COHERENTLY DEDISPERSED GATED IMAGING OF MILLISECOND PULSARS

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ABSTRACT

Motivated by the need for rapid localization of newly discovered faint millisecond pulsars (MSPs), we have developed a coherently dedispersed gating correlator. This gating correlator accounts for the orbital motions of MSPs in binaries while folding the visibilities with a best-fit topocentric rotational model derived from a periodicity search in a simultaneously generated beamformer output. Unique applications of the gating correlator for sensitive interferometric studies of MSPs are illustrated using the Giant Metrewave Radio Telescope (GMRT) interferometric array. We could unambiguously localize five newly discovered Fermi MSPs in the on–off gated image plane with an accuracy of ±1ʺ. Immediate knowledge of such a precise position enables the use of sensitive coherent beams of array telescopes for follow-up timing observations which substantially reduces the use of telescope time (∼20× for the GMRT). In addition, a precise a priori astrometric position reduces the effect of large covariances in the timing fit (with discovery position, pulsar period derivative, and an unknown binary model), which in turn accelerates the convergence to the initial timing model. For example, while fitting with the precise a priori position (±1ʺ), the timing model converges in about 100 days, accounting for the effect of covariance between the position and pulsar period derivative. Moreover, such accurate positions allow for rapid identification of pulsar counterparts at other wave bands. We also report a new methodology of in-beam phase calibration using the on–off gated image of the target pulsar, which provides optimal sensitivity of the coherent array removing possible temporal and spacial decoherences.

Key words: pulsars: individual (J1120-3618, J1207-5050, J1551-0658, J1646-2142, J1828+0625) – techniques: interferometric

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1. INTRODUCTION

Ongoing sensitive surveys (e.g., Fermi-directed radio searches, Ray et al. 2012; Green Bank drift scan Survey3; Green Bank North Celestial Cap (GBNCC) survey,4 High Time Resolution Universe (HTRU) survey at Parkes, Keith et al. 2010; Pulsar Arecibo L-Band Feed Array (PALFA) survey, Cordes et al. 2006) have discovered a number of intriguing fainter millisecond pulsars (MSPs). As a result, in the last three years the population of Galactic disk MSPs has increased by about 45%.5 Sensitive follow-up studies of these newly discovered MSPs using coherent beams of array telescopes, or at higher frequencies using single dishes, are hindered by the large uncertainties associated with the discovery positions. For example, discovery uncertainties range from 40ʹ for the Giant Metrewave Radio Telescope (GMRT) at 322 MHz (GMRT−322) to 4ʹ for the Arecibo at L band. Sensitive coherent array follow-up observations significantly reduce the use of array telescope time (∼20 × for the GMRT), which is important as arrays are the future of large radio telescopes. Such coherent array observations improve the uncertainties in times of arrival (TOAs) and allow us to generate more closely spaced TOAs in order to avoid an ambiguous phase connection while timing binaries with shorter orbits. Traditionally, long-term pulsar timing programs are used to reduce such positional uncertainties, requiring a significant amount of observing time. Simultaneous timing fits with discovery positions and unknown binary parameters can be affected from large covariances, especially for long-period binaries. In addition, the covariance between position and pulsar period derivative (P) limits the convergence of the timing fit even with a known binary model. The effects of such large covariances in timing fit can be minimized with a precise a priori astrometric position.

Being compact objects, pulsars are effectively seen as point sources in interferometric imaging. Pulsars, especially MSPs, are weak radio sources in the continuum image plane, having fluxes in the range of a few milliJanskys even at lower frequencies. The identification of a pulsar counterpart in the continuum image can also be confused with the other sources in the field of view. Considering the narrow duty cycle, 3%–10% (Henry & Paik 1969), the detection significance of a pulsating point source can be largely improved by removing the off-pulse noise. This is achieved through pulsar gating, where the continuum image is sampled synchronously with the pulsed signal to generate a number of gated images for different pulse phases (e.g., pulsar gating at the ATCA; Lazendic 1999). A background sky subtracted on–off gated image allows us to unambiguously identify the location of pulsed emission (Camilo et al. 2000). However, such a precise position determination using gating has not yet been reported for MSPs. High time resolution gating requirements for MSPs, with a gating window of ∼100μs, could be computationally challenging. More importantly for MSPs, since their periods and intrinsic pulse widths are quite small, dispersion correction is required (unlike normal pulsars) before such high time resolution gating in order to account for large dispersion delay. For example, considering an MSP with a dispersion measure (DM) of 30 pc cm−3, the dispersion delay at 322 MHz GMRT frequency across 32 MHz bandwidth is ∼247 ms, which is

