Evolution of atmospheric radars in SPL, V.S.S.C

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Remote sensing of the atmosphere using ground-based radars is a very powerful and cost effective method for obtaining very valuable scientific data on the various atmospheric phenomena with very good temporal and spatial resolution necessary for a better understanding of these phenomena. Since, from the very beginning, the main thrust of the various research activities in SPL was in the areas of Atmospheric sciences and Space sciences, ground-based radars occupied a major part of the resources in SPL.The main thrust in SPL was to design and develop in-house experiments for providing quality scientific data required for the various activities of SPL rather than seek data from outside or buy and operate commercial scientific equipments to gather data for research.

Scientific data on atmospheric phenomena can also be obtained using suitable payloads carried in balloons, rockets and satellites. But in general, these methods yield data for limited time duration and demand huge funds and very long lead time for giving data after conceiving the experiment. However, in many cases they can provide data which cannot be obtained by ground-based systems including radars and can also provide data with much better spatial resolution. Hence it can be said that in order to study the very complex atmospheric phenomena one has to obtain complementary data using all the above mentioned methods.

The task of indigenous development of radar systems was initiated as early as in late 1960s when the development of a VHF backscatter radar system was taken up at the Physical Research Laboratory, Ahmadabad as a project under INCOSPAR (Indian National Committee for Space Research). Though the development of the system was started in Ahmadabad, it was intended to be installed and operated at Thumba located near the magnetic equator. The construction of a building was also taken up at Thumba for the installation of the radar. This partially developed radar system was moved to the constructed building near the church in TERLS (Thumba Equatorial Rocket Launching Station) in the early 1970s. This marked the beginning of the design and development of a series of radar system in the Space Physics Division (SPD) of VSSC which was later renamed as the Space Physics Laboratory (SPL). The very exciting experience of the development of some of these major radar systems is the subject of this article.

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Coherent VHF backscatter radar

The radar was designed for the study of equatorial electrojet, which is an intense band of electric current situated at about 100 km altitude and which is responsible, directly or otherwise, for a number of interesting features observed in the equatorial ionosphere. It was also realized that such a radar system capable of continuous monitoring of the electrojet region of the ionosphere can give excellent ground support for the rocket experiments planned to be conducted from Thumba for the study of atmosphere, in addition to providing scientific data for comparison with those obtained from the rocket payloads. The signals obtained from the radar can be crucial to determine the optimum time of launch of the rockets carrying scientific payloads for obtaining intended scientific data.

This being the first radar system to be developed in house, the realization of a smaller system was targeted in the first phase to gain experience in the design and development of the various subsystems. Hence the development of a system with a 10 kW peak power transmitter, five- elementYagi Uda antennas for transmission and reception, receiver for the measurement of echo signal strength and analog data acquisition system with a provision to record the data on a pen chart recorder was taken up. It is worth mentioning that all the subsystems were designed and developed in house using components procured from the market. The partially developed subsystems of the radar were moved and installed in the backscatter radar building in TERLS in 1970. After conducting tests and making some minor augmentations, first signals from the equatorial electrojet were obtained in 1971. Essential modifications were made to improve the S/N ratio to acceptable levels and regular data collection was started in 1972. Simultaneously several augmentations were carried out to the various subsystems of the radar in the subsequent years to improve the quality of scientific data obtained from the radar.This was probably the first high power atmospheric radar system totally designed and built in India and successfully operated for several decades to obtain data from the equatorial ionosphere. The details of the final system are given in the subsequent paragraphs.

