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Ground based disc cone antenna with ultra-smooth spectral characteristics

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***Abstract*– Designing a wideband antenna free from spectral features of widths narrower than the operating bandwidth with frequency independent radiation and impedance characteristics is an engineering challenge. These stringent requirements are observed to be required for an antenna whenever it is used for detecting the faint feature imprinted in the radio spectrum of the cosmic microwave background. The present paper discusses in detail, the parameters, both electrical and structural, influencing the smoothness of the spectral response of the disccone antenna. They are modeled and optimized using WIPL-d an electromagnetic simulation software, to get a spectral smoothness of the order of few parts in 10^5 in the frequency range 50-100 MHz. A prototype has been built and tested for validating the design.**

1 INTRODUCTION

Smoothness in the spectral response of an antenna is a characteristic governed by both electrical and physical parameters of the radiating structure. Both of them have strong dependence on frequency and because of which undesired spectral features are generated in the spectral response of the antenna. These effects are observed to be more pronounced whenever the antenna is kept in close proximity to the real earth.

Generally in any radiator, an abrupt variation in its structural dimension results in non-uniformity of its input impedance as a function of frequency. This is one of the main reasons for the generation of undesired features in the frequency response of the antenna. In addition, finite dimension of the radiating structure also results in unwanted spectral features. Because of the structural discontinuity and hence abruptness of it, the surface current flowing on it, undergoes reflections producing standing wave patterns. These patterns manifest as ripples in the frequency response. In addition to these, if the discone antenna along with its metallic reflector is placed over the real earth, then surface current flowing on the reflector undergoes reflections because of an abrupt change in the dielectric constant and hence the impedance at the boundary of the reflector surface. These reflections end up with frequency dependent structures in the pass band. It is observed that [1] the proximity of real earth has its effect on the self impedance of the antenna. The frequency dependence of this effect also makes the antenna have non-uniform frequency response characteristics.

The scientific motivation in the design of spectrally smooth antenna is to detect faint features imprinted in the spectrum of cosmic microwave background radiation by the red shifted atomic hydrogen 21cm emission line. The magnitude of these features is of the order of 1 part in 10^5. Since these are very weak, antenna’s non-uniform spectral response is likely to confuse their detection. To overcome this problem, an antenna with smooth spectral characteristics is required. Probing these features help us understand the thermal history of the Universe.

The physical parameters of the discone antenna like i) gap at the feeding section ii) cone angle iii) slant length of the conic surface iv) diameter of the reflector v) termination of the cone were tuned for an optimal response. Our investigation has shown that a cone with 45 deg. half included angle exhibits smooth spectral characteristics when slant height of the cone is made equal to the radius of the reflector. A prototype of a discone antenna has been built in the frequency range 50-100 MHz and tested for its spectral smoothness. Section II describes the design objectives. Simulation and optimization of the discone antenna are described in Section III. Section IV contains the details of fabrication. The measurement results are presented in Section V-VI. Our work is summarized in Section VII.

2 Scientific Motivation

The scientific motivation for the design of an antenna with smooth spectral characteristics is to detect features arising from events during the epoch of reionization. These signatures in the band 50-100

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MHz are understood to be the absorption / emission features of spin flip transition line of neutral atomic hydrogen red shifted by a factor of 16.75 due to the cosmological expansion of the Universe. Typical feature as predicted by [2] is shown in Fig. 1. The absorption depth observed around 78 MHz is about 800 mK. Our primary motivation is to detect the entire absorption profile with better than 1 mK accuracy. This requires spectral response of the antenna to be smooth at a level, better than one part in 10^5 since the sky which is 700 K bright at this frequency produces about few milli kelvin feature at the output of an antenna having a radiation efficiency 30%, transmission coefficient of 0.5.

