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A report on PRL's interplanetary scintillation (IPS) radio telescopes

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Abstract. Physical Research Laboratory has two radio telescopes operating at 103 MHz. The telescopes are situated at Thaltej and Rajkot. This article briefly describes the various sub-systems of these telescopes. There has been several interesting astronomical findings from the observations of these telescopes e.g. on cometary plasma tail, solar wind, plasma blobs and holes in the interplanetary medium and radio enhancement of a pulsar. These will also be summarized here.

Key words : radio telescopes—solar physics—interplanetary scintillation

1. Introduction

The phenomenon of interplanetary scintillation is a radio analogy of the twinkling of stars in the night sky. When radio waves from a distant compact radio source (sub-arcsecond) enter the interplanetary medium containing solar plasma irregularities, random phase deviations are imposed on the wavefront which was almost plane before entering this medium. These random phase deviated waves propagate and interfere with one another. This process causes fluctuations of radio intensity of the source as seen by an observer on Earth. This is the basic mechanism of interplanetary scintillation. As the solar plasma irregularities continuously blow across the line-of-sight, one stationary observer (with the help of a sensitive radio telescope) can record this phenomenon of interplanetary scintillation as a function of time. The radio astronomers at the Physical Research Laboratory are exploiting phenomenon for a number of scientific objectives given below :

(1) to estimate the density deviation and the scale size of the plasma irregularities in the interplanetary medium;
(2) to estimate the solar wind velocity by comparing the spatial fluctuations of the pattern as it drifts across;
(3) to estimate the angular size of radio sources in the range of 0.1-1 arcsec.

There are two large radio telescopes operating at 103 MHz at Thaltej (near Ahmedabad) and Rajkot. In fact there was one more at Surat and three telescopes were operated simultaneously and gave some results on objective (2), but Surat telescope suffered many failures due to rain, local radio interference and security. This telescope had to be abandoned and PRL radio astronomers are planning for a better site for the third telescope. We describe the IPS radio telescopes at Thaltej and Rajkot in section 2 and the main scientific results using these radio telescopes in section 3.

2. The radio telescope

Each radio telescope consists of five sub-systems : (1) Antenna arrays, (2) Preamplifiers, (3) Beamforming network, (4) Receiver and (5) Data acquisition system. Details of individual sub-systems are given below.

2.1. *Antenna arrays*

There are 64 arrays in each radio telescope. The physical collecting area of the telescope is 5,000 m^2 and 20,000 m^2 at Rajkot and Thaltej respectively. Thaltej telescope initially had a collecting area of 5,000 m^2 which was increased to 20,000 m^2 in two phases. An individual array is laid along East-West and consists of full wave dipoles separated by half wavelength. The dipoles are alternately transposed so that the signal from two dipoles add in phase. There are 16 and 64 dipoles in each array at Rajkot and Thaltej respectively. To increase the efficiency of the dipoles, there is a reflecting wire mesh at $\lambda/4$ distance below the dipoles. Figures 1(a) and (b) show a portion of Rajkot and Thaltej antenna arrays. The signal received by each dipole is collected by an open wire transmission line. The transmission line feeds to a low noise preamplifier in the field.

2.2. *Preamplifiers*

The telescope has 64 preamplifiers one for each array. These are seen in figures 1(a) and (b) in white boxes. The preamplifiers are designed with an average noise factor of 2 or less and selectively amplifies 103 MHz. Another important and desired feature of the preamplifier is their phase stability. The good phase and gain stability of the preamplifiers ensures the accuracy of beam formation (to be discussed next). For good long-term stability of phase (± 1.5°) and gain (± 0.5° db), the bandwidth of each of the preamplifier is kept at 7 MHz. The preamplifiers are housed in a special type of metal box packed with thermal and electrical insulating material.

2.3. *Beamforming network*

The signal received by each array and amplified by stable preamplifiers is carried through the underground coaxial cable to the receiver building. The arrays are divided into two groups of 32 each (North and South). For each group there is one Butler Matrix (BM). Butler Matrix is a passive device which form a pattern of 32 fan beams from the outputs of 32 arrays. Thus two sets of 32 individual beams are formed. A test set up for this system is shown in figure 2. The angular coverage of each set is about ± 30° around the zenith. The envelope of the beams has a cosine taper such that the 16th beam is nearly 3 db down with respect to the beams near the zenith.

