Long-Term Scintillation Studies of Pulsars: I. Observations and Basic Results

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ABSTRACT

We report long-term scintillation observations of 18 pulsars in the dispersion measure range $3 - 35$ pc cm$^{-3}$ carried out from 1993 January to 1995 August using the Ooty Radio Telescope at 327 MHz. These observations were made with the aim of studying refractive effects in pulsar scintillation, and obtaining reliable estimates of diffractive and refractive scintillation properties. Dynamic scintillation spectra of pulsars were regularly monitored at $10 - 90$ epochs spanning $100 - 1000$ days. Significant changes are observed in the dynamic spectra over time scales as short as a few days. Large-amplitude fluctuations are observed in quantities such as decorrelation bandwidth, scintillation time scale, drift rate, and flux density. Several pulsars show organized features such as drifting bands in a highly pronounced manner. For some pulsars, gradual and systematic variations are seen in the drift rate of patterns which undergo several sign reversals during the observing time spans. Anomalous behaviour such as persistent drifts lasting over many months are seen for PSRs B0834+06 and B1919+21. Four pulsars were studied for $2 - 4$ well separated observing sessions, each lasting over $\sim 100$ days. In some cases, significant variations are seen in the average scintillation properties and/or flux densities between successive observing sessions. From our data, we have been able to obtain more accurate and reliable estimates of scintillation properties and flux densities than those from the earlier observations, by averaging out the fluctuations due to refractive scintillation effects. These measurements are used to derive parameters such as the strength of scattering and scintillation speeds. The scintillation speed estimates are found to be reasonably good indicators of proper motion speeds of pulsars. The present measurements are compared with earlier measurements and the long-term stability of scintillation properties and flux densities is discussed.

Subject headings: ISM:Structure – Pulsars:General – ISM:General – Scattering
1. Introduction

There are several classes of pulsar intensity variations seen at radio wavelengths. The large-amplitude, broadband, pulse-to-pulse variations seen for most pulsars are thought to be intrinsic to the pulsar emission mechanism. When averaged over many pulses to smooth out these variations, pulsar intensities show fluctuations occurring over time scales ranging from minutes to hours, which are explained in terms of propagation of radio waves through the irregular interstellar plasma (Scheuer 1968; Rickett 1969). Random variations of electron densities in the interstellar medium (ISM) give rise to phase perturbations, leading to scattering of radio waves. As they propagate, the scattered waves interfere with each other causing large variations of amplitude with frequency and position. The relative motion between the pulsar, observer and the density irregularities translates the spatial amplitude variations into temporal variations at a given position, leading to a typical time scale of intensity fading — called the scintillation time scale. Other observable consequences of this phenomenon are broadening of pulse profiles and angular broadening of compact radio sources at low frequencies. Observations of pulsar dynamic spectra (e.g. Roberts & Ables 1982; Smith & Wright 1985), which are records of intensity variations in the time-frequency plane, reveal that such intensity variations are fairly narrow band — decorrelation bandwidths \( \sim 100 \text{ kHz} \) to a few MHz — and exhibit modulations as large as 100%. This phenomenon, which has become known as Diffractive Interstellar Scintillation (DISS), has been extensively studied since the early days of pulsar observations and is quite well understood (see Rickett (1977) for a review). DISS studies have been used for probing the structure of electron density inhomogeneities in the ISM (e.g. Cordes, Weisberg & Boriakoff 1985; Armstrong, Rickett & Spangler 1995) and to estimate pulsar velocities (e.g. Cordes 1986).

The discovery of long time scale (\( \sim \) days to months) flux variations (e.g. Cole, Hesse & Page 1970; Huguenin, Taylor & Helfand 1973) and the subsequent correlation of these time scales with dispersion measure (DM) (Sieber 1982) led to the recognition of a second class of propagation effects (Rickett, Coles & Bourgois 1984), which has become known as Refractive Interstellar Scintillation (RISS). In RISS, flux variations arise due to focusing and defocusing of the scattered radiation by electron density irregularities that are large compared to the Fresnel scale. These modulations are fairly broadband in nature. Refraction through the large-scale density structures also produces the systematic “drifting patterns” that are often seen in pulsar dynamic spectra (e.g. Smith & Wright 1985; Hewish 1980). RISS is also thought to be responsible for the occasional occurrences of quasi-periodic intensity modulations in the dynamic spectra (e.g. Wolszczan & Cordes 1987; Hewish, Wolszczan & Graham 1985). RISS is also the preferred explanation for
other observed phenomena like slow flux variability at metre wavelengths (e.g. Rickett 1986), centi-metre wavelength “flickering” and discrete propagation events (e.g. Fiedler et al. 1987) see with compact extra-galactic radio (EGR) sources (see Rickett (1990) for a review). Besides flux modulations, RISS is also thought to produce slow modulations of decorrelation bandwidth and scintillation time scale. It has been suggested that the large irregularities responsible for RISS are part of the same spectrum of irregularities which give rise to DISS (Rickett et al. 1984), and studies of both phenomena provide us information on the spectrum over a very large range of spatial scales (several decades). While it is generally considered to be of a power-law form over the spatial scales of interest for ISS, the exact form of the spectrum, especially the slope, cutoffs, and above all, the validity of a simple power-law description, still remain to be well understood (cf. Narayan 1988; Rickett 1990; Armstrong et al. 1995).

On the theoretical front, several researchers have addressed the problem of DISS and RISS in terms of small-scale ($\sim 10^6$ to $10^8$ m) and large-scale ($\sim 10^{10}$ to $10^{12}$ m) electron density fluctuations producing two distinct regimes of scintillations (Rickett et al. 1984; Cordes, Pidwerbetsky & Lovelace 1986; Romani, Narayan & Blandford 1986). Besides predicting the long-term flux variations that characterize RISS, these models make predictions about the nature and levels of fluctuations for observables such as decorrelation bandwidth, scintillation time scale and the drift rates of intensity patterns in pulsar dynamic spectra. In the case of power-law models for the density irregularities, the refractive effects are expected to depend on the slope of the spectrum. For example, the magnitude of the fluctuations of all the above parameters is predicted to increase substantially with the slope (Romani et al. 1986, Blandford & Narayan 1985).

On the observational front, significant work has been done to measure the long-term flux modulations of several pulsars (Stinebring & Condon 1990; Kaspi & Stinebring 1992; Gupta, Rickett & Coles 1993; LaBrecque, Rankin & Cordes 1994). The results show that, for several pulsars, the measured flux modulation indices are larger than those predicted by the simple Kolmogorov model, indicating that the underlying density spectrum may be more complicated. Not much is known about the time scales and the magnitude of the flux variation due to RISS and of other scintillation variables like decorrelation bandwidth and scintillation time scale. A recent study of the long-term variations in pulsar dynamic spectra (Gupta, Rickett & Lyne 1994) has shown that the properties of scintillation patterns of several pulsars vary considerably with time, and to a first order, these variations were found to be consistent with expectations from RISS. However, several discrepancies with the predictions of a Kolmogorov model were also observed in these data. Observations also show occurrences of unusual scattering effects such as episodes of multiple imaging and extreme scattering events (ESE), which are thought to be due to refraction by discrete
structures in the ISM (e.g. Cordes & Wolszczan 1986; Fiedler et al. 1987). Most ESEs have been with EGR sources (Fiedler et al. 1994), and the only pulsar that is reported to have shown ESEs (in the form of unusual flux variations and timing perturbations) is PSR B1937+21 (Cognard et al. 1993; Lestrade, Rickett & Cognard 1998). More recently, there have been a couple of attempts to test the quantitative predictions of theories and for two pulsars (PSRs B0329+54, B1937+214), the correlations between the fluctuations of scintillation observables were found to be consistent with the predictions (Lestrade, Cognard & Biraud 1995; Stinebring, Faison & McKinnon 1996). However, the results are not conclusive and there is a need for more observations of this kind, which is one of the motivations for the observations described in this paper.

The fluctuations of the flux and the DISS parameters caused by refractive scintillation lead to unreliable estimates of flux densities, scattering properties and pulsar velocities, if obtained from only a few epochs of observations. In order to get reliable estimates of these quantities, the refractive fluctuations need to be averaged out by taking measurements at a large number of epochs spanning several refractive time scales. The time scales of the fluctuations due to RISS, largely determined by the strength of scattering and the pulsar velocity, can range from a few days (for nearby pulsars at metre wavelengths) to several years (in the case of distant pulsars at longer wavelengths). Most scintillation measurements made earlier (Roberts & Ables 1982; Cordes et al. 1985; Smith & Wright 1985; Cordes 1986) could not take into consideration such effects (probably due to limited observing time), and the scattering properties derived from such measurements are prone to errors due to refractive scintillation. For example, in the published literature, estimates of decorrelation bandwidth and time by different observers differ by factors of three to five. A second motivation of the present work is to examine whether such discrepancies are attributable to RISS and to make a better determination of the scintillation parameters.

In order to investigate refractive scintillation effects and to obtain reliable estimates of scintillation properties of nearby pulsars, we undertook long-term systematic scintillation observations of eighteen pulsars using the Ooty Radio Telescope during 1993–1995. Our observations and measurements of the scintillation properties are presented in this paper (referred to as Paper I). In Paper II (Refractive effects and the spectrum of plasma density fluctuations), we use our results to constrain the electron density spectrum in the local ISM. In Paper III (Testing theoretical models of refractive scintillation), we compare our results with existing theoretical models of RISS. In an earlier paper (Bhat, Gupta & Rao 1998), we have used our improved estimates of the average scintillation properties of several local pulsars to show that the distribution of scattering material in the local ISM is not homogeneous and that it supports the presence of the Local Bubble.
The layout for the rest of this paper is as follows. Our observations are described in Section 2. A description of the data analysis methods is given in Section 3, where we also present results on the diffractive and refractive scintillation properties. We discuss the reliability of the present measurements in Section 4, where we also compare the present measurements with those from earlier observations and address the issue of long-term stability of scintillation properties and pulsar fluxes. Section 5 gives a summary of our main conclusions from this work.

2. Observations

2.1. Instrument and Data Acquisition

The observations were made using the Ooty Radio Telescope (ORT), which is an equatorially mounted 530 m x 30 m parabolic cylinder operating at 327 MHz (Swarup et al. 1971). The telescope has an effective collecting area of 8000 m$^2$, system temperature of 150 K and is sensitive to linearly polarized radiation with electric field in the North-South plane. It has 9\$^{\frac{1}{2}}\$ hours of hour angle coverage and a declination coverage from $-55^\circ$ to $+55^\circ$. The ORT is a phased array, with 1056 dipoles at its feed, which was upgraded recently giving considerable improvement in sensitivity and stability (Selvanayagam et al. 1993). With the current sensitivity, a signal-to-noise ratio of 25 can be achieved for a 1 Jy source, for 1 sec integration and over a bandwidth of 4 MHz. The signals from the dipole array are combined to form two signals from the North and South halves of the telescope. These are input to a 1-bit correlation spectrometer (Subramanian 1989) to yield the cross power spectrum of the signals from the two halves. For our experiment, pulsar data were taken over a bandwidth of 9 MHz centered at 327 MHz. The data were obtained such that there are 64 frequency channels in the cross spectrum spanning the observing bandwidth, yielding a frequency resolution $\approx 140$ kHz.