Impedance match and the radiation pattern are the two most important characteristics of an antenna which need to have smooth characteristics as a function of frequency so that sky does not produce features similar to the low level EoR signal. The smoothness of the response is quantified with a maximally smooth polynomial function [3]. The salient feature of it is that it fits only to the smooth part of the response leaving behind regions of inflections. So by using this functional form, magnitude of the residuals representing the inflections are determined. Calculations indicate that the antenna is required to have a minimum transmission coefficient of 0.25 and radiation efficiency of 0.20 in order for ensuring a minimum signal to residual ratio of 10^5 over the band of 50-100 MHz. Several antennas having octave bandwidths are available off the shelf from either ETS-Lindgren or antenna products or Antenna Sys Inc. However none of them seems to meet our stringent design requirement of ultra spectral smoothness. We have achieved these in our work on antenna and presented results in this paper.

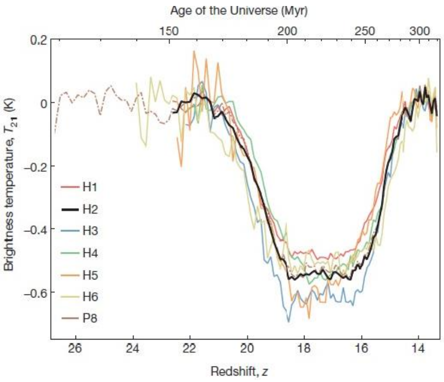


Fig. 1 Spectral signature depicting the deviation in the temperature of the cosmic microwave background radiation at redshifted 21cm frequency of around 80 MHz[2].

3. **Investigation of the effect of structural parameters on the smoothness of antenna's spectral response**

Generally an antenna will have smooth spectral response when i) its structural dimension varies uniformly along its length and ii) its material has uniform dielectric constant and iii) it has inherently structural symmetry. These factors are understood to play dominant roles in the reflection of surface current which gives rise to undesirable features in the frequency spectrum. In our work, we have considered all these factors while designing a discone antenna for measuring the spectrum of the sky background in the frequency range of 50-100 MHz. Initially the apex of the cone is brought very close to the reflector to ensure minimum structural discontinuity from feeding point as shown in Fig.2. However, constrained by the dimension of the SMA jack used to establish the electrical contact with the radiating structure, the base radius (r_0) at the apex and the gap (g) are maintained at 1mm each resulting in the half cone angle (θ) of 45 deg. In order to ensure that the spectral feature generated by the reflection of surface current on the reflector is broad enough to occupy the entire operating band of 50 MHz, the radius of the reflector (R1) is kept at 1/8 of the wavelength (75 cm) corresponding to operating band of 50 MHz. The slant length (L) is made equal to the radius of the reflector (R1) in order to minimize the number of undesired spectral features.

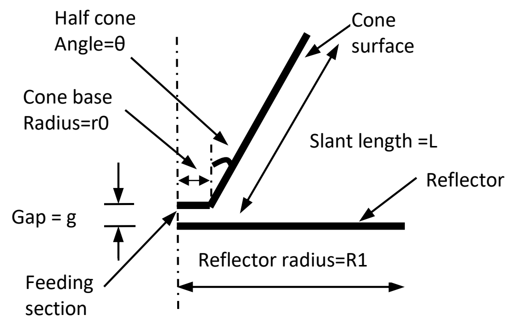


Fig. 2. Schematic diagram of the cross-sectional view of the discone antenna.

With these initial values of structural parameters as listed in the Table 1, optimization was carried out for each one of them using the ***Variation of Parameters*** technique over a range bound by their physical realizability.

Fig. 3 shows the effect of half cone angle on the return loss characteristics of the antenna. It was varied over the range 30 - 60 deg. in steps of 5 degrees. The return loss obtained for each of the angles indicate that for smaller cone angle antenna would have good return loss over the entire band resulting in large coupling of the sky signal (Refer Fig. 4) particularly at the lowest frequency. However, because of its non smooth spectral response, larger residuals (Refer Fig.5) are observed when fitted with a maximally smooth polynomial function. As cone angle increases, return loss worsens and the spectral response becomes smoother resulting in smaller residuals. So to have minimum residuals and larger coupling to sky at the highest frequency, half cone angle of 45 deg. was chosen.

