

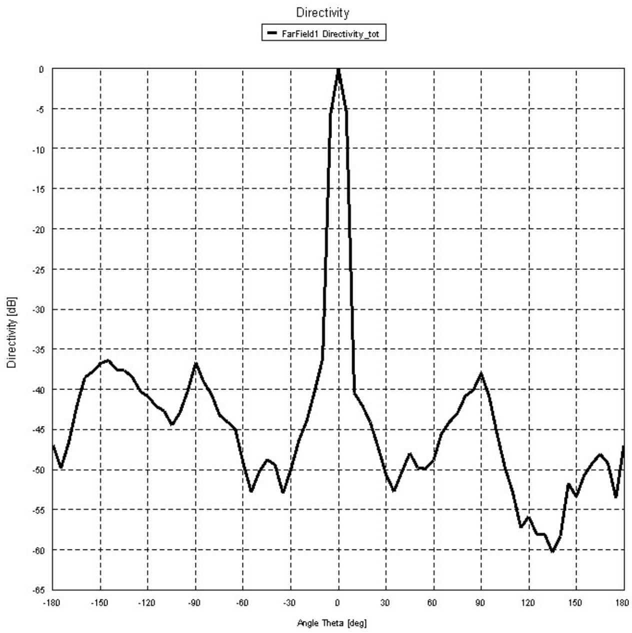

Fig. 10. 2 D Normalized Radiation Pattern 432MHz, φ = 90 °.

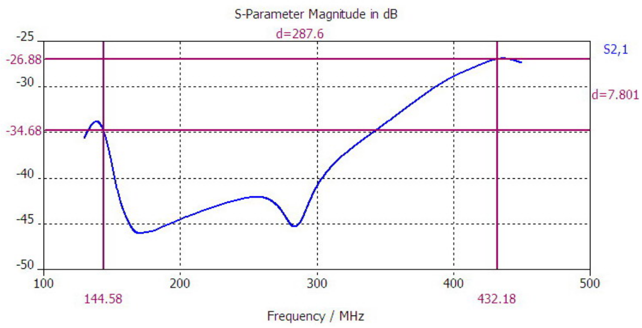

Fig. 11. S_{21} Isolation between loops.

6. Temperature Concerns for the KDDI Antenna System

For Cosmic-to-Earth radio communication systems, it is very important for the receiving system's noise budget to be as low as possible to permit reception of very weak signals. The antenna noise temperature interaction plays a very important role in the receiving chain. The antenna noise temperature performance calculation is conceptually described as multiplying the spatial function of antenna gain by the temperature distribution of the space surrounding the antenna, integrated over all the space:

$$T_a = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\pi} \mathrm{G}(\theta,\varphi)\mathrm{T_s}(\theta,\varphi)\sin(\theta)\mathrm{d}\theta\,\mathrm{d}\varphi \qquad (18)$$

where G is the antenna gain pattern and T_s is the angle-dependent blackbody radiation of the environment.

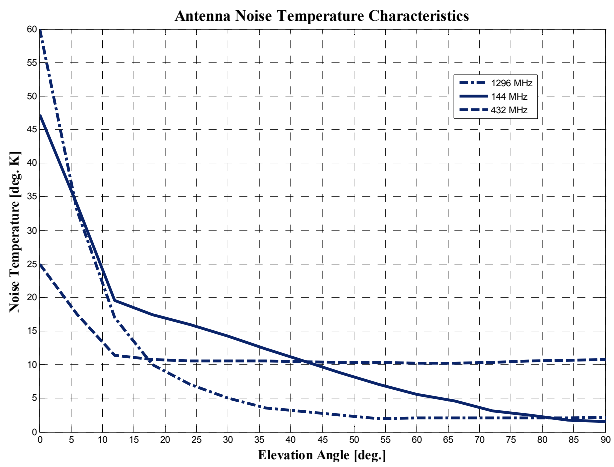

Fig. 12. The KDDI antenna calculated noise temperature characteristics.

