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Scintillation & Pulsar Timing: Low-level Timing Noise from the Kolmogorov Halo

Daniel A. Hemberger and Daniel R. Stinebring *

Oberlin College, Oberlin, OH 44074 USA

Abstract Many systematic effects need to be removed in order to obtain the highest quality pulsar timing data. Interstellar propagation effects may be reduced by employing coherent dedispersion and observing at 1 GHz or above to avoid strong scattering. However, these techniques may not adequately bring propagation effects below the level of other systematic or random errors in the observation. We show that low-level scattering in a Kolmogorov halo produces time delays that are much larger than normally recognized and are time variable. These may be a significant source of noise in some high precision timing efforts.

Key words: ISM — pulsars: individual (B1133+16, B1737+13, B1933+16) — pulsars: general — scattering

1 INTRODUCTION

Much new insight into multi-path scattering has been gained in the past five years. This progress has resulted from studies of pulsar dynamic spectra with high dynamic range and high frequency resolution. The analysis is most illuminating by taking the power spectrum of the dynamic spectrum and displaying the resulting secondary spectrum with a logarithmic intensity scale (Figure 1, left). Faint, but clearly visible scintillation arcs (Stinebring et al. 2001) are usually present, often with substructure that systematically moves along the main arc over weeks or months (Hill et al. 2005).

The scintillation arcs and accompanying substructure are due to a low-level scattering halo around the quasi-Gaussian core of the scatter-broadened image (Walker et al. 2004; Cordes et al. 2006). This halo is caused by relatively large angle scattering (5 – 10 times the width of the Gaussian core) from Kolmogorov turbulence in the interstellar medium and has an intensity that is typically 0.1% – 1% of the central core of the image.

This low-level halo is not generally included in time-domain analyses of the signal since it is hard to separate from low-level intrinsic pulse emission. The scattering tail that is normally studied is due to the Gaussian core of the scatter-broadened image. In the time domain, this gives rise to an exponential delay tail since time delay is proportional to scattering angle squared.

The presence of the Kolmogorov halo has important implications for high precision timing. Not only are time delays substantially longer than normally recognized, but we show here that they are time variable. The power in the halo component of the scattering tail is small, so only a quantitative study will indicate when these delays are important for a particular timing project.

2 ANALYSIS

The intrinsic pulse is convolved with the intensity impulse response function, $P(t)$, to yield the observed profile. If we could determine $P(t)$, we could deconvolve it from the observed pulse. However, only its autocorrelation function, $R_P(t)$, can be readily determined. $R_P(t)$ can be found by projecting the power