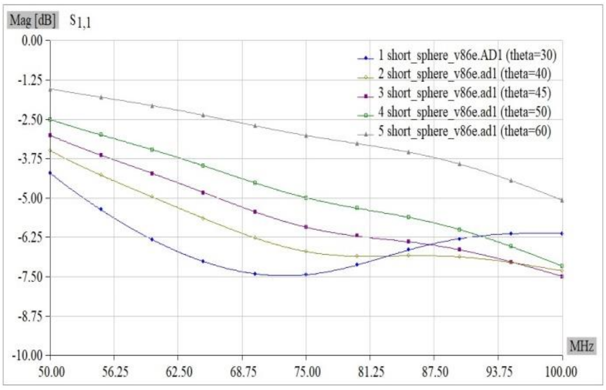


Fig. 3 The effect of half cone angle on the return loss characteristics of the discone antenna.

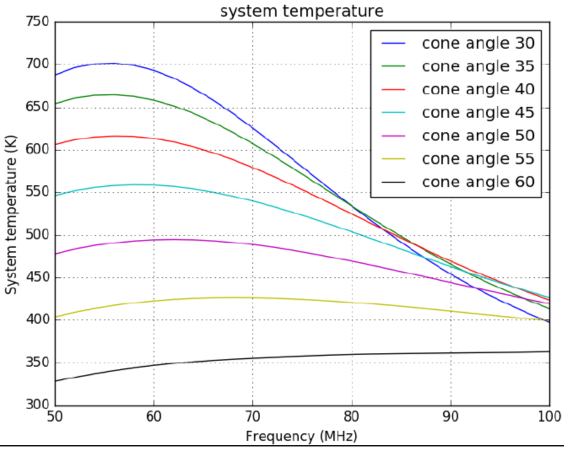


Fig. 4 The coupling of the discone antenna with the sky for various half cone angles. Graph indicates the power expected (expressed in Kelvin units) at the antenna output as a function of frequency for various cone angles. It is observed that antenna with smaller half cone angle will have large coupling to sky at lowest frequency.

Table 1 : Default values of the structural parameters of the discone antenna		
Sl. No.	Parameter	Value
1.	Reflector radius (R1)	750 mm
2.	Gap (g)	1mm
3.	Cone base radius (ro)	1mm
4.	Cone slant height (L)	750 mm
5.	Half cone angle	45 deg.

Then the gap at the feeding section of the discone antenna was varied from 0.5 mm to 2mm. It was noticed that the effect was insignificant (Refer Fig. 6) and hence the initial gap of 1mm was maintained.

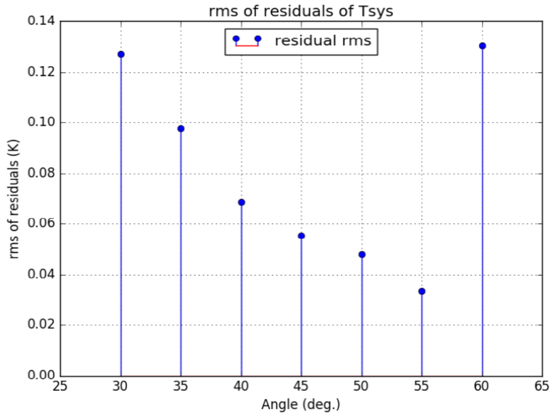


Fig. 5 The residuals obtained after fitting the return loss characteristics for various half cone angles, with maximally smooth function. For small cone angles, residuals are observed to be more than higher cone angles.

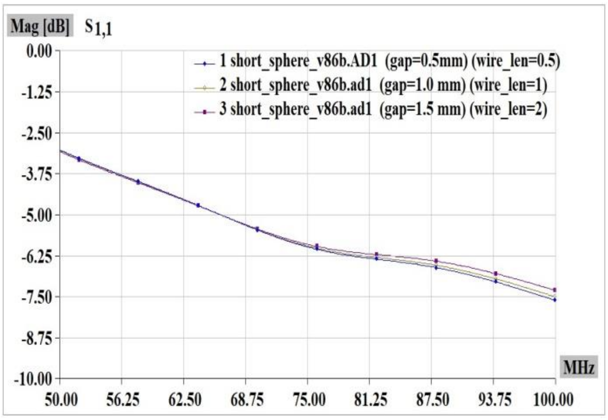


Fig. 6. Plot showing the effect of gap at the feeding point of the discone antenna on its return loss characteristics. The return loss does not seem to vary significantly over the gap of 0.5 to 2.00 mm.

