LWA"1+" Scientific Requirements

Namir Kassim, Tracy Clarke, & Wendy Lane

Key LWA Science Drivers

- Acceleration of Relativistic Particles in:
  - Hundreds of SNRs in normal galaxies at energies up to 10^{15} eV.
  - Thousands of radio galaxies & clusters at energies up to 10^{19} eV
  - Ultra high energy cosmic rays at energies up to 10^{21} eV and beyond.
- Cosmic Evolution & The High Redshift Universe
  - Evolution of Dark Matter & Energy by differentiating relaxed & merging clusters
  - Study of the 1st black holes & the search for HI during the EOR & beyond
- Plasma Astrophysics & Space Science
  - Ionospheric waves & turbulence
  - Acceleration, turbulence, & propagation in the ISM of Milky Way & normal galaxies.
  - Solar, Planetary, & Space Weather Science
- Transient Universe
  - Possible new classes of sources (coherent transients like GCRT J1745-3009)
  - Magnetar Giant Flares
  - Extra-solar planets
  - Prompt emission from GRBs

LWA Scientific Specifications

(update of specs originally presented in LWA Memo #49)

	Required#	**Desired#**
Frequency Range	20 MHz to 80 MHz	10 MHz to 88 MHz
Spatial resolution	$\theta \leq [8,2]''$	$\theta \leq [6,1.5]''$
Largest Angular Scale	$[8,2]^\circ$	$>[8, 2]^\circ$
Baseline range	107 m to 470 km	<107 m to 535 km
Sensitivity [20,80 MHz]: (1 hr, 4 MHz, dual pol.)	$\sigma = [1.0,0.5]$	$\sigma < [1.0, 0.5]$
Number of Stations	52 x 256 stands	>52 x 256 stands
Dynamic range:	10^4	$>10^4$ (per channel)
$\Delta\nu_{max}$ (per beam)	32 MHz (R<0.5 km) 8 MHz (R>0.5 km)	Full RF
$\Delta\nu_{min}$	0.1 kHz	0.01 kHz
Temporal Res ($\Delta\tau$)	1 msec	1 ns
FoV [20,80] MHz	$[8,2]^\circ$	$> [8,2]^\circ$
Polarization:	Dual orthogonal	Dual orthogonal
Sky Coverage	$z \leq 74^\circ$	$z \leq 80^\circ$
Simul. Beams	3 spatial & frequency	> 3

#: parameter range calculated for [20,80] MHz

Phased Development

Time	Phase	Description	Acronym
2004	0	Existing 74 MHz VLA	VLA74
2006-2008	I Funded!	Long Wavelength Development Array +Long Wavelength Array Station #1	LWDA LWA-1
2007-2008	**Ib**	**LWA Station #1 (LWA-1) + LWA Outlier Stations (LWA-2 & 3)**	**LWA-1+**
2008-2010	II	9 station Long Wavelength Intermediate Array	LWIA
2010-2012	III	LWA Core + Outliers	LWAC
2012-2014	IV	High Resolution LWA	LWA
2009-	V	LW Operations and Science Center	LWOSC

Focus here on science with LWA-1+

LWA-1 Scientific Value Assessment

- Scientific Value Scale
  - (1) Fundamental Advance (e.g. Nature paper)
  - (2) Good dissertation topic
  - (3) New, but not terribly exciting (i.e., unlikely to be funded solely for scientific merit)
  - (4) Not new, but worth doing because it helps validates the instrument or trains people

- Rating LWA-1 Science
  - Transients: ~1.5
  - RRL-based ISM studies: ~2.1
  - Pulsar-based ISM studies ~2.1
  - Pulsar studies: ~2.7
  - Solar system- Jupiter: ~3.3; Sun: ~3.3

LWA-1 Sensitivity

- Assumptions
  - 256 stands (aka 512 dipoles), $\Omega_{dipole} = [(\pi/180)*100^{o}]^2$
  - $T_{sys} \sim 2000$ K $[74/\nu\ (\text{MHz})]^{2.6}$
- Collecting Area
  - $A_{e\text{-dipole}} = \lambda^2 / \Omega_{dipole}$
  - $A_{e\text{-dipole}} \sim 74\ \text{m}^2\ (20/\nu\ (\text{MHz}))^2$ [5.4 m^2 @ 74 MHz]
  - $A_{e\text{-station}} \sim 1.9 \times 10^4\ \text{m}^2\ (20/\nu\ (\text{MHz}))^2$ [$\sim 1.4\text{x}10^3\ \text{m}^2$ @ 74 MHz]
    - $VLA_{74} \sim 2 \times 10^3\ \text{m}^2$
- Sensitivity: $\sigma_{rms} = 2\ k_B T_{sys} / [\varepsilon A_{e\text{-station}} * (2\Delta\nu\Delta t)^{1/2}]$
  - $\Delta\nu = 8$ MHz, $\Delta t = 1$ hr: $\sigma_{rms} \sim$ [74, 36] mJy at [20, 74] MHz
  - $\Delta\nu = 8$ MHz, $\Delta t = 5$ min: $\sigma_{rms} \sim$ [256, 124] mJy at [20, 74] MHz
    - Assume system efficiency $\varepsilon = 0.5$