Pulsar data were acquired with a sampling interval of 6 msecs. The data were recorded both on the pulse and also on part of the off pulse regions. The gated on pulse and off pulse regions were synchronously averaged in the correlation domain over a specified number of pulse periods and then recorded for off-line analysis. A continuum source at a declination close to that of the pulsar being studied was observed for calibration. The data from the calibrator were acquired for typical durations of 5 minutes and an equal stretch of data were acquired by pointing the telescope to a cold region of the sky. The calibration observations were generally made before starting the pulsar observations. A suitable calibrator was chosen for each pulsar so as to eliminate any possible bias in the flux calibration. The data from several calibrators taken on a given observing day were also used to monitor the
stability of the telescope gain over the observing periods.

### 2.2. Sample Selection

Our sample selection was made with the two-fold aim of (i) studying diffractive and refractive scintillations, and (ii) obtaining reliable estimates of scattering properties of nearby (distance \( \lesssim 1 \, \text{kpc} \)) pulsars. It was largely determined by our preliminary calculations of expected scintillation parameters based on the earlier scintillation measurements available from the literature and the instrumental constraints. For the pulsars that were known at the time of our observations, with DM \( < 40 \, \text{pc cm}^{-3} \) and within the sky coverage of ORT, the expected values of decorrelation widths in frequency (\( \Delta \nu_{\text{iss}} \)) and in time (\( \tau_{\text{iss}} \)) were calculated from published results, assuming the scaling laws for a Kolmogorov density spectrum (\( \Delta \nu_{\text{iss}} \propto f_{\text{obs}}^{4.4}, \tau_{\text{iss}} \propto f_{\text{obs}}^{1.2} \)). Pulsars whose scintillation patterns could be studied with a frequency resolution of 140 kHz over a 9 MHz band were selected. The temporal resolution required to resolve the scintillation patterns in time is typically 10 secs at 327 MHz. In order to have sufficient signal to noise with this integration time, we included in our sample only those pulsars whose flux at 327 MHz was greater than 25 mJy (\( S_{400} \gtrsim 20 \, \text{mJy} \)). The minimum integration time with the correlation spectrometer being 6 msecs, we eliminated from our sample short period pulsars (period \( \lesssim 100 \, \text{msecs} \)). We also left out pulsars that are known to show intrinsic intensity variations (such as nulling) over time scales comparable to that of ISS. Pulsars for which no prior scintillation measurements were available, but satisfied our selection criteria of DM, flux and period, were retained in the sample. The final sample consisted of 18 pulsars in a DM range 5 to 35 \, \text{pc cm}^{-3} , which are listed in Table 1 along with relevant observational details. Pulsar names are listed in column (2) and their DMs in column (3). Distance estimates adopted in our calculations (column (4)) are based on the electron density distribution given by Taylor & Cordes (1993), except for PSR B0823+26, for which we use the independent distance estimate available from parallax measurements (Gwinn et al. 1986). The period of observation and the total number of epochs of observation are given in columns (5) and (6). The instrumental resolutions in frequency and time used for each pulsar are listed in columns (7) and (8). The pulsar sample spans the DM range fairly uniformly and therefore allows us to study variations of diffractive and refractive properties over a range of DM, distance and strength of scattering.
2.3. Observing Strategy

Each pulsar was observed at several epochs spanning many months. For accurate estimates of diffractive scintillation parameters at each epoch, observations need to be made over a time duration much larger than the characteristic time scales \( (t_{\text{obs}} \gg \tau_{\text{iss}}) \) and over bandwidths much larger than characteristic frequency widths \( (B_{\text{obs}} \gg \Delta\nu_{\text{iss}}) \) of patterns. Since we had a fixed observing bandwidth of 9 MHz, pulsars which were expected to have large decorrelation bandwidths \( (\Delta\nu_{\text{iss}} \sim \text{MHz}) \) or decorrelation times \( (\tau_{\text{iss}} \sim 1000 \text{ secs}) \) were observed for longer durations (typically \( \sim 2-3 \) hours) in order to ensure sufficiently large number of scintles needed to obtain good ensemble averages of scintillation properties. Pulsars with relatively shorter decorrelation widths either in time or in frequency, were observed for shorter durations of about \( 1-2 \) hours. For refractive scintillation studies, dynamic spectra need to be monitored regularly for time spans much longer than their typical refractive time scales, with several observations within the time scale. We estimated the expected values of refractive time scales \( (\tau_{r,\text{exp}}) \) using the diffractive time scales available in the literature in order to decide the initial observing strategies for individual pulsars. The values of \( \tau_{r,\text{exp}} \) are given in column (9) of Table 1. Since these time scales range from days to weeks, observations were made over time spans of about \( \sim 100 \) days to ensure a sufficiently large number of refractive cycles of fluctuations. The final strategies in terms of number of epochs and their separations were largely influenced by the results from our own early observations.

Our final data are from four observing sessions during January 1993 to August 1995, with each session lasting over a period of 100 to 150 days. In every observing session, 6 to 8 pulsars were regularly monitored for their dynamic spectra. The number of epochs of observations \( (N_{\text{ep}}) \) has a wide range from 9 to 93, the reasons for which are as follows. Ten pulsars, with \( N_{\text{ep}} \geq 20 \), were primarily observed for studying the refractive effects in dynamic spectra, while for the remaining nine, our basic aim was to obtain reliable estimates of scintillation properties for the purpose of studying the Local Interstellar Medium. Four pulsars were re-observed in multiple sessions due to interesting scintillation properties observed during the initial sessions. In Table 2, column (3) gives the number of observing sessions \( (N_{\text{sess}}) \) for each pulsar. In columns (4)–(7), the break up of number of epochs for each session is given, where the quantity shown in brackets is the time span of observation in days. The total time span of observation \( (T_{\text{sp,max}}) \) is given in column (8). Pulsars PSR B0823+26 and PSR B1919+21 were observed over two sessions, the former due to unusual flux variations that were seen and the latter due to the presence of persistent drift slopes. The basic interest in the case of PSR B1133+16, which was observed for three sessions, was the dramatic changes observed in the characteristics of its scintillation patterns. Pulsar
PSR B0834+06 was observed for the largest time span of observation (four sessions) to study persistent drift slopes seen in its dynamic spectra. The data of these four pulsars also proved to be useful in investigating the long-term stability of both diffractive and refractive scintillation properties over time scales much longer than their refractive time scales.

3. Data Analysis and Results

3.1. Data Reduction Procedure

3.1.1. The Dynamic Scintillation Spectra

To calibrate the pulsar data, data were acquired both on a nearby calibration source and on a cold region of the sky. This data were used to estimate the gain of the telescope at the declination of the pulsar and to determine the bandpass of the correlation receiver. For most observations, frequency channels beyond the 3 dB range (about 7 MHz) were not used. The off-source data were examined for bad channels and line interference which were flagged for the pulsar data.

Pulsar data from the correlation spectrometer were edited for occurrences of instrumental malfunctions. The data were calibrated for the telescope gain as well as gain variations across the observing band. The data were de-dispersed, examined for any systematic pulse drifts due to instrumental effects which were corrected if detected. An integrated profile was obtained by averaging the pulsar data over the entire observing duration and over the usable range of the observing bandwidth. The on-pulse region was identified using a 5-σ (where σ is the rms of the off pulse region) threshold criterion above the mean off-pulse level. The mean off-level was subtracted from the corresponding on-pulse region and the dynamic spectrum was obtained by integrating this over the on-pulse time bins. A similar spectrum was created for the average value of the off-pulse region, which was used to detect regions of dynamic spectra corrupted by external interference. The data were checked for both narrow-band and broad-band spurious signals, lasting over very short durations to the entire observing time, and the corrupted data regions were given zero weights in the further analysis. The fraction of the data rejected in this manner seldom exceeds a few percent. The pulsar flux density (F), averaged over the bandwidth and duration of the observations and the intensity modulation index ($m_d$) were computed from the on-pulse dynamic spectra.
3.1.2. The Computation of Auto-covariance Functions

In order to quantify the average characteristics of scintillation patterns at any epoch, we make use of the two-dimensional auto co-variance function (2-D ACF), which was computed for frequency lags up to half the observing bandwidth and for time lag up to half the observing time. The function was corrected for the effect of receiver noise fluctuations and the residual, intrinsic pulse-to-pulse fluctuations, which remain uncorrelated and appear as a ‘ridge-like’ feature at zero time lag in the 2-D ACF. We computed a weight function for the 2-D ACF which represents the uncertainties in the ACF values and is given by

\[ \omega_d(\nu, \tau) = \sigma_n \left( \frac{N(\nu = 0, \tau = 0)}{N(\nu, \tau)} \right)^{0.5} \] (1)

where \( \nu \) and \( \tau \) are the frequency and time lags. \( N(\nu, \tau) \) is the number of data pairs averaged in computing the ACF value at \((\nu, \tau)\). The quantity \( \sigma_n \) represents the rms noise in the ACF at \( \nu = 0 \) and \( \tau = 0 \), and was computed from the region of the ACF where interstellar features are absent. This weight function was used while fitting the 2-D ACF with suitable functions.

3.2. Description of Data

Sample dynamic spectra are shown in Figs. 1(a)−1(h) and in Figs. 3(a)−3(m). These spectra have been selected to illustrate the general characteristics of pulsar scintillation as well as to highlight the observed variations from pulsar to pulsar and also from epoch to epoch. In Figs. 1(a)−1(h), there are a number of panels, each displaying the spectrum at a given epoch. Multiple panels are shown mainly to highlight the changing form of dynamic spectra with time. The observing durations are typically 2−3 hours, but often the displays have been restricted to shorter durations (∼100 minutes), as this is sufficient to illustrate the basic features. Most data have resolutions of 140 kHz in frequency and 10 secs in time. The date of observation is indicated at the top right corner of each panel and the mean flux density for each epoch is shown at the top left corner. In the gray-scale representation of the intensity, darker regions correspond to higher intensity values and lighter regions to lower values. The display saturates to black at four times the mean intensity and white regions are usually at about 20% of the mean. There are bright intensity regions, usually known as scintles, which are resolvable when their widths in frequency and time are larger than the instrumental resolution. A typical spectrum consists of a large number of such scintles of varying intensity, shape and widths. Such random, deep modulations of intensities, occurring over narrow frequency ranges and short time intervals are general features of all
spectra. Various time dependent instrumental problems as well as external broad band interference that have been identified and blanked out in our data reduction process appear as vertical white regions that are distinguishable from regions of real flux fading by their sharp boundaries. The horizontal white strips seen in some of the spectra (for example in Figs. 1.b and 1.g, ie., pulsars PSR B0834 + 06(I) and PSR B1919 + 21(I) ) are regions of the data corrupted by narrow band interferences. However, as seen in the figures, only a very small fraction of the data is corrupted by such spurious signals and therefore this does not affect the estimation of the scintillation parameters.