The radius of the reflector was varied over a wide range to know its influence on the spectral shape of the return loss characteristics. It is observed that (Refer Fig. 7) the return loss improves when the radius of the reflector is increased to larger dimension. However, the smoothness in its spectral response gets significantly affected if the reflector is made bigger. As an optimal value, reflector radius of 800mm was chosen to get modest return loss of about 3 dB at the lowest frequency and reasonably smooth return loss characteristics. It was subsequently tuned to 830 mm while conducting the field experiments. The optimized values of structural parameters chosen after simulation are shown in the Table 2. Fig. 8 shows the simulated structure.

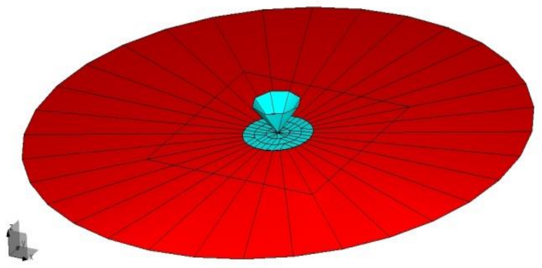


Fig.8.Simulated structure of the discone antenna over real Earth

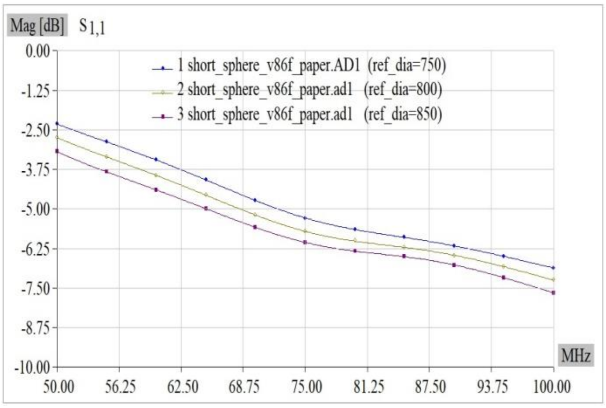


Fig. 7. The effect of reflector radius variation on the smoothness of the return loss characteristics. The response shown above indicates that higher reflector radius (referred as ref_dia in the plot).

Table 2 : Optimized values of the structural parameters of the discone antenna

Sl. No.	Parameter	Value
1.	Reflector radius (R1)	830 mm
2.	Gap (g)	1.00 mm
3.	Cone base radius (ro)	1.00 mm
4.	Cone slant length (L)	830 mm
5.	Half cone angle	45 deg.

4. **Fabrication of the prototype**

The discone antenna has two main parts : i) a circular metallic reflector and ii) a central cone shaped radiator. The metallic circular reflector is a finite sized thin sheet of aluminium of radius (R1) carrying an SMA connector at its center. The cone shaped radiator is realized in two parts. First part is a truncated conical base of 1mm radius at the feeding point and 100mm at the other end and the second part is a set of flared aluminium sheets attached to the top of the conical base. The conical base is fabricated by turning a single block of aluminium in a lathe. Four aluminium sheets of dimensions as given in Fig. 9(a) are used to form a radiator. Each of them is curved to form a circle of 50mm at the top of truncated cone and 567mm at the aperture. They are attached to the truncated cone using bolts. The radiator is excited using SMA Pin and Jack arrangement as shown in Fig. 9(b). This type of arrangement is adopted for making the antenna dismantlable so that it could be shifted easily from one geographical location to the other while testing. Circular ribs are given inside the conical structure for strengthening the antenna structure. The fabricated antenna structure is shown in Fig. 10.