3 http://www.as.wvu.edu/~ pulsar/GBTdrift350/
4 http://arcc.phys.utb.edu/gbncc/
5 http://astro.phys.wvu.edu/GalacticMSPs/GalacticMSPs.txt
many times the MSP period. In earlier studies, gating has been performed after correlation using incoherent dedispersion. But incoherent dedispersion errors across frequency channels can be five times larger than intrinsic pulse widths (considering a 2 ms MSP at 30 pc cc⁻¹ DM with 5% duty cycle for GMRT—322), significantly reducing the number of effective gates due to pulse smearing. Thus, reconstructing intrinsic pulse width with coherent dedispersion (Hankins & Rickett 1975) will be beneficial while performing gating with larger bin numbers requiring sufficient time resolution. In addition, since a majority of MSPs are in the binary system, the effect of orbital motion on the pulsar period must be accounted for in the MSP gating correlator.

Alternatively, the localization of newly discovered pulsars can be achieved by forming multiple coherent beams covering the primary beam of the telescope. For example, the grating response of a linear array like the Westerbork Synthesis Radio Telescope can be used for localization with an accuracy of a few arcminutes (Rubio-Herrera et al. 2012). However, with continuum imaging followed by the multi-pixel beamformer using a nonlinear array like the GMRT (Roy et al. 2012) we have achieved a positional accuracy of a few arcseconds (determined by the synthesized beam of the array). But this method is not efficient to localize relatively fainter MSPs having very low detection significance in the continuum image plane.

In order to improve the detection significance in the image plane and to achieve positional accuracy of the order of 1″, we have developed a coherently dedispersed MSP gating correlator at the GMRT. In addition to aperture synthesis at moderate time constants (∼seconds) and high time resolution incoherent and coherent beam formation (∼30 μs), the GMRT software backend (Roy et al. 2010) is equipped to stream the raw baseband samples from all the antennas to an array of storage disks. In this Letter, we describe the design and implementation of the MSP gating correlator using raw Nyquist-sampled baseband data and its application to obtain the precise locations of five newly discovered MSPs from Fermi-directed searches. In addition, we demonstrate a unique application of gated imaging, using the pulsar as a phase calibrator to achieve the optimal sensitivity for the coherent array.

2. THE MSP GATING CORRELATOR

The design of the MSP gating correlator, which can increase the signal-to-noise ratio (S/N) of a pulsar in the image plane by a factor of 3–6 (approximately proportional to the inverse square root of duty cycle), is described below.

1. Coherent dedispersion. Since the baseline-based incoherent dedispersion performed before folding the visibility time-series at the best-fit topocentric model is not adequate for the study of MSPs at lower frequencies, we implement an antenna-based coherent dedispersion. An antenna-based coherent dedispersion (∼N operations) can also be computationally favorable compared to a baseline-based incoherent dedispersion (∼N² operations) for future arrays with large numbers of elements (N). A coherent dedispersion module is running on the recorded raw baseband data prior to correlation, and is parallelized over the telescopes. The dedispersed voltage samples are written to a shared memory ring buffer.

2. Correlation and folding. Dispersion-corrected raw voltage samples read concurrently from the shared memory are correlated to generate the high time resolution visibility time-series. These visibilities are fed into a gating module that bins the data in multiple gates. For a given MSP, while folding using the best-fit topocentric rotational model, a number of gates and intermediate time resolution of dedispersed visibilities are empirically adjusted to obtain an optimal S/N. In order to retain this optimal S/N in a 1 hr gated image for a 2 ms MSP (considering a gate width approximately equal to its pulse width), the fractional period error per rotation (ΔP) is required to be below ~10⁻¹³, i.e., the MSP period (in ms) is required to be correct up to seven significant digits. Folding with a fixed topocentric period is sufficient for imaging isolated or loosely coupled binary MSPs. However, we have parameterized the rotational model to include the period (P), acceleration (P′), and jerk (P″) for folding MSPs in tighter orbits. For newly discovered MSPs, this topocentric rotational model is derived from the PRESTO-based periodicity search for the same observation using simultaneously generated incoherent beamformer output (Ransom et al. 2002). However, for MSPs with a known ephemeris we used TEMPO-based predictions⁶. The folded visibilities on each gate are then integrated up to a time resolution of 16 s and the complex correlation output from each gate is finally written to disks for further processing.