Sample ACFs of some selected pulsars are displayed in Figs. 2(a)−2(c), to illustrate the general characteristics of ACFs and to highlight the special features seen with some of the pulsars. Each figure has a number of panels representing the ACF of the dynamic spectrum obtained on the observing day indicated at the top of the panel. The displays are restricted to much smaller ranges in frequency and time lags than the maximum lag ranges for which the ACFs have been computed.

The sample data shown here (Figs. 1, 2 and 3) illustrate the diversity seen in the pulsar dynamic spectra. The properties of patterns, such as their sizes and shapes in the time-frequency plane, vary significantly from pulsar to pulsar. The widths of intensity patterns vary from \( \sim 100 \) secs (e.g. PSR B0823+26, PSR B0919+06, PSR B2045−16) to as large as \( \sim 1000 \) secs (e.g. PSR B1604−00, PSR B2016+28) in time and from \( \sim 100 \) kHz (e.g. PSR B0329+54, PSR B1540−06, PSR B2310+42) to several MHz (e.g. PSR B1133+16, PSR B1237+25, PSR B1929+10) in frequency. Organized drifting of scintles in the frequency-time plane is seen in the dynamic spectra of several pulsars. The data of PSR B0834+06, PSR B1133+16, PSR B1919+21 and PSR B2045−16 are some of the best examples with prominent drifting patterns.

The changing form of dynamic spectra with epoch is a common feature for all pulsars and significant variations are seen over time scales as short as a few days. The property is better illustrated through the plots of ACFs, whose widths and orientations show significant variations from epoch to epoch. Significant variations are also present in the average flux densities of pulsars. Generally, at a given epoch of observation, most of the intensity patterns appear with quite similar orientations in the time-frequency plane. But there are slow variations in the magnitudes of tilts from epoch to epoch, which is seen as a changing nature of elongations of the ACFs. For many pulsars, pattern tilts undergo sign reversals over time scales of the order of several days. Pulsars PSR B0823+26 and PSR B0919+06 are good examples showing such systematic variations of pattern slopes along with sign reversals.

Systematic slope variations and sign reversals are found to be common for most of the
pulsars observed. There are, however, some pulsars whose data are characterized by a very few or even an absence of sign reversals of pattern slopes over the observing time spans (typically $\sim 100$ days). Pulsars PSR B0834+06 and PSR B1919+21 are best examples of such “persistent drift slopes”. PSR B1919+21 is a unique case, where in addition to the usual intensity decorrelations, there are deep intensity modulations lasting over very short time scales (roughly one minute). This broadband phenomenon is found to be a stable feature of this pulsar over the entire observing session. Another special pulsar is PSR B1133+16, which shows remarkable changes in the nature of the dynamic spectrum between its successive observing sessions. On 30 April 1994 this pulsar shows periodic intensity modulations in the dynamic spectrum.

In the rest of this section, we briefly describe the observed properties of some of the pulsars that show typical behaviour and some with anomalous scintillation properties. This is followed by a brief summary of the general characteristics of the remaining pulsars.

### 3.2.1. PSR B0823+26

Sample data of this pulsar are shown in Fig. 1.a which has 9 dynamic spectra spanning a period of 57 days from the second observing session (October 1993–January 1994), and in Fig. 2.a which shows 9 selected ACFs spanning 54 days from the first observing session (March 1993–May 1993). These data illustrate a number of basic observable effects due to diffractive and refractive scintillations. The intensity scintillation patterns arising from rapid intensity modulations in time and frequency are clearly seen. The patterns decorrelate over a few 100 kHz in frequency and $\sim 100$ secs in time for this pulsar. Often, the patterns appear with preferred orientations in the time-frequency plane and, on a given day, most of them exhibit slopes of same sign — either positive or negative. The sloping features in the dynamic spectra produce tilted contours in the ACFs. In addition, there are fine variations of sizes and shapes of patterns from day to day, along with significant variations in the average flux density. The property is better illustrated in Fig. 2.a, where ACFs at various epochs differ in terms of their sizes and elongations. A systematic slope reversal can be seen in the 6 ACFs starting from 26 April 1993.

### 3.2.2. PSR B0834+06

Fig. 1.b show the dynamic spectra for this pulsar, at 25 epochs spanning a period of 110 days, taken from the first observing session (January 1993–May 1993). A similar data set (at 23 epochs spanning 100 days) from the final observing session (April 1995–July
1995) is displayed in Fig. 1.c. These data have been selected to illustrate a number of special properties seen with this pulsar. Drifting patterns are highly pronounced in the dynamic spectra of this pulsar (Fig. 1.b). Scintles are much broader than that of PSR B0823+26, with typical widths of $\sim 500$ kHz in frequency and $\sim 400$ secs in time. The variable nature of dynamic spectra is also much better pronounced here. In the data taken from the first session (Fig. 1.b), patterns appear with slopes of same sign for all the epochs and do not show any reversal in between. Such persistent drifting features are also seen in the data from the next two observing sessions – October 1993 to January 1994 and February 1994 to June 1994. However, quite dramatic changes are noticed in the data taken during the final session – April 1995 to July 1995 (Fig. 1.c), in which there are several occasions of slope reversals. In addition, there are a few examples of spectra with ‘dual slopes’ (e.g. 10 June 1995).

3.2.3. PSR B0919+06

Selected dynamic spectra and ACFs of this pulsar are shown in Figs. 1.d and 2.b where the data at 9 epochs spanning a period of 35 days are displayed. The behaviour of this pulsar is quite similar to that of PSR B0823+26. Intensity patterns fade over a few 100 kHz in frequency and $\sim 100$ secs in time and the widths vary significantly between successive epochs of observation. Gradual and systematic variations in the slopes of the patterns are highly pronounced here. In fact, the orientation of the major angle of the ACF reverses its sign twice – from 28 April 1994 to 14 May 1994 and then again from 16 May 1994 to 1 June 1994. In some ACFs there is evidence for a dual slope where the orientation is different for the higher and lower contours - data on 4 May, 14 May and 24 May are good examples. Such behaviours can be expected during the transition periods of drift reversals, which is clearly substantiated by the dynamic spectra. This means, for this pulsar, pattern slopes seem to undergo a sign reversal typically once in 20 days.

3.2.4. PSR B1133+16

Another special pulsar is PSR B1133+16, which shows remarkable changes in properties of its dynamic spectra from one observing session to another. The pulsar was observed for 3 well separated sessions over a 3-year period. Fig. 1.e displays the dynamic spectra of this pulsar from the observations during March 1994–June 1994. A similar data set from the third session (April 1995–July 1995) is shown in Fig. 1.f. Each figure consists of data from 16 epochs of observations. Data shown in Figs. 1.e and 1.f span 65 and 92
days respectively. A typical dynamic spectrum from the initial observing session (February 1993) is shown in Fig. 3.c, which is characterized by intensity patterns fading over ~ a few 100 kHertz in frequency and over ~ 100 seconds in time. In contrast, dynamic spectra taken during the second session (Fig. 1.e), in particular those from the first half of the session, show patterns that fade over much broader ranges in frequency (~ 1 MHz) and in time (~ 200 seconds). The spectrum on 30 April 1994 shows clear evidence of periodic intensity modulations in the frequency-time plane, known as ‘interstellar fringes’, which result from multiple imaging caused by refraction in the ISM (e.g. Wolszczan & Cordes 1987). It may be mentioned that such imaging events were reported earlier for this pulsar by Hewish et al. (1985) and Cordes & Wolszczan (1986). After this episode of fringes, the pulsar appears to return to the initial mode seen in session I, with intensity patterns fading over ~ a few 100 kHertz in frequency and over ~ 100 seconds in time. This mode of scintillation spectrum prevails until the last observing day of the session (1 June 1994). Surprisingly, the dynamic spectra data obtained from the subsequent observing session (Fig. 1.f) are markedly different from the earlier data, showing intensity patterns fading over much broader ranges in frequency (~ a few MHz), which is similar to the characteristics of the first half of session II, and sometimes seem to be broader than the observing bandwidth itself. The pulsar thus seems to exhibit drastic changes in the nature of its dynamic spectrum on time scales ~ 1 year. Behaviour of this kind is not seen for any other pulsar that was followed-up for multiple observing sessions.

3.2.5. PSR B1919+21

Selected dynamic spectra of PSR B1919+21 from the first observing session (March to May 1993) are shown in Fig. 1.g, while in Fig. 2.c are shown selected ACFs from the follow-up session (October 1993 to January 1994). The spectra in Fig. 1.g are from 9 observations spanning 23 days while the ACFs displayed in Fig 2.c are for 25 observations over a period of 87 days. These data have been selected to highlight some of the special properties seen with this pulsar. The dynamic spectra appear to be quite similar to that of PSR B0834+06 shown in Fig. 1.b, but substantial variations are seen in size and shape of ACF over a time interval as short as 1–2 days.

A noticeable property seen in the dynamic spectra of this pulsar is fine, deep modulations of intensity patterns, which are invariably broadband and last over ~ 100 seconds in time. The property is unique to this pulsar and is a stable feature in the data from both the observing sessions. These intensity modulations produce a narrow ridge in the ACF at zero time lag (see Fig. 2.c). Sometimes, this effect also leads to fine corrugations of the ACF along the time axis (see for example ACFs on 22 October 1993 and 29 November...
Because of its broadband nature and persistence over entire duration of observation, we believe that these modulations are intrinsic to the pulsar and are not a scintillation phenomenon. Thus, the ACFs of this pulsar are more complex than those of the rest of the pulsars.

Drifting patterns are highly pronounced in the dynamic spectra of this pulsar (Fig. 1.g) as is the persistent nature of drift slopes. The data from the follow-up observations (Fig. 2.c) during October 1993–January 1994 also show persistent tilts in the ACF. There seems to be occasional instances of reversals of drift slopes, but the overall appearance of the data are more like that of persistent drifts. No further observations were made and hence no information is available on how long the persistent drifting features last for this pulsar.

3.2.6. PSR B2045–16

Sample dynamic spectra of this pulsar are displayed in Fig. 1.h, which consists of observations at 9 epochs spanning a period of 40 days. The pattern drifts are quite prominent as in PSR B0834+06 and PSR B1133+16, and show large variations and a number of reversals of slope over a period of 3 months. In contrast with the data discussed so far, the intensity patterns of this pulsar show random occurrences of broadband intensity fluctuations lasting for a few time samples (~10 secs), thereby giving rise to white vertical strips in its dynamic spectra. Broadband features of this kind are due to an insufficient averaging of pulsar’s intrinsic intensity variations due to the presence of additional phenomena such as nulling.

