Fast Transient Science in the VLASS

C. J. Law[1], G. C. Bower[1,2], S. Burke-Spolar[3], G. Hallinan[3], T. J. W. Lazio[4]

ABSTRACT

We propose that the VLASS use the WIDAR correlator in a “fast dump” mode to produce subsecond integrations and search for fast transients, such as fast radio bursts, pulsars, and dwarf stars. Our group has used the VLA for visibility-based transient detection at timescales as fast as 5 ms. Generally speaking, the transients science case improves for integration times down to 100 microseconds, which is beyond our ability to sustainably produce and search for transients. Thus, careful planning is needed to consider the tradeoffs between the science potential and the technical requirements of fast dumps in the VLASS. In most cases, the lower frequency bands of the VLA are more fruitful for fast transients surveys.

1. Introduction

Single-dish telescopes have pioneered the study of sub-second radio transients, a field rich with physics. These instruments discovered pulsars via blind surveys for impulsive periodic radio emission (Hewish et al. 1968). New searches seek pulsars in binary systems, where precise timing of pulse arrival times can test general relativity (Thorsett & Chakrabarty 1999; Demorest et al. 2013), binary evolution models (Keane et al. 2010) and find exoplanets (Wolszczan & Frail 1992). These surveys have also discovered new classes of neutron star transients (McLaughlin et al. 2006) and cataclysmic extragalactic radio bursts that could be novel probes of the intergalactic medium (Lorimer et al. 2007; Thornton et al. 2013).

The science output of these single-dish fast transients surveys only begins to describe the potential of a large interferometric survey such as the VLASS. Interferometers, while technically more demanding, can improve on all of these science cases by their:

- **Precise localization:** Interferometers image with arcsecond precision, as shown in the image of a pulsar pulse shown in Figure 1.
- **High survey speed:** Interferometers have large fields of view and are powerful survey machines.
- **Robust calibration and interference rejection:** Interferometers can measure fluxes more accurately and reject interference that complicates single-dish fast transient searches.

Below, we describe science applications of fast (subsecond) integrations in the VLASS. This effort builds on years of effort by co-authors of this white paper, including building custom correlators, commissioning WIDAR, performing blind archival transient searches, and writing software for fast integration data analysis. These efforts have reduced the technical risk enough to make it feasible to incorporate fast transients science into the VLASS.

2. Fast Transient Science

2.1. Fast Radio Bursts

The recent discovery of six millisecond-long radio pulses by the Parkes Observatory has revealed a new population of radio transients: the FRB (Lorimer et al. 2007; Keane et al. 2011; Thornton et al. 2013). The key feature of the FRB is

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[1] UC Berkeley

[2] RCUH, ASIAA

[3] Caltech

[4] JPL

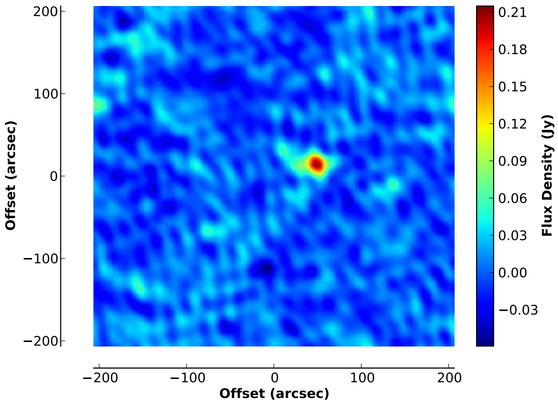

Fig. 1.— VLA image of a pulse from transient pulsar J0628+0909. This detection provided the first arcsecond localization of the pulsar, which excluded its association with luminous optical counterparts expected toward young pulsars (Law et al. 2012).

its frequency-dependent arrival time, the magnitude of which is quantified by the dispersion measure (DM). While values of 30 pc cm^{-3} are typical toward lines of sight at high Galactic latitudes, FRBs have DMs as high as 1100 pc cm^{-3}, consistent with propagation through the IGM from distances up to z$\sim$1. Unfortunately, the only successful FRB detector to date, the Parkes Radio Observatory, localizes FRBs to worse than 15′, rendering association of FRBs with hosts or higher-energy emission difficult. FRBs are so new, that we still need to answer two basic questions about them: *What are they?* and *How can we use them?*

