Indian Journal of Radio & Space Physics
Vol 43, February 2014, pp 124-129

Design and fabrication of crossed Yagi antennae for dual frequency satellite signal reception at ground

N Dashora[1,$,*], K Venkatramana[2] & S V B Rao[2]

[1]National Atmospheric Research Laboratory, Gadanki 517 112, India
[2]Department of Physics, S V University, Tirupati 517 502, India
[$]E-mail: ndashora@narl.gov.in

Received 5 July 2013; revised 14 August 2013; accepted 23 August 2013

Design and fabrication of two crossed dipole Yagi antennae have been accomplished with an aim of estimation of total electron content (TEC) through Faraday rotation technique from satellite signal in VHF/UHF band received at ground. The design simulations for 3 and 5 elements crossed Yagi were performed by multiple iterations and optimization through a latest version of an established numerical electromagnetic code (NEC). First, design parameters were calculated and then optimization schemes were tailored to achieve the requisite performance from the crossed dipoles. Some of the most important aspects for Yagi antenna, like radiation characteristics for forward and backward gain, input impedance, bandwidth, front to back ratio and voltage standing wave ratio (VSWR) of a typical 3 and 5-element antenna have been analyzed. Following the successful software design, a step-wise precise hardware fabrication was taken up. Mechanical drawings were made for achieving mm level accuracy in fabrication. Also, thin aluminum tubes were used that matched precisely with the designed parameters and lengths of elements. The impedance matching in hardware fabrication was achieved by connecting Baluns of exact calculated lengths and of particular cable type. Finally, RF characterization was performed. Both the crossed Yagi antenna passed the basic tests that could be crossed checked with software design. The results from each stage of this process have been given with analysis and elemental details. This paper will be a practical guide for in-house fabrication and also a ready reference for interested researchers and students for making a satellite signal receptor in VHF/UHF band at ground.

Keywords: Crossed Yagi antenna, Total electron content
PACS No.: 84.40.Ba

1 Introduction

Measurement of total electron content (TEC) of the ionosphere using beacon satellite signals has been in vogue for almost three-four decades now. Globally and regionally, TEC studies gained a new impetus with advent of Global Navigation Satellite Systems (GNSS) that has modernized the TEC measurements, not to mention its accuracy and simultaneous global observations. Due to much higher altitudes of GNSS satellites, the column integrated TEC comes as a sum of ionospheric and plasmaspheric electron densities. The variations in plasmaspheric TEC are drastically different than the ionospheric TEC (highly variable). The plasmaspheric TEC remains mostly stable than during geomagnetic storms. Therefore, during space weather events and storms, there remains a need of another source of measuring ionospheric TEC to accurately ascertain and remove the plasmaspheric TEC from GNSS-TEC. Polar orbiting satellites with an altitude more than 550-600 km are appropriate tools and have been found suitable for ionospheric tomography based experiments[1]. A user needs to have an antenna and back-end electronics to receive signals from such satellites.

Many beacon satellites transmit signal in VHF/UHF band with two frequencies around 130-140 and 400-450 MHz for various purposes (like beacon for ships, weather information satellites etc). A Yagi-Uda (hereafter, termed as Yagi) antenna is best suited for satellite signal reception at ground when compared to axial mode helical and parabolic antennae. A quadri-filler-helix (QFH) antenna[2] also serves as an alternate to Yagi. But, due to suppressed hemispherical radiation pattern, low gain at lower elevation angles and presence of nulls due to practically imperfect fabrication of QFH antenna, Yagi is preferred choice for a ground station. Moreover, Yagi provides larger directive gain which is best suitable for weak signals. For Yagi, a rotor based framework is only additional requirement for tracking a satellite. Yagi is also preferred with due consideration of comparable factors, like mutual independence of the crossed elements of the Yagi while measuring the signal strength in two perpendicular directions (for Faraday rotation measurement), the beam width, the cross and co-polarization levels, portability and reproducibility[3]. Moreover, the design and fabrication of Yagi antenna is mechanically simple and it can be accomplished in laboratory environment (without industrial support).