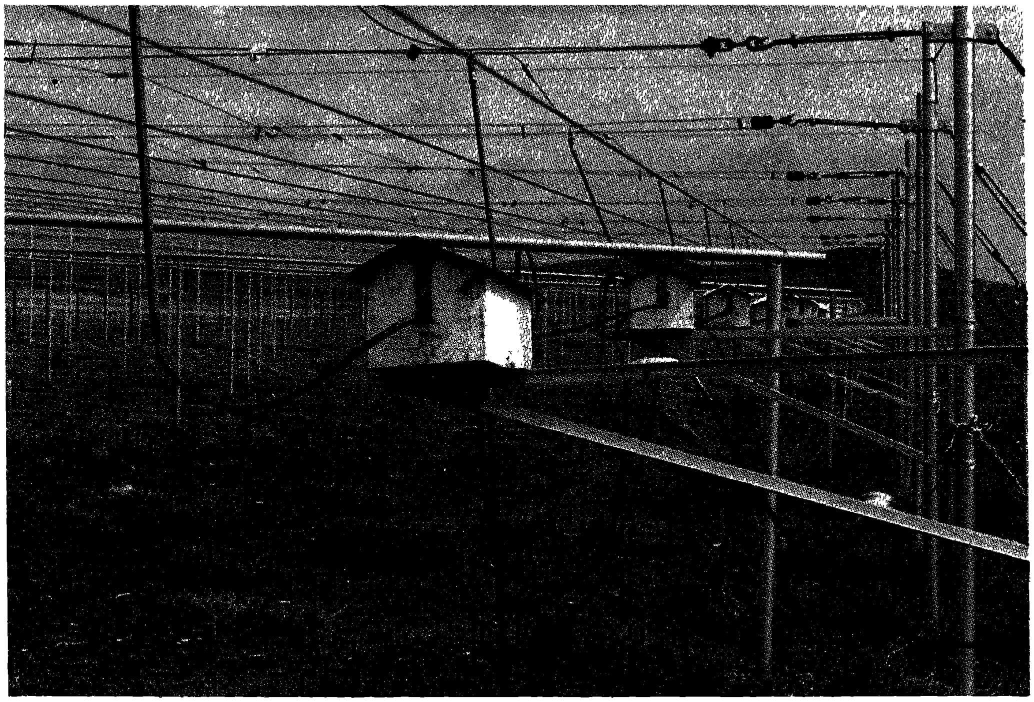

Figure 1(a). Antenna array of IPS radio telescope at Rajkot.