The major specifications of the radar system are given in table 1 and a condensed block diagram is shown in Fig.1. The radar system is designed to operate at a fixed frequency of 54.95 MHz the odd value being dictated by the frequency clearance requirements. The peak power of the transmitter is 20 kW and the pulse width and PRF are selectable within the range shown. The radar is usually operated with a pulse width of 20 μs for E region studies and 80 μs for F region studies. The average power aperture product,accepted as the figure of merit for comparison of performance of atmospheric radars, is 4.4 x 10^5 watt m^2. The 84.95 MHz local oscillator frequency signal generated using an crystal controlled oscillator (LO) is used to generate the 30 MHz reference signal for phase detection as well as to generate 30 MHz IF signal from the received 54-95 MHz signal thus forming a phase coherent radar system necessary for accurate velocity measurement. The antenna system consists of 64 five element Yagi Uda antennas in a 4x16 rectangular uniformly fed array configuration, 4 antennas in the magnetic N-S direction and 16 in the magnetic E-W direction. The beam orientation is fixed and its axis is inclined at an angle of 30° towards magnetic west and the half power beamwidth in the E-W plane is 4.5°.As beam scanning is not done, the individual antennas of the array are also inclined at the same angle of 30° towards magnetic west to get maximum gain in this direction. The same antenna array is used for both transmission and reception by the use of a PIN diode T/R switch. A coherent receiver with a low noise front end amplifier and selectable bandwidthto match with the selected pulse width is used for the reception of echo signals from the ionosphere.The coherent receiver provides I and Q outputs which are range- gated, digitized using a 12 bit A/D converter and are subjected to spectrum analysis using FFT algorithm. The number of range gates and the number of data points for spectral are selectable to suit the type of experiment being carried out. The power spectral computation is done on-line and the power spectra after averaging, if necessary, are displayed and also stored in the hard disk of the computer. The operating parameters of the radar can be selected using a PC based radar controller. This feature together with the on line processing capability makes it possible for the experimenter to optimize the operating parameters of the radar system as dictated by the study being carried out.

Table .1 VHF Backscatter Radar - System Specifications

Frequency	54.95MHz
Bandwidth	1MHz
Peak power	20 kW
Pulse width	10, 20, 40, 80 μs
Pulse Repetition Frequency	20-1000Hz
Duty ratio (max)	2%
Peak power aperture	2.2 X 10^7 Watt m^2
Average power aperture	4.4 X 10^5 Watt m^2
Type of Antenna	4 X 16 Array of 5-element Yagi Uda antennas
Effective Aperture	1100 m^2
Gain	26.5 dB
Beam orientation	30°W (magnetic)
One-way Beamwidth	4.5° (E-W plane)
Receiver maximum gain	120 dB
Receiver dynamic range	40 dB
A/D converter	12 bits, ±10V
Number of range gates	8, 16, 32, and 64
Acquisition rate	10s (min), variable in 10s steps
Data Processing	128, 256, 512, 1024 complex point FFT, power spectral computation, spectral averaging, spectral display on VDU

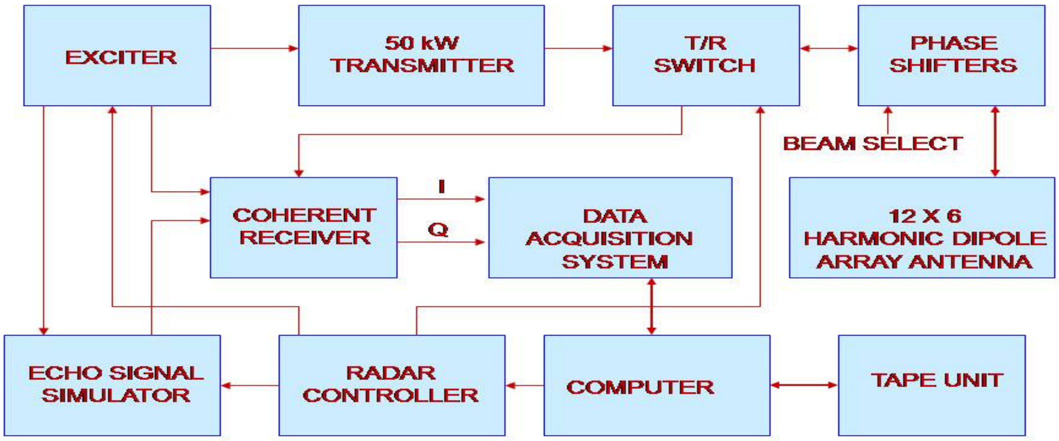

Figure 1 VHF BACKSCATTER RADAR SYSTEM BLOCK DIAGRAM

The data obtained from the radar has been extensively used for research work on ionospheric phenomena, especially on equatorial Electrojet. Several research workers have used the data from the radar for theirPhD theses. Radar data was provided for several national and international campaigns of scientific experiments and also for rocket experiments conducted from Thumba and SHAR for several years.