One of the objectives of the present work is to contribute towards a ground station for receiving signals in VHF/UHF band from PRATHAM satellite[4] at National Atmospheric Research Laboratory (NARL), Gadanki. Nevertheless, on a broader perspective, this work provides a step-wise procedure for design and fabrication of crossed Yagi antenna for an interested researcher. Although, designing and fabrication of Yagi antenna is an established techniques but the classical approach of such designs follow standard tables and graphs[5] for estimation and optimization of lengths and spacing of various elements. Chen & Cheng[6] introduced optimization schemes for Yagi and later Burke & Poggio[7] developed now famous, generalized numerical method and computer codes for any target antenna design. The accessibility of these very complex computer codes in public domain and handling various optimization schemes has hindered a beginner's interest in building an antenna. Moreover, variety of applications required flexible and accessible tools for multi-element, multi-frequency optimized Yagi design.

For the purpose of measurement of Faraday rotation and thence, TEC using satellite signals at 145 and 437 MHz, the authors could not find a guiding paper. Therefore, a procedure for making Yagi antenna for aforementioned purpose has been developed and provided. The rotation of the planes of polarization of the signals, which have passed through the ionosphere, can be measured by crossed Yagi antennae at the ground station[8]. Since the initial phase (rotation) of the polarization is unknown, two frequencies are used. Then, the dispersive medium like ionosphere would induce different rotations on these two frequencies. Finally, the differential Faraday rotation between $\Delta\varphi_{f1}$ and $\Delta\varphi_{f2}$ provides a direct measure of the TEC, where the mean magnetic field becomes a constant quantity for a given altitude of ionospheric layer (~300 km). Measurement of Faraday rotation of the radio signal has been a topic of intense research since 1970's, wherein beacon signals from BE and ATS series[9] of satellites were used to obtain ionospheric TEC. The differential Faraday rotation will be measured using two crossed Yagi antennae designed and developed for this purpose.

2 Design and Optimization of antenna

The fundamental antenna design parameters that determine the characteristics of antenna are gain, band width, front-to-back ratio, beam width, return loss, radiation pattern, input impedance and directivity[10]. Each of these parameters was simulated for a Yagi antenna.

2.1 First estimate of elements of Yagi

The first estimate of lengths and spacing of reflector, driven and director elements are obtained from the standard formulas as given by Prasad[3]. But in practical sense, these lengths may not meet all the constraints imposed by an application. Hence, optimization of these lengths is of prime importance as a follow up. Table 1 gives the first length estimates for 3-element and 5-element antennae for respective crossed Yagi at 145 MHz ($\lambda 1$=206.896 cm) and 437 MHz ($\lambda 2$=68.649 cm).

2.2 Software design and optimization of antenna parameters

The numerical methods and computer codes developed by Burke & Poggio[7] were based on numerical solution of electromagnetic field integrals for thin, perfectly conducting wire segments using the method of moments. It was called numerical electromagnetic code (NEC). Such segments can be freely arranged in three-dimensional space and excited in different ways. Different analysis functions were built-in to calculate the electromagnetic properties of antennas (e.g. input impedance, current distribution or

Table 1 — First length estimates for 145 MHz (3-element) and 437 MHz (5-element) antennae

	Element/spacing	Multiplier factor for respective λ	Lengths for 145 MHz, cm	Lengths for 437 MHz, cm
A.	Reflector	0.48	99.310	32.951
B.	Driven /Dipole	0.46	95.172	31.578
C.	Director 1	0.44	91.034	30.205
D.	Director 2	0.44	NA	30.205
E.	Director 3	0.44	NA	30.205
F.	Reflector spacing	0.22	45.517	15.102
G.	Director spacing	0.16	33.103	10.983
H.	Dipole arm spacing	0.02	04.137	01.372

radiation pattern). The computer codes written in FORTRAN were later released in public domain in late 1990s. Now the same code is available in many different versions for PCs and UNIX platforms augmented with visualization. The Windows based software called 4NEC2 (version 5.8.7) developed by a Dutch radio amateur is available and is obtained from http://www.qsl.net/4nec2/. The 4NEC2 provides a very general simulation environment for designing, optimization and 3-D visualization of various types of antennae and radiation patterns. A user shall be knowledgeable enough (in theory of NEC and thence skill of using it) for a very specific design of antenna, e.g. crossed Yagi in present case.