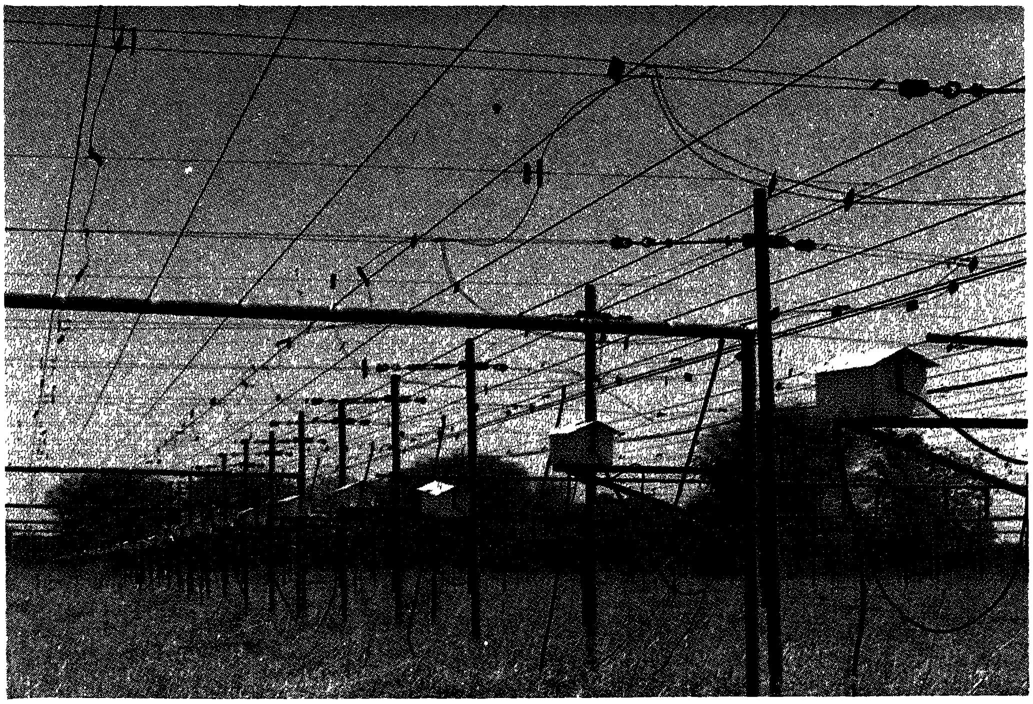

Figure 1(b). Antenna array of IPS radio telescope at Thaltej.

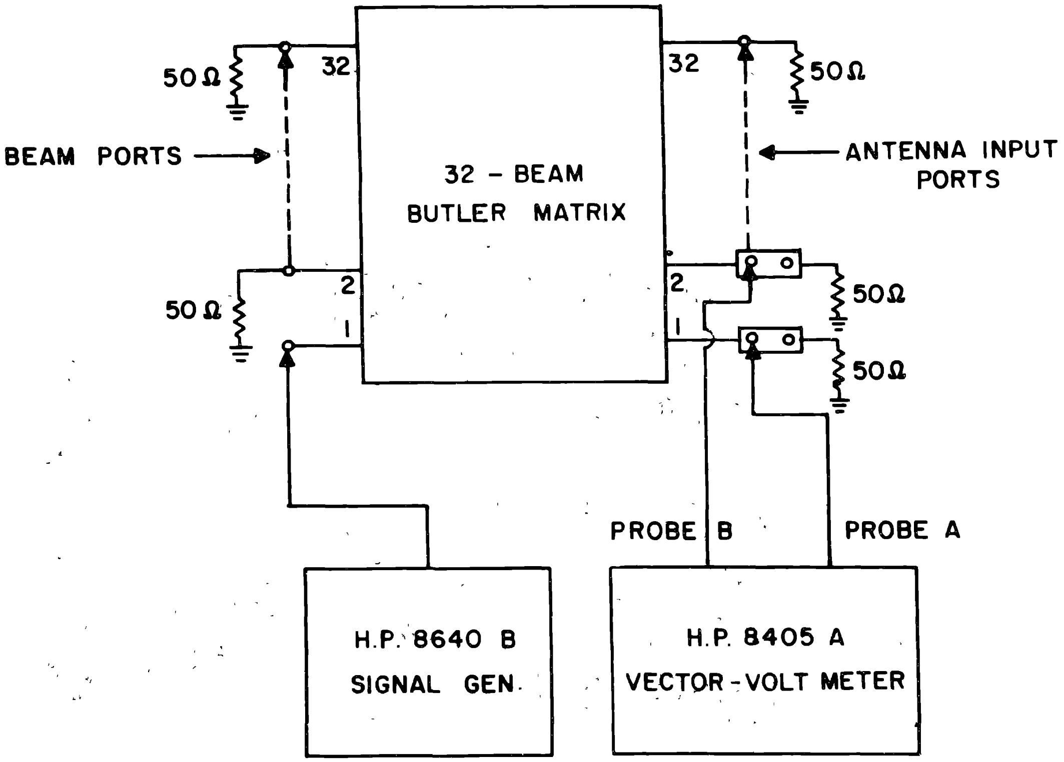

Figure 2. Experimental set up for testing Butler Matrix.