3.2.7. Summary of the Remaining Pulsars

The data of PSR B2020+28 (typical spectrum is shown in Fig. 3.k) show a behaviour quite similar to that of PSR B0919+06 and PSR B0823+26. The data of pulsars PSR B0628–28 and PSR B2327–20 are also found to be quite similar to that of PSR B0823+26 and PSR B0919+06, except that patterns fade over much longer durations, typically ~500 secs. Typical spectra of these pulsars are shown in Fig. 3.b and Fig. 3.m respectively. There are frequent, broadband striations in the spectrum of PSR B2327–20, which are presumably due to residual intrinsic intensity variations. Typical spectra of PSR B1604–00 and PSR B2016+28 are shown in Figs. 3.g and 3.j, where the intensity patterns fade over much longer durations in time, typically ~1000 secs. The sloping patterns are not quite noticeable in the spectra of PSR B2016+28. In contrast, PSR B1604–00 shows prominent
drift slopes, which vary systematically and show a sign reversal in between. The spectra of this pulsar are rather poorly sampled and there are only 10 epochs of observations over a time span of 94 days. Fig. 3.d and 3.i show typical spectra of pulsars PSR B1237+25 and PSR B1929+10. For these pulsars, patterns are much broader in frequency, and fade over a range \( \sim 1 \) MHz. Often, their spectra are characterized by a few bright scintles that dominate over others and last for \( \sim 1000 \) secs, which are followed by long fading over similar time scales. The presence of bright scintles also cause apparent intensity modulations that are somewhat greater than 100\%. In the case of pulsars PSR B0329+54, PSR B1540−06 and PSR B2310+42, typical spectra of which are shown in Figs. 3.a, 3.f and 3.l respectively, the intensity patterns fade over a very narrow frequency range, sometimes as small as \( \sim 100 \) kHz, which is close to our spectral resolution limit. The patterns are thus significantly smoothed in frequency due to the instrumental resolution and this smoothing effect reduces apparent intensity modulations to somewhat below 100\%. The spectra of pulsars PSR B1508+55, PSR B1747−46 and PSR B2310+42 (Figs. 3.e, 3.h and 3.l respectively) are characterized by poor signal-to-noise ratio because of a significant reduction in the telescope gain at high declinations.

3.3. Estimation of Scintillation Properties

3.3.1. ACF Fitting and Estimation of Scintillation Parameters

The 2-D ACF can be characterized by its widths along the frequency lag and time lag axes and its orientation in the frequency lag-time lag plane. The parameters corresponding to these widths are the decorrelation bandwidth, \( \nu_d \), defined as the half-power width along the frequency lag axis at \( \tau = 0 \), and the scintillation time, \( \tau_d \), defined as the \( e^{-1} \) width along the time lag axis at \( \nu = 0 \). The 2-D ACF is fitted with a two-dimensional elliptical Gaussian function (see Gupta et al. (1994) for justification) of the following form.

\[
\rho^m_{\nu, \tau} = C_0 \exp \left[ - \left( C_1 \nu^2 + C_2 \nu \tau + C_3 \tau^2 \right) \right]
\]  

The amplitude of the Gaussian function, \( C_0 \), is unity, since the ACF itself is normalized to unity. In the fitting algorithm, the deviations between the ACF and the model Gaussian are weighted by their uncertainties given by the weight function, \( \omega_d \), as described in equation (1). This weighting scheme accounts for the measurement uncertainties in the ACF values due to finite data stretch, and does not take care of the ‘scintle-lumpiness’ effect arising due to finite number of scintles (this is addressed later in this section). The model Gaussian parameters, \( C_1, C_2 \) and \( C_3 \), are estimated by a \( \chi^2 \)-minimization procedure.
The scintillation parameters $\nu_d$ and $\tau_d$ are obtained from these fitted parameters as

$$
\nu_d = \left( \frac{\ln 2}{C_1} \right)^{0.5} \quad ; \quad \tau_d = \left( \frac{1}{C_3} \right)^{0.5}
$$

The decorrelation widths $\nu_d$ and $\tau_d$ obtained in this manner are corrected for smearing due to finite instrumental resolutions in frequency and in time using a quadrature subtraction scheme. Barring a few exceptions, such as $\nu_d$ measurements of pulsars PSR B1540–06 and PSR B2310+42, this correction is not significant for our measurements.

To characterize the drifting features in the dynamic spectra (or equivalently, the tilt or orientation of the fitted Gaussian $\rho_k^m$), two issues need to be addressed. The first is the choice of an appropriate quantity for describing the effect. Usually the sloping features have been characterized by the frequency drift rate, measured as $d\nu/dt$ (Hewish 1980; Smith & Wright 1985). More recently, the inverse of this quantity, i.e., $dt/d\nu$, has been suggested as a more appropriate choice (Spangler 1988; Rickett 1990; Gupta et al. 1994), as it has a more meaningful connection with theory. $dt/d\nu$ is proportional to the refractive scattering angle $\theta_r$, and will have the same statistical properties — zero mean random variable, in the simplest case. We therefore prefer to use $dt/d\nu$ in place of $d\nu/dt$ in characterizing drift slopes.

The second issue concerns the correct method of estimating $dt/d\nu$. At first sight, it may appear that the slope of the major axis of the ellipse fitted to the ACF is a good measure of $dt/d\nu$. However, this is not true since the ellipticity and hence the slope of the major axis depends on the plotted scale and can give results that are not meaningful when the major axis happens to be aligned along one of the axes. The basic effect of refraction due to a linear phase gradient is not a tilting of the entire pattern, but rather a ‘shear’ resulting from the frequency-dependent displacements of patterns in the observing plane. Therefore, in the quantity $dt/d\nu$, $dt$ should refer to the time interval corresponding to the differential displacement of intensity patterns separated in frequency by $d\nu$. The proper measure of $dt/d\nu$ would be the slope of the line joining the points on the ellipse with the highest correlation at a given frequency offset. This definition is similar to that suggested by Gupta et al. (1994). It results in a zero drift slope in the absence of sloping patterns and is also free from the ambiguity of determining the major axis. In terms of the fitted Gaussian parameters, this slope can be expressed as

$$
\frac{dt}{d\nu} = -\frac{C_2}{2C_3}
$$

The uncertainties in $C_1$, $C_2$ and $C_3$ due to the Gaussian model fitting are obtained
from the $\chi^2$ analysis and translated into corresponding uncertainties in $\nu_d$, $\tau_d$ and $dt/d\nu$, and are referred to as $\sigma_{\text{mod}}$. We also take into account the statistical uncertainties in the scintillation parameters arising due to finite number of scintles, given by

$$\sigma_{\text{est}} = \left[ f_d \left( \frac{B_{\text{obs}}}{\nu_d \tau_d} \right) \right]^{-0.5} \quad (5)$$

where $\sigma_{\text{est}}$ is the fractional error and $f_d$ is the filling fraction for number of scintles, which is assumed to be 0.5 in our calculations. This is just a moderate value, and may overestimate the number of scintles (hence underestimate $\sigma_{\text{est}}$) if typical separation between the scintles is much larger than their sizes. For the parameters $\nu_d$, $\tau_d$ and $dt/d\nu$, errors from the Gaussian fitting ($\sigma_{\text{mod}}$) are added in quadrature with the statistical errors to get their final uncertainties. The typical values of $\sigma_{\text{mod}}$ and $\sigma_{\text{est}}$ correspond to errors of 10% and 5% respectively.

Similar statistical errors are also applicable for the measurements of pulsar flux densities and intensity modulation indices, which are directly obtained from the dynamic spectra. The intensity modulation index, which is known as the diffractive scintillation index, $m_d$, is usually found to be close to unity, within the measurement uncertainties. Moreover, the measured fluctuations of $m_d$ are found to be comparable to the uncertainties in $m_d$ values, and hence $m_d$ can be treated as a stable quantity. The observed 100% intensity modulations are in accordance with the strong scintillation expected for pulsars at metre wavelengths. However, there are a few exceptions (such as PSRs B1237+25 and B1929+10) with significant deviations of indices from unity and they are found to result from dominance of a few bright scintles. Occasionally, indices greater than unity are seen when a few bright scintles dominate the dynamic spectrum. However, no pulsar shows any systematic, large variations of $m_d$.

3.3.2. Time Series and Average Values of Scintillation Parameters

The results from the analysis are presented in the form of time series of four quantities: the three scintillation parameters $\nu_d$, $\tau_d$ and $dt/d\nu$, and average flux density (F). These are shown in Figs. 4(a)–4(x), where results for each session of every pulsar are shown as a separate panel, which is divided into 4 sub-panels showing variations of the four quantities. In each figure, day number 1 corresponds to the starting day of observation. When the pulsar was observed for more than one session, the results are shown separately since we find that the successive sessions show significant difference in the scintillation properties. Thus there are four panels for PSR B0834+06 and two each for PSR B0823+26, PSR
B1133+16 and PSR B1919+21 (see Table 2 for details). The uncertainties of individual measurements are estimated as described in the previous section. The length of the error bar represents ±1-σ uncertainty in the measurement. The data points are joined with dotted lines merely to illustrate the general trends seen in the variations of the quantities. We now use these time series to derive the average properties characterizing the diffractive and refractive scintillations for each pulsar.

The parameters $\nu_d$ and $\tau_d$ form two basic observables of diffractive scintillation that are measurable from our data. The present observations show that they vary significantly with time, which is presumably due to refractive effects. We discuss the details of the modulation characteristics in a later section. The important point here is that scintillation measurements from only a few observations would lead to erroneous conclusions about average scattering parameters. Most earlier measurements in the literature could not take into consideration such effects, probably due to limited observing time. It is necessary to average out these fluctuations in order to get reliable estimates of the quantities. Our observations were made over time spans much longer than the expected time scales of fluctuations and we were able to obtain many more scintillation measurements on each pulsar in our program. Thus the data allow us to reduce the errors due to refractive scintillation effects, as a result of which we are able to estimate DISS parameters more robustly than previous attempts. The average values thus obtained $\langle \nu_d \rangle$ and $\langle \tau_d \rangle$ are listed in columns (2) and (3) of Table 3. It may be mentioned that our data span may be insufficient to yield stable ISS parameters for pulsars which show persistent drifting features lasting over many months.

The third parameter $dt/d\nu$ is basically related to refractive scattering. Nevertheless, we briefly describe it here since the quantity is measured from the dynamic spectra, which is due to DISS. Like $\nu_d$ and $\tau_d$, the drift slopes of intensity patterns also show significant variations with time. The theoretical expectation is that these slopes should vary randomly about a zero mean over refractive time scales. In general, most pulsars show this basic property where the slopes change their magnitudes and show frequent sign reversals. However, PSR B0834+06 and PSR B1919+21 seem to be exceptions; the former does not show sign reversals in the first three sessions, and the latter shows quite similar property though there are a few epochs of opposite drift slopes. Thus, excepting a few pulsars, the mean value of the drift rate $\langle dt/d\nu \rangle$ (given in the column (4) of Table 3) is zero within the estimation errors.
3.3.3. The Global ACF Computation

Here we describe an alternative method which gives more reliable estimates of average values of $\nu_d$, $\tau_d$ and $dt/d\nu$ than obtained by averaging the time series. The method makes use of a weighted average 2-D ACF, which we refer to as the Global 2-D ACF (GACF). It is computed from the ACFs at all the epochs of observation for a given pulsar using the definition

\[
\rho_g(\nu, \tau) = \frac{\sum_{k=1}^{N_{ep}'} \omega_k(\nu, \tau) \rho_k(\nu, \tau)}{\sum_{k=1}^{N_{ep}'} \omega_k(\nu, \tau)}
\]

where $\rho_k$ is the ACF of dynamic spectrum at $k^{th}$ epoch. $N_{ep}'$ is the number of observations made with identical resolutions in time and frequency. $\omega_k$ is the weight function for the GACF, which is simply the number of data pairs averaged to get $\rho_k$ (note that it is different from the quantity, $\omega_d$, as defined in eq. [1]). Estimating the average scintillation parameters from the GACF has the following advantages over the time series averages. First, the individual ACFs are given weights proportional to their statistical reliabilities, which would make the average values less sensitive to ACFs computed from very short data stretches. The GACF has higher signal-to-noise ratios than the individual ACFs and is less sensitive to outliers, which results in smaller uncertainties in the fitting procedure. Further, while computing the GACF, deviations of the individual ACFs from their model gaussians get averaged out and so the GACF will be much closer to its model gaussian form than the case of individual ACFs. The uncertainties due to the model fitting ($\sigma_{mod}$), which are largely due to the deviation from the gaussian shape, will be smaller than that in the case of normal ACFs. Thus, the estimates of average values obtained from this technique will be more robust than those from the time series. The only limitation is that the data should be taken with identical resolutions in time and frequency, which is the case with most of our data.