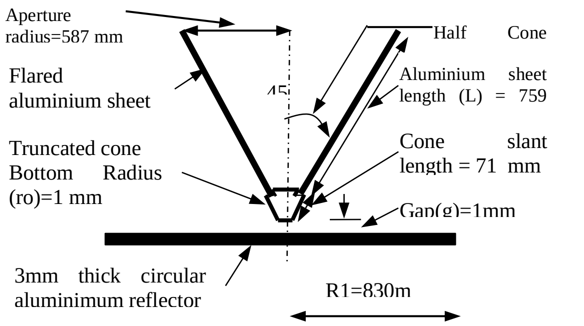


Fig.8.Schematic indicating different parts of the discone antenna along with their dimensions.

Pink Styrofoam is used to support the radiator while placing it on the reflector.

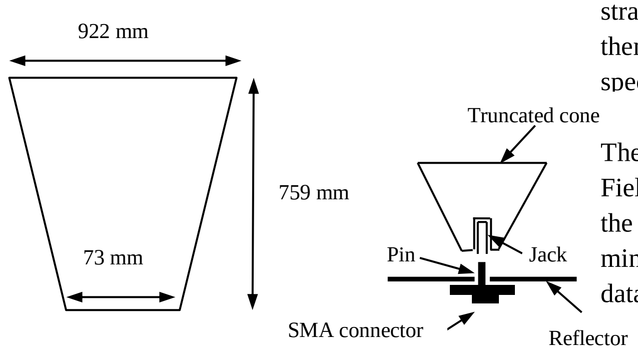


Fig.9. (a) Dimension of the rectangular sheet forming the conical radiator (b) Pin and Jack arrangement in the truncated cone for establishing electrical contact with the radiator.

Fig. 10. Front view of the prototype discone antenna placed over a metallic reflector using electromagnetically transparent pink Styrofoam.

5. Measurement of the Return Loss

Return loss is one of the important figures of merit of an antenna indicating the capability of an antenna to efficiently transform a given electrical signal into electromagnetic radiation. It is a function of impedance mismatch between the antenna and the measuring instrument at the point of excitation. Care was taken during the calibrating the instrument not to introduce any EoR signal like feature in the spectrum. This was done by using a shortest possible cable in the measurement setup between the antenna and the measuring instrument. In addition, the environment was also was kept free from reflecting objects like trees, stray wires, metal objects etc.to avoid reflections from them and hence undesired features in the frequency spectrum.

The measurement was made using Keysight N9915A-Field fox microwave hand held analyser. Before making the measurement, instrument was calibrated for minimizing instrumental effects in the measurement data. To ensure that the uncertainties in the calibration ess do not degrade the accuracy in the measurement, the same instrument settings which were used for the measurement were used for the calibration as well. The experimental setup used for the measurement had the antenna placed over the real earth with a pit dug below it to house the measuring instrument (Refer Fig.11). A shortest possible cable was used to connect the antenna with the instrument so that the spectral features caused by the multiple reflections in the cable due to the impedance mismatch are broad enough to occupy the entire operating bandwidth.

Several readings of return loss were taken in order to minimize the errors in the measurement. All of them were averaged and finally compared with the simulation as shown in the Fig.12. The measurement is found to closely follow the simulation in magnitude. The deviation is observed to be at few percent level. However, the measured data seems to have better smoothness than predicted in the simulation. The smoothness is quantified by fitting the measurement data with a maximally smooth polynomial function. The residuals obtained in this process are a few parts in 10^4 as shown in Fig. 13. This is found to be an order of magnitude higher than what is required as discussed in Section II.

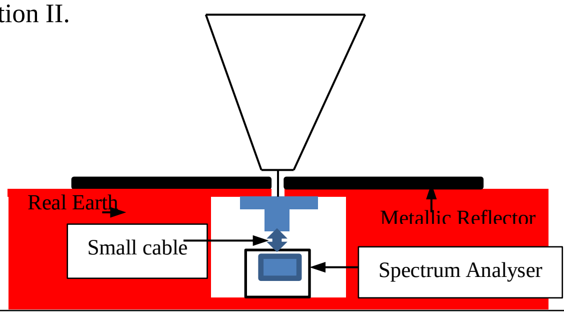


Fig. 11 Experimental setup used for the measurement of the return Loss.