No step-wise procedure is available in literature for design and optimization of Yagi using NEC. The authors devised step-wise procedure as an outcome of multiple efforts and test trials. This procedure has been shared for any interested user. It is first demonstrated for 437 MHz and the same is reproduced for 145 MHz Yagi antenna.

2.2.1 Design of 437 MHz Yagi antenna (5 elements)

2.2.1a Basic element design input (unoptimized)

(i) Selection of frquency (437 MHz), wire and metal (aluminium in this case).

(ii) Take lengths of elements from Table 1 and creat variables for respective elements symbols. Assuming a cartesian coordinate system at the centre of dipole on boom, creat geometry for all the defined elements.

(iii) Add voltage source to dipole and free space as ground.

(iv) Generate output of the design. Then select far field pattern for a full 3-D at resolution of 5 degrees.

(v) Figure 1 shows a basic radiation pattern as the first product from formula based calculation. It may be noted that this pattern is not optimized for desired performance.

2.2.1b Optimization

(i) Open optimization window to provide desired performance parameters.

(ii) For present case, the following values of design parameters were set. SWR=100 with target value 4, Gain=100 with target value 10 dB, F/B ratio=50 with target to maximize, F/R=0 with target to maximize, R-in=100 with target=200, X-in=100 with target to minimize, Rad=0 with target to minimize, Theta value=90 and 90 and Phi value=360 and 180 and finally Resolution=5 degrees.

(iii) Start optimization process and after few seconds (not more than 100 sec) the optimized output is provided. This output may not match with required values set in step (ii) above.

(iv) Repeat the optimization till the desired output is obtained. A user can check this process through the calculated results, variable sensitivity and variable values for reference.

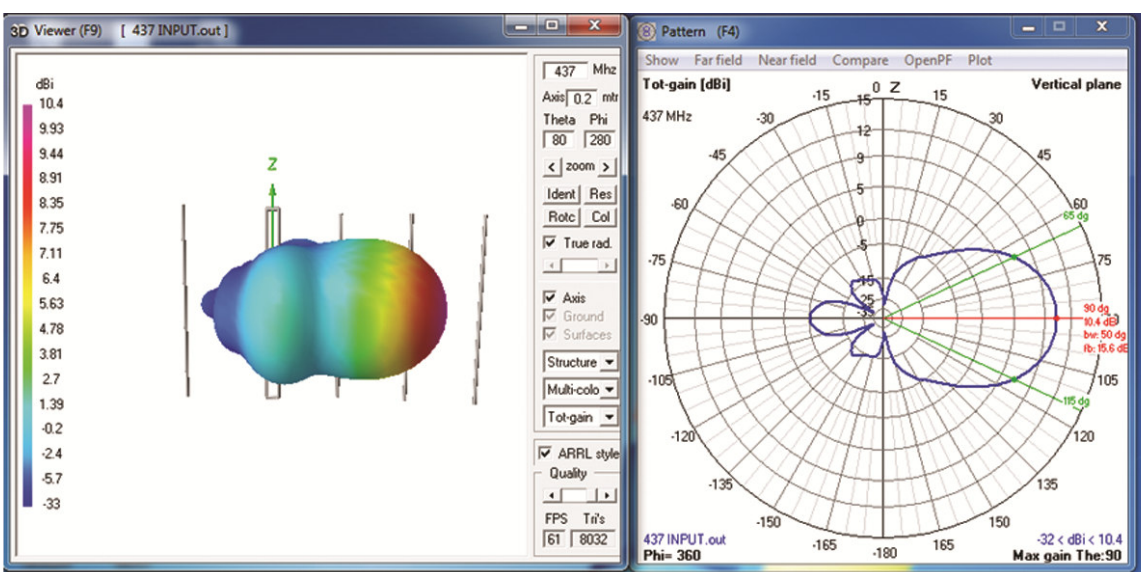

Fig. 1 — 3-D (left) and 2-D (right) radiation patterns from un-optimized design of 437 MHz antenna

(v) Once desired results are obtained, upload the NEC file. This would update all the variables and save the final design in new file.