The GACFs obtained from our data are shown in Fig. 5. For pulsars with multiple sessions of observations, GACF is computed for each session separately. In some cases, part of the data in a given session was obtained with a different resolution either in time or in frequency, in which case GACFs are computed for the corresponding data sets separately. In such cases, the labels A and B are attached alongwith the session ID (e.g. PSR B0823+26(IA)) or pulsar name (e.g. PSR B1508+55(A)) to distinguish between the different parts of data. The GACF is fitted with a gaussian of the form described in equation [2] to yield parameters $\nu_{d,g}$, $\tau_{d,g}$ and $(dt/d\nu)_g$ – which are the average estimates of $\nu_d$, $\tau_d$ and $dt/d\nu$ respectively. These are presented in columns (5), (6) and...
respectively of Table 3. The values are, in general, comparable to the corresponding time series averages. However, there are some exceptions. For PSR B1237+25, the two methods give significantly different values. The estimates of $\nu_{d,g}$ and $\tau_{d,g}$ are larger than the time series averages. But, interestingly, the drift slope obtained from the GACF is very close to zero, in comparison to a significant value indicated by the time series. A similar property is also seen for PSR B1929+10. For PSR B1133+16(I), both methods yield significant average drift slopes, which may be due to its poor statistics ($N_{\text{ep}} = 6$). The discrepancy between the $\nu_d$ values of PSR B2310+42, could be due its being close to the frequency resolution of our setup. This can be clearly seen from the time series, where $\nu_d$ values corrected for instrumental smearing become lower than the resolution in frequency. For PSR B2327–20, the discrepancy seen between $\langle \tau_d \rangle$ and $\tau_{d,g}$ seem to be due to some ‘outlier’ data points in the initial epochs of observation. We believe the results from the GACF technique to be more robust than those from the time series and hence use them in our further analysis in this paper.

\subsection*{3.3.4. Estimates of Derived Scattering Parameters and Pulsar Flux Densities}

Using the results obtained from the GACF method, we estimate some quantities characterizing the strength of scattering and scintillation pattern speed. The conventional way of describing the strength of scattering is in terms of $C_n^2$ (e.g. Rickett 1977; Cordes et al. 1985), where the spectrum of the plasma density fluctuations is considered to be a power-law, given by $P_{\delta n}(\kappa) = C_n^2 \kappa^{-\alpha}$, where $\kappa$ is the spatial wavenumber. The quantity $C_n^2$ is a measure of rms electron density fluctuations which give rise to scattering. The line-of-sight average of $C_n^2$ is given by (Cordes et al. 1985),

$$
C_n^2 = 2 \times 10^{-6} \left( f_{\text{obs,MHz}} \right)^{11/3} (D_{\text{pc}})^{-11/6} (\nu_{d,\text{kHz}})^{-5/6} \text{ m}^{-20/3} \tag{7}
$$

for a Kolmogorov form of density spectrum ($\alpha = 11/3$). Our estimates of $C_n^2$ are given in column (3) of Table 4, where the uncertainties are due to the measurement errors in $\nu_{d,g}$. In all our calculations, we make use of the most recent pulsar distance estimates available from Taylor, Manchester & Lyne (1993), except for PSR B0823+26, for which an independent distance ($\approx 380$ pc) from the parallax method is available (Gwinn et al. 1986). The new, improved estimates of $C_n^2$ derived from our measurements have been used to study the distribution of scattering material in the local interstellar medium (Bhat et al. 1997, 1998).

Another quantitative measure of the strength of scattering is the parameter $u$ which is
defined as the ratio of the fresnel scale \((s_f)\) to the ‘coherence scale’ \((s_o = (k\theta_s)^{-1})\). In terms of decorrelation bandwidth, this quantity can be expressed as (Rickett 1990; Gupta et al. 1994)

\[
u = \left(\frac{2 \nu_{\text{obs}}}{\nu_d}\right)^{0.5}
\]

The values of \(u\) obtained from \(\nu_{d,g}\) are given in column (4) of Table 4 and they range from 20 to 75. The observable effects of refractive scintillation are thought to critically dependent on this parameter, and the condition \(u > 1\) is considered to be the strong scattering regime. The quantity \(C_n^2\) is representative of average scattering along the line-of-sight, while \(u\) is an indicator of the integrated scattering at a given frequency of observation.

The scintillation pattern speed, \(V_{\text{iss}}\), which measures the relative motion between the scintillation pattern and the observer, is estimated from measurements of decorrelation bandwidth and scintillation time scale (e.g. Cordes 1986), and is given by

\[
V_{\text{iss}} = AV \left[\frac{\sqrt{D_{\text{kpc}} \nu_{d,\text{MHz}}}}{(f_{\text{obs},\text{GHz}} \tau_{d,\text{secs}})}\right] \text{ km sec}^{-1}
\]

For the constant \(A_V\), we adopt the value \(3.85 \times 10^4\) given by Gupta et al. (1994). In the above expression, we have considered a thin screen placed at the midway between the pulsar and the observer. Values of \(V_{\text{iss}}\) derived from measurements of \(\nu_{d,g}\) and \(\tau_{d,g}\) are given in column (5) of Table 4, with uncertainties that reflect the measurement errors in \(\nu_{d,g}\) and \(\tau_{d,g}\). For pulsars PSRs B1747–46, B2310+42 and B2327–20, scintillation speeds are reported for the first time. Though \(V_{\text{iss}}\) represents the net effect of pulsar’s proper motion (\(V_{\text{prop}}\)), Earth’s orbital motion around the Sun (\(V_{\text{obs}}\)) and bulk flow of the density irregularities in the ISM (\(V_{\text{irr}}\)), contributions due to \(V_{\text{obs}}\) and \(V_{\text{irr}}\) are usually small in comparison to that due to \(V_{\text{prop}}\). Therefore, scintillation speeds are generally considered to be useful indicators of pulsar’s proper motion speeds.

The long-term nature of our observations have enabled us to obtain reliable flux density values by averaging out the fluctuations due to refractive scintillation. The average flux densities \((S_{327})\) are given in the column (7) of Table 4, and have measurement errors of the order of 5%. The uncertainties are due to absolute flux calibration and estimation error due to finite number of scintles. Since the ORT is sensitive to linearly polarized radiation with electric field in the local North-South plane, our flux densities may turn out to be underestimates, especially for pulsars which have significant linearly polarization.
4. Discussion

We have presented results from a long-term systematic study of the scintillation properties of a large number of pulsars. Before we compare these average scintillation measurements with earlier studies and discuss the long-term stability of the scintillation parameters, we estimate the various errors in our computations of average scintillation properties. Two main sources of errors are (i) errors due to finite number of independent epochs of observations, which we denote as $\sigma_{\text{meas}}$, and (ii) errors due to limited number of refractive cycles of fluctuations spanned by the measurements, denoted as $\sigma_{\text{stat}}$. A direct estimation of the latter is not practical; hence, we get first order estimates by assuming a stationary statistics for RISS. This assumption may not be true for some pulsars, in which case our values of $\sigma_{\text{stat}}$ will be less reliable. In Appendix A, we describe the details of our scheme for estimating these errors. The results of our error calculations are summarized in Table 5, which gives the percentage errors for $\nu_{d,g}$, $\tau_{d,g}$ and $\langle F \rangle$. In general, the second kind of errors dominate over the first kind; typical values of $\sigma_{\text{meas}}$ are $\sim 2-5\%$, while that of $\sigma_{\text{stat}} \sim 5-15\%$. Overall, our data represent a significant improvement in terms of accuracy and reliability of scintillation measurements compared to those available in the literature, most of which were obtained from observations at a few epochs. We now compare the present measurements of diffractive scintillation parameters ($\nu_{d,g}$ and $\tau_{d,g}$) and flux density ($\langle F \rangle$) with earlier measurements. We also examine the agreement between our estimates of scintillation speeds and the proper motion speeds of pulsars.

4.1. Comparison with Earlier Measurements

4.1.1. Decorrelation Bandwidth and Scintillation Time Scale

Measurements of decorrelation bandwidth and scintillation time scale reported in five papers – Cordes (1986), Cordes, Weisberg & Boriakoff (1985), Smith & Wright (1985), Roberts & Ables (1982) and Gupta et al. (1994) – have been scaled to our observing frequency assuming scaling laws $\nu_d \propto f_{\text{obs}}^{4/3}$ and $\tau_d \propto f_{\text{obs}}^{1/2}$, which correspond to a power-law spectral index $\alpha = 11/3$. The $\nu_d$ and $\tau_d$ estimates calculated in this fashion are given in Tables 6A and 6B. While the measurements of Gupta et al. (1994) are from similar observations, i.e., from several epochs over a long period, the remaining ones are from a fewer epochs.

As seen from Table 6, there is a general lack of agreement between various measurements. Since refractive scintillation is thought to be the cause of slow fluctuations of diffractive observables, we first examine how well the discrepancies can be accounted for
in terms of RISS-induced fluctuations. For pulsars PSR B1929+10 and PSR B2045–16, the differences between the measurements are within the rms fluctuations seen in our time series for $\nu_d$ and therefore can be explained in terms of RISS. However, the discrepancies are much larger for the remaining pulsars. If we allow a 2-$\sigma$ deviation from our average values, the discrepancies of ten pulsars can be explained by RISS. For pulsars PSR B0919+06, PSR B1508+55 and PSR B1540–06, the discrepancies are much larger and an RISS explanation may not be adequate. A partial explanation for pulsars PSR 0329+54 and PSR B1540–06 might be our instrumental limitations, due to which the intensity patterns are barely resolved in frequency, thereby making the $\nu_d$ values less accurate.