2.4. *Receiver*

The telescope is normally used in the interferometric mode. For this signal from two identical beams, one from North sub-group and the other one from South sub-group are connected to a correlation type receiver. The block diagram of receiver is shown in figure 3. In the receiver signal of 103 MHz from the two identical beams is converted to IF signal of 30 MHz with a bandwidth of about 2 MHz. These two IF outputs are multiplied. As a result time-averaged uncorrelated noise voltages produce zero dc voltage at the multiplier output. A compact radio source, however, produces correlated signal power and hence the multiplier output is proportional to the intensity of compact radio source and its temporal variation (which is mainly due to the solar plasma irregularities). The outputs of the receiver is in the form of two component Cos and Sin. Since this interferometer is in North-South, a radio source during transit stays on the same Sin and/or Cos fringe. The Fringes are shown in figure 4. A part of the Sin and Cos signals is fed to a scintillometer. This unit squares the scintillating part of the two signals and adds them, integrating over a long time constant of 47 sec. The output of this unit is proportional to square of the scintillating flux of the radio source.

2.5. *Data acquisition system*

This system consists of two parts, (1) analog recording and (2) digital recording. Analog recording in the form of three channels; Sin, Cos and scintillometer is carried on a strip chart. The main purpose of this is monitoring and preliminary data analysis. The detailed

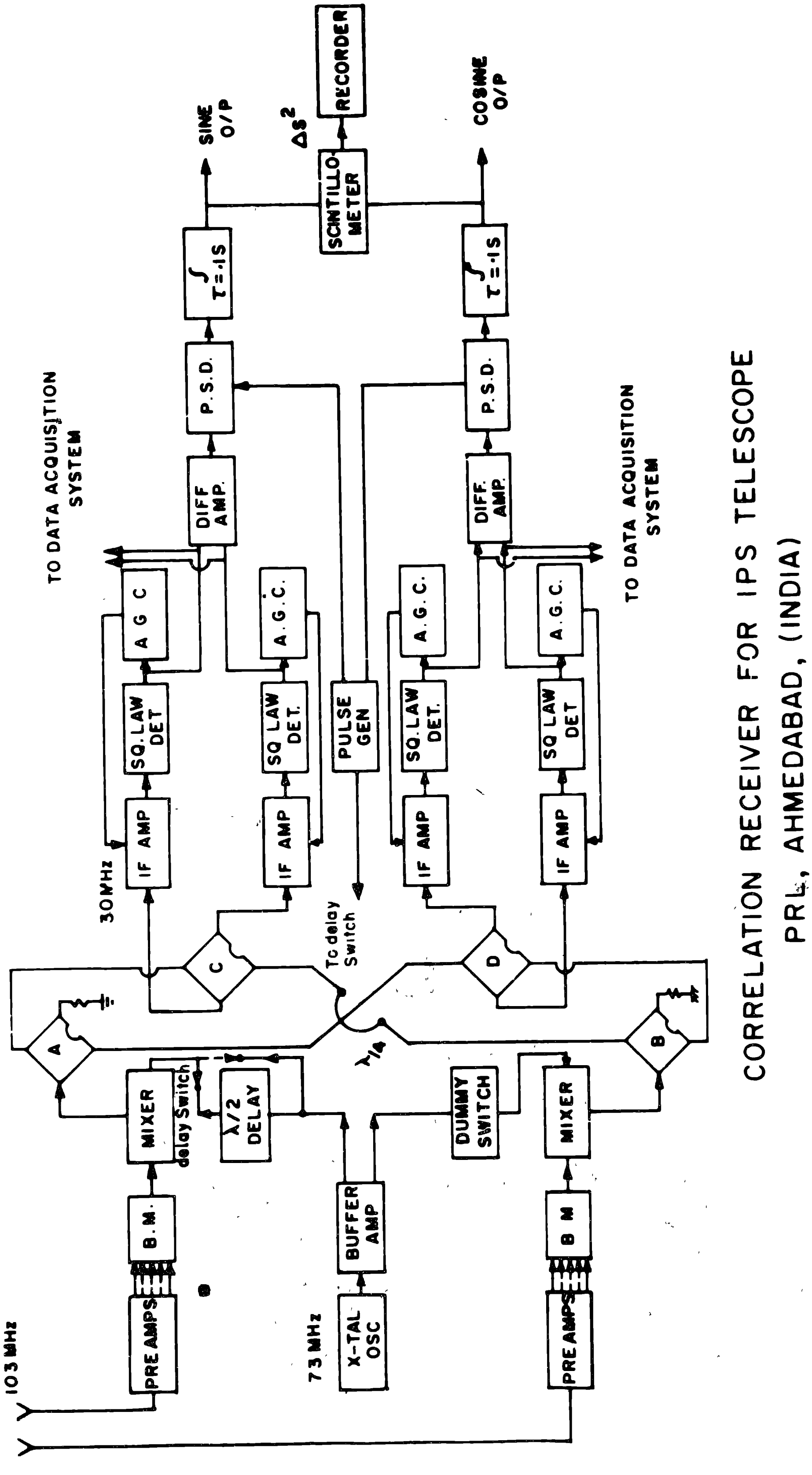

Figure 3. Block diagram of correlation receiver.