2.2.1c Results of Optimization

The process of optimization modifies the lengths and spacing of the elements. A comparison is given in Table 2. The final value of the design parameters as obtained from 4NEC2 software are SWR=1; GAIN=9.94 dB; resistance=200 ohm and X-in (impedance)=0.23 ohm. The final radiation patterns created from optimized output are shown in Fig. 2. A direct comparison of Fig. 1 and Fig. 2 is possible now, wherein one could observe a substantial enhancement in forward radiation pattern and total gain when the design is optimized.

A very important plot given in Fig. 3 is obtained from the 4NEC2 software that shows variation of reflection coefficient with respect to change in frequency. It shall be noted that reflection coefficient (or VSWR) is tending to be minimum around the central frequency of 437 MHz. This signifies that the design of antenna is almost perfect with regard to losses due to reflection within desired frequency band.

Table 2 — Optimized performance comparison for 437 MHz

	Element/spacing	Lengths for 437 MHz, cm before optimization	Lengths for 437 MHz, cm after optimization
A.	Reflector	32.951	32.872
B.	Driven /Dipole	31.578	30.577
C.	Director 1	30.205	28.802
D.	Director 2	30.205	28.802
E.	Director 3	30.205	28.802
F.	Reflector spacing	15.102	15.144
G.	Director spacing	10.983	10.852
H.	Dipole arm spacing	01.372	02.000

2.2.2 Design of 145 MHz Yagi antenna (3 elements)

The step-wise procedure as given above was repeated except changing central frequency to 145 MHz and creating variables accordingly. For brevity, the comparison of unoptimized and final lengths of elements is given in Table 3. The plot of reflection coefficient *vs* frequency is given in Fig. 4 to show the performance of design. The final values of design parameters are SWR=1; Gain=7.3 dB; resistance=200 ohm and X-in (impedance)=0. 3 ohm.

3 Hardware fabrications of antennae

3.1 Mechanical drawing

The driven element is given as a wire in the 4NEC2 simulations. However, according to a typical Yagi design, total length of the driven element has to be folded into a dipole with finite spacing between arms and spacing between feed points at the ends. The curved folding on both sides of dipole has to be symmetric and calculated (not shown here). The spacing between feed points is taken equal to 2.0 cm. Figure 5 shows a general mechanical drawing annotated by length of respective elements given in Tables 2 and 3. All elements are placed on a boom of length equal to 50.0 cm (for 437 MHz) and 90.0 cm (for 145 MHz) and diameter equal to 2.0 cm. The diameter of all the antenna elements is equal to 0.6 cm. A nylon cube couplers of dimensions

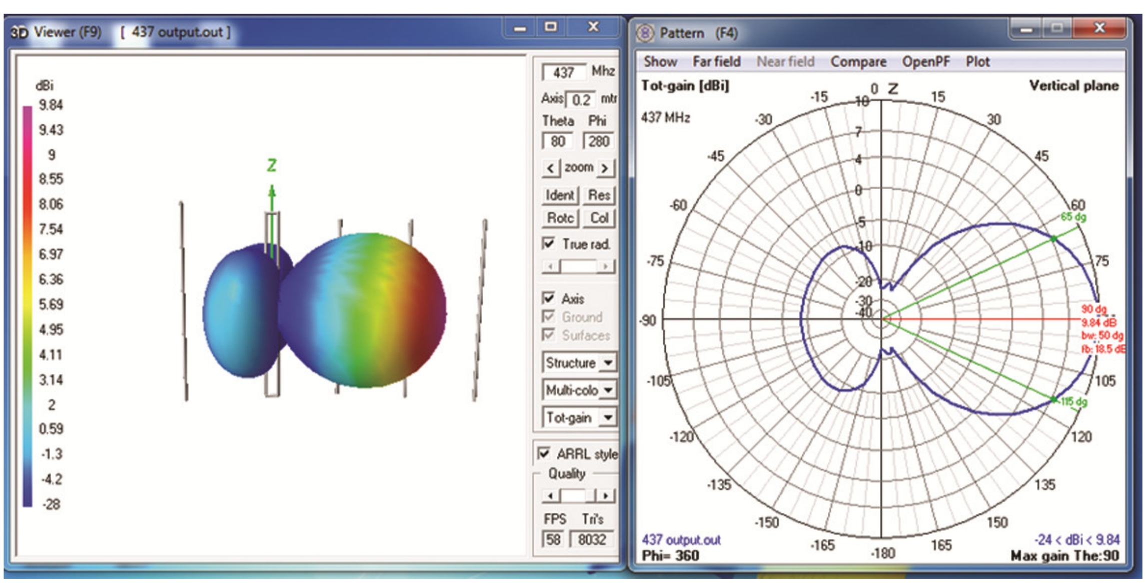

Fig. 2 — 3-D (left) and 2-D (right) radiation patterns from optimized design of 437 MHz antenna