Evidence for another reason that can give rise to large discrepancies can be found in our data itself. Interestingly, our observations show that average $\nu_d$ values do not remain stable for pulsars PSR B0834+06, PSR B1133+16 and PSR B1919+21 from session to session, despite averaging over a time span of about 100 days for each session, much larger than their RISS time scales. Variations between the successive sessions of observations are found to be considerable — in some cases as much as factor of 2 to 3. Thus our data show evidence for significant long-term variations of strengths of scattering on time scales $\sim$ years, something that has not been reported before. It is not very clear what can cause such effects, but they are difficult to understand in terms of RISS models based on simple power-law forms of density spectrum and a stationary statistics. Whatever be the cause, such effects could explain the discrepancies seen in Table 6. For example, PSR B1133+16 shows a systematic variation of $\langle \nu_d \rangle$ from 434 kHz to 1434 kHz over a period $\sim$ 900 days, where $\langle \nu_d \rangle$ from the first session is in agreement with values from literature. Similarly, for PSR B0834+06, $\langle \nu_d \rangle$ values range from 350 kHz to 610 kHz, which is comparable to the differences between our data and the earlier measurements (except the value from Cordes et al. 1985). Therefore, it is possible that the differences might be simply due to the measurements from observations made over separations of years.

The frequency scaling of decorrelation bandwidth is highly sensitive to the nature of the density spectrum assumed. The values listed, which are calculated for $\alpha = \frac{11}{3}$, will substantially differ if the spectrum is steeper. The exact value of $\alpha$ is still uncertain and there are conflicting interpretations from different scintillation experiments. Recently, Armstrong et al. (1995) have shown that the overall density spectrum in the nearby ISM ($\lesssim$ 1 kpc), extending over about 10 orders of magnitude of scale sizes, is closer to a Kolmogorov form, but it is not clear if this is valid for all lines of sight. It is possible that an incorrect frequency scaling has also contributed, at least partially, to the present discrepancies.

The situation with $\tau_d$ measurements is similar, though the disagreements are less pronounced. Like the case with $\nu_d$ values, RISS based on simple models fail to account
for some of the observed discrepancies. It is possible that effects that can account for the discrepancies of \( \nu_d \) might explain the \( \tau_d \) measurements as well. In addition, an apparent change in the scintillation pattern speed, due to reasons such as earth’s orbital motion (\( V_{\text{obs}} \)) and bulk motion of the medium (\( V_{\text{irr}} \)), can also lead to changes in \( \tau_d \). For example, in the case of PSR B2016+28, the variation of scintillation time due to earth’s motion is substantial (Gupta et al. 1994), and therefore dependent on the epoch of observation. Other pulsars where this effect is likely to be important are PSRs B1540–06 and B1604–00.

By and large, we find the discrepancies between our measurements (of both \( \nu_d \) and \( \tau_d \)) and others to be more or less unbiased, except with those from Cordes et al. (1985). But we also note that the measurements given in Cordes (1986) are from a more extensive data set and later than those reported in Cordes et al. (1985). RISS seems to be the likely explanation for some of the discrepancies, but there are several exceptions for which an RISS explanation is inadequate. Long-term variations seen with \( \langle \nu_d \rangle \) (e.g. for PSR B1133+16) can also be interpreted as large-scale spatial variations in \( C_n^2 \) (say, over \( \sim 50–100 \) AU), and this could be, at least partly, responsible for some of the unexplained discrepancies. Another possible source of discrepancies is an incorrect scaling of the measurements with frequency.

### 4.1.2. Flux Density

We compare our flux density measurements (\( S_{327} \)) (column 7 of Table 4) with the known values from the literature. Measurements at 400 MHz (\( S_{400} \)) taken from Gould (1994) (hereinafter G94) (for 15 pulsars) and Taylor, Manchester & Lyne (1993) (hereinafter TML93) are listed in columns (8) and (9) of Table 4. Our values, though less prone to errors due to RISS-induced fluctuations, may underestimate the true flux densities in the case of pulsars with a substantial fraction of linearly polarized radiation. On the other hand, it is possible that measurements from G94 and TML93 are not averaged out for fluctuations due to RISS. Our observations show large-amplitude variations in the flux density, where the individual measurements differ as much as by a factor 3–5. The considerable discrepancies (as much a factor 2–3) seen between the values from G94 and TML93 are, therefore, explicable in terms of RISS. Because of this, a detailed comparison between \( S_{327} \) and \( S_{400} \) may not be meaningful.

A first order comparison shows that, for 9 pulsars, the two values are comparable. For PSRs B1540–06, B1604–00, B1747–46 and B2310+42, \( S_{327} \) is comparable to \( S_{400} \) from TML93. For PSR B1133+16, \( \langle S_{327} \rangle \approx S_{400} \) from TML93 and for PSR B1919+21, \( \langle F \rangle \) from session II agrees with \( S_{400} \) of TML93. Similarly, the average value from sessions
II–IV of PSR B0834+06 is comparable to $S_{400}$ of G94. For PSR B0628–28, $S_{327} \approx \langle S_{400} \rangle$ (ie, the average of $S_{400}$ from G94 and TML93), and for PSR B2327–20, $S_{327} \approx S_{400}$ from G94. For PSRs B0823+06, B0919+06 and B2045–16, our values are larger than $S_{400}$ by a factor $\sim 1.5–2.5$, whereas for PSRs B0329+54, B1508+55, B2016+28 and B2020+28, they are somewhat lower ($\sim 0.4–0.8$ $S_{400}$). Two special cases are PSRs B1237+25 and B1929+10, for which $S_{327}$ is considerably lower; by $\sim 4$ times for the former and by $\sim 6–12$ times for the latter. Such a large discrepancy can be attributed to the fact that these pulsars show a large fraction of linearly polarized radiation (with fractional linear polarizations (at 400 MHz) of $\approx 0.6$ and $\approx 0.8$ respectively), which can make our values to underestimate the true values by a factor as much as $\sim 3–5$.

4.1.3. Scintillation Pattern Speeds and Proper Motion Speeds of Pulsars

Scintillation speeds are considered to be good indicators of pulsar velocities and several authors have studied the correlation between the two (Lyne & Smith 1982; Cordes 1986; Gupta 1995). In estimating scintillation speeds, different authors use different values for the constant $A_V$ in equation (9). It was taken to be $2 \times 10^4$ by Lyne & Smith (1982), $1.27 \times 10^4$ by Cordes (1986), while Gupta et al. (1994) suggest a value of $3.85 \times 10^4$, which has been adopted by us. Our estimates (column (5) of Table 4) are for a thin screen placed midway between the pulsar and the observer. More refined estimates can be obtained using the method described in Cordes & Rickett (1998) for distributed scattering medium. It may be mentioned that the thin-screen method overestimates the scintillation speed compared to a uniformly distributed medium with a simple Kolmogorov form of density spectrum.

Proper motion measurements are available for 15 of our pulsars (Taylor et al. 1993, and references therein). We have used them in combination with most recent distance estimates (Taylor et al. 1993) to estimate the pulsar velocities ($V_{\text{prop}}$) and these are given in column (6) of Table 4. Values of $V_{\text{prop}}$ are highly uncertain for 4 pulsars (PSRs B0628–28, B1604–00, B1919+21, B2016+28) as the error in the measurement is larger than the estimate of the proper motion itself. Also, for PSRs B0919+06 and B1540–06, there are considerable uncertainties (60–70%). For the rest of the pulsars, the uncertainties in $V_{\text{prop}}$ are $\leq 25\%$. These uncertainties are solely due to the measurement errors in proper motions. Taking into consideration the errors in distance estimates (typically 25%), the actual errors in $V_{\text{prop}}$ will be much larger for most pulsars.

Taking into consideration the uncertainties in $V_{\text{iss}}$ and $V_{\text{prop}}$, one can see that, for a number of pulsars, $V_{\text{iss}}$ is a reasonably good indicator of the proper motion speed. A plot of $V_{\text{prop}}$ vs $V_{\text{iss}}$ is shown in Fig. 6, where a significant correlation between the two can be
seen (correlation coefficient of 0.75). The best agreement between $V_{\text{iss}}$ and $V_{\text{prop}}$ is seen for PSR B1237+25. The measurements are consistent for PSR B0919+06, but here the uncertainty in the proper motion is very large (70%). For PSRs B0834+06 and B1133+16, $V_{\text{iss}}$ estimates from part of the data agree with $V_{\text{prop}}$. If we consider 3-$\sigma$ uncertainties in both $V_{\text{iss}}$ and $V_{\text{prop}}$, the two speeds are consistent for a fairly large number of measurements. Two exceptional cases are PSR B1508+55 with $V_{\text{iss}} \approx 0.5 \, V_{\text{prop}}$, and PSR B2020+28 with $V_{\text{iss}} \approx 2.5 \, V_{\text{prop}}$. For PSR B1508+55, the observed discrepancy is consistent with the estimated “z-height” of this pulsar and the expected “z-height” of the electron density layer in the Galaxy, as discussed in detail in Gupta (1995) (hereinafter G95). For PSR B2020+28, our observations confirm the discrepancy noted by G95. The likely explanation for this is enhanced scattering from the Local Orion Arm of the Galaxy, as postulated in G95. Significant discrepancies are also seen for PSR B0823 + 26(II), PSR B1133 + 16(II) and PSR B1133 + 16(III).

By and large, scintillation speeds can be used as rough indicators of proper motion speeds. The discrepancies seen can result from the distance estimate used and/or an asymmetric location of the effective scattering screen (cf. G95). Estimates of $V_{\text{iss}}$ are comparatively less prone to distance uncertainties, but critically depend on the relative location of the scattering screen with respect to the pulsar and the observer. A detailed treatment of such discrepancies is beyond the scope of the present work. The question of long-term stability of $V_{\text{iss}}$ also seems to have some relevance, as we find some evidence for significant variation in $V_{\text{iss}}$ between different observing sessions for PSRs B0834+06, B1133+16 and B1919+21, much in contradiction with the general expectations. We discuss the issue of long-term ($\sim$ year) stability of $\nu_d$, $\tau_d$ and $V_{\text{iss}}$ in the following section.

4.2. Long-term Stability of Scintillation Properties and Pulsar Fluxes

On the basis of results obtained from the observations of four pulsars for which we have multiple observing sessions — PSR B0823+26, PSR B0834+06, PSR B1133+16 and PSR B1919+21, we briefly discuss the issue of long-term stability (i.e., over time scales much larger than RISS time scales) of scintillation properties and pulsar fluxes. Observations were made over a fairly large number of epochs, spanning sufficiently long time spans (66 to 120 days), except PSR B1133 + 16(I), where the statistics is poor in terms of number of measurements ($N_{\text{ep}} = 6$) and observations span only 19 days. The two sessions of PSRs B0823+26 and B1919+21 span 305 days and the data of PSRs B0834+06 and B1133+16 cover $\approx$ 930 days. This data allow us to examine the stability of measurements over time scales much larger than RISS time scales for these pulsars.
In general, we find the basic scintillation properties $\nu_d$ and $\tau_d$ vary significantly between successive observing sessions. Sometimes, considerable variations are seen in the average flux densities as well. The observed long-term variations in the average values $\langle \nu_d \rangle$, $\langle \tau_d \rangle$, $\langle F \rangle$ and $V_{\text{iss}}$ (i.e., computed using $\nu_{d,g}$ and $\tau_{d,g}$, as described in §3.3.4) are summarized in Fig. 7. The uncertainties shown by the vertical error bar are estimated as $(\sigma^2_{\text{meas}} + \sigma^2_{\text{stat}})^{0.5}$. The horizontal bar represents the time span of observation.

