VLBI and Transients

Very Long Baseline Interferometry and Pulses

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Outline

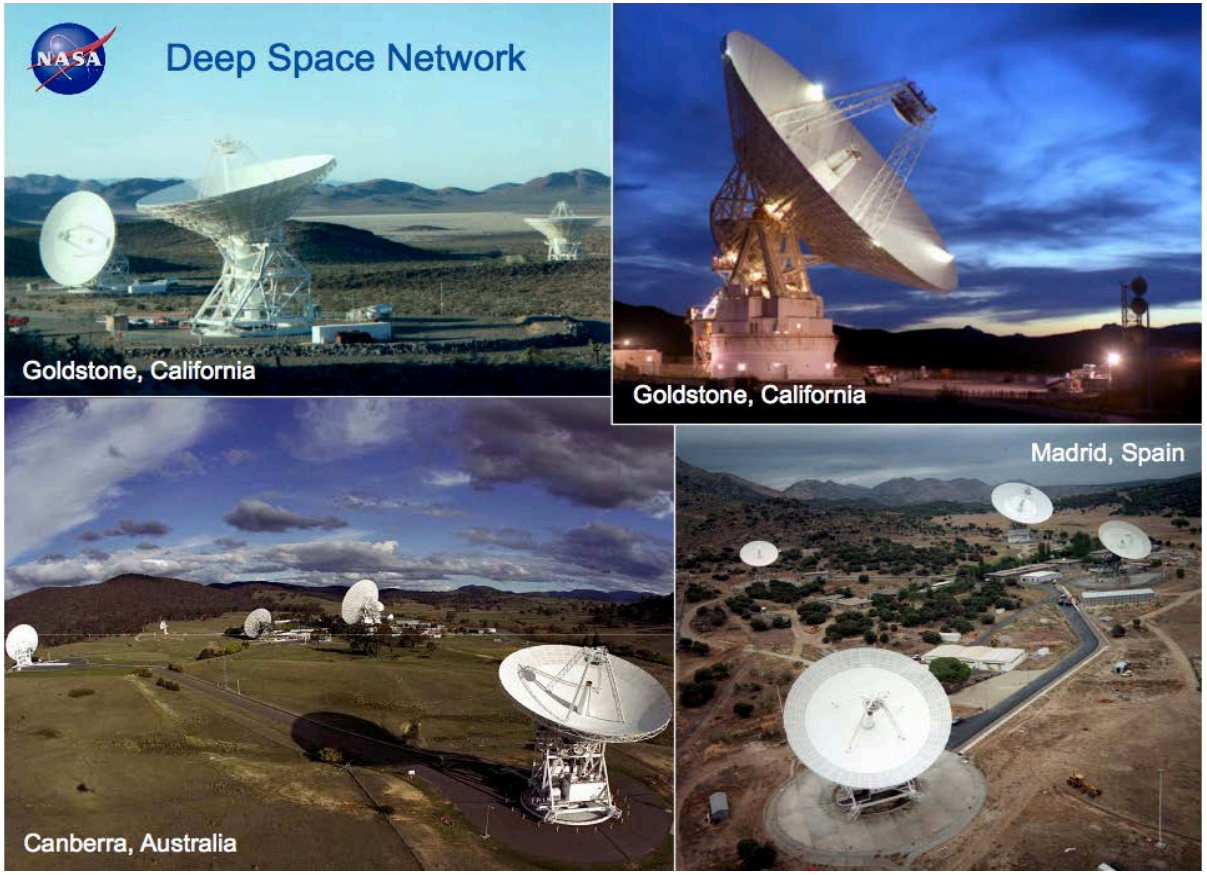
- Overview of the Deep Space Network (DSN)
- JPL's Use of VLBI
  - Mission Tracking Support
  - Radio Reference Frame
  - Earth Orientation Parameter Estimation
- Transients in General
- Recent JPL Transient Studies
  - GLUE
  - Crab Giant Pulses
  - VLBI transients

JPL's Interest in VLBI?