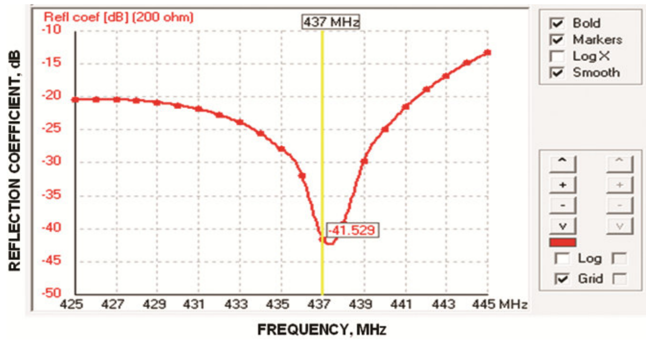

Fig. 3 — Reflection coefficient (dB) with respect to frequencies around 437 MHz

Table 3 — Optimized performance comparison for 145 MHz

	Element/spacing	Lengths for 145 MHz, cm before optimization	Lengths for 145 MHz, cm after optimization
A.	Reflector	99.310	104.720
B.	Driven /Dipole	95.172	92.191
C.	Director 1	91.034	85.862
D.	NA	NA	NA
E.	NA	NA	NA
F.	Reflector spacing	45.517	45.282
G.	Director spacing	33.103	37.801
H.	Dipole arm spacing	04.137	04.200

40 × 40 × 25 mm has been selected considering its insulation properties.

3.2 Calculation for balun

The balun length depends upon wavelength (λ) of the signal and velocity factor of the cable:

$$\text{Balun length} = \frac{\lambda^{*}\ \text{velocity factor}}{2}$$

The velocity factor depends upon the dielectric constant of the cable wire used for balun. The dielectric constant is the ratio of the permittivity of a substance to the permittivity of free space.

$$\text{velocity factor} = \frac{1}{\sqrt{\text{dielectric constant}}}$$

The velocity factors for cable RG-223 used for 437 MHz and cable LMR-400 used for 145 MHz antennas are 0.66 and 0.85, respectively. Thus, balun length for 437 MHz antenna is 27.63 cm and for 145 MHz antenna is 87.89 cm.

3.3 Fabrication of crossed Yagi and connection of baluns

Solid aluminum bars of specific diameter (0.6 cm) have been used to construct antenna elements. As noted earlier, the Faraday rotation measurement requires crossed Yagi antenna to estimate differential rotation of plane of polarization of received signal. So, the crossed Yagi for both the frequencies has been designed. The baluns connection are so made that each crossed Yagi has a common ground connection on boom. An aluminum boom for both the antennas has been used. One end of feed line is soldered on one of the feed point on respective dipoles for each crossed Yagi and other end is fixed into a TNC connector. The final output of the present work is a fully fabricated crossed Yagi antenna for respective central frequency. Figure 6 shows photograph of the fabricated antennae at NARL.