Backscatter radar with interlaced phased array antenna

As mentioned earlier, the VHF backscatter radar operates with a fixed antenna beam. For certain studies (Spread ‘F’, East-West asymmetry etc), two additional switchable beam orientations (zenith and 30˚E) are necessary. A separate array antenna was designed and constructed for this purpose which used a novel concept called interlaced phased array(IPA). A brief description of this array antenna is given here. (References 2 and 4 given at the end may be seen for full details).

The HF, VHF and UHF radars used in atmospheric studies very often require narrow beam antennas with a few (three or five) selectable beam orientations. Some radar systems use a large number of transmitters feeding individual elements or different sections of a phased array antenna with phase control at the input of the transmitters for meeting the above requirement. But the complexity and high cost of these systems cannot be justified when the required beam orientations are only a few. The cost of a single high power transmitter usually works out to be much less than the combined cost of several medium power transmitters giving out the same total power. Moreover, in a multiple transmitter system phase control of several medium power transmitters is required leading to increased complexity of the overall system.

In a single transmitter system, the conventional method of achieving beam switching is to bring the feeder cables of all the individual element antennas of the phased array to a common point and feed them using power splitters and variable phase shifters. The typical number of antennas forming the array antenna in an atmospheric radar system range from a few hundreds to about a thousand. Thus a very large number of high power splitters, variable phase shifters and large length coaxial cables are required if the conventional feed system is used. Generally, if the number of antennas in the array is N, N feed points and (N-1) phase shifters are required to tilt the beam in one plane. When the desired number of beam orientations is large or when continuous beam scan is required, this method is attractive. But even when the number of beam orientations required is small, the number of phase shifters and the lengths of cables required are the same as those required for a large number of beam orientations. The concept of Interlaced Phased Array (IPA) can be advantageously made use of in these circumstances. Hence a 4x15 phased array antenna with three switchable beam orientations was designed, constructed, tested and used with the VHF backscatter radar.

The array antenna consists of 60 vertically mounted four element Yagi Uda antennas in a 4x16 configuration, four in the magnetic N-S direction and 16 in the E-W direction. Since no beam scanning is required in the N-S direction, the antennas along the N-S direction in each of the 15 sections are combined together with suitable transmission lines to get 15 feed points spread along the E-W direction. These 15 sections are grouped into 3 interlaced sub arrays. Sub array 1 consists of sections 1, 4, 7, 10 and 13. Similarly sub array 2 consists of sections 2, 5, 8, 11 and 14, the remaining sections 3, 6, 9, 12, and 15 forming sub array 3. Thus each sub array consists of 20 antennas. The above interconnection reduces the number of feed points from 15 to 3. If the three feed points are excited with signals having a phase progression of $2\pi/3$ from East to West all the 15 sections in the E-W direction gets illuminated with a progressive phase shift of $2\pi/3$ and the resulting beam direction from zenith towards west θ is given by the equation

$$\phi = 2\pi/\lambda \; d \sin\theta$$

Where ϕ = the progressive phase shift, $2\pi/3$ in this case

d = separation between antennas in the E-W direction, $0.8\,\lambda$ in our case and

λ = wavelength corresponding to the radar operating frequency of 54.95 MHz.

The resulting beam orientation is 24.6° in our case towards west from zenith. By reversing the phase progression of signals fed to the three feed points the beam orientation shifts towards East from zenith by the same angle. Feeding in- phase signals to the three feed points results in a vertical beam. Thus by using only three phase shifters each giving two selectable phase shifts three beam orientations are obtained. The main limitation of IPA is that the value of the progressive phase shift cannot be chosen at will, but is determined by the number of interlaced sub arrays and the separation distance d between the adjacent antennas of the array.

