Validation of the Radiation Pattern of a Fully Active Phased Array Wind Profiler using Cosmic Radio Sources

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Abstract:

The paper describes the design and configuration of the antenna array for a fully active phased array system intended for wind profiling applications at a rocket launching station. The design of individual antenna element is also discussed. The method of validating the whole design by using extraterrestrial radio sources is detailed. The results obtained using the Sun, Virgo A and Taurus A are presented.

Key Words: Yagi, Phased Array, Virgo A, Taurus A

I INTRODUCTION

A fully active phased array system, consisting of 576 elements and operating at a VHF frequency of 49 MHz, is configured as a wind profiler, to support the launch requirements at Satish Dhawan Space Center, Sriharikota. The system provides three dimensional atmospheric wind data on a continuous basis with good spatial and temporal resolution, which is very useful for studying the development of wind shears in near real time over the rocket launching site. Further, it is important to have wind profile data prevailing over the launch station for the optimum design of new launch vehicles. Wind profilers are Pulsed Doppler Radars, which come under the category of 'Clean Air Radars'. The radar uses the scattering and reflection from the variation in radio refractive index of neutral atmosphere. The variation in refractive index, in turn depends on the variability of humidity, temperature and electron density, induced by the turbulence in the lower and middle atmosphere. The clear air turbulence is essentially a volume target and the volume reflectivity in the atmosphere ranges between 10^{-13} m^2/m^3 to 10^{-19} m^2/m^3 or lower. Hence the system is designed to have very high sensitivity in order to receive these echoes.

The large diameter of the array is to achieve the narrow beam width requirement of 3 deg at the chosen operating frequency of 49 MHz and the requirement of an average power aperture product of nearly 6.5 x 10^8 Wm^2. The characterization of array patterns of such large antenna arrays has always been a difficult task owing to their size and the distance to the far field of the antenna array. The range to the Fraunhoffer region or “far field” of the antenna array is typically taken to be $R_F = 2D^2/\lambda$, where D is the diameter of the array aperture and λ is the signal wavelength .The far field for the array is therefore calculated to be at 4.8 Kms and the beam formation is the near field is not considered to be appropriate for measuring the beam parameters. Also, it is unable to calibrate such large antenna arrays by conventional methods such as bore sight tower, anechoic chamber, etc. The idea of using a stationary aircraft or a 'non-drifting balloon' positioned in the far field for calibrating the array is only imaginative and is certainly not worthwhile, owing to the cost implications, feasibility issues etc. Further, any earth bound range at a low elevation angle will increase the risk of spurious ground reflections causing calibration errors.

Further, these antenna arrays typically depend on reflections from the ground to create their antenna pattern. The ground reflection can vary with season due to the change in moisture content of the soil. Hence, the most appropriate method is 'in situ calibration' and the method adopted should definitely be cost effective and capable of being repeated periodically. Stellar sources such as radio stars that radiate in the VHF spectrum are hence the ideal choice for calibration of these antenna array systems owing to the high sensitivity of the clear air radar systems to observe such a source.

II ANTENNA ARRAY CONFIGURATION

The antenna of atmospheric radars usually consists of either an array of individual elements to form a large antenna array (Phased Array) or a large dish antenna. The aperture of the phased array and the transmitter power is used to calculate the power aperture product which is the ‘Figure of Merit’ of profiler and thereby determines its sensitivity. Dish antenna is rarely used at VHF frequencies, even though no complicated power distribution and phasing network is required to feed the antenna. Because of the large dish diameter of about 120 m and the steerability requirements, dish antenna does not offer an elegant cost effective solution at these wavelengths. Thus the Phased Array Antenna is chosen for Wind Profiler.

The radiation pattern of the Wind Profiler has to be carefully designed in order to obtain selectively, the back scattered signal, as compared to interfering external influences like ground clutter, sea clutter, radio interference and the scatter received through antenna side lobes. To achieve a high sensitivity and angular resolution, the gain of the antenna array should be large and the beam width should be small. The main parameter determining the antenna array gain and corresponding beam width is the area of the antenna array which is called the antenna aperture. An optimization of the aperture increases the sensitivity. Side lobe suppression by tapering attenuates undesirable signals but broadens the antenna array beam.