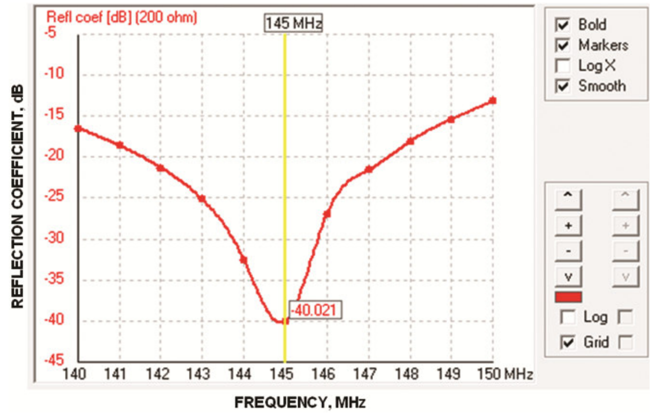

Fig. 4 — Reflection coefficient (dB) with respect to frequencies around 145 MHz

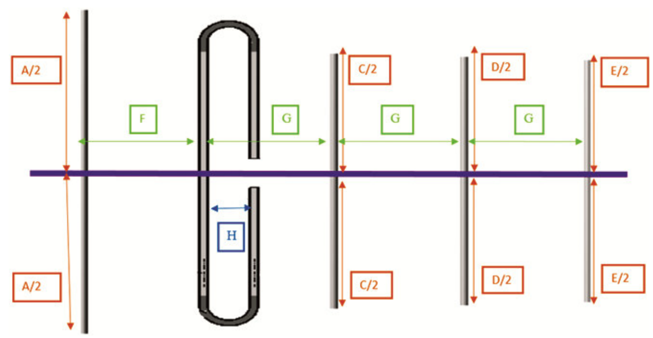

Fig. 5 — Mechanical drawing for the optimized lengths as given in Tables 2 and 3 [A-H correspond to lengths of the respective elements given in tables]

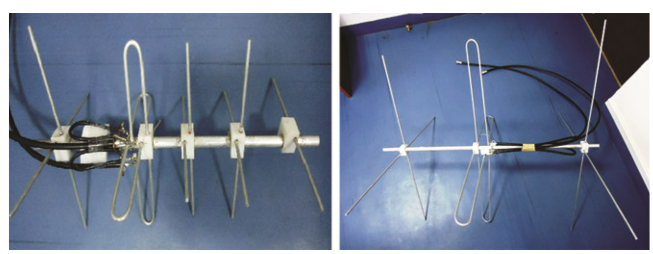

Fig. 6 — Photograph of fabricated crossed Yagi for 437 MHz (left) and 145 MHz (right)

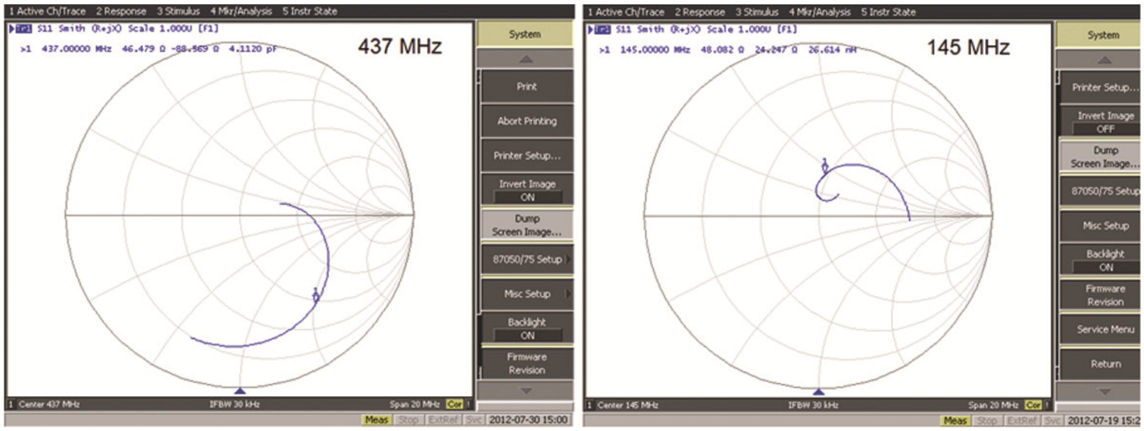

Fig. 7 — Input impedance of antenna at 437 MHz (left panel) and 145 MHz (right panel) taken from display of Agilent Technology's (E5061A) network analyzer

Fig. 8 — Observed return loss curves for 437 MHz (left panel) and 145 MHz (right panel) [panels show the photographs of front display of the Anritsu's site master S311d]

4 RF characterizations and testing of antenna

The designed parameters for both the antenna are given earlier. The input impedances of both antenna designs are 50 ohm and designed VSWRs are given in Figs 3 and 4, respectively for 437 MHz and 145 MHz. RF testing facility is available in Radar and Application Development Group at NARL. Two of the first basic test parameters, i.e. input impedance and return loss[11] are measured using Agilent Technology's ENA-L RF Network Analyzer (E5061A) and Anritsu's S311d Antenna Site Master, respectively. The advantage of a network analyzer is its ability to measure both the magnitude and the phase of the power received. It provides the Smith chart so that one can easily measure impedance at desired band width. In another test, the return loss is measured across the frequency range that provides a proxy to VSWR[12]. Figure 7 gives the Smith charts for 437 MHz and 145 MHz, while Figure 8 gives the plot of return loss with respect to frequency in both the cases, respectively.