The 4x15 array was constructed and the resulting beam orientations in the receive mode were verified using the Sun as a radio source when it transited over the beam. The antenna array was used with the VHF backscatter radar for studying the East west asymmetry and spread ‘F’.

Meteor Trail radar

Neutral wind velocities in the height region of 80-110 km can be measured using ionized meteor trails as naturally occurring tracers. Due to the high energy of moving particles when they travel through the earth’s atmosphere ionized trails are formed especially in the mesospheric region. These ionized trails move with the velocity of neutral winds in the region. These ionized trails form good radar targets and each meteor echo received using a high power radar lasts for tens to hundreds of milliseconds. The neutral wind velocity can be determined by measuring the Doppler shift associated with the echo. In order to determine the wind velocity vector and its vertical profile it is necessary to determine the position of each echo in space and also look at two orthogonal directions. The position of each meteor echo is determined by measuring the range by using the time delay of echoes and angled of arrival using an interferometer system. A pulsed Doppler radar system for the measurement of mesospheric winds was designed and developed in the Space Physics Division of VSSC and was operated during the 1980’s. To extract full information from the echo signal, the system is designed to record the following parameters for each meteor echo:

(i) amplitude
(ii) Doppler shift
(iii) range
(iv) Angles of arrival and
(v) time of occurrence

A block diagram of the Meteor Trail Radar system is shown in Fig.2 and the main specifications are given in table 2. This is a pulsed Doppler radar operating at a fixed frequency of 54.95 MHz A PRF of 300 Hz and a pulse width of 280 µs are used resulting in a large duty ratio of 8.4 per cent. A frequency synthesiser unit generates signals of frequency 50 MHz, 4.95 MHz, (4.95 MHz-40 Hz), 4.5 MHz, and a 500 KHz clock signal from a 1 MHz crystal oscillator. The 4.95 MHz signal is pulsed using the transmitter pulse and mixed with the 50 MHz signal and the sum frequency 54.95 MHz is generated. This carrier is phase modulated in accordance with a 28 bit pseudorandom code which is necessary to realise the desired range resolution of 1.5 km. The phase modulated RF signal undergoes several stages of amplifications in the transmitter. The peak power output of the transmitter is 40 kW. The transmittingantenna system consists of two arrays each consisting of 4 five element Yagi antennas. The antennas are mounted with their axes inclined at an elevation angle of 45˚. The direction of the beam axis is