- Why does JPL have a 30+ VLBI program?
  - JPL is responsible for operation of NASA's Deep Space Network (DSN)
  - Support for Deep Space Missions
    - Time: Need accurate clocks and earth rotation data
    - Positions and velocities:
      - Need accurate tracking and reference frames
      - Must tie reference frames together
        - » Planetary and Celestial frames

NASA's DSN

- The **Deep Space Network**, or **DSN**, is a global network of large antennas and communication facilities that supports interplanetary spacecraft and selected Earth-orbiting missions. In addition it performs radio and radar astronomy observations for the exploration of the solar system and the universe. DSN is part of the NASA Jet Propulsion Laboratory (JPL)



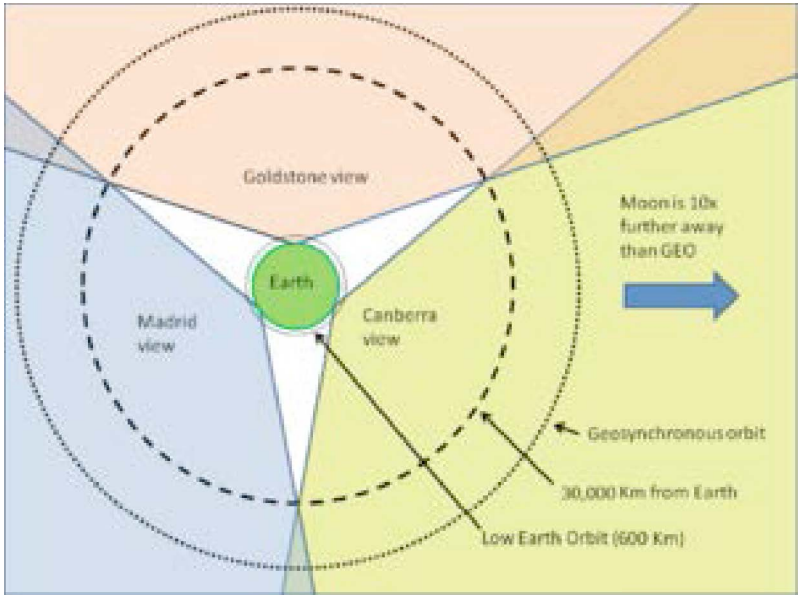
The DSN

DSN Capabilities

- Acquires telemetry data from spacecraft.
- Transmits commands to spacecraft.
- Uploads software modifications to spacecraft.
- Tracks spacecraft position and velocity.
- Performs Very Long Baseline Interferometry observations.
- Measures variations in radio waves for radio science.
- Gathers science data.
- Monitors and controls the performance of the network.

- Three tracking and communication sites
  - ~120 degrees apart
- Each Site:
  - 70m antenna, (L,S,X,K-bands)
  - 34m HEF, several 34-BWG (S,X,Ka)