FRBs may be powerful probes of the IGM. At low redshift, the baryons in the IGM are difficult to detect, despite the fact that they represent about half of the local baryonic mass. The strongest evidence of this massive reservoir comes from a handful of disputed detections of X-ray absorption by ionized metals (Nicastro et al. 2005; Rasmussen et al. 2007). The difference between simulations and measured baryonic mass in the IGM is known as the "missing baryon problem". However, millisecond transients are unique probes of the IGM because dispersion leaves a signature that is very easy to measure. Combining DM with knowledge of the distance to the source directly measures the electron density, an unambiguous proxy for baryonic density. Detailed models of the Galaxy's electron density have been built this way (Cordes & Lazio 2002, 2003; Bower et al. 2013) and FRBs could allow us do the same for the IGM.

To use FRBs as probes of the IGM, they must be associated with host galaxies to measure their distance. A VLA localization of arcsecond or better precision makes it easy to identify counterparts to a redshift of 1. In this way, *a single FRB association* could make the first unambiguous measurement of the mean baryon density of the low-redshift IGM. Fast dumps in the VLASS could detect *a sample of FRBs* to allow unique statistical constraints on the halo mass near the virial radius, which will constrain models of galaxy formation and feedback (McQuinn 2013).

Beyond using FRBs as probes, understanding the origin of FRBs may have relevance to gamma-ray bursts and sources of gravitational waves. Models for the origin of FRBs must account for radio luminosities of order 10^{43} erg s^{-1}, far beyond that of the most common source of millisecond radio pulses, Galactic neutron stars ($\sim 10^{34}$ erg s^{-1}; McLaughlin & Cordes 2003). Yet, with an estimated rate of roughly 10^3 galaxy^{-1} yr^{-1}, these events are roughly as common as core-collapse supernovae (Diehl et al. 2006).

Since the establishment of FRBs as a new class of transient, a host of models have been developed to explain their properties. Two popular processes are the births of degenerate objects (WD, NS, and BH) and mergers of binary degenerate objects (Falcke & Rezzolla 2013; Zhang 2013; Totani 2013; Kashiyama et al. 2013). Each model predicts association with a cataclysmic event with counterparts in the optical or at high-energies. Models involving merging binary neutron stars are further justified by existing models that argue for the presence of a "protomagnetar" as an energy source for extended emission in short GRBs (Metzger et al. 2008). These mergers are also the most likely GW events detected by Advanced LIGO and will also have detectable electromagnetic counterparts (Metzger & Berger 2012). Fast dumps in the VLASS could detect a sample of FRBs and associate their hosts to test these origin models.

2.2. Pulsars, RRATs

Interferometric searches would also be powerful in the study of a new class of sporadic Galactic pulsars known as Rotating Radio Transients

(RRATs). RRATs were discovered using the same single-dish telescope and technique used to find FRBs (McLaughlin et al. 2006). Several surveys have now identified a few dozen RRATs, but their relation to the larger population of NSs is not clear. RRATs may be aged magnetars, as suggested by their long period and the association of one source (J1819–1458) with a magnetar (Lyne et al. 2009). In contrast, it has been suggested that RRATs are actually ordinary pulsars with extreme pulse amplitude modulation (Weltevrede et al. 2006) or "nulling" behavior (Burke-Spolaor & Bailes 2010). Since the radio emission represents a trivial part of the energy emitted by NSs, it is difficult to develop physical models from radio phenomenology.

Associations between radio and X-ray bands are critical, since the radio emission defines the class, but X-ray emission dominates the energy output of the NS (Kaplan et al. 2009). Are all RRATs X-ray luminous, indicating a strong magnetic field? Or can we limit the X-ray luminosity from RRATs to show that the categorization of "RRAT" is more complex? These questions are best addressed by precisely localizing the radio emission of RRATs and searching for X-ray luminous counterparts. The VLASS would be sensitive to a sample of RRATs, which would allow statistical tests of models for their origin and association with multiwavelength counterparts.