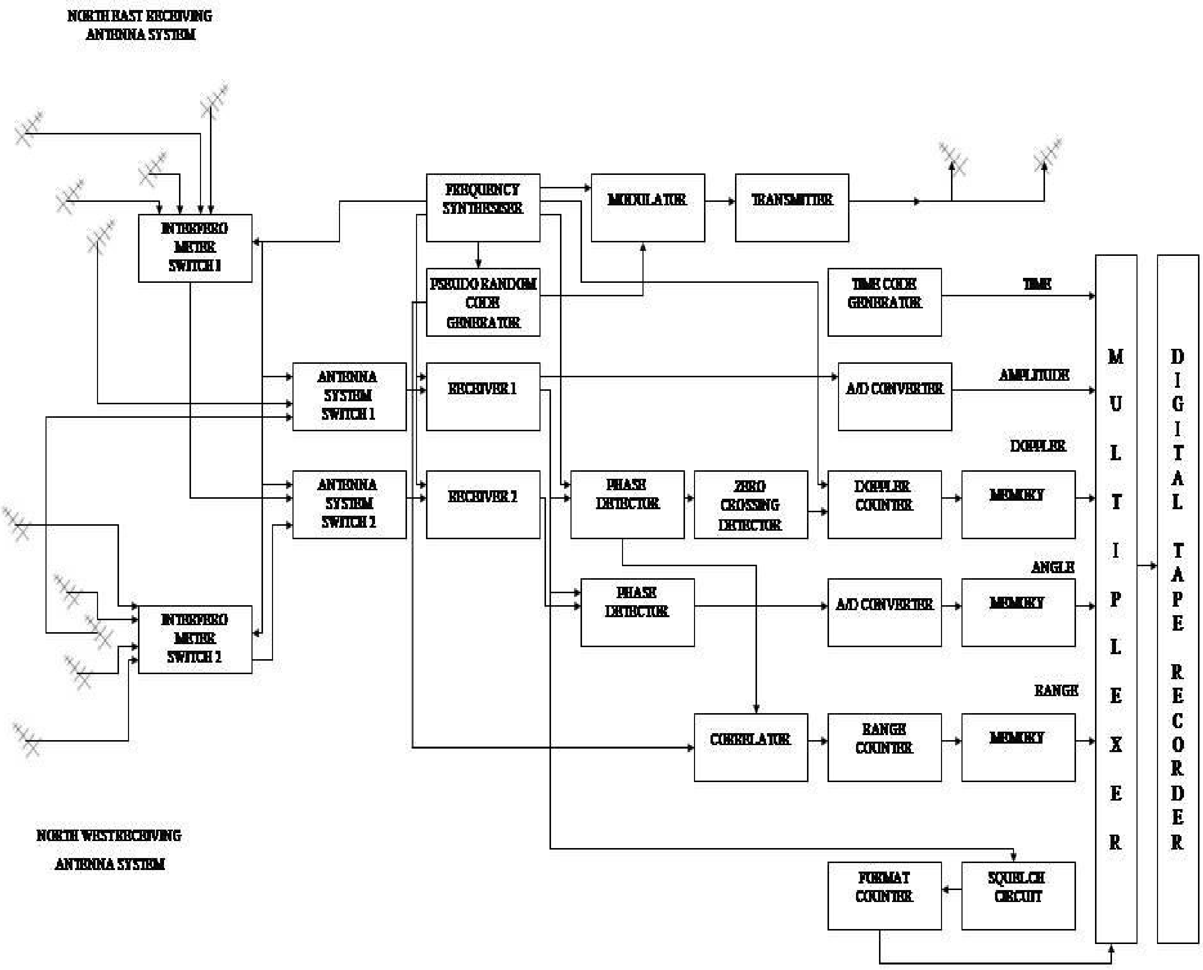

Figure2 METEOR TRAIL RADAR BLOCK DIAGRAM

Table 2 Meteor Trail Radar Specifications

Frequency	:	54.95 MHz
Peak Power	:	40 kW
Total Pulse width	:	280 μs
Phase coding	:	28 bit pseudorandom code
PRF	:	300 Hz
Doppler frequency resolution	:	± 2.0 Hz
Altitude resolution	:	± 2.0 km

either along theNorth-West or along the N-E direction and the estimated beam widths are 26° and 32° in the azimuth and elevation respectively. The direction and beam width are selected to minimize the interference from Electrojet signals. Each of the two receiving antenna systems consists of five yagi antennas forming an interferometer system. Low noise pre-amplifiers mounted on each antenna amplify the received signals before feeding them to the long co-axial cables running between the antennas and the receivers.

The receiving system consists of two receivers which are identical up to their first IF amplifiers. The receivers are enabled for reception from 380 μs to 3310 μs after the start of each transmitter pulse. The necessary timing pulses are generated by the format control and timing unit. The subsystems of the two receivers up to their first IF amplifiers have carefully matched characteristics which is necessary for the accurate measurement of phase differences of the signals at the receiving antennas. All the pre-amplifiers also have identical characteristics and transmission lines between the pre-amplifiers and the receivers are of identical electrical length. The first receiver has a narrow band second IF amplifier for amplitude measurement. The outputs of the two receivers are processed to obtain the amplitude, Doppler shift, range, angles of arrival and time of occurrence of each meteor echo. All the above data are recorded on a digital tape recorder for off line analysis: The operation of the system was discontinued after obtaining significant amount of data spreading over several years.

Two frequency HF radar

Coherent backscatter radar operating in the HF range is a powerful tool for studying the characteristics of equatorial spread F and Electrojet irregularities of different scale sizes. Operation of the radar in the HF range results in the following advantages as compared to its operation in the VHF or higher frequency ranges:

(i). improvement in Signal/Noise ratio due to the larger power associated with larger size irregularities and

(ii). unambiguous velocity and range measurement capability due to the smaller values of Doppler shift frequencies associated with smaller carrier frequencies.