analysis of IPS data is carried out from digital data. The digital data acquisition system consists of a microprocessor-based analog to digital converter (ADC). This has a Z-80 processor, its associated memory, peripheral chips, 12 bit A/D, timer/counters, multiplexer, sample and hold. At present the sampling frequency is 20 Hz but can be varied through software and hence provides flexibility. The system is menu-driven and can be programmed

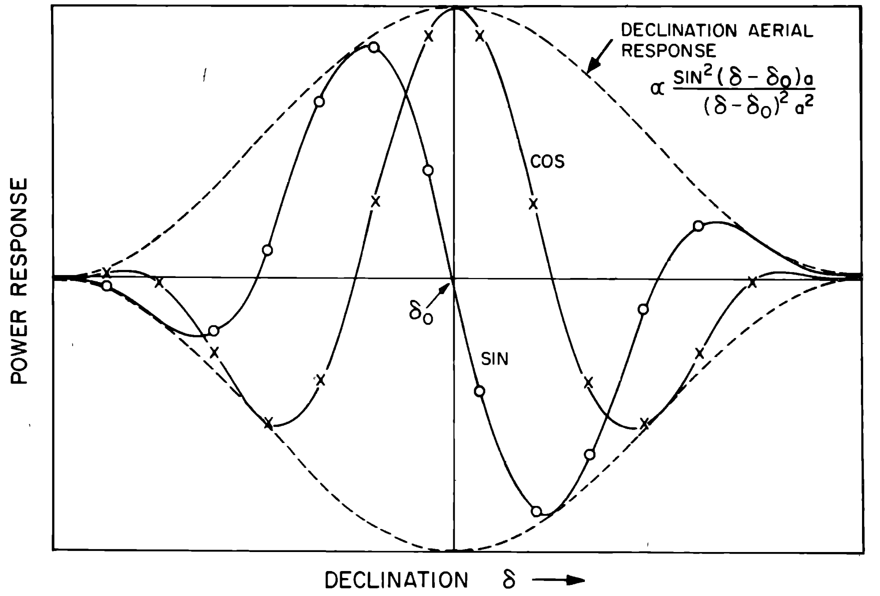

Figure 4. Fringe pattern of the radio telescope.