The VLASS could also be used to search for individual pulses from pulsars in nearby galaxies. Recently, (Rubio-Herrera et al. 2013) used the WSRT to detect a sample of millisecond pulses (including one repeating source) toward M31. Pulsar "giant pulses" are the most likely source of these pulses and detections from M31 would be the most distant detected and associated with a host galaxy (McLaughlin & Cordes 2003). The dispersion measure of of any pulses known to be in M31 would constrain the baryon content of the halo of the Milky Way and M31 (Fang et al. 2013). This approach would make the first unambiguous measurement of the baryon content, which would help address the missing baryon problem in a new way (Nicastro et al. 2005; Bregman 2007). Our group is using the VLA for a full imaging search of M31 using P band at 10 ms cadence, which we expect will detect of order 10 pulses. A fast dump mode on the VLASS could also detect a sample of extragalactic pulses from galaxies in the local group.

A new application of fast interferometers is the search for periodic millisecond pulses from pulsars. Single-dish telescopes have discovered nearly all known pulsars via blind surveys for periodic emission (e.g., Keane et al. 2010). After detection, a pulsar's pulse arrival times are used as clocks to measure their motion and spin down rate, which helps identify interesting binary systems or neutron stars with strong magnetic fields. Unfortunately, each pulsar must be timed over a year (using timing parallax) to build a reliable model and know whether it is interesting. Interferometry can help address this problem by simultaneously detecting, localizing, and timing pulsars. The precision of a VLA localization is better than $1''$, comparable to a year's worth of single-dish timing observing and good enough to break degeneracies between pulsar spin-down (related to magnetic field and binarity), dispersion measure, and location.

2.3. Flare Stars, Ultracool Dwarfs, Exoplanets

At radio frequencies below about 40 MHz, Jupiter emits intense radio bursts that make it the brightest astronomical object in the solar system. The bursts are caused by the electron cyclotron maser instability, which is driven by coupling of the stellar wind to the planet's magnetosphere and its interaction with moon Io (Farrell et al. 1999). The intensity of these outbursts suggest that magnetic exoplanets and stars (flare stars, M dwarfs, brown dwarfs) could be identified in blind radio transient surveys on timescales from milliseconds to seconds (Osten & Bastian 2006). If so, they could be used to measure magnetic activity and infer stellar/planetary rotation periods based on burst repetition rates (Hallinan et al. 2007). In fact, blind VLA surveys toward the Galactic center at 330 MHz may have already identified such a stellar transient (Hyman et al. 2005). Targeted efforts to detect hot Jupiters at GHz frequencies have been unsuccessful, which suggests their either their burst duty cycle is low or their magnetic fields are too low to allow the radio emission to escape (Bastian et al. 2000; Lazio et al. 2004).

Coronal mass ejections, powerful analogues of those seen in our own sun, also drive radio coherent radio flares via a variety of physical mechanisms. These events are both unique diagnostics of stellar plasmas and are expected to profoundly affect the habitability of orbiting exoplanets (Tarter et al. 2007). Stellar radio bursts have been detected at frequencies as high as several GHz, particularly in M dwarfs (Berger 2002; Hallinan et al. 2006; Osten & Bastian 2006). Extremely bright bursts up to ~ 1 Jy (Lovell 1963) have been detected for decades from nearby M dwarfs, at luminosities that are up to 5 orders of magnitude more intense than any equivalent solar bursts.

Both of these mechanisms should be detectable to the VLASS at subsecond timescales. A GHz-frequency survey, combined with the V-LITE project studying 330 MHz emission, will detect stars as transients to probe stellar plasmas and magnetospheres over a range of magnetic field strengths. Blind interferometric surveys will identify the location of the radio transient, which will allow follow-up optical lightcurves and spectroscopy for typing the star and understanding its multiplicity. This application of the VLASS would be especially powerful if done in coordination with optical syoptic surveys, such as PTF and Pan-STARRS.

3. Use Cases

Here we outline how the VLASS could produce fast dumps and what science is accessible for each case. Table 1 shows the performance of a few possible correlator configurations. Almost all the science topics discussed above are accessible at lower VLA frequencies, so we only discuss the two lower bands being seriously considered for the VLASS, S and C band.