The radiating element is a Yagi antenna and 576 such antennas are located in a circular array, in square grid pattern. An array beam width of 3deg was specified for the system taking into consideration the required height coverage of 21 Kms. With a width of 3 deg, the beam would have a cross sectional spread of around 1.1 Kms at a height of 21 Kms. Further, such a value for beam width decides the diameter of the antenna array to be equal to 120 m. Array is chosen to be circular in shape so as to achieve a first side lobe level of -17.6 dB with respect to the main lobe, in case of a uniform illumination. The inter-element spacing is decided by the individual antenna gain and the maximum off-zenith angle for tilting the beam. The maximum off-zenith angle requirement was specified at +/- 20 deg for the profiler. The antennas are spaced at 0.7λ so as to keep away the grating lobes from entering the visible region, according to the equation:

$$\frac{d}{\lambda} \leq \frac{1}{(1+sin\theta)}$$

Where θ is the maximum off zenith scan angle, λ is the operating wavelength and d is the inter element spacing. The antenna array is shown below.

Figure-1 Wind Profiler Antenna Array

This array has to now meet the required Average Power Aperture Product of about nearly 6.5 x 10^8 Wm^2 so as to obtain a 3dB SNR from a range bin at 21kms, when the worst case value of volume reflectivity exists in the atmosphere. The power radiated by each element in the array is thereby arrived at a value of 1kWatt (peak), with 10% duty ratio.

III ANTENNA SELECTION

Different choices for the individual antenna element were Patch, CO-CO and Yagi. Patch antenna is used for wind profilers in the UHF range, but for 49MHz, it is not a suitable option. The simplest patch antenna would be 3mx3m in size and would have to be mounted at a precise distance above a larger ground plane and that too with a spacer made of a dielectric between them. Electrically large ground planes produce stable patterns and have lower environmental sensitivity, but at the same time would make the antenna bigger. When a ground plane is close to the size of the radiator it can couple and produce currents along the edges of the ground plane which also radiate. Thus such an antenna pattern becomes the combination of the two sets of radiators. The gain of a square patch antenna with air dielectric, is about 7-9 dB, and is in good agreement with more sophisticated approaches. But, the design of a patch antenna with 10 MHz bandwidth is difficult and would require very stringent mechanical tolerances for the array, more length of cables etc. Further, the alignment of these antennas so as to achieve a completely flat surface for the entire array would be very complicated and their periodical maintenance would be cumbersome.

The coaxial collinear array has the advantage of feeding the elements in one line by interchanging the inner and outer conductor of a coaxial cable every half wavelength. But the successive phase from one collinear element to the next degrades the bandwidth of the antenna. Instead of coaxial cable as a radiator, half wave dipoles can be used, which are fed in a properly adjusted phase to form a collinear antenna. Both CO-CO and half wave dipole array again require a ground plane, so this is not preferred though the cost is less.

The advantage of Yagi is that no ground plane is needed because of its reflector. The multi element structure of a single Yagi provides a higher gain and a negligible coupling between adjacent antenna in an array. The Yagi antenna was chosen as the radiating element owing to the wide bandwidth the antenna can provide, the easiness of mechanically aligning the antenna, the high power handling capability and the ease of maintenance. The losses of a Yagi system are also considerably lower than those of a CO-CO antenna. Hence a 3-element Yagi antenna is chosen for the Phased Array for Wind Profiler.

IV ANTENNA DESIGN

Yagi antenna designed has reflector, driven element and a director. The driven element is a λ/2 folded dipole and is the only member of the structure that is directly excited. It is electrically connected to the feed line through λ/2 balun which is used to match the 50 ohm impedance of the coaxial cable to that of the Yagi. Low loss coaxial cable RG 214 is used and the balun acts like a 1:4 transformer. The reflector and director being parasitic elements of unequal length lead to a unidirectional radiation pattern and a Front to Back lobe ratio of 16.5 dB is achieved. The Yagi is optimized for gain of 7.37 dB, VSWR of 1.2:1 and a bandwidth of 5 MHz at 20dB Return Loss.