It is obvious from Fig. 8 that the return loss of the fabricated antennae shows a clear dip at the desired central frequency, respectively. As a matter of fact, Figs 3 and 4 exhibit reflection coefficients of software design and Fig. 8 confirms that the same return loss has been obtained by a precise hardware fabrication. Thus, both the crossed Yagi antenna successfully passed the fundamental RF test for designed antennae.

5 Conclusions

Two crossed Yagi antenna at the central frequencies of 437 MHz and 145 MHz have been indigenously designed, fabricated and tested. First, the calculated parameters were optimized, then precise fabrication was followed, that showed basic radiation patterns and VSWR plots. Finally, these VSWR plots were compared with measured plots and comparison comes very satisfactorily. At present, a software defined radio receiver is being designed using USRP boards that would receive the signals from these antennae. The scientific utilization of these antennae would be to measure Faraday rotation and this would lead to estimation of ionospheric TEC.

Acknowledgment

The authors acknowledge the comments, suggestions and support during lab testing by P Srinivasulu, M Durga Rao and P Kamraj of NARL at various levels of this work. One of the authors (KV) is thankful to ISRO for M Tech fellowship. They gratefully acknowledge Director, NARL for his encouragement.

References

1 Austen J R, Franke S J & Liu C H, Ionospheric imaging using computerized tomography, *Radio Sci (USA)*, 23 (1988) pp 299-307.

2 Kraus J D, Marhefka R J & Khan S A, *Antenna and wave propagation*, 4th edition (Tata McGraw Hill Publication, New Delhi), 2010.

3 Prasad K D, *Antenna and wave Propagation*, 3rd edition (Satya Prakash Publications, New Delhi), 2007, pp 777-781.

4 Bandyopadhyay S, Jha J, Haripriya, Damle A, Thakur D, Mulay S, Sachdeva P, Joshi J, Unhelkar V, Chati Y, Chaturvedi M, Parab N, Rachh M, Tamaskar S, Bommanahal M, Goel A, Neema K, Das S, Sresht V, Pai R & Chiplunkar A, *Introduction to Pratham, IIT Bombay's Student Satellite Project*, Paper presented at Indian Small Satellite Systems Conference (ISSSC), Bangalore, India, April 2010.

5 Viezbicke P P, *Yagi antenna design: NBS technical note 688* (Time and Frequency Division, National Bureau of Standards, U S Dept of Commerce), December 1976.

6 Chen C A & Cheng D K, Optimum element lengths for Yagi-Uda arrays, *IEEE Trans Antennas Propag (USA)*, 23 (1) (1975) pp 8–15.

7 Burke G J & Poggio A J, *Numerical electromagnetics code (NEC) — method of moments* (Lawrence Livermore National Laboratory, Livermore, California, USA), 1981.

8 Klobuchar J & Mendillo M, *Total electron content studies of the ionosphere, report on air force survey in geophysics* (Air Force Cambridge Research Laboratories, Massachusetts, USA), 1973.

9 Davies K, Recent progress in satellite radio beacon studies with particular emphasis on the ATS-6 radio beacon experiment, *Space Sci Rev (Netherlands)*, 25 (1980) pp 357-430.

10 Balanis C A, *Antenna theory, analysis and design*, 3rd edition, (John Wiley, New York), 2005.

11 Raju G S N, *Antennas and wave propagation* (Dorling Kindersley India Pvt Ltd, Pearson Education, New Delhi), 2004.

12 Bird Trevor S, Definition and misuse of return loss, *IEEE Antennas Propag Mag (USA)*, 51 (2) (April 2009) pp 166–167.