For comparison, the most advanced Parkes pulsar survey, the High Time Resolution Universe (HTRU; Keith et al. 2010) survey has a sensitivity in 5 ms of 18 mJy. The fastest and most sensitive VLA mode is the 5 ms, 256 MHz bandwidth mode listed in Table 1, which has a sensitivity of 12 mJy. The HTRU survey time on sky is comparable to that planned for the VLASS and its instantaneous sky coverage is roughly 6 times larger than the VLA at 2 GHz. In effect, a fast dump VLASS mode would be equivalent to a deeper, narrow-field HTRU survey.

3.1. Temporary Fast Dumps with Real-Time Transient Detection

Fast dump correlator modes produce large amounts of data that will strain the archive. A goal of our group is to detect candidate transients in real time and save data only associated with candidate events. This would be ideal for a fast-dump VLASS mode, since this would help contain the total archived data volume. Real-time transients searching is also a priority of the V-LITE/LOBO project, so developing this software is of broader interest.

One way to integrate fast transients science into the VLASS would be to configure the correlator to produce two data streams, fast and slow. The slow (~ 1 s) stream can produce the normal VLASS data product, while the fast stream can be searched in real-time for transients. The fast transient search can be done as computation and disk space allows. WIDAR is already partially designed around a small compute cluster that could be used for real-time transient detection. Our dispersion-based imaging transient search pipeline can process in real time for a 5-ms integration time in configurations C or smaller. This search parallelizes well, so larger arrays can be supported by expanding the compute cluster.

Our ongoing VLA search for FRBs uses the 5 ms mode described in Table 1 in L band. For the nominal rate of 10^4 events sky^{-1} day^{-1} (Thornton et al. 2013), we infer an L band search in that mode will detect one event in 30 hours of observing, with an order of magnitude uncertainty based on Poisson errors on the number of detected events. For a nominal VLASS observing time of 5000 hours, we scale our L-band detection rate to S band and expect 15–150 events; for a C band survey, we expect to detect 5–50 events. As described above, each detection would allow us to associate the FRB with a host, measure the density of the IGM, in addition to their spectral index and luminosity.

The rate of detection of RRATs can be scaled from the HTRU survey. Burke-Spolaor et al. (2011) report detections from initial analysis and extrapolate a total of roughly 200 detections of RRATs and other transient neutron stars in the HTRU survey. The VLA 5 ms, 256 MHz fast dump mode is more sensitive than the HTRU at

TABLE 1
SENSITIVITY AND DATA RATE FOR FAST DUMPS IN VLASS

Band, BW	t_{int} (ms)	Sensitivity (Stokes I, 1σ [a])	Data Rate (MB s^{-1}, dual-pol)
S Band, 1.5 GHz, 2 MHz chans	1 s	0.34 mJy	4 MB/s
S band, 1.5 GHz, 2 MHz chans	50 ms	1.5 mJy	82 MB/s
S band, 256 MHz, 1 MHz chans	5 ms	12 mJy	280 MB/s
C band, 3.4 GHz, 2 MHz chans	1 s	0.26 mJy	9 MB/s
C band, 3.4 GHz, 2 MHz chans	50 ms	1.2 mJy	185 MB/s
C band, 256 MHz, 1 MHz chans	5 ms	12 mJy	280 MB/s

[a] Assumes a bandwidth sufficient to cover known RFI-free parts of the band.

5 ms timescales, which is adequate to sample the width of most pulses. The HTRU detection rate can be scaled to the VLASS by their relative time on sky and instantaneous field of view and spectral index effects. A typical neutron star pulse has a spectral index of –0.7, which reduces their brightness by roughly 40% in S band and 60% in C band. Assuming a similar survey duration as the HTRU, this fast dump S band survey would detect roughly 50 transient neutron stars and a C band survey would detect 10. Each detection would have arcsecond or better localization, which would allow them to be unquely associated with X-ray counterparts to test models for their origin and emission processes.

Incorporating a fast correlator data products into the VLASS would open access to timing of pulsars. The VLASS would be sensitive to pulsars with periods longer than a few times the integration time up to the dwell time on a single field. Since the VLASS will likely use on-the-fly mapping, the dwell time per field will be less than a few minutes.