Folded dipole was used in order to meet the operating bandwidth of 47 – 51 MHz. The antenna was tested for 1 kW power handling at 10% duty cycle with a maximum PRF of 8 KHz. The antenna is shown in Figure 2(a) and its measured pattern is shown in Figure 2(b). Aluminum was chosen as the material due to its light weight and due to the phenomenon of passivation, it has the ability to resist corrosion, which justifies its selection for the use in this coastal and saline environment. The Yagi along with the Transmit Receive Module (TRM) is mounted on a concrete pedestal.

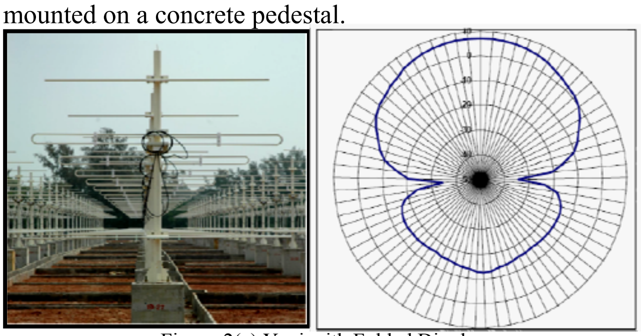

Figure-2(a) Yagi with Folded Dipole,
Figure-2(b) Radiation Pattern (E-Plane) of Single Element

V SYSTEM CONFIGURATION

In the active aperture system, each antenna of the array is connected to a Transmit/Receive Module popularly called TR Module or TRM. The basic building blocks of the TRM of this radar are a 1kWatt Solid State Power Amplifier (SSPA), a 6 bit phase shifter; Low Noise Amplifier(LNA), Timing Signal Generator Card and fast switching switches to switch between the transmit and receive paths. RG214 co-axial cable is used for connecting the TRM to the antenna. Since the SSPA and LNA are very close to the antenna, the transmit and receive losses are typically less than 0.5 dB. The total power of the radar is distributed over a number of TR modules and any failure of few of the TRMs does not significantly affect the performance of the radar. Since each TR Module is individually phase controlled through software, any number of beams can be generated in azimuth and elevation thereby giving a capability of scanning from 0 to 30 deg in off zenith angles and 0 to 360 deg in azimuth.

The Wind Profiler has been designed and installed in such a way that the antenna is oriented along the geomagnetic meridian. The antenna array has a circular geometrical aperture of 11304m^2 and a gain of 34dB.The active aperture is divided in to 16 sub arrays of which 12 are symmetrical and 4 are asymmetrical owing to the circular shape of the entire array. Each sub array consists of 36 antennas which are grouped using four 1:9 Power Divider/Combiners (PDCs) and one 1 to 4 way power divider/combiner. As the antenna is oriented along the geomagnetic meridian, half of the entire array is north facing and the remaining half is facing towards the southern direction. Equal cable lengths are maintained throughout the array in order to assure equal loss so as to achieve uniform illumination. Further, the residual phase errors are eliminated by phase calibration, thereby assuring phase coherency in the radiation from 576 elements.

The cables from 16 sub arrays are connected to a 1:16 PDC located in the instrumentation room. In the actual operation of the radar, a ‘Feeder Transmit Receive Module’ provides a gain of 30dB to the signal received by the antenna array. It is in this module that the transmit and receive paths get separated at the instrumentation room. The receive channel further has a high gain receiver which apart from amplifying the received signal by 60dB, also down converts the RF signal to an IF frequency at 14 MHz. A digital receiver then does the signal processing algorithms and doppler extraction.

VI COSMIC RADIO SOURCES FOR RADAR CALIBRATION

Strong cosmic radio sources provide a constant broadband as well as accurately positioned test transmitter for measurements on large antenna installations as they always satisfy the far-field criterion. To be an ideal test source for such conditions, the following properties (as summarized by Jacob W., M. Baars) are desirable for the transmitter or source. 1) A precisely known location in the sky and when seen from the location of the antenna array the source should cover a considerable range in the radar elevation angle on its daily path along the sky. 2) Very small angular dimensions, so that it would appear as a point source for the radar beam which is very narrow. 3) An absolutely and accurately known power flux value over a large frequency range, without showing variation over time or any polarized component. 4) A large flux density so as to allow a considerable dynamic range in the pattern measurements with presently available equipments of moderate sensitivity. However no source exhibits all properties simultaneously and there are several sources satisfying one or more of our requirements. Therefore by taking the afore-mentioned factors into consideration, the sources selected for our study are the Sun, Virgo-A and Taurus-A.