http://dsnra.jpl.nasa.gov/RA_Capabilities.html



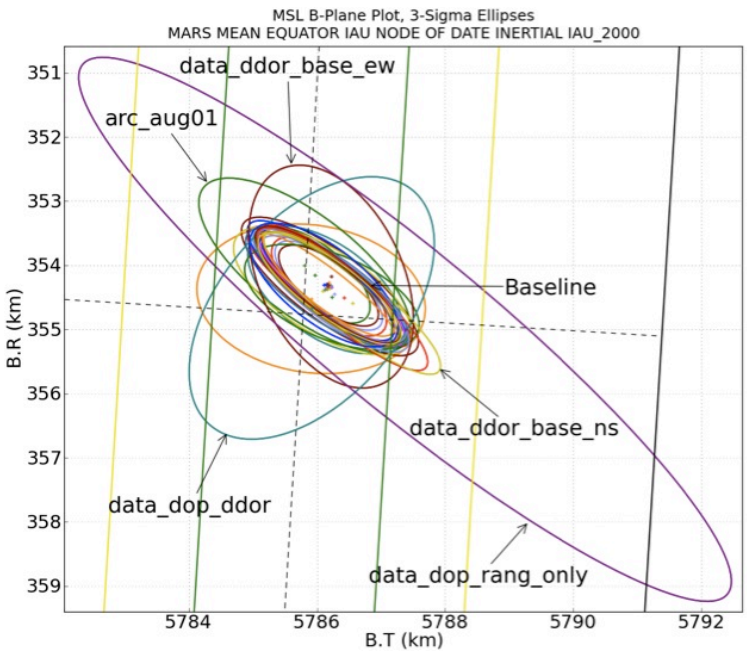
DSN Spacecraft Tracking

The DSN uses range, Doppler and Δ–VLBI to support Spacecraft tracking

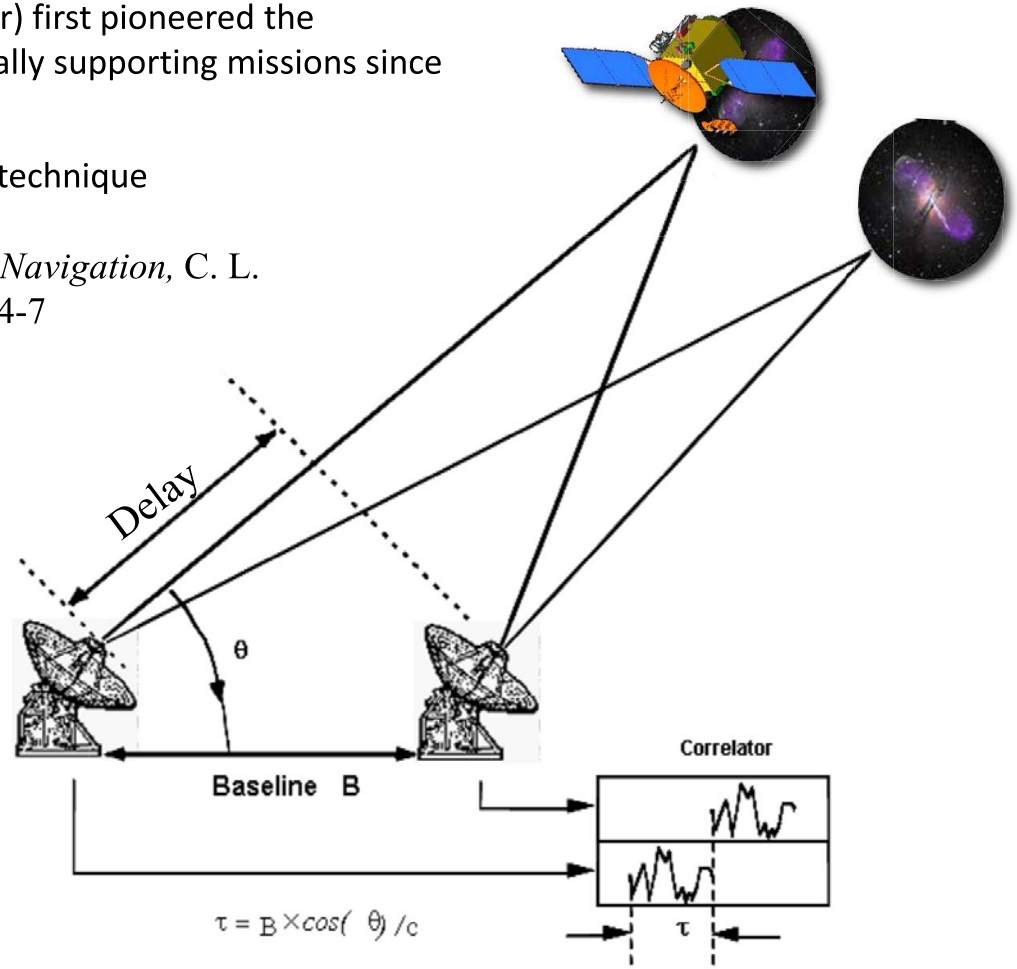
The D-VLBI team at JPL (Team Lead: James Border) first pioneered the technique using Voyager and has been operationally supporting missions since 2001 Mars Odyssey.