The changes in $\langle \nu_d \rangle$ of PSR B0823+26 between the two sessions are within their statistical uncertainties, but the 18% reduction in $\langle \tau_d \rangle$ and the $\sim 13\%$ increase in $V_{\text{iss}}$ are larger than the uncertainties. The increase in $V_{\text{iss}}$ can be explained by the transverse component of Earth’s orbital motion ($V_{\text{obs}}\perp$) to the line-of-sight to this pulsar, which increases from $\approx -1$ km sec$^{-1}$ in the first session to $\approx 19$ km sec$^{-1}$ in the second. This naturally explains the apparent reduction in $\langle \tau_d \rangle$. However, the 35% reduction in $\langle F \rangle$ from session I to II is not reconcilable within the uncertainties (at $\pm 1\sigma$ level).

For PSR B0834+06, measurements of $\langle \nu_d \rangle$ are stable (within the uncertainties) for the first three sessions, but there is $\sim 75\%$ increase from III to IV. $\langle \tau_d \rangle$ also shows a similar trend between these two sessions showing a 24% increase, while $V_{\text{iss}}$ and $\langle F \rangle$ remain stable within the measurement errors. The variation of $\langle \nu_d \rangle$ and $\langle \tau_d \rangle$ between the sessions III and IV can be understood by a reduction of effective scattering strength ($\int C_n^2 \, d\theta$) by $\sim 30\%$. The expected $\langle \tau_d \rangle$ of 340 secs ($\tau_d \propto \theta -1$), is consistent with the measured value $322 \pm 17$ secs. The reason for such a variation of $C_n^2$ is, however, unclear.

Although $\langle \nu_d \rangle$ remains more or less stable from session I to III for PSR B0834+06, there is a steady and significant reduction in $\langle \tau_d \rangle$, which is also reflected as an increase in $V_{\text{iss}}$. This pulsar is known to have a proper motion of $174 \pm 20$ km sec$^{-1}$, which is consistent with $V_{\text{iss}}$ measurements from the sessions I and II. The change in $\langle V_{\text{obs}} \rangle$ from $\approx 11$ km sec$^{-1}$ to $\approx 19$ km sec$^{-1}$ can only partly account for the decrease in $\langle \tau_d \rangle$ between the sessions I and II. Similarly, $\langle V_{\text{obs}} \rangle$ values of sessions I and IV, 11 km sec$^{-1}$ and $-15$ km sec$^{-1}$, imply a relative change of $\sim 26$ km sec$^{-1}$ in $V_{\text{iss}}$, which is about $50\%$ of the observed variation. Thus the variations of $\langle \tau_d \rangle$ are only partially explainable in terms of $V_{\text{obs}}$. Further, there is a significant reduction (by $30\%$) in $\langle F \rangle$ from session I to II, which cannot be reconciled to RISS modulations.

Long-term variations of scintillation characteristics of PSR B1133+16 are much more complex than the rest of the pulsars. There is a factor of two increase in $\langle \nu_d \rangle$ and $\langle \tau_d \rangle$ between the sessions I and II. The variations in $\langle \nu_d \rangle$ and $\langle \tau_d \rangle$ are not consistent with a simple reduction in the scattering strength ($C_n^2$). $\langle \nu_d \rangle$ shows a remarkable increase between the sessions II and III, whilst $\langle \tau_d \rangle$ and $\langle F \rangle$ remain more or less stable. These variations are reflected in the estimated $V_{\text{iss}}$ values, which range from 335 $\pm 10$
km secs$^{-1}$ (in session II) to $490 \pm 38$ km secs$^{-1}$ (in the initial session). This pulsar also exhibits remarkable long-term changes in the dynamic spectra where $\nu_d$ ranges from values as low as $\sim 300$ kHz (at some epochs of initial session) to as large as $\sim 7$ MHz (at some epochs of session III). This is a unique pulsar which shows three different ‘modes’ of scintillation —, (i) $\nu_d \sim$ a few 100 kHz and $\tau_d \sim 100$ secs (sessions I and second half of session II), (ii) $\nu_d \sim 1$ MHz and $\tau_d \sim 200$ secs (first half of session II), and (iii) $\nu_d \sim$ several MHz and $\tau_d \sim 200$ secs (session III). The long-term variability of scintillation properties of this pulsar cannot be explained in terms of RISS, variations in the strength of scattering ($C_n^2$) or the effect due to the Earth’s orbital motion. It may also be mentioned that this pulsar is fairly close-by ($D \approx 270$ pc) and is known to have shown multiple imaging events (Hewish et al. 1985; Cordes & Wolszczan 1986; our observations).

For PSR B1919+21, substantial changes are seen in $\langle \nu_d \rangle$ and $\langle \tau_d \rangle$, but with opposite trends. This is also reflected as a remarkable ($\sim 70\%$) increase in $V_{\text{iss}}$ from session I to II. This pulsar is known to have a proper motion $V_\mu \sim 122 \pm 228$ km secs$^{-1}$, which will be consistent with $V_{\text{iss}}$ estimate from either of the sessions. The increase in $\langle \nu_d \rangle$ from 279 kHz to 510 kHz between the two sessions implies a reduction in the small-scale scattering ($\int C_n^2$) by $\sim 35\%$, which would have resulted in $\langle \tau_d \rangle \sim 555$ secs if $V_{\text{iss}} \approx V_\mu$ for both the sessions. The discrepancy in the two $V_{\text{iss}}$ values are not reconcilable within the uncertainties due to refractive modulations. On examining the effect of the earth’s orbital motion on $V_{\text{iss}}$ measurements of this pulsar, we find the relative change in $\langle V_{\text{obs}} \rangle$ to be $\approx 30$ km secs$^{-1}$ ($\langle V_{\text{obs}} \rangle$ values are $\approx 5$ km secs$^{-1}$ and $\approx 25$ km secs$^{-1}$ for the sessions I and II respectively). The effect of observer’s motion can, therefore, only partly account for the discrepancy. The bulk flow of the density irregularities ($V_{\text{irr}}$) is another possible explanation of discrepancy, but the required $V_{\text{irr}} \sim 55$ km secs$^{-1}$ is highly improbable. Bondi et al. (1994), based on their one-year flux modulation studies of low frequency variables, argue that $V_{\text{irr}} < 10$ km secs$^{-1}$. Thus the observer’s motion and the motion of the medium do not satisfactorily account for the observed variability of $V_{\text{iss}}$ values. Another effect that can give rise to modulation of $V_{\text{iss}}$ is the angular wandering of the source position caused by the refractive effects, which we will discuss in a subsequent paper. There is 42$\%$ reduction in $\langle F \rangle$ from session I to II, which is significantly larger than the statistical fluctuations that can be expected due to RISS.

Systematic observations to study the long-term stability of basic scintillation properties ($\nu_d$ and $\tau_d$) and pulsar fluxes have not been attempted before. The present observations show some evidence to suggest that these quantities do not remain stable for some pulsars despite averaging over periods much longer than the RISS time scale. Such a property is unexpected from the current RISS models. Normal RISS is expected to give rise to fluctuations of scintillation observables over refractive time scales and no ISS effect is
known to date which can cause long-term (session-to-session) variations seen in the present observations. Since the measurements have been made with the same experimental set-up, an observational bias is highly unlikely. The observed variations of $\langle \nu_d \rangle$ and $\langle \tau_d \rangle$ cannot be fully attributed to effective changes in scattering strength $C_n^2$ and/or the effect due to earth’s orbital motion around the Sun. Substantial variations of $C_n^2$ are not expected over the transverse extents of $\sim 50–100$ AU that has been probed by the present data. The observed variability of the flux is also anomalous and there are no intrinsic or extrinsic effects known that can produce significant flux variations over time scales $\sim 1–2$ years. All these conclusions are, however, based on only three pulsars and systematic observations of more pulsars are needed for understanding these effects better.

5. Summary and Conclusions

We have made an extensive series of scintillation observations for 18 pulsars in the DM range $3 – 35$ pc cm$^{-3}$ using the Ooty Radio Telescope at 327 MHz. The dynamic scintillation spectra of these pulsars were monitored at $10 – 90$ epochs over time spans of 100 to 1000 days during 1993–95. In this paper, we have presented the basic results from these observations. Some of the implications of these results, such as constraints on the spectrum of electron density fluctuations in the ISM and implications for the theoretical models of refractive scintillation, are addressed in two subsequent papers.

Two-dimensional auto-covariance function (2-D ACF) were computed for the dynamic spectra, and are used to estimate the quantities such as decorrelation bandwidth ($\nu_d$), scintillation time scale ($\tau_d$) and the drift rate of intensity patterns ($dt/d\nu$) for each observation. Time series of these quantities and flux density (F) are presented, and can be used to investigate various refractive effects in pulsar scintillation. All the four quantities show large-amplitude fluctuations (as much as by a factor $3 – 5$) over time spans of about 100 days, and are also found to vary significantly over time scales as short as a few days.

Several pulsars show pronounced drifting of intensity patterns in dynamic spectra; of which PSRs B0834+06, B1133+16, B1919+21, B2045–16 form some of the best examples. For many pulsars, the measured drift slopes ($dt/d\nu$) show gradual variations with time, and undergo several sign reversals during the observing time spans. Data of PSRs B0823+26, B0919+06 and B2020+28 illustrate this property, which is in accordance with the expectations of RISS theory. However, there are some pulsars for which no sign reversals of the drift slopes are seen over many months. Data of PSRs B0834+06 and B1919+21 are best examples of such “persistent drifts”. Out of the four well separated observing sessions of PSR B0834+06 spanning $\sim 1000$ days, persistent drifts are observed in the first three,
whereas the data from the final session show several occasions of sign reversals of pattern slopes.

PSR B1133+16, which was observed for 3 sessions spanning ~ 1000 days, shows remarkable changes in its dynamic spectrum from one session to another. The data from the initial session are characterized by scintles that are fairly narrow in both time (~ 100 sec) and in frequency (~ 300 kHz). The data taken one year after show much broader scintles (~ 200 sec and ~ 1 MHz). An episode of “interstellar fringing” is observed on 30 April 1994, which is followed by data characterized by narrower scintles (similar to the first session). Data from the final session show patterns that decorrelate over a wider range of frequency (~ 2 MHz) and time (~ 200 sec). Such dramatic variations are not seen for any other pulsar. The pulsar PSR B1919+21 is found to show fine, deep intensity modulations over and above random intensity modulations in time and frequency caused by ISS. These modulations occur over typical time scales of a minute (much shorter than DISS time scale) with level of modulations as much as 50%. The modulations are broadband and persist throughout our observations which suggests that they are intrinsic to the pulsar.

To obtain more reliable estimates of the average values of $\nu_d$, $\tau_d$ and $dt/d\nu$ from all the observations of a given pulsar, we have computed the Global ACF (GACF) for each pulsar. While the results from GACF and time series methods agree in general, there are considerable differences in some cases, specially when the statistics is poor. Since the GACF method is expected to yield more robust estimates of the average properties, we prefer them over the time series averages. Estimates of decorrelation bandwidth ($\nu_{d,g}$) and scintillation time scale ($\tau_{d,g}$) from GACFs are used to estimate parameters such as the line-of-sight averaged strength of scattering ($C_n^2$), the strength of scattering parameter ($u$) and the scintillation pattern speed ($V_{iss}$). A comparison between the scintillation speeds derived from our measurements and proper motion speeds of pulsars show that scintillation speeds are reasonably good indicators of proper motion speeds.