3. On–off gating. The on-pulse gate is also identified using the coherent, or incoherent where the position of the MSP is poorly known, beamformer output as the arrival time of the pulse is unknown a priori for new pulsars. The gates containing the pulsed emission are grouped to form the on-pulse data, and the off-pulse data are formed with the same number of gates covering the off-pulse phases. In order to unambiguously identify the location of pulsed emission we have generated an on–off visibility bin. In addition, by subtracting the nearby off-gate from the on-gate underlying systematics generated from the instrumental effects as well as from the radio frequency, interferences are canceled out, resulting in further improvement in noise statistics.

4. Calibration and imaging. Coherently dedispersed folded on–off visibility data are then flagged for removing the outliers and calibrated for solving the complex gains (Prasad & Chengalur 2011). Calibrated visibilities are imaged and deconvolved using the standard imaging package AIPS.⁷ MSP is the only source in this on–off gated image, considering that on and off gates contain equal flux for other sources.

3. LOCALIZATION OF MSPs USING THE GATING CORRELATOR

The MSP gating correlator is efficient in localizing fainter MSPs, where fluxes are around 1 mJy resulting in a very low detection significance on the continuum image plane (rms noise in 1 hr at GMRT—322 ~ 500 μJy). Positional accuracy achieved from an on–off gated image depends upon the hour angle of the observations and the S/N of the pulsar detection. Considering the GMRT—322 synthesized beam (FWHM) ~ 16″, the positional accuracy of an MSP scales according to FWHM/(2×S/N). For a typical S/N of 5 (Table 2), an accuracy of ±1″ is determined by the AIPS task JMFIT. Such a priori astrometric accuracy accelerates the convergence in pulsar timing. The newly discovered MSPs have large uncertainties in the a priori position, requiring a timing span of the order of a year to overcome the effect of covariance between the

⁶ http://www.atnf.csiro.au/research/pulsar/tempo
⁷ http://www.aips.nrao.edu
position and $\dot{P}$. However, while fitting with a more precise a priori position having $\pm 1''$ uncertainty, the positional accuracy of $\sim 1$ mas and a convergence in the detection of $P$ (with $\Delta P/P \sim 0.04$) can be achieved only in about 100 days.

We performed gated imaging for five MSPs discovered in Fermi-directed radio searches. Among those, PSR J1120−3618, J1646−2142, and J1828+0625 were discovered by us in GMRT−322, whereas PSR J1207−5050 in GMRT−607 (Ray et al. 2012) and PSR J1551−0658 were discovered in GBT−350 (P. Bangale et al. 2012, in preparation). The parameters of these MSPs such as period, DM, and mean flux are listed in Table 1. The quoted mean flux is obtained using the simultaneous incoherent beamformer output. For PSR J1207−5050 the gating observations were done at 607 MHz while the rest of the MSPs were observed at 322 MHz.

PSR J1120−3618 is a serendipitously discovered MSP in the GMRT−322 field of view of the known Fermi MSP J1124−3653. This is a very faint MSP (mean flux $\sim 300$ mJy) in a relatively tighter orbit. The PRESTO-based search pipeline reports an acceleration equal to 0.1 m s$^{-2}$, corresponding to a significant measurement of $\dot{P}$ equal to $2 \times 10^{-12}$ s s$^{-1}$. This introduces a period (in ms) error at 1 part in $10^5$ over 3 hr of observation, whereas for optimal folding an accuracy up to 1 part in $10^6$ over 3 hr is needed. Thus, accounting for acceleration is required to retain the S/N of this MSP in the on−off gated image plane. The pulse phase is binned in 11 gates (gating window $\sim$ pulse width) at the intermediate time resolution (491.52 $\mu$s) of the dedispersed visibilities. The on−off gated image for this MSP is shown in Figure 1. Interestingly, this MSP is located at 57$'$ offset from the pointing center, which is outside the GMRT−322 beamwidth ($\sim 40''$). To localize the MSP, we have performed multi facetted (Perley 1999) gated imaging that is also corrected for the primary beam effect as the pulsar is located at the edge of the beam. In order to obtain the gated image of the full field of view, separate facet images are interpolated and averaged onto a larger grid using the AIPS task FLATN. A 10$'\times$10$'$ facet of the on−off gated image shows the MSP (Figure 1) with a 5$\sigma$ detection significance, resulting in gated flux of 1.2 mJy, which is 4$\times$ the mean flux as expected from gating. The parameters related to the gated imaging are listed in Table 2. A sensitive coherent beam is formed toward the pulsar location by steering the phase center and an expected sensitivity improvement $\sim 4$ of the incoherent array detection is achieved (Roy et al. 2012).