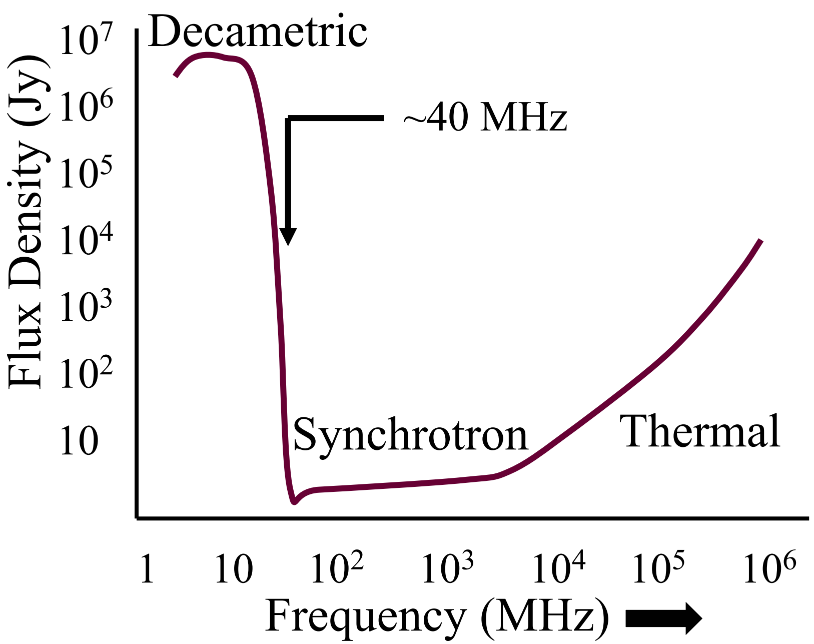
LWA-1 Science: Transients

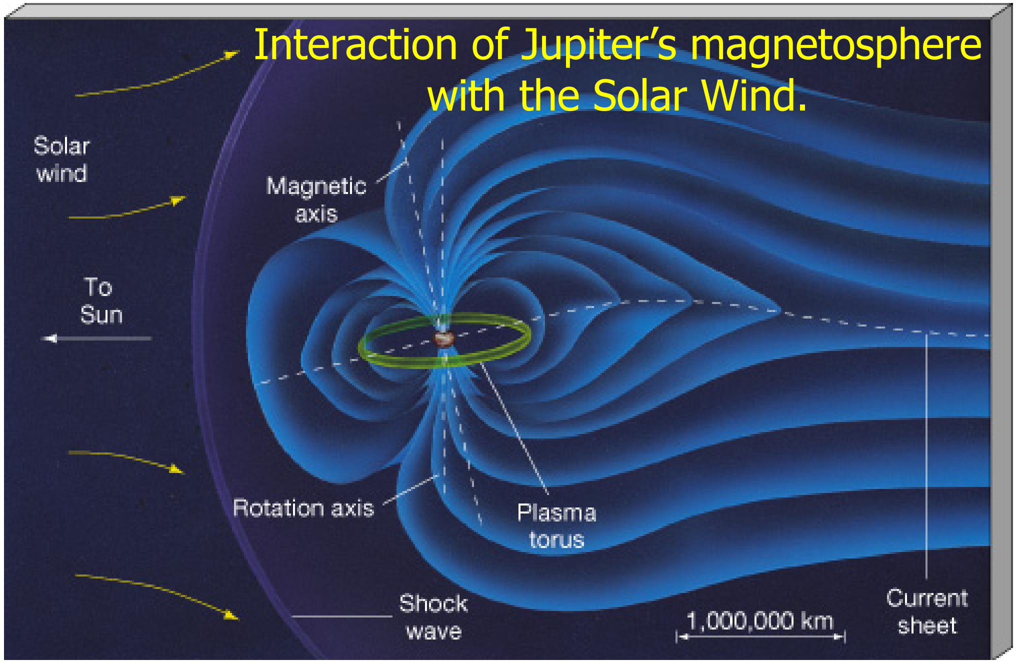
- Background: Existing HF/VHF experiments - ETA & GASE
  - Emphasize all-sky observing and real-time de-dispersion capability
  - Focused on search for prompt, coherent radio emission from GRBs
- Advantage/complement of station-based LWA-1 observations is angular resolution & sensitivity – suggested programs include
  - Target known candidates at multiple frequencies
    - Multiple beams at different ν to provide wide bandwidth measurements
    - Targets inc. GRBs, Crab Pulsar, Galactic Center, nearby flare stars, known exo-planetary systems
  - Serendipity-driven – target numerous fields
    - Survey entire sky by pointing multiple-ν beams at a different field each day, or
    - Form fan-beam by stacking multiple single-ν beams along meridian
      - Latter emphasizes sky coverage over bandwidth
  - Gaining rudimentary experience now with LWDA drift scans

Key advantage over VLA: ability to inflate Ω*t through long dwell times

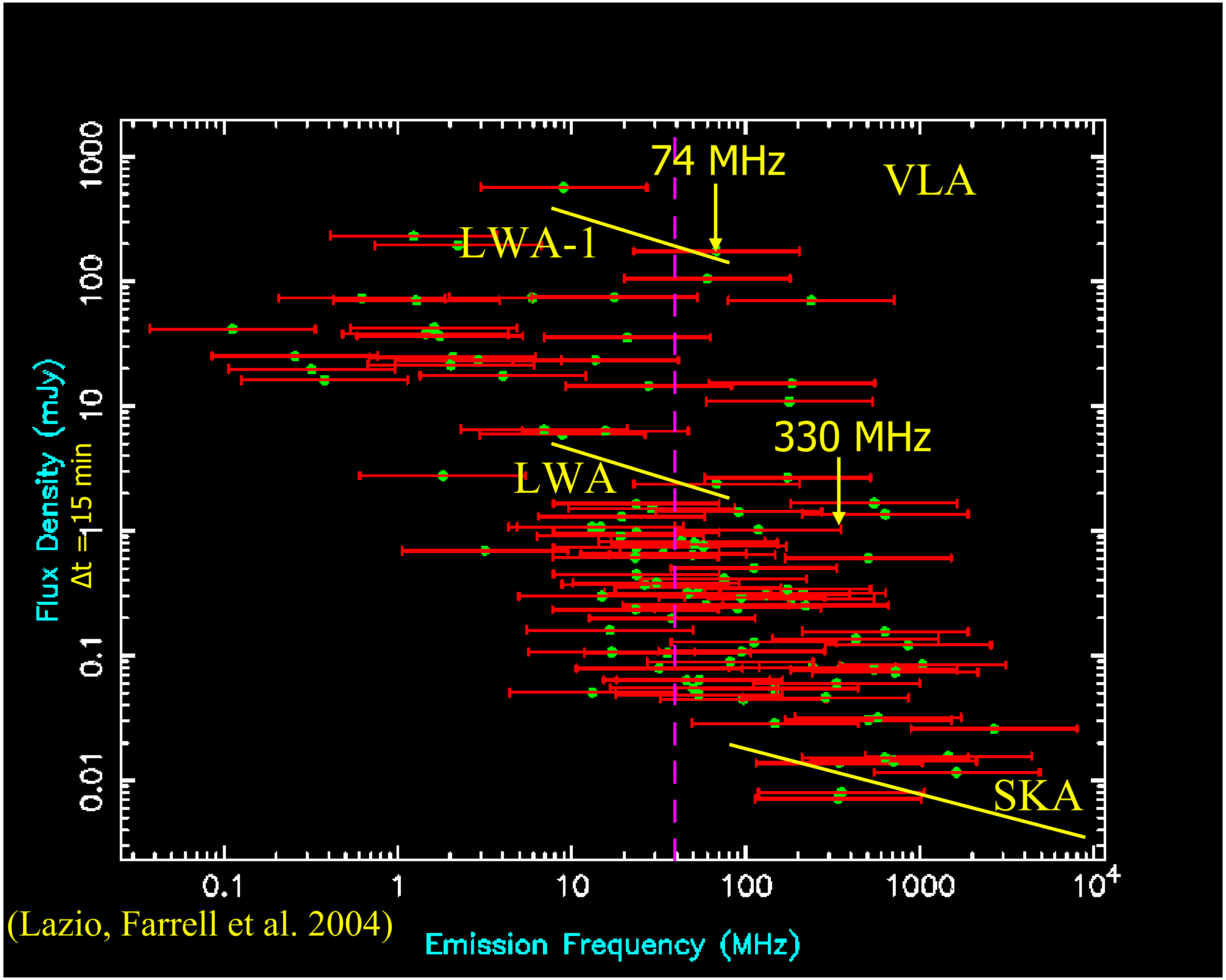
LWA-1 Transient Science: Exo-Planet Magnetospheres

- Below 40 MHz, Jupiter, when bursting, is brightest object in solar system
- LWA might detect emission from extra-solar "Jupiters"
  - Independent verification of planetary systems using new technique.
  - Proof of magnetosphere – magnetic shield of cosmic rays pre-requisite for life?
  - LWA-1 pathfinder observations – long shot, but advantage over current VLA searches through longer integrations and at lower frequencies