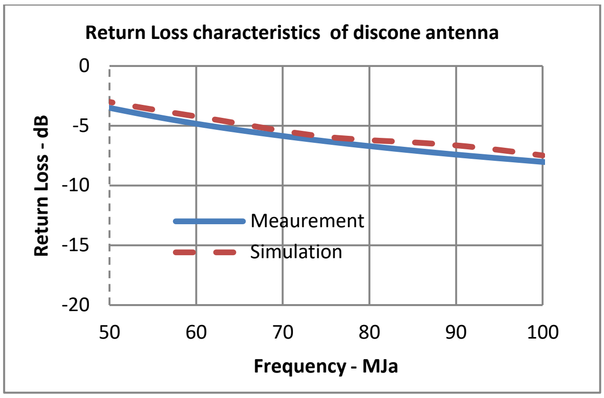


Fig. 12 Return Loss characteristics of discone antenna. Dotted line indicates simulation and the solid one is the measurement.

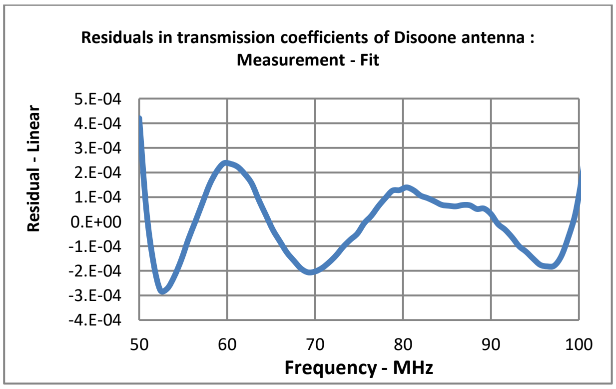


Fig. 13. Residual obtained when transmission coefficient desired from the return loss data is fitted with maximally smooth function.

6. Measurement of Radiation Patterns

The radiation pattern of the discone antenna was measured at three discrete frequencies 50, 80 and 100 MHz over the band 50-100 MHz. The measurement setup

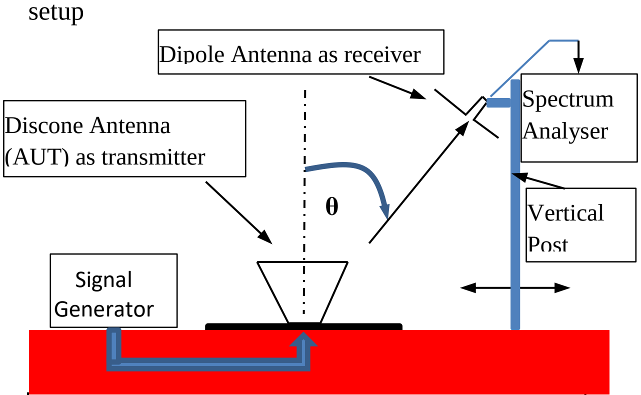
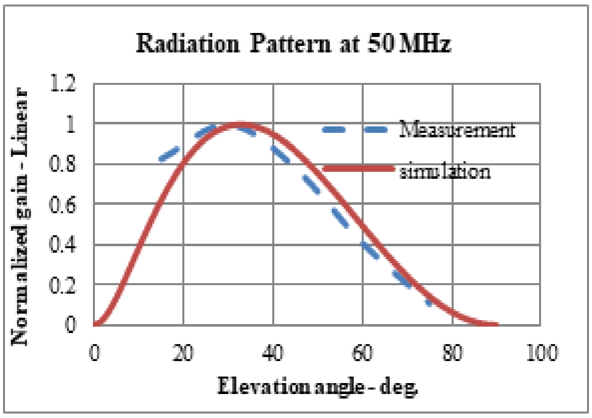