* E-mail: dan.stinebring@oberlin.edu

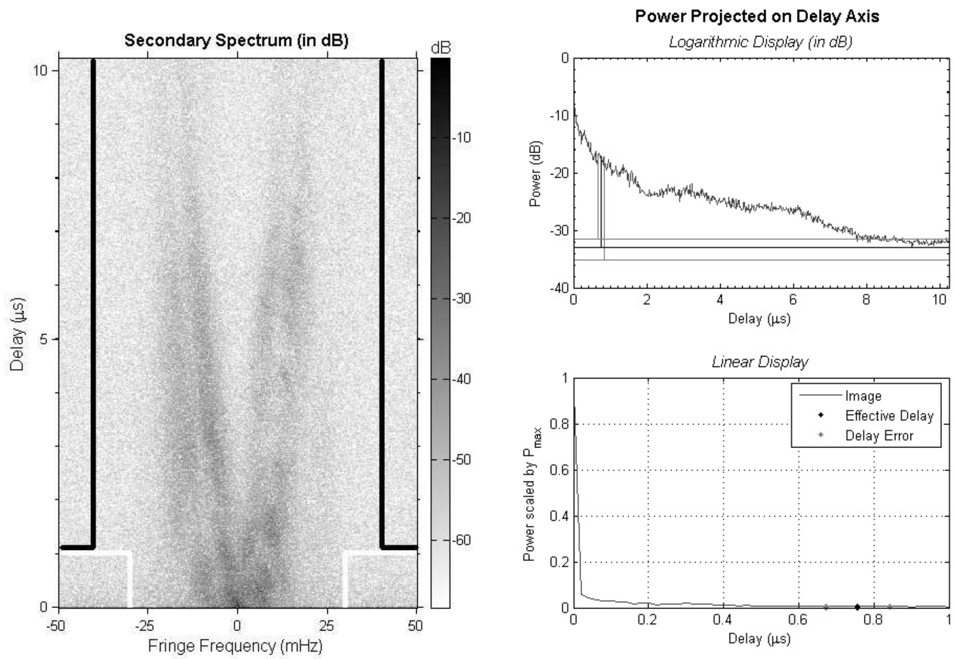

Fig. 1 LEFT: Secondary spectrum (power spectrum of the dynamic spectrum) for PSR B1737+13 observed at 1400 MHz with the Arecibo telescope on MJD 52636. The scintillation arc structure is seen to be patchy, and it translates systematically from left to right as the pulsar moves through space. The white and black boxes are regions used in our analysis for bias correction (measure of the sidelobe response) and noise determination (measure of the average background intensity, the noise baseline) respectively. RIGHT: Secondary spectrum power is projected onto the delay axis. This is the autocorrelation function $R_P(t)$ of the impulse response $P(t)$ (Rickett 2005). After subtracting a noise baseline and correcting for sidelobe response, we calculate the centroid of $R_P(t)$. We use this as an approximate indicator of the signal's effective delay. The uncertainty in delay is determined by propagating the uncertainty in baseline level through the algorithm. The narrow spike near the origin in the linear plot is due to the sidelobe response and is subtracted out in the centroid analysis.

in the secondary spectrum onto the delay axis or by working directly from the dynamic spectrum (Rickett 2006).

In contrast to a time-domain analysis of the scattered pulse profile, it is important to realize that the intrinsic pulse shape (and low-level pulsar emission) does not influence the determination of $R_P(t)$. For example, even though the pulsar PSR B1737+13 (Figure 1) has an average pulse width of 30 ms, the interstellar scattering delays extend only to $\sim 10\,\mu$s.

Referring to Figure 1, left, an example for a pulsar with moderate DM observed at 1400 MHz, there is substantial power out to a delay of 10 μs. When the power in the secondary spectrum is projected onto the delay axis, it produces $R_P(t)$, which is shown on a logarithmic display in the upper right panel. We determine the centroid of $R_P(t)$ after empirically finding a noise baseline and correcting for the sidelobe response near the origin. The centroid and the uncertainty in its determination (due to uncertainty in the baseline subtraction) are also indicated and redisplayed on a linear scale in the lower right panel. The Kolmogorov halo not only adds significant delay, but the delay also varies in time, sometimes significantly over multi-year timescales, as can be seen for two pulsars in Figure 2. In the analysis of PSR B1737+13 (Figure 2, top), substantial time variability in the centroid of $R_P(t)$ is seen at all three frequencies. This presumably reflects time variability in $P(t)$ through fluctuations in the low-level scattering tail. We have