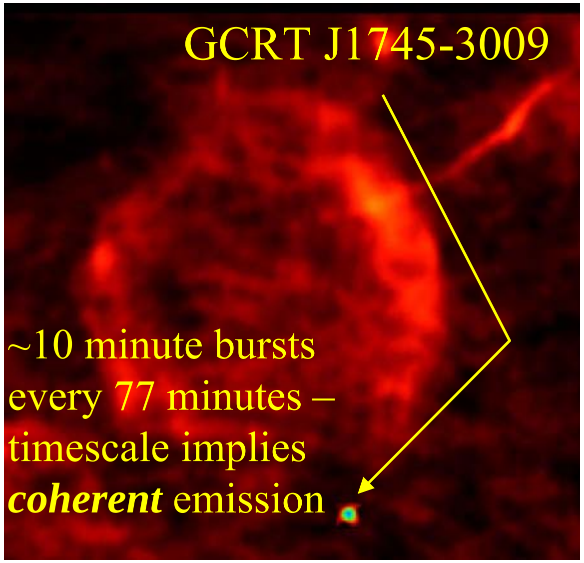


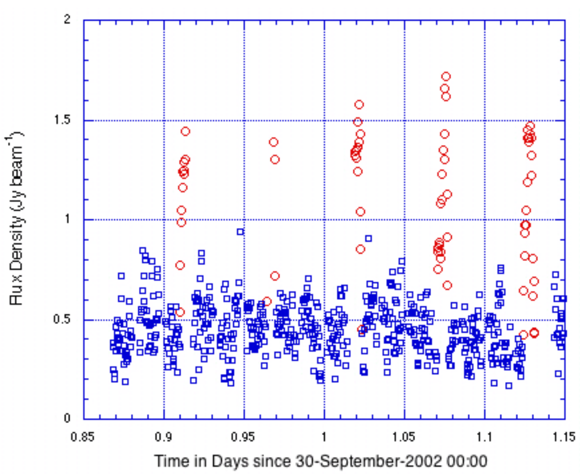


LWA-1 Transient Science:
Predicted Planetary Radio Emission



LWA-1 Transient Science: Known Galactic Examples





- Consider GCRT J1745-3009 (Hyman et al. 2005)
  - Bursts: ~ 1 Jy at 330 MHz, ~10 minutes duration
    - If coherent ($S \propto \lambda^6$) – up to 10^4 boost at 74 MHz
  - LWA-1 Detectability
    - 5 min, 8 MHz, 74 MHz: 1σ ~63 mJy
    - Situation 10X worse towards GC
      - T_{sys} ~10^4 K towards GC, A_e down by 2X
      - 1σ ~0.6 Jy; $\geq 5\sigma$ detection if $\alpha \leq -1$
- Consider recent eruption of SGR 1806-20
  - ~ 0.5 Jy at 240 MHz
  - α ~ -2.1 => 5 Jy at 74 MHz – lasts for many days
  - 1 hr, 8 MHz, 74 MHz: 1σ~0.4 Jy➔ >12 σ detection
- These known cases look very feasible
  - Especially considering leverage in Ω*t space

LWA-1 could do exciting transient work!

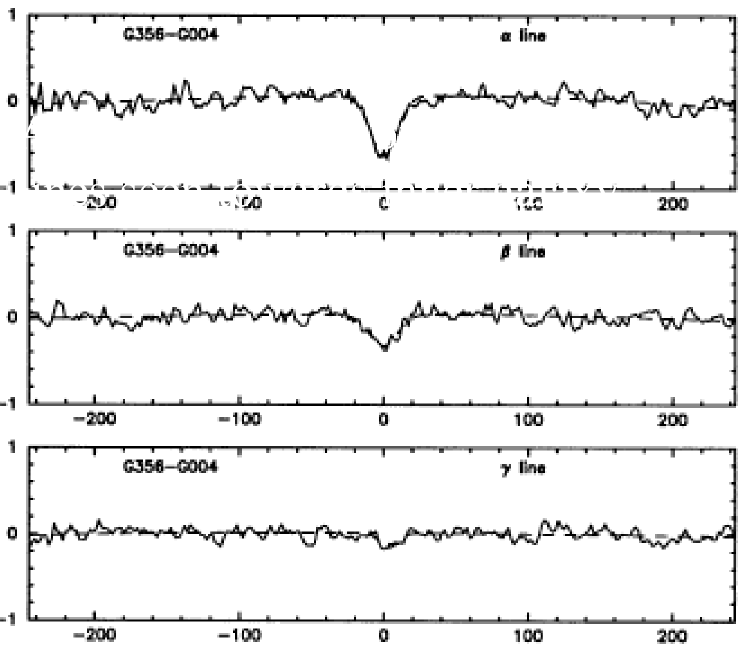
LWA-1 Science: ISM Studies Using RRLs

Carbon & Hydrogen Radio Recombination Lines are unique diagnostics of the cold ISM at very low frequencies

- Carbon RRLs are of particular interest
  - Detected to very high Rydberg states (up to n~768)
  - Absorption lines below 150 MHz (in emission above that)
  - Atoms very sensitive to interstellar environment - permit excellent measurements of ρ, T, & ionization levels (Payne et al. 1994).
  - Seen all along inner Galactic plane (Erickson et al. 1995)
- LWA-1 offers improvements over other instruments
  - Parkes 64 m: 100 m LWA-1 improves resolution
  - NRAO 300 ft (transit instrument): tracking ability of LWA-1 superior
  - Frequency range: LWA-1 could study the lines at multiple frequencies
    - Essential for understanding underlying physics
    - Wider ν range than Parkes or UTR-2
- RFI will make detection very challenging
  - Lines no longer detectable at Parkes
  - LWA-1 detection: excellent demonstration of ability to do sensitive work in the SW-US

LWA-1 will improve over current capabilities.

LWA-1 Science:
ISM Studies using RRLs



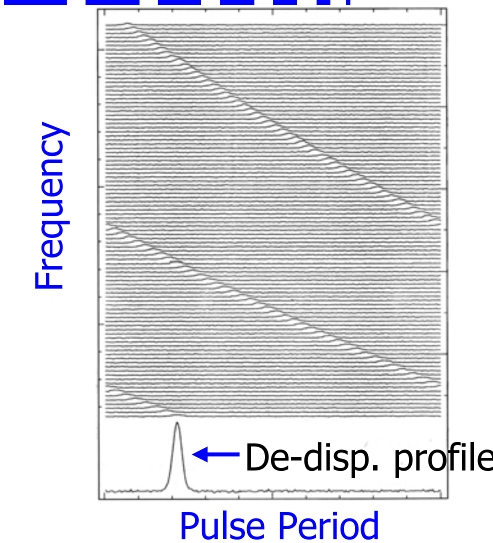
Erickson et al. 1985

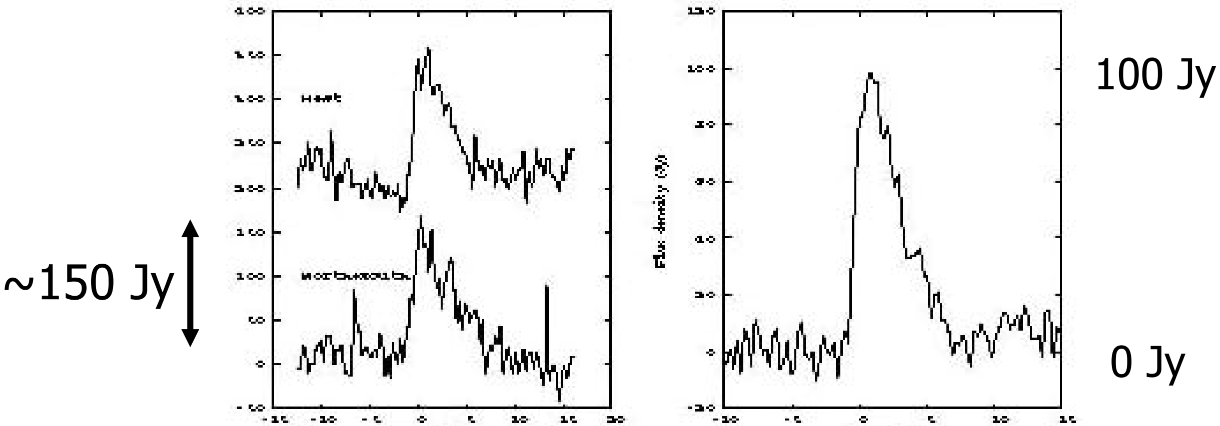
- Sensitivity Calculation
  - 1 line, 1 polarization: 10 hours
    - Frequency independent
    - $\propto$ [filling factor]$^{-2}$
- Single LWA Station
  - Can do several lines at once, 2 pol
  - Detect in ~ [5,25] hrs @ [≤40,74] MHz
  - Higher frequency work takes more time
    - Need access to lowest LWA ν range
  - Need Δν=0.1 KHz (1-2 km/s @25 MHz)

LWA-1 will push beyond Parkes - a Galactic plane survey (student thesis?) is very feasible.