A powerful HF radar system capable of operation at 18 or 9 MHz is another high power radar system designed, built and operated in the Space Physics Laboratory of VSSC. The system was indigenously designed and developed and is located at Thumba .The frequencies used correspond to irregularity scale sizes of 8.3 m and 16.7 m respectively. The major specifications of the system are given in Table 3 and a condensed block diagram is shown in Fig.3.

The main constituents of the radar are:

(i). 50 kW peak power transmitter which can be manually tuned to 18 or 9 MHz and a wideband duplexer.

(ii). A phased dipole array antenna capable of operation at the harmonic frequencies of 18 & 9 MHz and having an effective aperture of 10^4 m^2.

(iii). A high gain coherent receiving system with a built in test signal generator.

(iv). A PC based radar controller, data acquisition system and an on-line data processing system.

Table 3. HF Radar - System Specifications

Type of Radar	Coherent, Monostatic, Pulse Radar using Doppler Beam Swinging Technique
Frequency of operation	18 MHz or 9 MHz
Bandwidth	80 kHz
Peak power	50 kW
Pulse width	20, 60, 80, 100 μs
Pulse Repetition Frequency	100, 167, 200, 250 Hz
Duty ratio	2.5 %
Peak power aperture	5 X 10^8 Watt m^2
Average power aperture	1.25 X 10^7 Watt m^2
Type of Antenna	12 X 6 Phased dipole array
Physical Aperture	1.33 X 10^4 m^2
Effective Aperture	10^4 m^2
Gain at 18 MHz	26.5 dB
Beam orientations	Zenith, 30°E & 30°W off zenith
One-way Beam width (EW)	18 MHz : Zenith : 6.3°, Oblique : 7.3° 9 MHz: Zenith: 12.6°, Oblique: 14.6°
Receiver maximum gain	110 dB
Receiver dynamic range	40 dB
Receiver Noise figure	4 dB
A/D converter	8 bit
Acquisition rate	programmable
Number of range gates (max.)	32
Sampling rate	20 μs onwards, programmable
Data Processing	On-line spectrum analysis using FFT with provision for averaging up to 64 spectra

The radar system has the capability of observing both zonal and vertical plasma drifts by using Doppler beam swinging technique. Being coherent radar, scattered signals are obtained from irregularities of scale size equal to half the radar wavelength. Though the system is designed to operate at 18 or 9 MHz, it is optimized for 18 MHz operation. The peak power capability of the transmitter is 50 kW and the maximum duty ratio is 2.5 %. The pulse width and Prf options are given in the table.

The phased dipole array antenna consists of 72 wire dipoles in a rectangular 12x6 configuration. The dipoles are aligned in the magnetic N-S direction. The physical aperture of the array antenna is 1.33×10^4 m^2 and the effective aperture is close to 10^4 m^2giving a gain of 26.5 dB at 18 MHz The radar system has a peak power aperture product of 5x 10^8 watt m^2 and a maximum average power aperture product of 1.25×10^7 wm^2. The antenna beam axis can be positioned towards zenith or tilted from zenith by an angle of 30˚ towards magnetic west or east. The computed half power beam widths are 6.3˚ and 7.3˚ for the zenith nd oblique beams respectively.