For the KDDI antenna system, "Kelvin Sum" software [9] was used to calculate the temperature characteristics. Based on a published program [10] modified by Miroslav Prochazka, this software assumes a rotationally symmetrical radiation pattern along the z-axis and incorporates the defined temperature behavior of antenna surroundings in its calculations. The KDDI antenna temperature characteristics calculated for Earth temperature T_O = 290 K, as a function of elevation angle are plotted in Fig. 12. To better investigate and distinguish antenna noise temperature functionality for a parabolic reflector with prime-focus feed and Cassegrain antenna configuration, a frequency independent galactic noise source was assumed and calculated. From this figure it is apparent that for the 23cm band and very low elevation angles, a Cassegrain antenna configuration has higher noise temperature than a configuration consisting of a parabolic reflector equipped with a prime focus feed. (We are considering these configurations for the 2m and 70 cm bands.) This is mainly due to spillover illumination of the hyperbolic subreflector. On the other hand, at higher elevation angles, the Cassegrain configuration exhibits very low noise temperature, which is very suitable for EME communication.

7. Considerations for Practical Feed Construction

Feed construction and realization for immense antennas entail several specific challenges. One must consider that the mounting location of primary feeds for 70cm and 2m bands at an antenna elevation angle of 90 degrees is about 40 meters above ground level. This implies that to maintain safety at the high elevation, all montage and changes to the antenna system must be performed with the aid of special cranes (at great expense) and only by specially qualified personnel under strictly determined conditions. Any additional parameter settings or adjustments made directly to the antenna during this operation are not allowed, since it could additionally impact the economic budget of the project.

The feed for 23cm was assembled and tested on the ground and then installed in the KDDI system. Feeds for 2m and 70cm consisted of loop antennas made from copper tubing affixed to an insulating plate. See Figs. 13, 14, 15. This assembly was placed in its calculated location relative the hyperbolic subreflector by authorized personnel using a "marionette style" pull-up/pull-down tension cable mechanism. The distance between the loop antenna feed and hyperbolic subreflector was set by foam-plastic blocks affixed to the insulating plate. Later, no further adjustment was deemed necessary for optimizing VSWR.

Fig. 13. 144 and 432 MHz loops.

Fig.14. Feed installation.

Fig. 15. "Marionette style" tension cable mechanism.

8. Practical Results

Since special measurement equipment was not available at the time, Sun noise was measured several times on each band only to functionally verify the antenna's beaming system and receiving chain. Measurement precision was not sufficient to provide an accurate antenna characteristic; however, measured results indicate satisfactory agreement between calculated and actual antenna gain. The measured value of gain was found to be somewhat higher than the calculated value; the calculation error being attributed to the inability of the simulation to take into consideration all factors influencing antenna performance, such as actual sub- and dish reflector shapes and especially the actual amount of feed defocusing.

On 4 March, 2007, at 00.00 UTC, values of 8.5 dB @ 144 MHz and 15.0 dB @ 432 MHz were measured for Sun to cold sky differential noise levels. The measurement on 1296 MHz, however, was not successful due to the receiver's limited dynamic range.

An alternate method of antenna performance verification is to statistically evaluate the contact success rate i.e. number of established contacts with other stations, taking into account an Earth-Moon-Earth link energy budget. The 8N1EME [11] station worked with 154 stations on the 2m band, 67 stations on 70cm and 71 stations on 23cm. Also, this analysis confirms calculated antenna performance.

9. Conclusions

The opportunities and challenges presented by Project Big Dish made quite the "dream project" for each member of the working team. We had the opportunity to design, fabricate, test and use an antenna system based on the KDDI Cassegrain antenna, and transformed it into a multi-band antenna touting a unique *triple* reflector configuration on the 23cm band! See Fig. 16.

Project Big Dish was not only a significant amateur radio event, but also provided many antenna engineering, ham-radio and RF electromagnetic propagation learning opportunities. More details about Project Big Dish may be found at [11].

Fig. 16. KDDI antenna equipped with 2m, 70cm and 23cm feeds.

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