LWA-1 Science: Pulsars

- Detect single pulses via de-dispersion – use to
  - Investigate physics of PSR emission mechanisms
    - Drifting pulses, profiles, inter-pulses
  - Derive pulse-averaged low frequency spectra over LWA range
    - ***Poorly known, especially in lowest LWA frequency range***
- Giant pulses (GPs) & other spurious PSR emission
  - Crab GPs now observed at 23 MHz (Popov et al. 2006)
    - GP spectra do not appear to follow simple power law
  - LWA-1 will search for spurious emission from other nearby, bright PSRs
    - Crab-like GP "echoes" lasting days – possible new probe of small-scale structure within inner synchrotron nebula (Crossley et al. 2006, astroph/0612109)

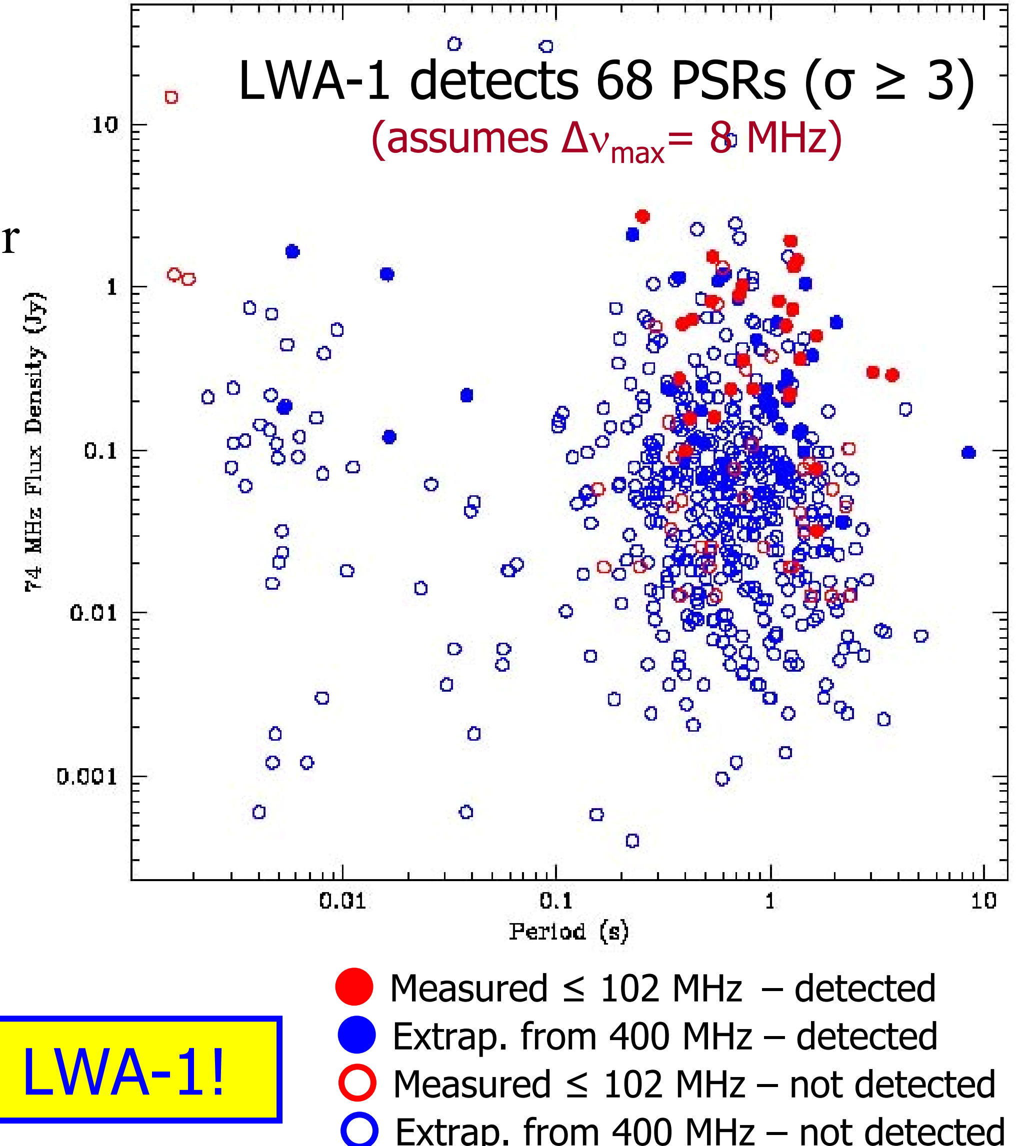




Crab Giant Pulses at 23 MHz: left panel – single pulse in two adjacent frequency channels; right panel – average of 10 strong pulses

LWA-1 Science: Feasibility of Detecting Pulsars

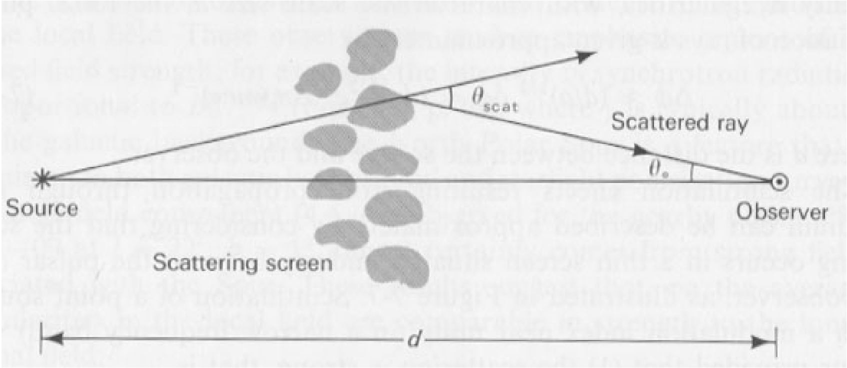
- Target bright, low DM pulsars
- Source list developed from
  - Flux density based on measured or extrapolated spectrum
  - NE2001 scattering model used to estimate pulse broadening
    - Combined with known PSR periods to pick sources that will not be scatter broadened away
  - LWDA "Pilot search" now underway for B0329+54
    - S/N for LWA-1 much higher due to greater collecting area & bandwidth



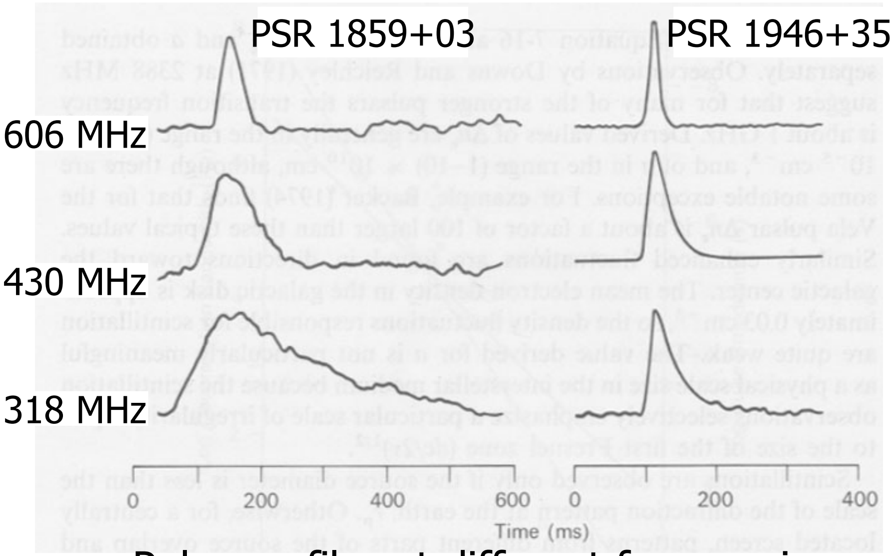
Over 60 PSRs detectable with LWA-1!