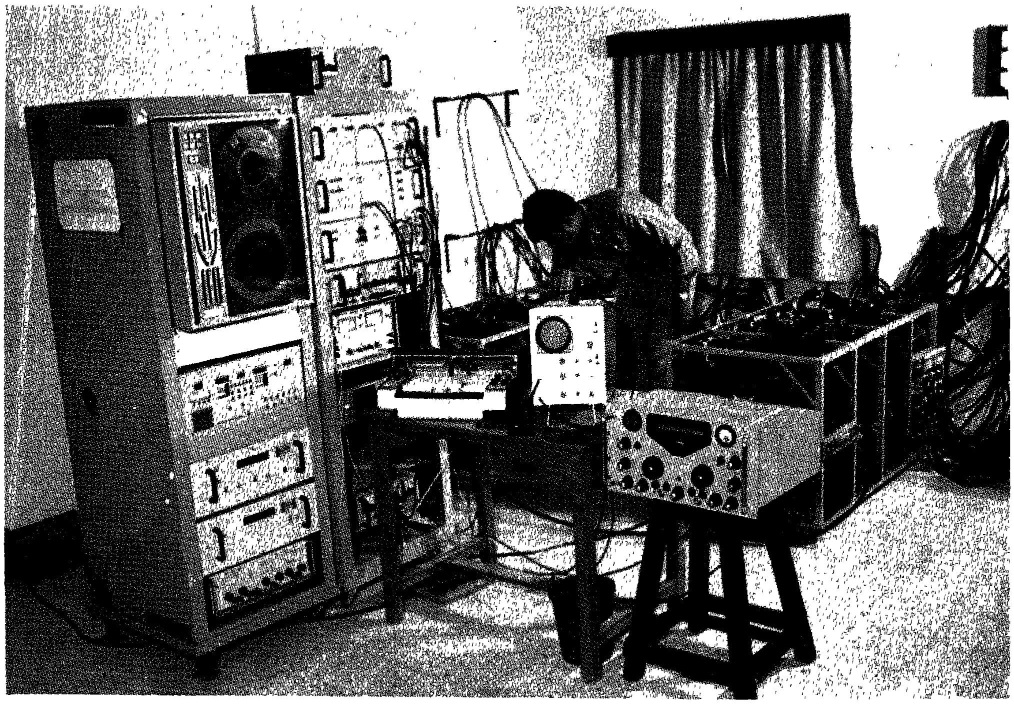

Figure 5. Receiver and data acquisition system at Rajkot.

for the observations of radio sources in advance. The system is extendable to monitor and record more channels. A view of the receiver and data acquisition system for Rajkot are shown in figure 5.

The radio telescope at Thaltej and Rajkot has been in regular use since 1983. Several scientific investigations have been carried out using IPS observations of these telescopes. Important scientific results are briefly described in the next session.

3. Important scientific results

3.1. *Occultation of a quasar by the ion tail of comet Halley/P*

Strong interplanetary scintillation (IPS) like signal fluctuations of the quasar 2314+03 were recorded, for the first time, at 103 MHz at Thaltej, Ahmedabad, on 18, 19 and 20 December 1985, as the compact radio source having 43 Jansky flux in 0.5 arcsec was predicted to be occulted by the ion tail of the comet Halley. The geocentric and heliocentric distances of the comet were about 0.9 and 1.2 AU respectively with the axis of the comet making an angle of about 66° with the true North.

On 17th, when the quasar was not yet occulted by the comet's ion tail, weak background scintillation due to solar plasma were observed. However, on 18th through 20th very strong to moderate scintillation with periodicities of 1 second (average) were observed (Alurkar *et al.* 1986). The scintillation amplitude progressively decreased as the source approached the tail-end. The values of rms flux variations of the source on 18, 19 and 20 were about 18, 11 and 4.7 Jy when the comet-earth-source angle was about 5°. In contrast, the rms flux values on the control days 17th and 21st were about 3.3 Jy for solar elongation of 87°. The measurements will help develop a model for the cometary tail plasma.

Scintillation spectra on 18th-20th resemble IPS spectra, with high cut-off frequencies around 2.0, 1.2 and 0.6 Hz respectively. Assuming Gaussian plasma density irregularities with weak scattering, the rms density variations, ΔN, from the comet nucleus towards its tail-end, vary as $(\Delta N) \propto r^{-3.5}$ for cometary cylindrical plasma as against $(\Delta N) \propto r^{-2.6}$ in the solar plasma with circular symmetry. Their values for a thickness of 10^5 kilometers of the ion tail of Halley's comet work out to be about 10, 6 and 3 electrons per cubic centimeter on 18, 19 and 20 December 1985 respectively. The plasma tail length scanned during this period works out to 1.5×10^7 km. Assuming the reported range of plasma velocity in the comet tail of 20-90 km s^{-1} the observed periodicity of 1 sec implies scale sizes of inhomogeneities in the range of 20-90 km. Modulations at 2.5 min period of the scintillating flux were observed. These were attributed to possible irregular refractive effects caused by plasma density inhomogeneities of scale size 10^4 km travelling at 100 km s^{-1} in the cometary tail.

Radio Astronomers at Ooty observed occultation of three radio sources by the Halley's comet during February-April 1986. They failed to observe enhancements of scintillation attributable to the comet (Ananthakrishnan *et al.* 1987). Hajivassiliou and Duffett-Smith (1987) analysed their IPS data at 81.5 MHz collected during 1978-81, when a survey of about 2000 scintillating sources was made. They reported no convincing evidence of enhanced scintillation during the occultations.