The radio emission from UCDs and other stars with strong magnetic fields is only beginning to be observationally constrained. Stellar flares, such as from M dwarfs, is easiest to detect at low frequencies, but has also been detected in all proposed VLASS observing bands (Berger 2002; Hallinan et al. 2006). In the case of emission by the cyclotron maser instability, the radiation is beamed over a few degrees and requires rapid rotation, so only 9% of late M dwarfs are detectable as persistent sub-mJy, GHz sources (Antonova et al. 2013). The detectability of the impulsive, mJy-level emission (i.e., a VLASS, subsecond transient) is smaller by an unknown fraction, since inclination effects and secular changes are poorly constrained (Hallinan et al. 2008). Fast, coherent bursts originating in coronal mass ejections are more common and luminous, with some nearby M dwarfs expected to be visible to distances of hundreds of parsecs. Local M dwarfs have a volume density of of 0.1 stars pc^{-3}, which means that a volume of 100 pc radius will have a projected density of 10 M dwarfs per square degree. Thus, a typical C band field of view will likely include an M dwarf, while an X band field will include one per 5 unique pointings. This fact, combined with the duration of the VLASS, means that a transient survey will either detect or make new constraints on the duty cycle of such bursts.

3.2. Full VLASS with Fast Dumps

A second approach to fast transients science in the VLASS is to set the integration time as low as is feasible. As shown in Table 1, using maximal bandwidth (as expected for the VLASS) will more likely to be limited by high data rate than integration time. For wide-band, continuum observing, a fixed data rate of 60 MB s^{-1} corresponds to a integration time for S band will be 70 ms, while for C band the limit is 150 ms. This observing strategy could be combined with a real-time transient detection system described above to reduce the total archived data volume. The transient detection could be run on the fast data stream, which can also be integrated down to a 1-s data stream for archiving as the normal VLASS data product.

The sensitivity to underresolved pulses drops as the square root of time, since time diluation is partially countered by improved sensitivity. For integration times of order 50 ms, we expect to detect roughly 3 (1) FRBs in a 5000-hr VLASS survey at S (C) band (Figure 2). While detected at a reduced detection rate, any detected FRBs would have a localization precision better than an arcsecond and a dispersion measure known to a prcision of 100 pc cm^{-3}, adequate to do the IGM science described above.

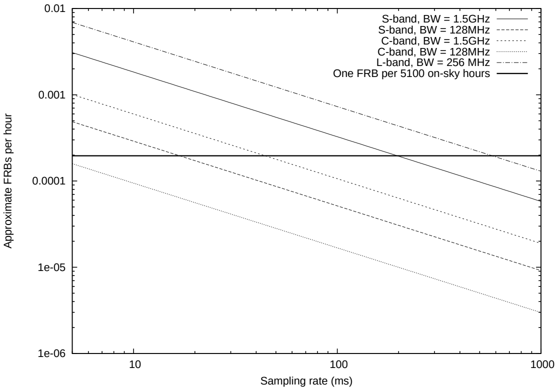

Fig. 2.— Estimate of the rate of FRB detection for fast dump VLASS modes longer than 50 ms.

Most science cases presented here have diminished impact for timescales of 100 ms or longer. The application to stellar flares is probably not impacted, since they are known to be variable on timescales ranging from milliseconds to minutes.

4. Conclusion

The study of fast (< 1 s) radio transients is an great example of a "needle in the haystack" problem. The signal is rare and weak, but has structure (e.g., dispersed, broadband, impulsive) that distinguishes it from all other signals. These features make the study of fast radio transients limited both by the amount of observing time (the haystack) and our ability search the data efficiently (finding the needle). With a careful consideration of the correlator and computational resources, the VLASS offers a great opportunity for discovery of fast radio transients.

REFERENCES

Antonova, A., Hallinan, G., Doyle, J. G., Yu, S., Kuznetsov, A., Metodieva, Y., Golden, A., & Cruz, K. L. 2013, A&A, 549, A131