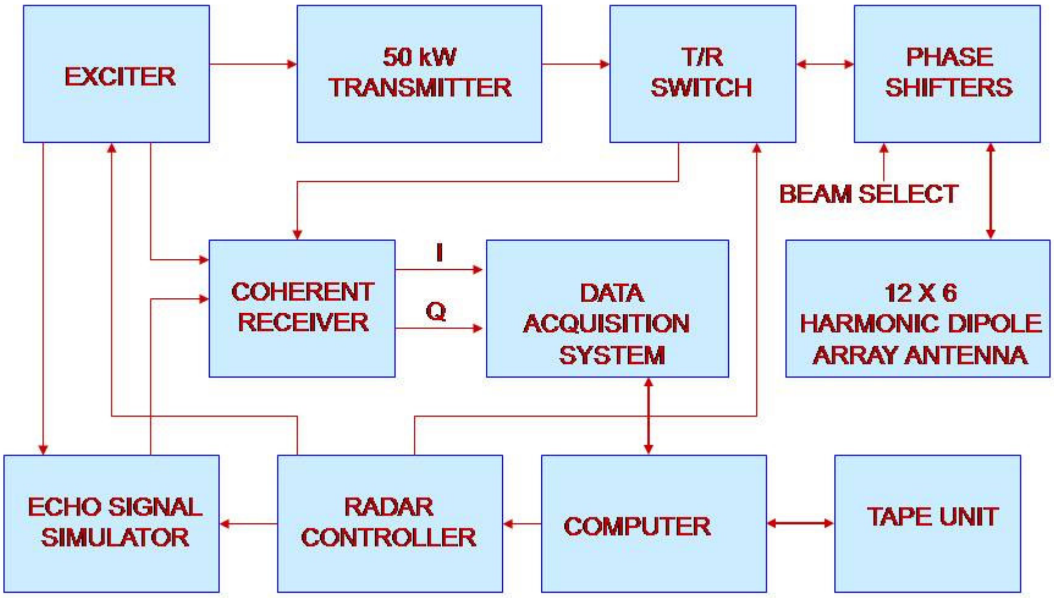

Figure 2 Block diagram of HF radar system

A coherent receiver is used to amplify the low power signal captured by the antenna. It has a maximum gain of 110 dB, a dynamic range of 40 dB and a noise figure of 4 dB. As the cosmic noise is very high at the operating frequencies, it is not advantageous to to use a very low noise figure receiver for the radar. In phase and quadrature phase detectors are used to give out I and Q channel outputs from which the Doppler shift and its polarity can be determined.

The radar controller provides choice of the various operating parameters of the radar such as carrier frequency, pulse width, PRF, beam position, height range for data collection, number of range bins, sampling interval, number of transmitter pulses for each data set and acquisition interval. The maximum number of range bins is 32. The data acquisition system digitizes the I and Q channel outputs of the receiver using 8 bit A/D converters. The sampling rate is programmable from 20 µs onwards. The data samples are separated for each range bin and spectrum analysis is done by discrete Fourier transform (DFT). Provision is made to integrate the power spectra over a specified number of sets. The integrated spectra are normalized and displayed as frequency Vs power plots for all the range bins in a single screen.

The 18 MHz radar system became operational in May, 1995 and the 9 MHz system in 1997. A large amount of scientific data has been collected using the 18 MHz system from the equatorial Electrojet and `spread F' phenomena. Also on certain occasions appreciable signals have been observed at lower altitudes in the height range of 80-85 km.

Partial Reflection radar

The HF radar system described in the previous section included a provision for operation at a frequency of 2.5 MHz with a single vertical beam antenna for measuring vertical drifts of Ionosphere layers. Later scientific need was felt for the design and development of an independent radar system using the spaced antenna drift (SAD) technique for the measurement of neutral winds in the mesosphere. The development of this partial reflection radar system was completed in 2004 and was operated for several years for scientific data collection.

The major specifications of the radar system are given in table 4 and the block diagram of the system is shown in Fig. 4. The 2.5 MHz signal is generated from a highly stable oven

Table 4. Specifications of PR radar

Radar type	: Coherent monostatic pulsed radar
Measurement technique	: Spaced Antenna (SA) drift
Frequency of operation	: 2.5 MHz
Peak power	: 50 kW
Type of antenna	: Inverted V type crossed dipoles
Pulse repetition frequency	: 100 Hz
Pulse width	: 20 µs
Band width	: 50 KHz
Probing altitude	: 65-95 Km