PSR J1207−5050, J1551−0658, J1646−2142, and J1828+0625 are also successfully localized in their respective on−off gated images (shown in Figure 2). Table 2 lists the related parameters. PSR J1207−5050 and J1646−2142 are found within the error radius of the associated Fermi sources. However, PSR J1551−0658 and J1828+0625 are located at an offset of 20$'$ and 26$'$, respectively, from their pointing centers (outside

![Figure 1](image-url) Localization of the PSR J1120−3618 using the MSP gating correlator. The MSP (marked in the image) is detected in the on−off gated image at 57$'$ offset from pointing center.

(A color version of this figure is available in the online journal.)

### Table 1

| PSR        | Period (ms) | Dispersion Measure (pc cc$^{-1}$) | Mean Flux (mJy) |
|------------|-------------|-----------------------------------|-----------------|
| J1120−3618 | 5.55        | 45.1                              | 0.3             |
| J1207−5050 | 4.84        | 50.7                              | 0.2             |
| J1551−0658 | 7.09        | 21.6                              | 1.0             |
| J1646−2142 | 5.85        | 29.7                              | 2.1             |
| J1828+0625 | 3.63        | 22.4                              | 1.3             |

*Note. The quoted mean flux of PSR J1207−5050 is measured at 607 MHz, while the rest are in 322 MHz.

### Table 2

| PSR        | Gated J2000 Position (Errors in $'$) | Offset from Pointing Center | Number of Gates | Observing Duration (min) | Gated Flux (mJy) | Gated S/N |
|------------|--------------------------------------|-----------------------------|-----------------|--------------------------|-----------------|----------|
| J1120−3618 | 11$^h$20$^m$22$^s$.045 (1$''$); 36$''$.1832/17 (2$''$) | 57$'$ | 11 | 180 | 1.2 | 5 |
| J1207−5050 | 12$^h$07$^m$21$^s$.811 (0$''$4); 50$''$.050/327 (1$''$4) | 6$'$/2 | 10 | 120 | 1.1 | 6 |
| J1551−0658 | 15$^h$51$^m$07$^s$.215 (0$''$6); 06$''$.58/0651 (0$''$6) | 20$'$ | 14 | 60 | 5.8 | 11 |
| J1646−2142 | 16$^h$46$^m$18$^s$.127 (0$''$9); 21$''$.42/0896 (1$''$4) | 10$'$ | 12 | 60 | 11.3 | 11 |
| J1828+0625 | 18$^h$28$^m$28$^s$.030 (1$''$0); 06$''$.25/0052 (1$''$3) | 26$'$ | 15 | 45 | 3.5 | 6 |

*Note. The gated flux of PSR J1207−5050 is measured at 607 MHz, while the rest are in 322 MHz.*
Figure 2. On–off gated images for PSR J1207−5050, J1551−0658, J1646−2142, and J1828+0625. All the MSPs are marked in the respective 10′×10′ facet images. (A color version of this figure is available in the online journal.)

The on–off gated images show the on–off gated images for PSR J1207−5050, J1551−0658, J1646−2142, and J1828+0625. All the MSPs are marked in the respective 10′×10′ facet images. (A color version of this figure is available in the online journal.)

4. IN-BEAM PHASE CALIBRATION USING THE PULSAR

The sensitive coherent beamformer allows the study of high time resolution temporal variations of pulsars. In order to form a coherent beam using an array telescope like the GMRT, antenna-based complex gains (amplitudes and phases) must be solved using recorded visibilities on a calibrator source. The optimal baseline length over which the array can be coherently added is limited by the perturbations in ionospheric phases which are more severe at lower frequencies. Coherent array sensitivity degrades with time due to the temporal decoherences caused by instrumental as well as ionospheric phase fluctuations. Such degradation can be reduced with interleaved calibrator observations. However, applying the phases derived from a distant calibrator into a pulsar field can cause further decoherences due to underlying different ionospheric inhomogeneities (Thompson et al. 1986). We have used the on–off gated image of the target pulsar as a sky model to solve for antenna-based residual stochastic phase errors (affecting the data on a short timescale) as well as the broadband phase offsets applying self-calibration in AIPS. This process produces a set of phase solutions with time, written in an S/N table generated by AIPS. While forming the coherent array, these residual phase solutions are recursively applied in addition to initial narrowband phase corrections derived from the calibrator visibilities. A background sky subtracted on–off gated image of the target pulsar provides a better model to solve for phases since the effects of instrumental as well as RFI artifacts are canceled out. A pulsar with about 10 mJy flux density allows this in-beam calibration process to converge (ensuring a more than 3σ detection in each frequency channel during calibration with 10 minute cadence). This in-beam calibration is the optimal way of coherently adding all the working antennas of an array telescope.