The present observations have resulted in a significant improvement in terms of accuracy and reliability of the scintillation measurements compared to those available in the published literature. For pulsars PSRs B1747−46, B2310+42, B2327−20, scintillation parameters are reported for the first time. There are considerable differences between our measurements of decorrelation bandwidth and scintillation time scale and various earlier measurements. Though RISS seems to be a likely explanation for some of the differences, it does not satisfactorily account for all discrepancies.

There is some evidence from our data for fluctuations of scintillation properties and flux densities over time scales much longer than that of RISS. For pulsars studied over multiple sessions, significant variations from session to session are sometimes seen in one
or more of the parameters $\langle \nu_d \rangle$, $\langle \tau_d \rangle$ and $\langle F \rangle$. Long-term ($\sim$ year) variations of this kind are not expected from current RISS models. Some of the variations of $\langle \tau_d \rangle$ can be accounted for by variations in scintillation pattern velocities due to the earth’s orbital motion. The $\langle \nu_d \rangle$ variations indicate variations of strengths of scattering along certain lines-of-sight. No obvious explanation can be found for the variations of $\langle F \rangle$. Possible implications of these results are a non-stationary nature of the ISM over $\sim 50–100$ AU or some hitherto unidentified form of ISS.

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A. Sources of Errors on the Average Scintillation Properties and Flux Densities

Here we estimate the errors on the average values of scintillation properties ($\nu_{d,g}$, $\tau_{d,g}$ and $(dt/d\nu)_{g}$) and flux density ($\langle F \rangle$). These include (i) the measurement error ($\sigma_{\text{meas}}$), and (ii) the statistical error due to the number of refractive cycles spanned by the measurements ($\sigma_{\text{stat}}$). The measurement error depends largely on the number of epochs of measurements ($N_{\text{ep}}$). For $\nu_{d,g}$, $\tau_{d,g}$ and $(dt/d\nu)_{g}$, which are estimated from GACF, $\sigma_{\text{meas}}$ has contributions mainly from 2 sources – the error from the gaussian fit (as described in §3.3.1) to the GACF (denoted as $\sigma_{\text{mod},g}$ and the estimation error due to finite number of scintles contributing to the GACF (denoted as $\sigma_{\text{est},g}$). To compute $\sigma_{\text{est},g}$, we treat $\nu_{d,g}$ and $\tau_{d,g}$ to be representatives of a single dynamic spectrum of duration $\sum_{i=1}^{N_{\text{ep}}} t_{\text{obs},i}$, where $t_{\text{obs},i}$ is the duration of observation at $i^{th}$ epoch. The fractional estimation error ($\sigma_{\text{est},g}$) is given by

$$\sigma_{\text{est},g} = \left[ f_d \left( \frac{\sum_{i=1}^{N_{\text{ep}}} B_{\text{obs},i} t_{\text{obs},i}}{\nu_{d,g} \tau_{d,g}} \right) \right]^{-0.5}$$  \hspace{1cm} (A1)

where $B_{\text{obs},i}$ is the observing bandwidth used at $i^{th}$ epoch and $f_d$ is the filling fraction of the number of scintles, for which we assume a moderate value of 0.5. The measurement error on the above 3 quantities is estimated as

$$\sigma_{\text{meas},g} = \left[ \left( \sigma_{\text{mod},g} \right)^2 + \left( \sigma_{\text{est},g} \right)^2 \right]^{0.5}$$  \hspace{1cm} (A2)

The errors obtained in this manner are given in columns (3) and (4) of Table 5, for $\nu_{d,g}$ and $\tau_{d,g}$ respectively. Typical values range from 2 to 5%, with somewhat larger values for PSRs B1237+25 and B1929+10, for which $\sigma_{\text{meas},g} \sim 10\%$.

The measurement error in the flux density, $\sigma_{\text{meas},F}$, is estimated as

$$\sigma_{\text{meas},F} = \left[ \left( \frac{1}{N_{\text{ep}}} \right)^2 \left( \sum_{i=1}^{N_{\text{ep}}} \sigma_{F,i} \right)^2 \right]^{0.5}$$  \hspace{1cm} (A3)

where $\sigma_{F,i}$ is the measurement error in flux density at $i^{th}$ epoch, and it includes the errors due to calibration ($\sigma_{\text{cal}}$) and estimation error ($\sigma_{\text{est}}$) due to finite number of scintles at that epoch. We have adopted a conservative approach of 10\% uncertainty in calibration for all the epochs. The column (5) of Table 5 gives $\sigma_{\text{meas},F}$, typical values of which range from 2 to 5\%, except for PSRs B1237+25 and B1929+10, for which $\sigma_{\text{meas},F} \sim 8\text{–}9\%$. 
A direct estimation of the statistical error is not possible as our time series are not good enough to estimate the time scale of fluctuations of the quantities. However, we get a first order estimate based on the expected refractive time scale ($\tau_{\text{ref}}$), which can be estimated from measurements of decorrelation bandwidth and scintillation time scale. We estimate the statistical uncertainty as

$$\sigma_{\text{stat}} = \left( \frac{x_{\text{rms}}}{\sqrt{N_{\text{ref}}}} \right)$$

where $x_{\text{rms}}$ denotes the rms estimate of the quantity $x$ under consideration, and obtained from the time series. A rough estimate of the number of refractive cycles of fluctuations ($N_{\text{ref}}$) is given by $T_{\text{sp}} / \tau_{\text{ref}}$, where $T_{\text{sp}}$ is the time span of observation. The refractive time scale is taken as $\tau_{\text{ref}} \approx u^2 \tau_d$ (Rickett 1990). We use values of $\nu_{d,g}$ and $\tau_{d,g}$ to get estimates of $\tau_{\text{ref}}$. The errors computed in this manner are given in columns (6), (7) and (8) of Table 5, for $\langle \nu_d \rangle$, $\langle \tau_d \rangle$ and $\langle F \rangle$ respectively. Typical values range from 5 to 15% for $\langle \nu_d \rangle$, 3 to 10% for $\langle \tau_d \rangle$ and 5 to 20% for $\langle F \rangle$. 
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Figure Captions

**Figure 1** Sample dynamic spectra of selected pulsars shown as a gray-scale plot of intensity versus time and frequency. The darker regions represent higher intensity values. The white regions correspond to 20% of the mean intensity and the black regions to four times the mean intensity; in between, the intensity values are linearly represented by the gray-scale. The average flux density at each epoch of observation is given at the upper left corner of each panel, and the observing day is indicated at the upper right corner. (a) PSR B0823+26 at 9 epochs spanning 57 days during October–December 1993, (b) PSR B0834+06 at 25 epochs spanning 110 days during January–May 1993, (c) PSR B0834+06 at 23 epochs spanning 100 days during April–July 1995, (d) PSR B0919+06 at 9 epochs spanning 35 days during March–June 1994, (e) PSR B1133+16 at 16 epochs spanning 65 days during March–May 1994, (f) PSR B1133+16 at 16 epochs spanning 92 days during April–July 1995, (g) PSR B1919+21 at 9 epochs spanning 23 days during April–May 1993, and (h) PSR B2045–16 at 9 epochs spanning 40 days during December 1993–January 1994.

**Figure 2** Contour plots of two-dimensional auto-covariance functions (2-D ACF) of dynamic spectra shown for three pulsars. There are 20 contours over the range zero to unity; successive contours are separated by an interval 0.05, and dashed contours represent negative values. The date of observation is indicated at the top of each panel. (a) PSR B0823+26 at 9 epochs of observations spanning 54 days during April–May 1993, (b) PSR B0919+06 at 9 epochs of observations spanning 35 days during April–June 1994, and (c) PSR B1919+21 at 25 epochs of observations spanning 87 days during October 1993–January 1994.

**Figure 3(a)–(m)** Typical dynamic spectra of 13 pulsars shown to illustrate their general characteristics. The name of the pulsar is given at the top of each panel. The average flux density is given at the upper left corner and the date of observation at the upper right corner of each panel. The nature of gray-scale representation is similar to Fig. 1, except for the intensity levels corresponding to the white and black regions. The white and black correspond to 20% and four times the mean intensity respectively for PSRs B0628–28, B1237+25, B1604–00, B1929+10, B2020+28 and B2327–20. They correspond to 30% and four times the mean for PSRs B1133+16, B1540–06 and B2016+28, 30% and thrice the mean for PSRs B0329+54 and B1747–46, and 40% and thrice the mean for PSRs B1508+55 and B2310+42.

**Figure 4** Time series of basic scintillation measurements: decorrelation bandwidth ($\nu_d$), scintillation time scale ($\tau_d$), flux density (F) and drift rate of patterns ($dt/d\nu$).
The uncertainties in the measurements indicate ±1-σ error estimates. The name of the pulsar and session ID (wherever needed) are given in the topmost panel of each figure. The solid markers (at either ends of the panel) indicate the average estimates of each time series. The dashed line in the plot of \( \frac{dt}{d\nu} \) corresponds to the zero drift slope. The starting date corresponding to the day number 1 is given at the bottom of each figure (X-axis label). (a) PSR B0329+54, (b) PSR B0628−28, (c)–(d) data from the two observing sessions (I and II) of PSR B0823+26, (e)–(h) data from the 4 observing sessions (I to IV) of PSR B0834+06, (i) PSR B0919+06, (j)–(k) data of PSR B1133+16 for the observing sessions II and III, (l) PSR B1237+25, (m) PSR B1508+55, (n) PSR B1540−06, (o) PSR B1604−00, (p) PSR B1747−46, (q)–(r) data from the two observing sessions (I and II) of PSR B1919+21, (s) PSR B1929+10, (t) PSR B2016+28, (u) PSR B2020+28, (v) PSR B2045−16, (w) PSR B2310+42, and (x) PSR B2327−20.

**Figure 5** The Global 2-D ACFs (GACF) of 18 pulsars (25 data sets). The name of the pulsar is given at the top of each panel. For PSRs B0823+26, B0834+06, B1133+16 and B1919+21, there are multiple plots, which are GACFs computed for different observing sessions. The labels A and B represent the part of the data for which GACF is computed (see Table 3). GACFs represent the average scintillation properties. The plots shown here illustrate the general characteristics observed with the dynamic spectra of various pulsars and also variations in scintillation properties from pulsar to pulsar.

**Figure 6** The available proper motion speeds (\( V_{\text{prop}} \)) of 11 pulsars are plotted against their scintillation speeds (\( V_{\text{iss}} \)) derived from the present scintillation measurements. The dashed line is of unity slope.

**Figure 7** Plots illustrating the long-term (\( \sim \) several months to year) variations in the average scintillation properties (\( \langle \nu_d \rangle \), \( \langle \tau_d \rangle \) and \( V_{\text{iss}} \)) and pulsar flux densities (\( \langle F \rangle \)). The pulsar name and the quantity plotted are given at the top of each panel. The vertical bar is the total uncertainty due to measurement and statistical errors. The horizontal bar represents the length of observing time span. The measurements are normalized to unity for their lowest values.