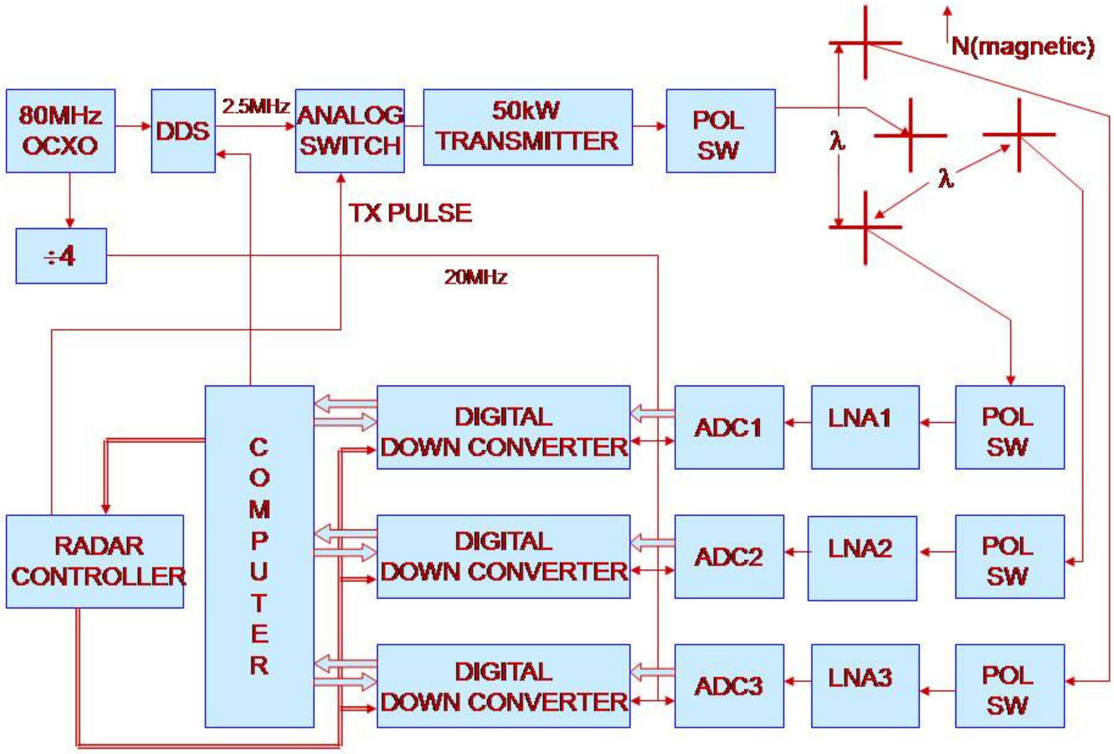

Figure 4 PARTIAL REFLECTION RADAR BLOCK DIAGRAM

controlled crystal oscillator at 80 MHz using a Direct Digital Synthesiser. After pulse modulation the signal is fed to a 50 kW peak power transmitter unit. The transmitter developed for the radar has a high peak power of 50 kW and incorporates all safety interlocks for reliable operation. The antenna system consists of one pair of crossed dipole transmitting antennas mounted on a 25 m high tower and three pairs of crossed dipole receiving antennas mounted on 8 m high towers located at the corners of an equilateral triangle of side λ with the transmitting antenna located at its centroid. Inverted `V' type dipole antennas are used for transmission and reception. The individual dipoles are oriented along magnetic north-south and eat-west directions and the required polarization is selected using polarization switches. The three identical coherent digital receivers used provide in-phase (I) and quadrature phase (Q) outputs which are used for cross correlation analysis. On-line processing of data is done using an industrial grade PC provided in the system. Digital receivers with 32 bit floating point outputs are used for the radar due to their programmability, computer compatibility, wide dynamic range and minimum temperature related and component tolerance problems. The radar is located in the TERLS area.

Conclusion

The design and development of four major atmospheric radar systems in SPL have been described. All these radar systems have been indigenously built in SPL. In addition to the expertise gained in these areas of technology this methodology has helped to make improvements and augmentations as demanded by the scientific studies with very little delay and cost. As can be seen, care has been taken to make use of the state of the art technologies in designing the experiments. Close interaction between the scientists proposing and using the data from experiments and the engineers designing and building the experiments has helped to make sure that the data from the systems are used in an optimum manner. More detailed information regarding these radar systems are contained in the following published papers and reports.

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