We have generated an on–off gated image for PSR B1804−08 using 1 minute of baseband data, which is shown in the upper left panel of Figure 3. With the in-beam calibration, a sensitivity improvement of 3.5× compared to the conventional coherent array is seen in the folded profile (upper right panel of Figure 3). This improvement includes contributions from
Figure 3. In-beam phase calibration using PSR B1804−08. The upper left panel shows the on–off gated image with a close-up view around the pulsar. The upper right panel shows the coherent array sensitivity improvement in the folded pulse profile using the in-beam phase calibration. The dispersed pulse phase with frequency is shown in the bottom panel. A similar sensitivity improvement with the reduction of spectral noise (SNR are mentioned in the right corners of the respective plots) is seen in the right panel with respect to the left panel.

(A color version of this figure is available in the online journal.)

the increased coherence length of the array (achieved from a 50% increase in the number of antennas) and better modeling of phase errors. Since the spectral voltages from the antennas are optimally added in phase, the sensitivity improvement can also be visualized as a reduction in the spectral noise in the dispersed pulse phase versus frequency plot (bottom panel of Figure 3) generated with DSPSR (Straten & Bailes 2011). In addition, the temporal decoherence affecting the long observing scans of target pulsars can be avoided by recursive in-beam calibrations on a short timescale without slewing to a distant calibrator location. The use of a pulsar as an in-beam phase calibrator can introduce a lateral shift in the image domain while the pulsar is not at the phase center. This can be calibrated using the known position of any in-field catalog source allowing us to perform an astrometric measurement of the pulsar.

5. SUMMARY AND FUTURE SCOPE

We report the design and implementation of a coherently dedispersed MSP gating correlator that accounts for orbital motions while folding the visibility time-series. In this Letter, we have unambiguously determined the precise positions, with ±1" accuracy, for five newly discovered MSPs using the on–off gated imaging. Localizations of such relatively fainter MSPs have greatly benefited from the significant enhancement in S/N on the gated image plane compared to the normal synthesis observations. Knowledge of such accurate positions in immediate observations after discovery allows for follow-up observations with sensitive coherent array, substantially reducing the use of telescope time by an order of magnitude. Inaccuracy of the astrometric model, associated with large uncertainties in discovery positions, increases the length of data span required to reduce the effect of covariance between position and $\dot{P}$ in timing fit. While determining an unknown binary model, a large covariance between position and the binary parameters, especially for long-period binaries, can influence the timing fit, which can be minimized with an accurate astrometric position ($\sim \pm 1''$). In addition, for pulsars located near the ecliptic plane, the astrometric inaccuracy in ecliptic latitude from the timing fit is much larger (Lorimer & Kramer 2004), indicating the need for interferometric gated observations. This accurate localization will also facilitate the search for a pulsar counterpart and possible binary companions in the optical and X-rays. Current astrometric positional accuracy (±1") is
decided by array size and the S/N of detection. The application of an MSP gating correlator in the very long baseline interferometry (Deller et al. 2009) and the Square Kilometre Array (SKA) scale improves this a priori astrometric accuracy (e.g., at 1.4 GHz, 3000 km SKA baseline can give astrometric precision as 15 μas Smits et al. 2011).

In addition, we have used the on-off gated image of the target pulsar to correct the residual phase errors in order to avoid degradation of the coherent array sensitivity caused by decoherences from instrumental and ionospheric phase fluctuations. Such in-beam phase calibration using a target pulsar ensures optimal sensitivity of the coherent array. We believe that this methodology will be very fruitful for recently commissioned and upcoming array telescopes (e.g., LOFAR, de Vos et al. 2009; MWA, Lonsdale et al. 2009; ASKAP, Johnston et al. 2008; MeerKAT, Jonas 2009).