Sun is by far the strongest object in the sky and is always used in order to obtain a sufficient Signal to Noise Ratio (SNR). But, the limitations are the large angular size and the strong variations in the signal strength due to solar activity. Virgo-A is a super giant elliptical galaxy which is the largest and the brightest near the Earth, and is a strong source of multi wavelength radiation, particularly radio waves. The Radio source 3C274 (Messier 87) is identified with Virgo-A. The declination of this radio source is +12.667° and is ideally suited for calibration of this Wind Profiler antenna array. The source transits from east to west, everyday over the radar due to the earth’s rotation. The transit time at particular location is accurately calculated with Right Ascension and Declination of the source. Taurus A (3C 144) is a Supernova , which subtends a comparatively larger angle (declination 21.982°) over the radar site, is used in order to measure the gain reduction due to beam broadening issue when the beam is pointed to a larger off zenith angle such as +/- 20 degrees. The important characteristics of the Sun, VirgoA and Taurus A are summarized in Table-1.

<table>
<tr><th rowspan="2">Source</th><th rowspan="2">Type</th><th rowspan="2">Spectral Index</th><th colspan="2">Flux Density (fu)</th></tr>
<tr><th>1 GHz</th><th>3 GHz</th></tr>
<tr><td rowspan="2">Taurus A (TauA, 3C144)</td><td>SuperNova</td><td>-0.263</td><td>986 +/-12</td><td>739 +/-10</td></tr>
<tr><td colspan="4">Right Acension = 05h31m31s,
Declination = +21deg, 59'.0,
Angular Diameter 3' by 4'.5</td></tr>
<tr><td rowspan="2">Virgo A (Vir A, 3C 274)</td><td>Galaxy</td><td>-0.853</td><td>285 +/-5</td><td>112 +/-3</td></tr>
<tr><td colspan="4">Right Acension = 12h28m17s,
Declination = +12deg, 39'.9,
Angular Diameter - core 0'.6, halo ~ 6'</td></tr>
<tr><td rowspan="2">Quiet Sun</td><td>Star</td><td>_</td><td>~2,00,000</td><td>~1000000</td></tr>
<tr><td colspan="4">Right Acension = 04h55m26s,
Declination = +22deg, 36'.35,
Angular Diameter ~0.5',computefulx density using daily value of angular size</td></tr>
</table>

Table-1 Important characteristics of the Sun, VirgoA and Taurus A

The flux S, from a source is proportional to υ^{α} , where, υ is the frequency and α is called the spectral index. A thermal source has $\alpha = 2$ and majority of the radio sources as radio galaxies, quasars and supernova remnants are non thermal with α = -0.25 to -1.The power flux S is expressed in terms of flux units (1 fu = $10^{-26}Wm^{-2}Hz^{-1}$) or in equivalent brightness temperature T_b, where,

$$S = \frac{2k}{\lambda^2}\int_{\Omega_s} T_b d\Omega$$

Where Ω_s is the solid angle of the source and k the Boltzmann's constant. If the flux values, say $S(f_1)$ and $S(f_2)$ are accurately known at two frequencies f_1 and f_1, then the value at the frequency, f, of our interest, can be calculated using the equation.

$$S(f) = S(f_2).[\,S(f_1)/S(f_2)]^{[\log\left(\frac{f}{f_2}\right)/\log\left(\frac{f_1}{f_2}\right)]}$$

The above formula was helpful in calculating the flux density for the cosmic sources at 49 MHz from available literature.