LWA-1 Science: ISM Studies Using Pulsars

- Breakdown of cold plasma dispersion law?
  - DM ≠~ $\Delta\nu^2$?
    - But Phillips & Wolszczan (1992) find no breakdown at 25 MHz
- ISM tomography from single pulse studies
  - Shapes of Crab giant pulses determined by scattering on interstellar plasma irregularities (Popov et al. 2006)
- Combine pulse broadening time with measured angular broadening to constrain distribution of line-of-site medium (Chatterjee et al. 2001)
  - Anomalous scattering at low frequencies? (Cordes & Lazio 1997)



Schematic showing geometry of source, scattering region, & observer.

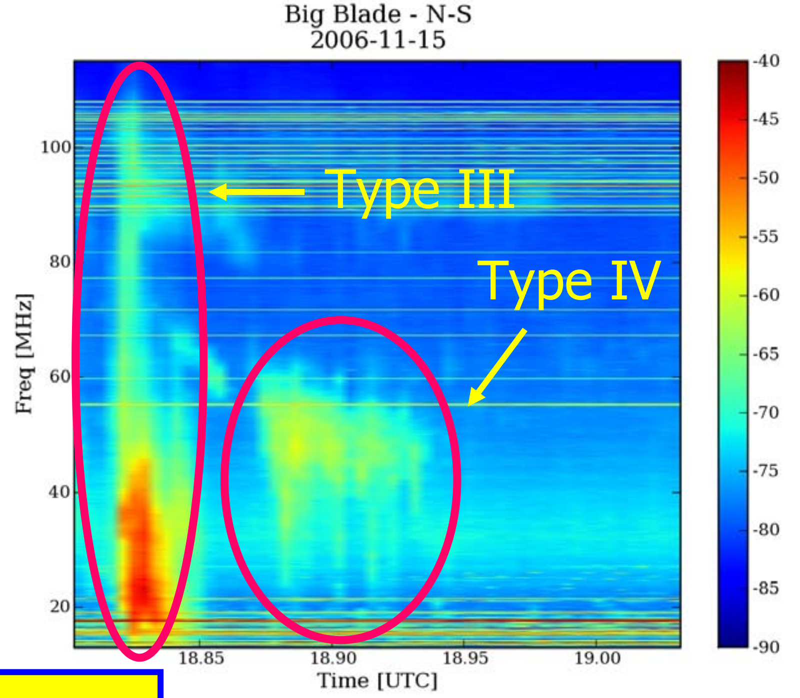


Pulse profiles at different frequencies.

LWA-1 Science: Solar System Studies

- Solar
  - Some solar bursts may have fast (~50 ms), narrow-band (<10 kHz) structure requiring more sensitivity than existing single-dipole monitoring systems (e.g. Big Blade, GBSS or BIRS)
    - See papers by G. Mann & G.P. Chernov
  - LWA-1 will allow 16X higher temporal or spectral resolution at comparable S/N to ongoing single dipole monitoring programs
- Jupiter
  - Voyager saw wealth of fine temporal & spectral structure in decametric bursts that require sensitivity of LWA-1 to observe from Earth
    - ms time resolution useful

Solar bursts are currently being studied with a single LWA dipole (aka "Big Blade")



Both applications need broad frequency range

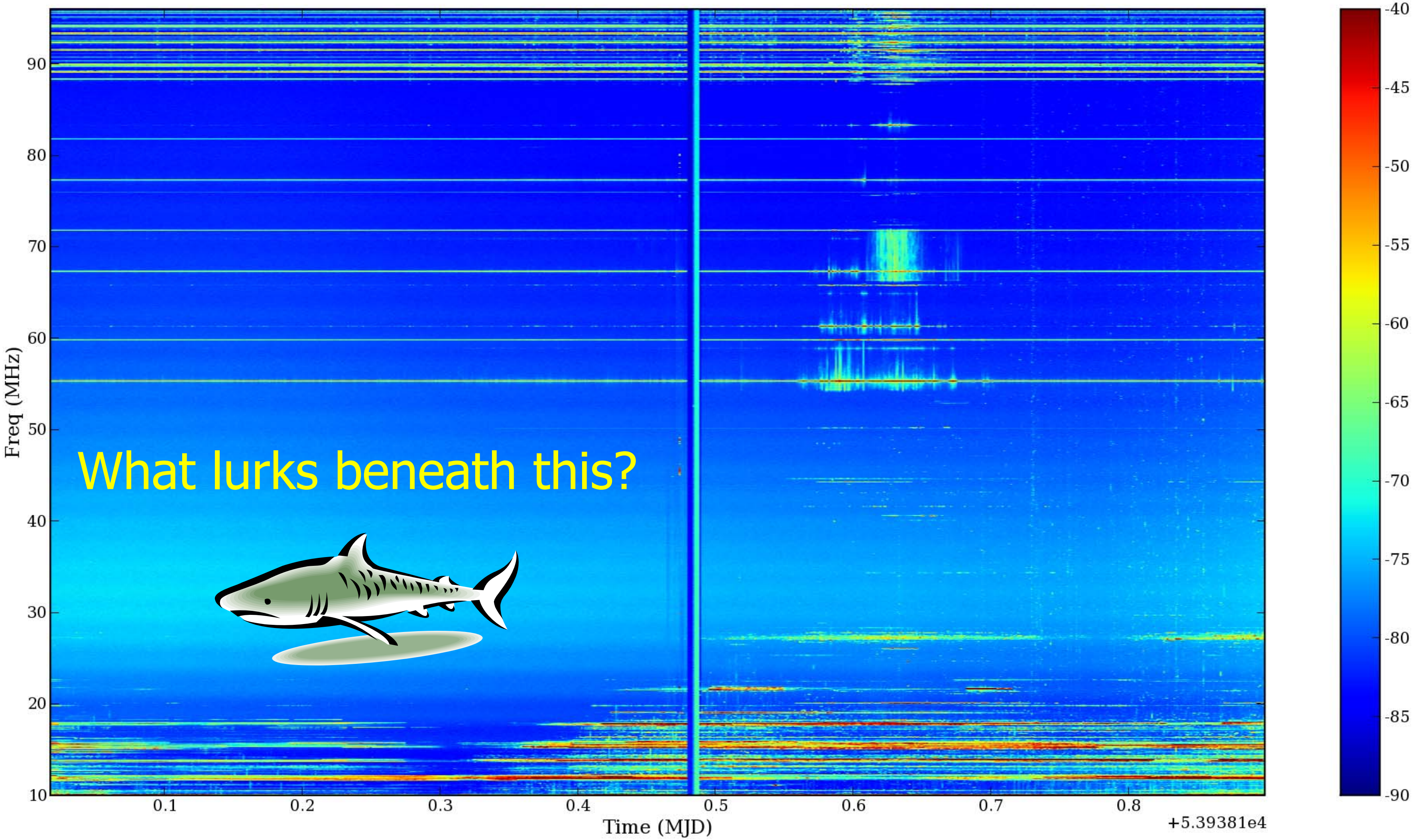
LWA-1: Pushing the Limits

Key HF/VHF scientific goals rely on assuming thermal noise limited sensitivities for very deep integrations