Bastian, T. S., Dulk, G. A., & Leblanc, Y. 2000, ApJ, 545, 1058

Berger, E. 2002, ApJ, 572, 503

Bower, G. C., et al. 2013, ArXiv e-prints

Bregman, J. N. 2007, ARA&A, 45, 221

Burke-Spolaor, S., & Bailes, M. 2010, MNRAS, 402, 855

Burke-Spolaor, S., et al. 2011, MNRAS, 416, 2465

Cordes, J. M., & Lazio, T. J. W. 2002, ArXiv Astrophysics e-prints

—. 2003, ArXiv Astrophysics e-prints

Demorest, P. B., et al. 2013, ApJ, 762, 94

Diehl, R., et al. 2006, Nature, 439, 45

Falcke, H., & Rezzolla, L. 2013, ArXiv e-prints

Fang, T., Bullock, J., & Boylan-Kolchin, M. 2013, ApJ, 762, 20

Farrell, W. M., Desch, M. D., & Zarka, P. 1999, J. Geophys. Res., 1041, 14025

Hallinan, G., Antonova, A., Doyle, J. G., Bourke, S., Brisken, W. F., & Golden, A. 2006, ApJ, 653, 690

Hallinan, G., Antonova, A., Doyle, J. G., Bourke, S., Lane, C., & Golden, A. 2008, ApJ, 684, 644

Hallinan, G., et al. 2007, ApJ, 663, L25

Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., & Collins, R. A. 1968, Nature, 217, 709

Hyman, S. D., Lazio, T. J. W., Kassim, N. E., Ray, P. S., Markwardt, C. B., & Yusef-Zadeh, F. 2005, Nature, 434, 50

Kaplan, D. L., Esposito, P., Chatterjee, S., Possenti, A., McLaughlin, M. A., Camilo, F., Chakrabarty, D., & Slane, P. O. 2009, MNRAS, 400, 1445

Kashiyama, K., Ioka, K., & Mészáros, P. 2013, ApJ, 776, L39

Keane, E. F., Kramer, M., Lyne, A. G., Stappers, B. W., & McLaughlin, M. A. 2011, MNRAS, 415, 3065

Keane, E. F., Ludovici, D. A., Eatough, R. P., Kramer, M., Lyne, A. G., McLaughlin, M. A., & Stappers, B. W. 2010, MNRAS, 401, 1057

Keith, M. J., et al. 2010, MNRAS, 409, 619

Law, C. J., Bower, G. C., Pokorny, M., Rupen, M. P., & Sowinski, K. 2012, ApJ, 760, 124

Lazio, W., T. J., Farrell, W. M., Dietrick, J., Greenlees, E., Hogan, E., Jones, C., & Hennig, L. A. 2004, ApJ, 612, 511

Lorimer, D. R., Bailes, M., McLaughlin, M. A., Narkevic, D. J., & Crawford, F. 2007, Science, 318, 777

Lovell, B. 1963, Nature, 198, 228

Lyne, A. G., McLaughlin, M. A., Keane, E. F., Kramer, M., Espinoza, C. M., Stappers, B. W., Palliyaguru, N. T., & Miller, J. 2009, MNRAS, 400, 1439

McLaughlin, M. A., & Cordes, J. M. 2003, ApJ, 596, 982

McLaughlin, M. A., et al. 2006, Nature, 439, 817

McQuinn, M. 2013, ArXiv e-prints

Metzger, B. D., & Berger, E. 2012, ApJ, 746, 48

Metzger, B. D., Quataert, E., & Thompson, T. A. 2008, MNRAS, 385, 1455

Nicastro, F., et al. 2005, Nature, 433, 495

Osten, R. A., & Bastian, T. S. 2006, ApJ, 637, 1016

Rasmussen, A. P., Kahn, S. M., Paerels, F., Herder, J. W. d., Kaastra, J., & de Vries, C. 2007, ApJ, 656, 129

Rubio-Herrera, E., Stappers, B. W., Hessels, J. W. T., & Braun, R. 2013, MNRAS, 428, 2857

Tarter, J. C., Backus, P. R., Mancinelli, R. L., Aurnou, J. M., Backman, D. E., & Basri, G. S. 2007, Astrobiology, 7, 30

Thornton, D., et al. 2013, Science, 341, 53

Thorsett, S. E., & Chakrabarty, D. 1999, ApJ, 512, 288

Totani, T. 2013, PASJ, 65, L12

Weltevrede, P., Stappers, B. W., Rankin, J. M., & Wright, G. A. E. 2006, ApJ, 645, L149

Wolszczan, A., & Frail, D. A. 1992, Nature, 355, 145

Zhang, B. 2013, ArXiv e-prints

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