VII MEASUREMENTS AND RESULTS

The radio source transits the antenna array from east to west due to the earth's rotation. As such 8 sub arrays forming a half circle are grouped as east facing sub arrays and the remaining half is grouped as west facing sub arrays. A Sigma-Delta Pattern generator is designed which generates the sum and difference patterns. The Sigma-Delta pattern generator has two 8:1 power combiners which independently sum the signal power from the radio source as received by the half arrays during its transit. A 2-way power divider is kept at the output of each 8:1 power combiner. One output of each of the 2-way power dividers is combined using a 2:1 power combiner, using two cables of equal length (say ' l_1 ').Output of this 2:1 power combiner is the sum output, which we call the 'Sigma' Channel. The remaining outputs of the two 2-way power dividers are connected to another 2:1 power combiner using two cables of different length. Among this, one of the cables has the length ' l_1 ' and the other cable has a length ' $l_1 + \lambda/2$ ' so that the output of this second 2:1

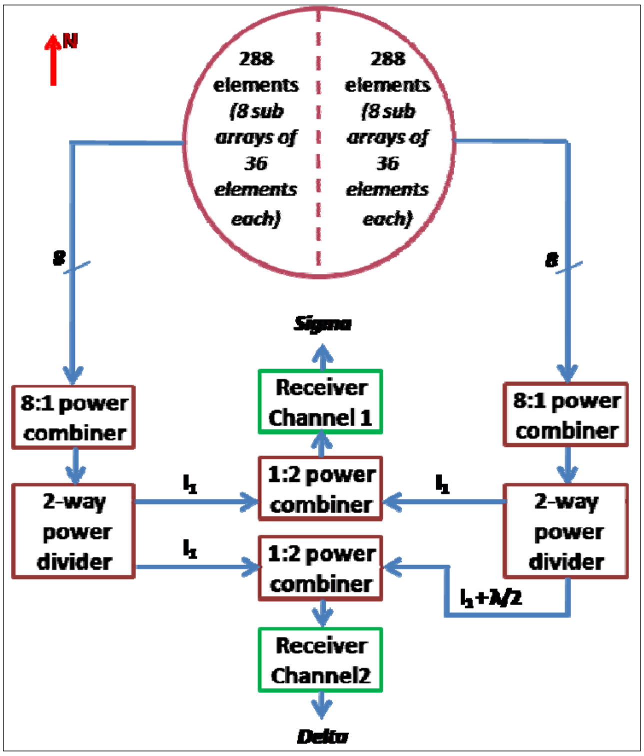

Figure-3 Configuration of the array for the measurement

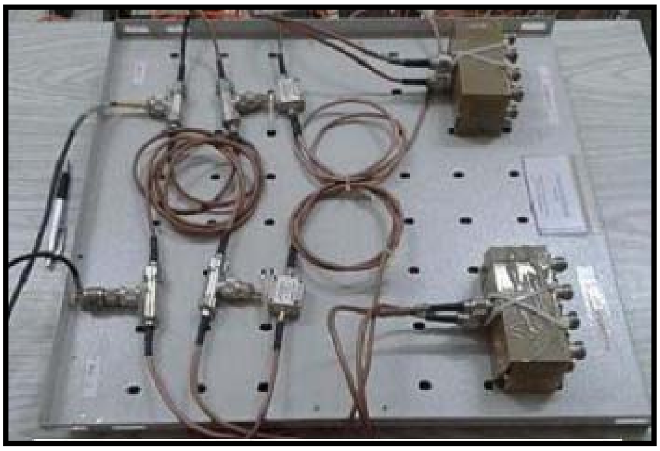

Figure-4 Sigma Delta Pattern Generator

power combiner would be the difference output of the two half arrays, which we call the 'Delta' Channel.

Both the Sigma and Delta Channel outputs are amplified using two identical channels of an RF Receiver. The channel gain, stability and filter characteristics of the two channels of the RF receiver match each other very closely. Sensitivity of the receiver channels is at -110 dBm at 1 MHz bandwidth centered at 49 MHz. Data is archived using two spectrum analyzers as the radio star transits the antenna beam and the Sigma and Delta patterns are recorded and plotted.