- LWA-1 can explore how deep we can go before ***something unexpected*** stops us & address technical questions not answerable with one dipole
  - How well can we remove RFI, & what is the effect of low level RFI not seen in normal integrations?
  - How do noise characteristics vary with time & position on the sky?
  - How stable are our pass-bands?
  - How well can we form beams & what are the effects of dipole drop-outs?
  - Can be done concurrently with ongoing science programs
  - Need measurements at different frequencies & positions in the sky

More engineering tests & commissioning experience than science – still one of the most important things we will do

LWA-1 Science: Dynamic Spectrum at VLA site



Multi-Tasking with LWA-1

- Scientific breadth of data encompassed by 1 LWA-1 beam is impressive
  - Each station beam provides rich sampling of time-frequency domain
  - Suggests multiple concurrent science & engineering programs
- Deep integrations on Galactic plane
  - Search for Galactic transients - and
  - Search for RRLs – and
  - De-disperse for fields containing known pulsars - and
  - Provide engineering experience
- Deep integrations off Galactic plane
  - How deep we can go? - and
  - Extra-solar planet searches - and
  - Pathfinder experiment for future EOR/Dark Ages studies
    - As planned by many new low frequency instruments – big & small

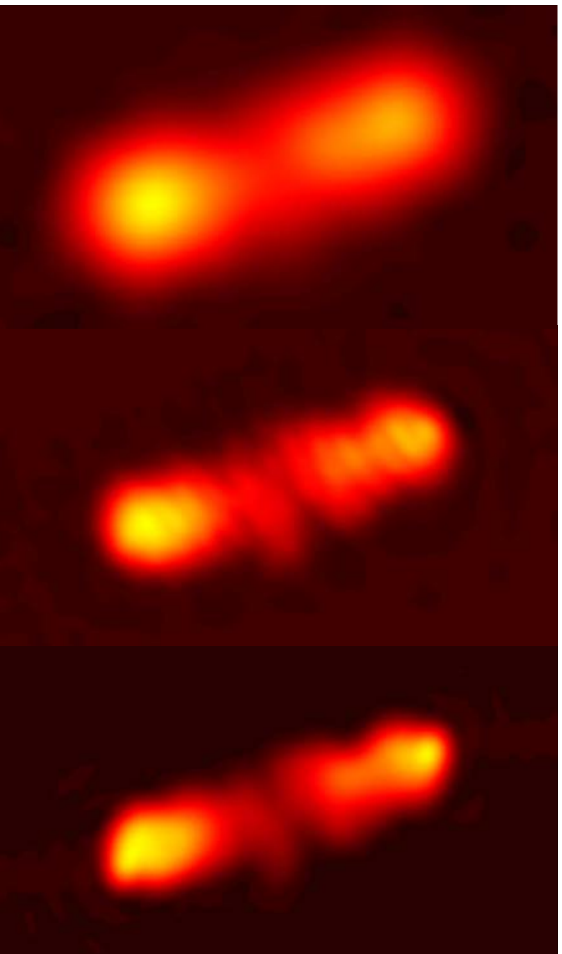
Demonstrates utility of future LWA observations with large FoV, multiple beams, & broad-band digital receivers

Science with LWA-1+

- LWA-1 with LWA-2 & 3
  - Independent operation
    - Anti-coincidence RFI avoidance for transient observations
  - Interferometry
    - Phase & model fitting to constrain accurate source positions
    - 3 stations increase accuracy via closure phase, ability to measure fluxes
    - Angular broadening/scattering measurements – is 400 km the right limit?
    - Explore deep, interferometric integrations
      - ~65 km baseline: confusion limit ~ few mJy
      - Takes days to reach with larger array – ***can we get anywhere close?***
    - Explore ionospheric scaling laws as tests of future calibration schemes
- LWA-1 with 74 MHz VLA
  - Monitor selected VLA observations simultaneously with LWA-1.
    - E.g., X-ray & radio triggered searches are planned for the GC
    - 74 MHz VLA observations of *SWIFT* triggered GRBs are planned
      - Monitor with LWA-1 at lower frequencies – dispersion an advantage.
- LWA-1+ with 74 MHz VLA
  - Imaging with LWA-2 & 3 outliers as next step beyond PT link

Science with LWA-1+: LWA 2 & 3 with the VLA

LWA-1 has 10X sensitivity of 1 VLA dish – partial LWA outlier stations can compliment VLA 74 MHz for improved angular resolution on bright objects

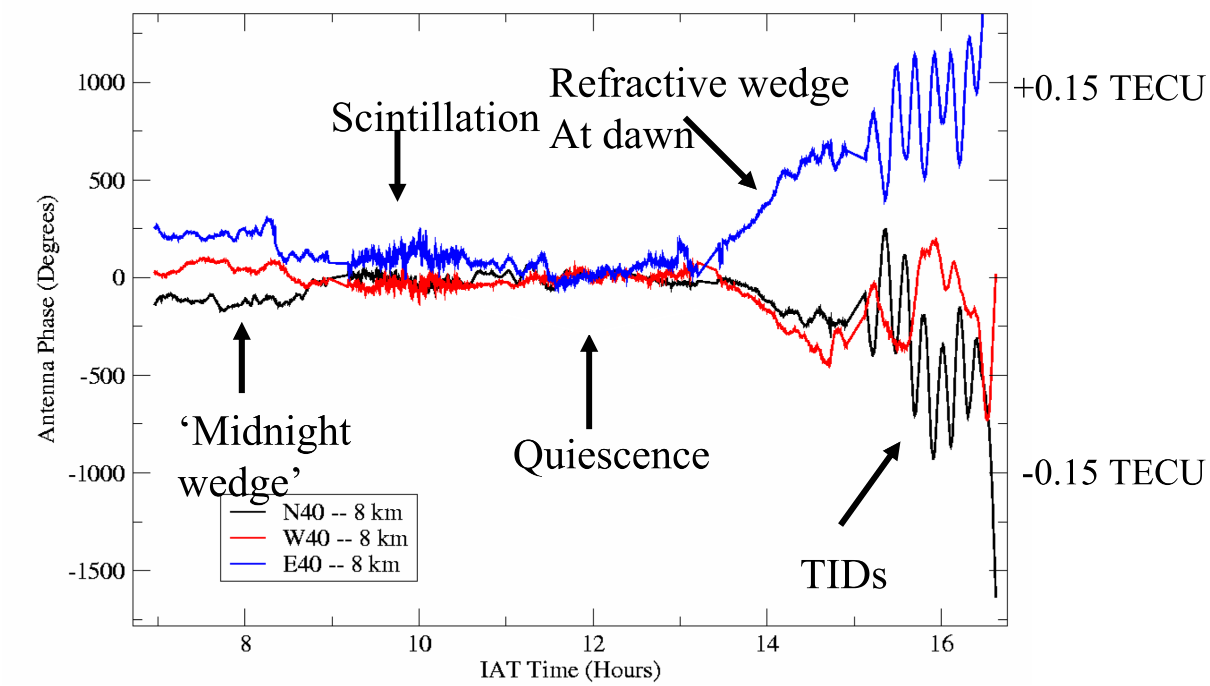


- VLA A configuration
  - Limited resolution
- VLA A+ PT
  - Resolution better, fidelity poor because of “lonely” outlier
- VLA A + PT + LWA-1+
  - Image fidelity improved with single outlier at Horse Springs