In our critical analysis of the observations of Ooty and Cambridge, we have shown why the Ooty astronomers failed to observe the enhancement of scintillation. This was due to the fact that the occultation occurred very close to the perihelion, thereby only observing strong scintillation of the solar wind, since the Sun was only 10° away from the line of sight. Also during two of their occultations, the plasma tail of the Halley's Comet was affected by disconnection events and hence no fully developed tail was available for occultation. In the Cambridge work, their comets were very weak and they had no report on Cometary tails. Also due to very short observing time (2 min) for each source, there was 58% chance of missing the occultation event. On the other hand, the observing geometry as well as the strength of the Halley's plasma tail were very favourable during our observations at 103 MHz in December 1985 (Sharma 1992). We, therefore, concluded that the enhanced scintillations observed by us were genuinely produced by the Halley's plasma tail.

3.2. *Spectral analysis of enhanced IPS of 3C 459 caused by Comet Halley*

A critical look at the observations of enhanced scintillation of quasar 3C 459 during its occultation on 16-21 December 1985 yielded interesting results. Assuming a linear increase of the ion velocities in the cometary tail from 100 km s^{-1} at the tail axis to 400 km s^{-1} at the edges where the tail merges with the normal solar wind, power spectral analysis of the scintillation shows a range of rms electron density variations and their scale sizes. From about 3-6 cm^{-3} and 10-30 km respectively near the axis they change to 0.6 to 2 cm^{-3} and 100-270 km near the edges of the tail.

The IPS spectra on consecutive days during the period 16-21 December 1985 indicate systematic shift of the peak of the power spectra at 0.16, 0.34, 0.24 and 0.16 Hz on 16/17, 18, 19 and 20/21 respectively. The tail-lag played a very crucial role in deciding the correct occulting geometry and path of the source through the tail (Janardhan *et al.* 1992).

3.3. *Enhanced radio source scintillation due to Comet Austin (1989 cl)*

Enhanced scintillation of quasar 2204+29 (3C 441) were observed with the Thaltej telescope at 103 MHz when the ion-tail of comet Austin swept across the source. Comparison with earlier observations of comet Halley at 103, 327 and 408 MHz and of comet Wilson at 408 MHz underscored the importance of the relative positions of the source, comet, Sun and the observer. During the occultation by comet Austin the scintillation index increased by a factor of 3 over that expected for 3C 441. The rms electron density at 0.9 AU from the Sun 7.3° downstream of the nucleus was 6 cm^{-3} whereas that for the normal solar wind at 1 AU is 1 cm^{-3} (Janardhan *et al.* 1991). The corresponding scale sizes of plasma turbulence were much finer than normally found in IPS due to solar wind.

3.4. *Plasma blobs and holes*

Using the Thaltej radio telescope operating at 103 MHz, we make observations of several compact radio sources. Since the telescope is a transit instrument, a radio source stays at the fixed location on a beam during the observations. One of the compact radio sources, 3C 298, happens to be at a maximum of the antenna beam used for its observations. These observations are regularly made since 1983. Following remarks can be made on the careful investigations of these observations.

The COS channel always has a positive deflection, whereas deflection on SIN channel shows a marked variation, namely, on some days it is positive, on other days it is negative and in addition, there are days on which no deflection is seen on this channel (SIN channel).

The positive deflection on SIN channel could be explained by the presence of a large plasma blob on the radio path (Vats 1986). The negative deflection on SIN similarly is due to the presence of a large plasma hole on the radio path. When there is no deflection on SIN channel, no large plasma blob or hole exists on the radio path.

These plasma blobs and holes have a physical dimension of 10^5 km or so (Alurkar *et al.* 1985). Because of large dimension, these do not contribute significantly in the process of scattering of radio waves of the compact radio sources; instead they tilt the passing wavefront. The origin of these blobs and holes is yet not understood. We calculated the magnitude of angular refraction which is found to be several arc minutes. This angular refraction means that the plasma density deviations in the blobs and holes could be up to about 10%.