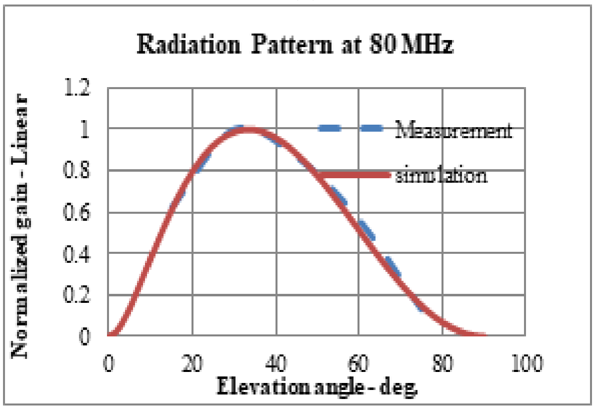
Fig.14. Experimental setup used for the measurement of radiation pattern of discone antenna.

used is shown in Fig. 14. The discone antenna under test (AUT) was kept stationary on the ground and was used as a transmitter and a tuned dipole antenna mounted on a vertical post at a fixed height (about 8m which is more than two times the far field distance of a half wave dipole tuned to 50 MHz) from the ground as a receiver. A signal generator APSIN 2010HC was used to transmit signals of different frequencies. Keysight N9915A- Field fox microwave hand held analyser was used to measure the signal received by the tuned dipole. The analyser was kept very close to the dipole at the top of the vertical post and connected to it using a short co-axial cable. This minimized the effect of signals picked up directly by the cable between the dipole and the analyser. Accurate measurement of pattern at low frequencies is challenging because of multiple reflections from the surrounding objects. Statistical and systematic errors in the measurements were minimized by making multiple measurements under different configurations of the receiving dipole antenna. During the measurement dipole antenna was tuned to different frequencies - 45, 60, 75 and 90 MHz and under each tuned condition, patterns were measured over an ± 15 MHz band around the band center in the elevation angle range (90 - θ) 15-75 deg. in 5 deg. step. This was done by moving horizontally the vertical post. The required correction to compensate for the decrease in signal because of varying distance between the transmitter and receiver was applied appropriately to the measured data before analyzing them. The measurements made at each frequency under four different tuned conditions were averaged and normalized. The radiation patterns measured are plotted in Fig. 15 a-c along with the simulation results.

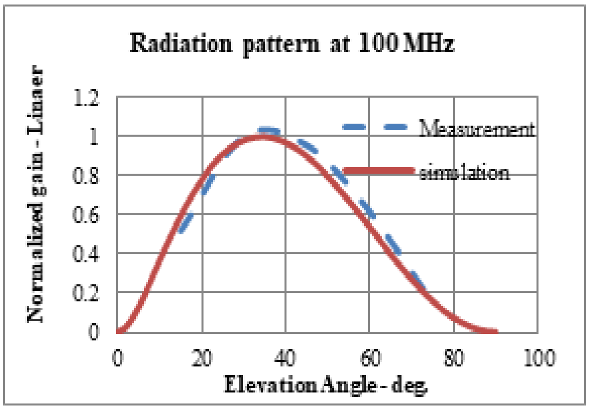
It is observed that the measured patterns match very closely with the simulation. They appear very similar over the octave band indicating the frequency independent performance of the antenna. The gain towards horizon is tending towards very low value. This seems to meet the desired requirement of having NULL response towards horizon to make antenna insensitive to the man made interference. The deviation between the measurement data and the simulation result is observed to be more at the lowest frequency. We attribute this to the errors in the measurement and the influence of nearby structures like vertical post carrying the dipole antenna in the measurement setup.



(a)



(b)



(c)

Fig.15(a-c). Radiation patterns of Discone antenna measured at 50, 80 and 100 MHz. Measurements shown by dotted lines match closely the simulation results.

7. Available sky signal at the antenna output terminals

The radiation efficiency of the antenna is calculated using the following relationship (Ref. Fig.16).

$$\eta = \frac{1}{4\pi}\iint_{0\ 0}^{2\pi\ \pi/2} G(\theta,\Phi)(\cos(\theta)d\theta d\Phi$$

where η is the radiation efficiency and

θ, Φ are elevation and azimuth angles.

With the knowledge of radiation efficiency η and transmission coefficient (Ref. Fig.17). from return loss, sky temperature available at the antenna terminals can be calculated using the following relation

Available sky temp. = $\eta * (1-\Gamma^2)*T_{sky}$

where Tsky is the foreground temp.(Ref.Fig.18) calculated assuming a spectral index of -2.4 and 150 K at 150 MHz.