Significant impact even from only 1-2 outlier stations

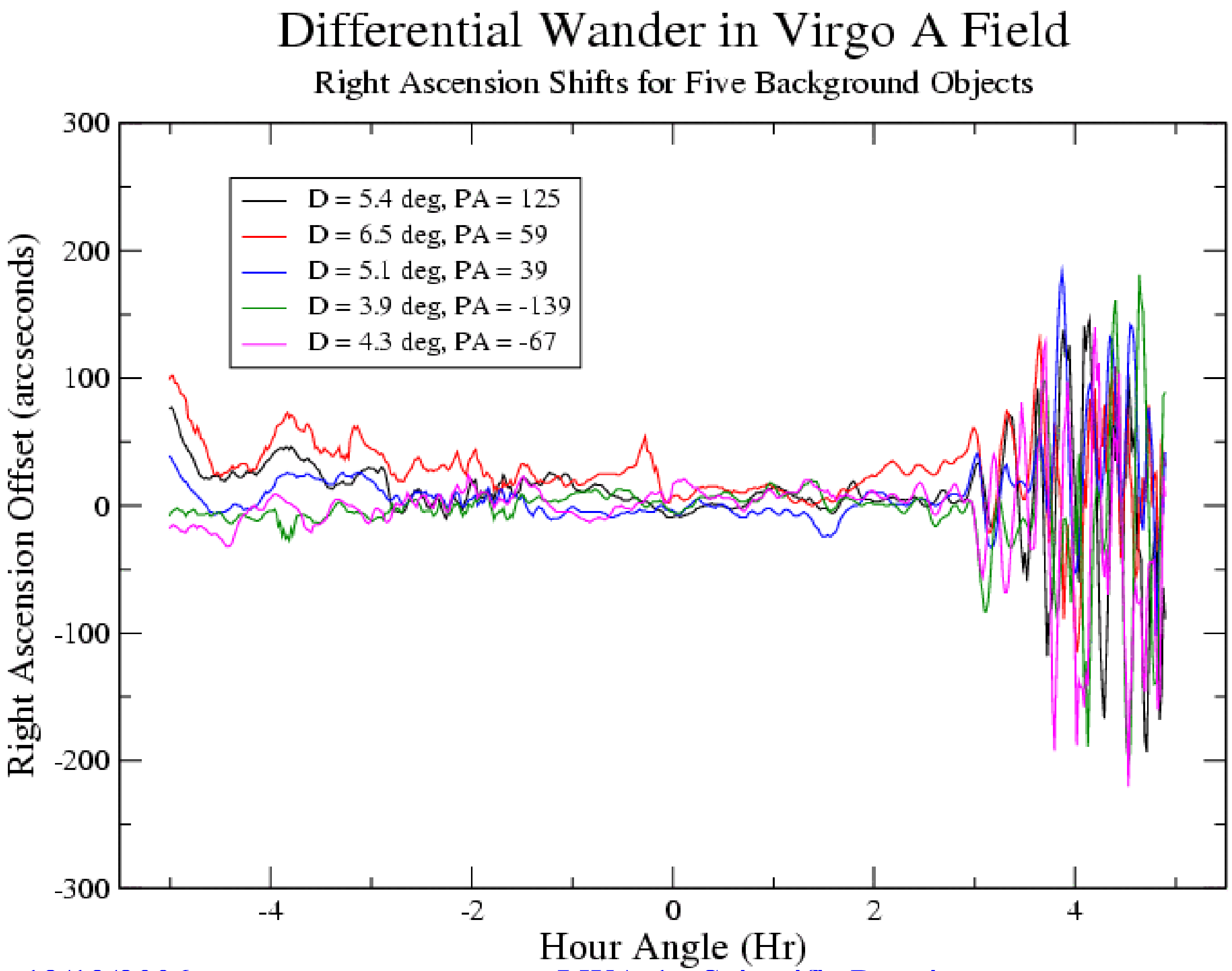
Science with LWA-1+: Ionospheric Measurements

- A LW interferometer is extremely sensitive to ΔTEC
  - Current VLA has ΔTEC precision ≤ 10^{-3} TECU [1 TECU ≡ $\int n_e dl \sim 10^{17}$ m^{-2}]
- LWA's power is ability to measure ΔTEC towards <u>many</u> simultaneous directions
- Basic building blocks of those measurements are the phase measured between any two stations
- As soon as LWA-2 is available, we can start exploring those kinds of measurements!



Science with LWA-1+: Ionospheric Measurements

Differential phase offsets – crucial to future angle-variant calibration schemes



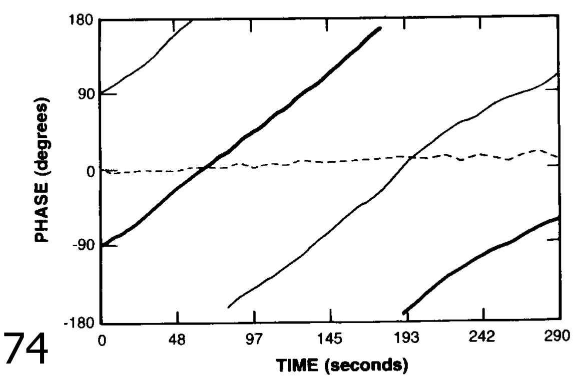
RA differential shifts for 5 background objects after removal of Virgo A.

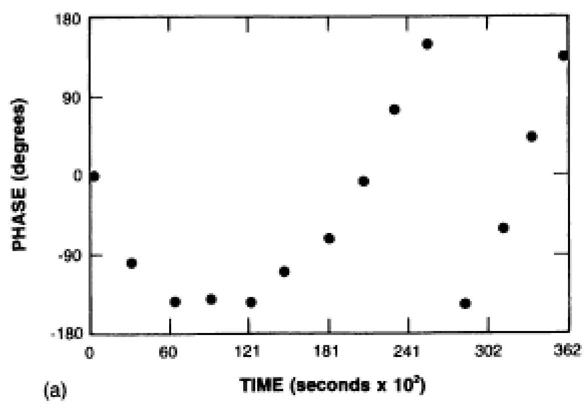
Science with LWA-1+: Ionospheric Measurements

- How well do ionospheric phases & phenomena vary with frequency?
  - Potentially crucial tool for future calibration schemes

5 minutes

10 hours



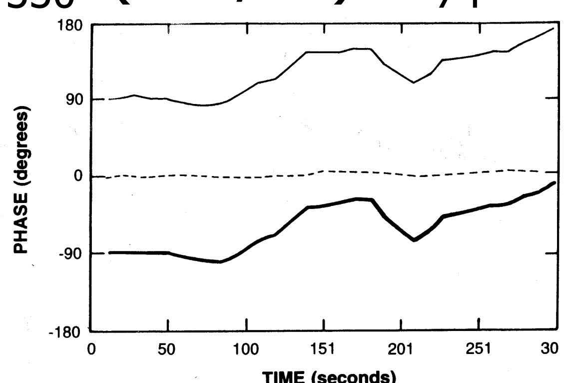


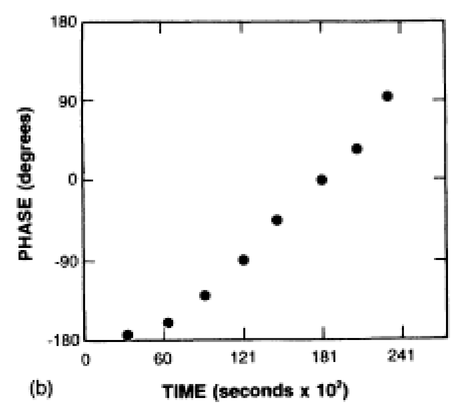
"Phase transfer" works on time-scales of few minutes, but over many hours "mystery drift" sets in – what causes it?