3.5. *Source diameter measurements and interstellar scattering (ISS)*

A consequence of 100-1000 km scale size rms density variations speeding at 400 km s^{-1} through the IPM is that the IPS phenomenon occurs in the case of compact radio galaxies with angular sizes in the range of about 0.1 to 1 arcsec. This fact can be used around to estimate angular diameters of scintillating radio sources. Diameters of 14 radio galaxies were measured at 103 MHz using IPS observations made with the 10,000 m^2 Thaltej radio telescope between mid-1984 and end of 1987 (Janardhan & Alurkar 1992). This was done by studying the variation of scintillation index as a function of solar elongation and assuming a spherically symmetric model of the solar atmosphere with Gaussian density irregularities. The results agreed well with those available at other frequencies and with VLBI measurements.

Using the measured diameters at 103 MHz and those available at 151.5 MHz, the interstellar scattering (ISS) at 103 MHz was estimated to be (0.07 ± 0.01). The effect of ISS is to broaden a radio source. This sets a limit to high resolution observations or to the minimum detectable source diameter.

3.6. *Solar wind measurements for the period 1984-90*

There is now widespread evidence of the existence of solar wind, although gusty and variable, blows continuously from the solar corona into the interplanetary space. There are two basic approaches for the measurement of solar wind velocity, namely, *insitu* measurements by satellite and space probes and indirect measurements by radio astronomical observations of the phenomenon of interplanetary scintillation (IPS). The former, provides measurements only near the earth i.e. in the ecliptic plane whereas the later method provides good spatial coverage both in and out of ecliptic plane. Radio astronomical observations of IPS using the Thaltej radio telescope were mainly used to estimate solar wind velocity and to make its maps (called V-maps).

Intensive observations of several compact radio sources using an array radio telescope operating at 103 MHz were made at Thaltej since 1984. Recently a method for determining the solar wind velocity using single station interplanetary scintillation observations has been developed (Manoharan & Ananthakrishnan, 1990). Using this method we analysed data for the period 1984-1990 and prepared velocity maps (V-maps). These maps are made by back projecting the observed velocity using the expression shown below :

$$\phi - \phi_0 = R\omega/V$$

where ϕ is the heliolongitude of the point of closest approach (at a distance R from the Sun) at which the solar wind V is measured, ω is the angular solar rotation velocity and ϕ_0 is heliolongitude from which the observed solar plasma must have emanated. The heliolongitude (ϕ_0) for each observation during a year is converted into a Carrington longitude and the 'V-maps are prepared for each year.

An attempt was made to study these observed velocity maps in terms of the evolution of the solar corona as well as the neutral magnetic line structures which strongly depends on the solar activity cycle. Almost all high speed regions correspond to the coronal holes and low-speed regions appear in the vicinity of the neutral magnetic lines (Alurkar *et al.* 1993). During solar minimum (1986) very low-speed is seen to emanate from the giant bipolar magnetic regions (GBMR) derived from line of sight (LOS) component of the photospheric magnetic field.

3.7. *Sudden burst from PSR 0950+08*

PSR 0950+08 is an old pulsar ($10^{7.2}$ years) having average flux ~3 Jy. This pulsar happen to be observed about 17 minutes before the transit of a regular IPS source 3C 237. On most occasions either no trace of pulses or few very weak pulses were recorded from the pulsar during its transit. On July 29, 1992, the pulsar suddenly bursted and very strong pulses were seen by both the radio telescopes (at Rajkot and Thaltej). The average enhancement in pulsation activity of this pulsar is around 80 times during this event and several pulses exceeded 850 Jy which is exceedingly large (Deshpande *et al.* 1993). The examination of ionogram of Ahmedabad (ionosonde is only 6 km away from Thaltej radio telescope) did not show the presence of plasma irregularities in the E and F regions of the ionosphere. However the ionograms showed strong non-deviative absorption of HF radio waves. There occurred three absorption peaks of these one peak coincided with the local transit of the pulsar and the observation of enhanced radio intensity at 103 MHz. Thus we believe that during this event pulsar gave enhanced radio pulses as well as X-rays (of large magnitude) which produced excess ionisation in the D region of the ionosphere (Vats *et al.* 1993). The detailed calculations show that a comet like object possibly was accreted by PSR 0950+08 during this event. The accretion produced sudden enhancement of radio and X-ray emission from the pulsar. This work requires further experimental and theoretical investigations of such objects.

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