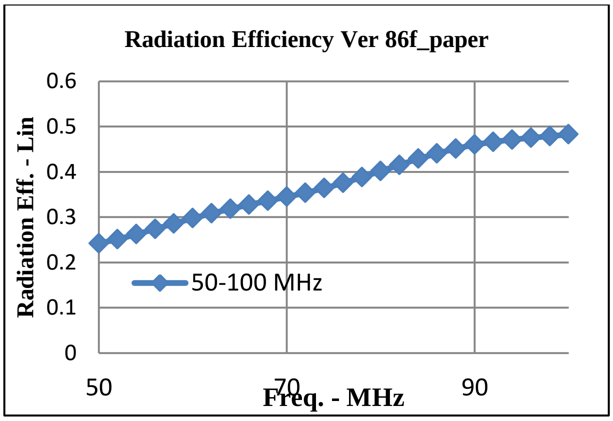


Fig.16 Radiation Efficiency of the conical antenna.

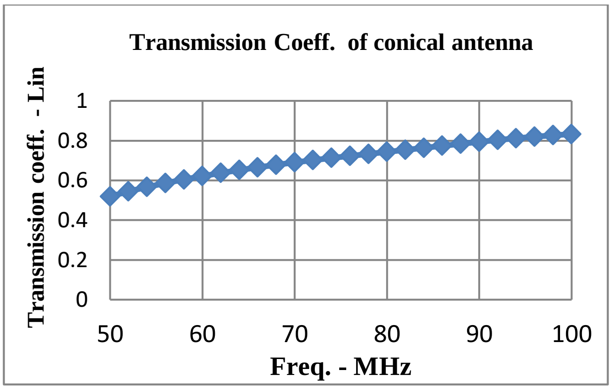


Fig.17 Transmission coeff. of the antenna

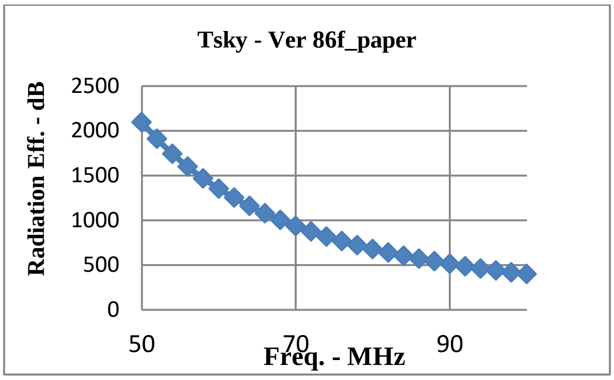


Fig.18 Sky Temperature assuming a spectral index of -2.4 and 150 K at 150 MHz

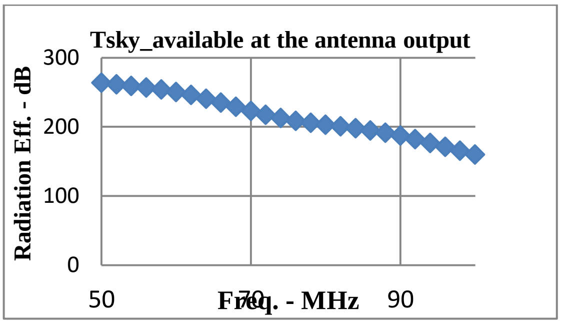


Fig.19 Sky Temperature available at the antenna terminals taking into account radiation efficiency and transmission coeff.

8. Conclusion

This report presents the details of the conical antenna designed to operate in the freq. range of 50-100 MHz. Its radiation efficiency ranges from 25% to 50 % over the designed freq. range resulting in a sky temperature of 250 K to 500 K respectively.

Acknowledgments

The authors would like to thank the members of the Electronics Engineering Group for helping design the balun. The mechanical workshop headed by Ibrahim fabricated antenna. Aswathappa and his group members in the Gauribidanur observatory helped setup the field experiments for carrying out the radiation and impedance measurements of the antenna.