The antenna half-power beam width can be calculated from the time elapsed between the half intensity points of the drift curves. One minute of time is equal to 15 minutes of arc times the cosine of the declination of the source. This method involves precisely locating the peak of the sum pattern. Alternatively, the Delta pattern is subtracted from Sigma pattern and the two nulls in the resultant pattern are clearly identified. The null-to-null spacing is then multiplied by a factor of 0.517 to derive the array beam width. This factor is obtained from array simulations. Such a method is found to be more accurate as it involves the locating of two nulls, rather than locating only a peak of the sum pattern and then deriving the beam width. The gain estimate is done by combining the received signal from all the 16 sub arrays (entire array) and archiving the data after subsequent amplification using an RF receiver. The exact flux density of the radio star is ascertained from the data available and by extrapolation methods. It is a pre-requisite to calibrate the losses and gains of all the individual elements of the entire chain. Using the peak value of the 'Sigma' pattern generated by the entire array during the transit of radio source, and by incorporating the net effect of the different elements in the receive chain which are quantifiable and calibrated; it is possible to exactly determine the array gain achieved with 576 Yagi elements. Once the array gain is calculated, the effective aperture area is thereby derived which when divided by the geometrical aperture would yield the array efficiency. For the estimation of beam pointing accuracy, the exact time at which the Sigma minus Delta pattern peaks is established and it is then correlated with the expected time of peak signal strength (for that particular beam position) from star trajectory predictions. By noting the time at which the received power is maximum, the corresponding look angles of the radio source provide the beam pointing accuracy. The difference can be attributed to the inaccuracy or error in beam pointing. The results obtained for beam width, array gain, efficiency and beam pointing accuracy, closely in match with simulations and are presented in Table-2 and a patterns recorded are shown in Figure-5

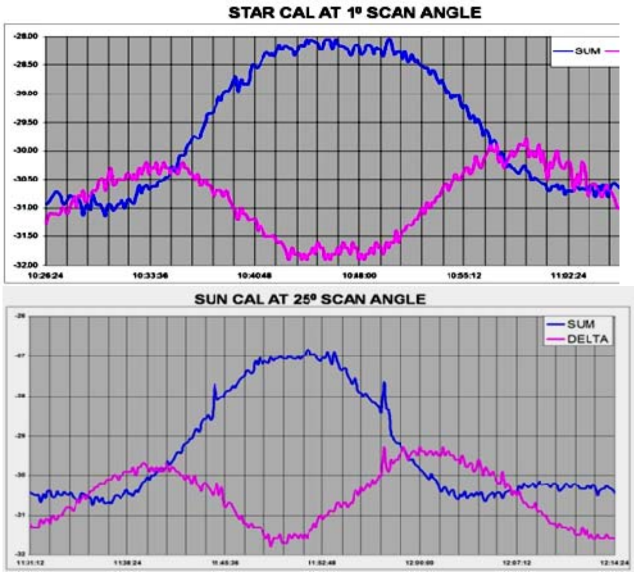

Figure-5 Patterns recorded with Virgo A at 1 deg scan angle and Sun at 25 deg scan angle.

These experiments when conducted with Taurus, which subtends a comparatively larger angle over the radar site, would help to measure the gain reduction due to beam broadening as the beam is pointed to a larger off zenith angle such as +/- 20 degrees. Gain reduction is seen by about 1dB. Sun is not suitable for measurement of beam pointing accuracy due to its larger angular diameter, but may be used for array gain calculation.

Results		
	Design Value	Measured Value
Beam Width	3 deg	3.01 deg
Array Gain	34 dB	33.8 dB
Beam Pointing Accuracy	0.02 deg	0.02 deg
Array Efficiency	65 %	65 %

Table-2 Results obtained with Virgo A

VIII CONCLUSITIONS

There exist a set of cosmic radio sources which can be used as a test transmitter source for calibration of Radar. These sources provide a remarkably constant source of broad band radiation and they daily traverse the sky along a precisely known path which is available as look up angles. Thus, they are ideal for the in - situ measurement of antenna array parameters, thereby validating the array design and the element design. By the use of sources of different angular sizes, different declination etc, it is possible to obtain certain additional information. The sources are always in the far field and the problem of ground reflections because of low elevation is no longer an issue. To use the afore-mentioned methods effectively, one needs to have a good knowledge of the source(s), especially in terms of its flux density, its transit path etc and even the presence of other sources in the sky at the time of conducting the experiment.

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