Even though the design is primarily motivated by the requirement of localization of newly discovered Fermi MSPs, this gated imaging has the potential to unfold some other interesting properties of MSPs. First, the MSP gating correlator will allow us to perform independent measurement of parallaxes and proper motions even for relatively fainter binary MSPs, which will largely benefit from pulsar timing and will probe the interstellar medium (ISM) at various lines of sight (McGary et al. 2001; Lorimer & Kramer 2004; Smits et al. 2011). Second, the study of un-pulsed emission associated with pulsar wind nebulae (PWNs) can be performed by imaging the pulsar field when pulsed emission is off (Gaensler et al. 2000). The angular extent of PWNs for high energy pulsars in the low density ISM can be as large as a few arcminutes (e.g., Frail et al. 1994), which can be detected with low frequency gated imaging using this MSP gating correlator. Finally, the pulsar itself may have a weak off-pulse emission, having a magnetospheric origin, coming from close to the light cylinder (Perry & Lyne 1985; Basu et al. 2012). The origin of a possible off-pulse emission from MSPs can be probed with the gated images as a function of pulse longitude and any possible co-location with the gamma-ray emission region will be interesting to investigate. Thus, the design of coherently dedispersed MSP gated imaging assures broader scientific returns while also having importance for SKA applications.

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REFERENCES

Basu, R., Mitra, D., & Athreya, R. 2012, ApJ, 758, 91
Camilo, F., Kaspi, V. M., Lyne, A. G., et al. 2000, ApJ, 541, 367
Cordes, J. M., Freire, P. C. C., Lorimer, D. R., et al. 2006, ApJ, 637, 446
Deller, A. T., Tingay, S. J., & Brisken, W. 2009, ApJ, 690, 198
de Vos, M., Gunst, A. W., & Nijboer, R. 2009, IEEE, 97, 1431
Frail, D. A., Goss, W. M., & Whiteoak, J. B. Z. 1994, ApJ, 437, 781
Gaensler, B. M., Stappers, B. W., Frail, D. A., Moffett, D. A., & Johnston, S. 2000, MNRAS, 318, 58
Hankins, T. H., & Rickett, B. J. 1975, MComP, 75, 55
Henry, G. R., & Paik, H. J. 1969, Natur, 224, 1188
Johnston, S., Taylor, R., Bailes, M., et al. 2008, ExA, 22, 151
Jonas, J. L. 2009, IEEE, 97, 1522
Keith, M. J., Jameson, A., van Straten, W., et al. 2010, MNRAS, 409, 619
Lazendic, J. S. 1999, Australia Telescope Compact Array Users Guide (Sydney: ATNF)
Lonsdale, C. J., Cappallo, R. J., Morales, M. F., et al. 2009, IEEE, 97, 1497
Lorimer, D. R., & Kramer, M. 2004, Handbook of Pulsar Astronomy, Vol. 4 (Cambridge: Cambridge Univ. Press), 211
McGary, R. S., Brisken, W. F., Fruchter, A. S., Gross, W. M., & Thorsett, S. E. 2001, AJ, 121, 1192
Perley, R. A. 1999, in ASP Conf. Ser. 180, Synthesis Imaging in Radio Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley (San Francisco, CA: ASP), 383
Perry, T. E., & Lyne, A. G. 1985, MNRAS, 212, 489
Prasad, J., & Chengalur, J. 2011, ExA, 33, 157
Ransom, S. M., Eikenberry, S. S., & Middleditch, J. 2002, AJ, 124, 1788
Ray, P. S., Abdo, A. A., Parent, D., et al. 2012, 2011 Fermi Symposium Proceedings (arXiv:1205.3089)
Roy, J., Bhattacharyya, B., & Gupta, Y. 2012, MNRAS, 427,L90
Roy, J., Gupta, Y., Pen, U.-L., et al. 2010, ExA, 28, 55
Rubio-Herrera, E., Stappers, B. W., Hessels, J. W. T., & Braun, R. 2012, MNRAS, in press (arXiv:1210.4660)
Smits, R., Tingay, S. J., Wex, N., Kramer, M., & Stappers, B. 2011, A&A, 526, 108
Straten, W. van, & Bailes, M. 2011, PASA, 28, 1
Thompson, A. R., Moran, J. M., & Swenson, G. W. 1986, Interferometry and Synthesis in Radio Astronomy (New York: Wiley)