θ_{74}

θ_{330}

$\theta_{330} x(330/74) - \theta_{74}$



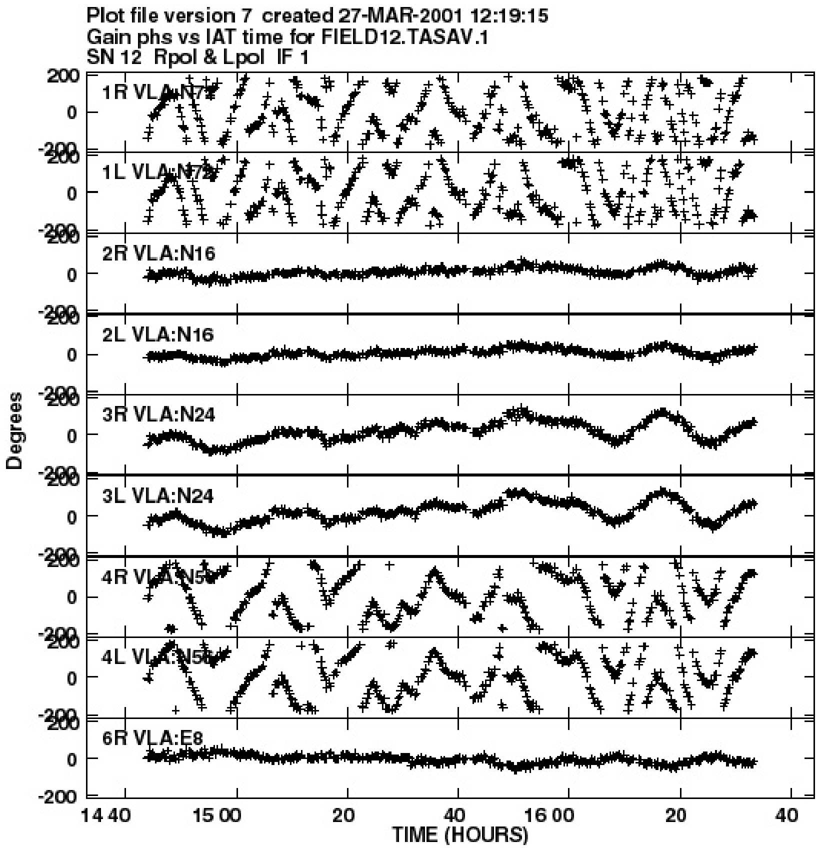


Can't explore how phenomena scale without access to large frequency range

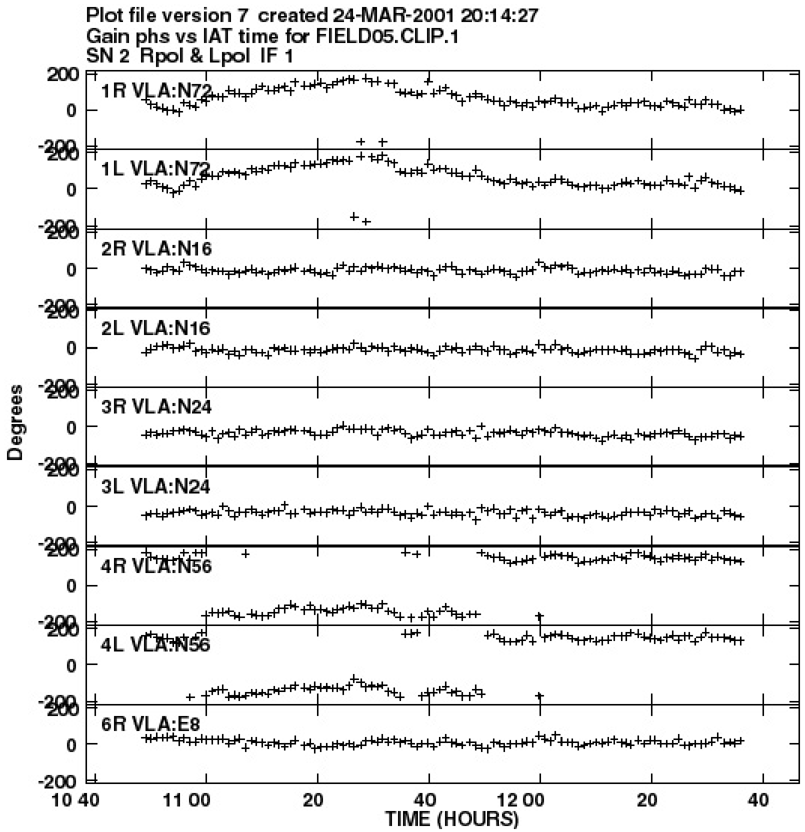
Science with LWA-1+: Ionospheric Measurements

- Begin to build up an ionospheric weather almanac

Bad Day



Good Day



Memo 35 (M35) Specs vs. LWA-1+ Science Requirements

Science	Desirable Memo 35 (M35) Modifications
	M35: http://www.ece.vt.edu/swe/lwa/memo/lwa0035.pdf
Transients	Benefits from more spatial beams – M35 has two
ISM via RRLs	Needs $\Delta\nu_{min}$= 0.1 kHz – M35 is 4 KHz (for 1.5 km/s @ 20 MHz)
ISM via Pulsars	Needs $\Delta\nu_{min}$= 1 kHz – M35 is 4 KHz (for Δt = 1 ms)
Pulsars	Needs $\Delta\nu_{min}$= 1 kHz – M35 is 4 KHz (for Δt = 1 ms)
Sun	Needs full RF or $\Delta\nu_{max}$= 60 MHz – M35 is 10 MHz (need 6 x M35 bandwidth)
Jupiter	Needs $\Delta\nu_{max}$ = 20 MHz - M35 is 10 MHz (need 2 x M35 bandwidth)

Large $\Delta\nu_{max}$ & broad tuning range key to most LWA-1 science – even M35 specs need minor tweaks

LWA, M35, LWA-1+: Science Requirements Comparison

Parameter	LWA Spec.	Memo 35	LWA-1+
Freq Range	20-80 MHz	Yes	Yes
# Stands	256	Yes	Yes
Antenna Sens	Sky noise dom	Yes, >+ 6 dB	Yes, >+6dB
$\Delta\nu_{min}$/beam	0.1 kHz	4 kHz	0.1 kHz (RRLs)
$\Delta\nu_{max}$/beam	8 MHz	5.33 MHz	Yes (with # beams)
# Beams	$\geq$ 3 dual pol. (ν & spatial)	2 dual pol. (4 spatial, 2ν)	$\geq$ 6x M35 (sun) (ν)
Δt_{min}	1 msec	TBD (mod 256 μsec)	1 msec
Polarization	Full	Yes	Yes
Field of View	[8,2]^o at [20,80] MHz	Yes	Yes
Sky Coverage	z $\leq$ 74^o	Yes	Yes

Changes to M35 specs – increased spectral resolution, more beams.

Summary

- LWA-1 will do good science – ranging from:
  - Potentially very exciting - transients
  - More modest – pulsar, ISM, & solar system studies we know we can do
    - Both extremes represent good science
    - Serendipitous discoveries possible
    - Viable student thesis projects
  - Invaluable technical lessons - including deep, efficient, multi-purpose integrations as path-finders towards future LWA experiments

- With LWA 2 & 3 – aka LWA-1+
  - Standalone with LWA-1
    - Anti-coincidence RFI avoidance for concurrent transient observations
    - Demonstrate station-based interferometry
    - Determine source locations & flux densities
    - Explore ionospheric scaling laws & phenomenology - test future calibration schemes
  - With VLA
    - Monitor VLA transient observations for lower frequency counterparts.
    - LWA-2 & 3 outliers for 74 MHz imaging - next step beyond PT-link
- Useful because LWA stations are BIG.
  - 512 dipoles/station = 75% of Clark Lake array - each 100-m station like GBT
  - Large $\Delta\nu_{max}$ & broad tuning range key to most early (non-imaging) science
  - Realism: power of LWA lies in imaging that is mainly unavailable to LWA-1+