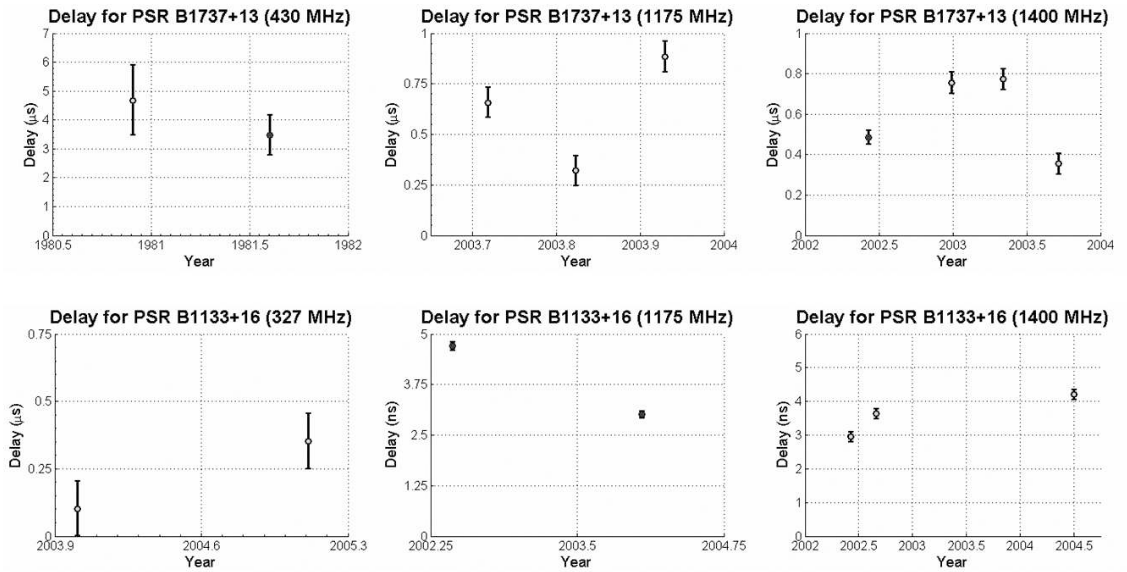

Fig. 2 Results for two pulsars at three observing frequencies. TOP: An application of the algorithm to the pulsar PSR B1737+13 (dist = 4.8 kpc, DM = 48.7 pc cm^{-3}). The darker points represent the average of several closely spaced observations. BOTTOM: Results for the nearby pulsar PSR B1133+16 (dist = 0.36 kpc, DM = 4.87 pc cm^{-3}).

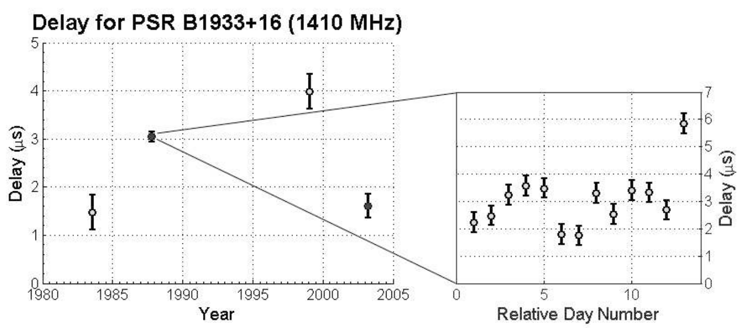

Fig. 3 Results for the distant pulsar PSR B1933+16 (dist = 7.9 kpc, DM = 158.5 pc cm^{-3}) at 1410 MHz. The inset shows more closely spaced observations.

seen many examples of time variable delay in high sensitivity scintillation arc observations (e.g. Hill et al. 2005; Cordes et al. 2006).

Although the delays are smaller in the case of PSR B1133+16 (Figure 2, bottom), they can be measured very precisely with this method. In Figure 3, multi-year timescale variability in delay is seen again for PSR B1933+16. As shown in the inset, the delay values vary smoothly in closely spaced observations.

3 DISCUSSION

The effect of interstellar scintillation on high precision timing of pulsars has been recognized for decades (e.g. Cordes et al. 1990) and new insights continue to emerge (Ramachanran et al. 2006). A push toward 100 ns residuals (or better) for the highest precision timing efforts requires attention to the smallest details.

It is important to deal with scattering effects explicitly rather than by observing at higher frequencies and hoping that the effects are below those of other noise sources.

We have shown that low-level scattering effects can be present in data at the sub-microsecond level and that the resulting time delays can be time variable. It is important to develop correction techniques for this time-variable delay. This is hampered by the unavailability of the intensity impulse response, $P(t)$. We are investigating the correlation between moments of $R_P(t)$ and the time delay in $P(t)$ itself. If a significant correlation can be found, it will be possible to do a first-order correction of timing data. We are also exploring techniques for estimating $P(t)$ using the modeling method of Walker and Stinebring (2005).

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