D-VLBI is a Spacecraft-Quasar differential angular technique

Radiometric Tracking Techniques for Deep-Space Navigation, C. L. Thornton and J.S. Border ISBN-0-471-44534-7



3-sigma error < 1 Km with MSL at low Dec (~ -25 degrees)

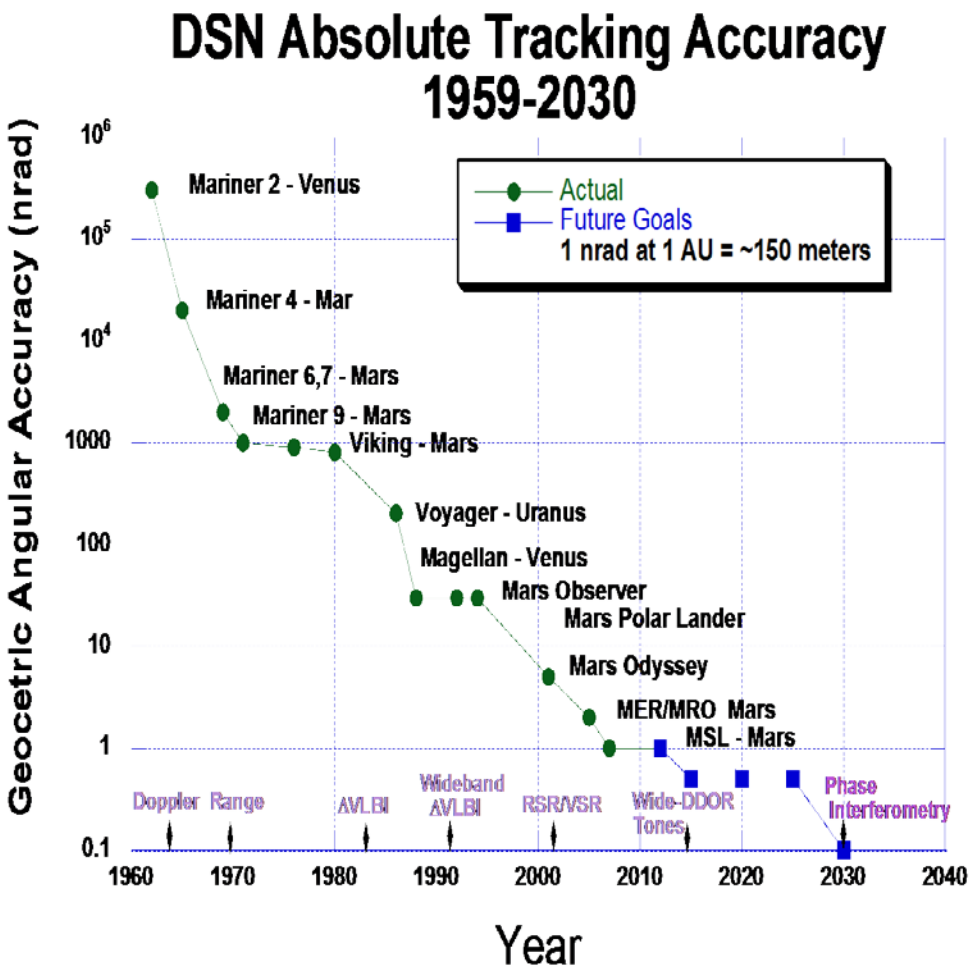


- Measures geometric delay by cross-correlating signal from two (2) stations

NASA Navigation System Accuracy

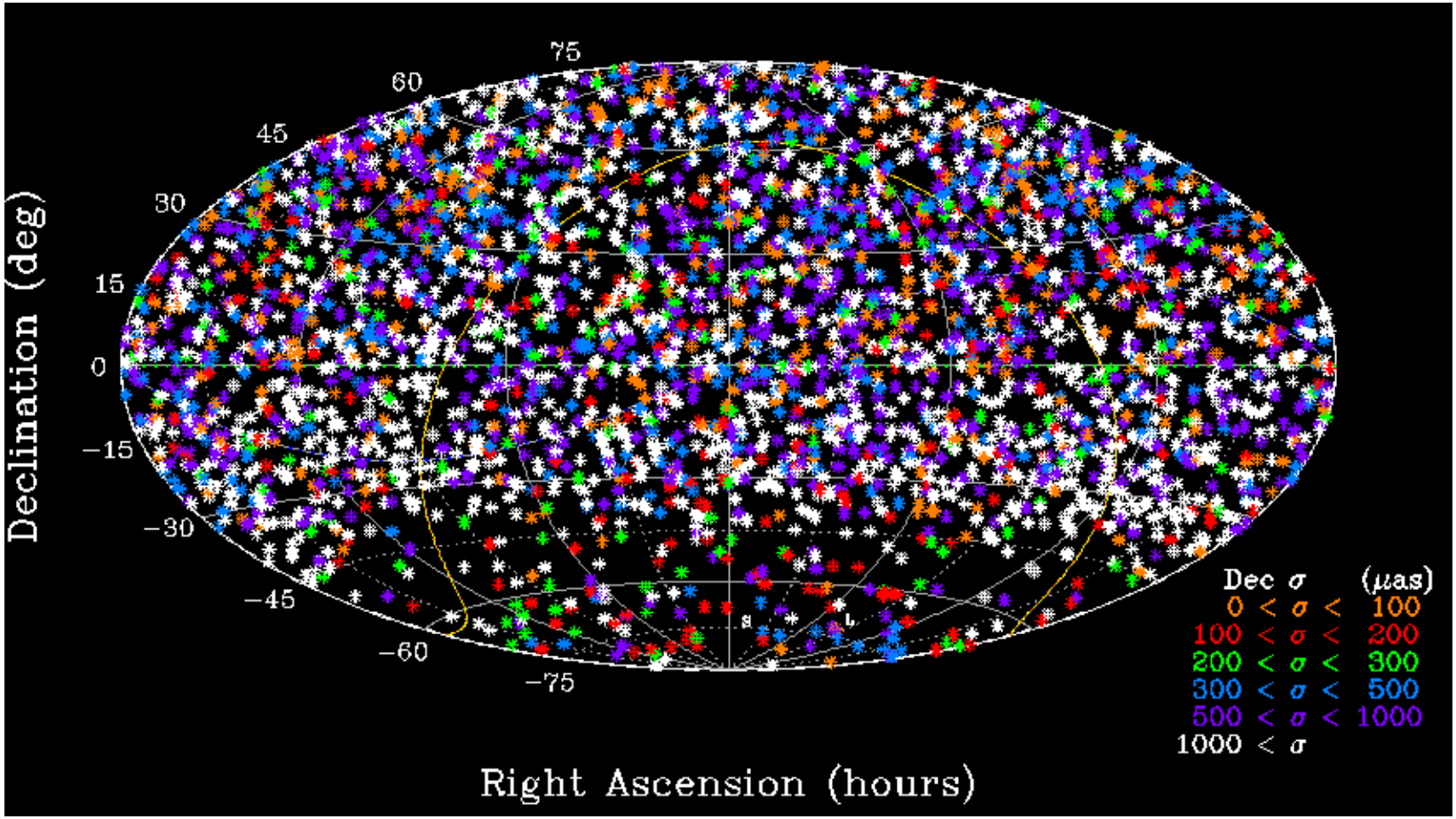
The high angular angular accuracy of Δ–VLBI techniques are due to:

- The common mode error cancellation:
  - Clocks
  - Propagation media
  - Station platform errors
- Improved Quasar reference frames
  - More quasars sources
  - Higher astrometric accuracy
- Improved Earth Orientation parameter estimation
- Improved Frame Ties: Quasar & Planetary



The DSN's Radio Reference Frame

ICRF-2 S/X 3.6cm: 3414 sources



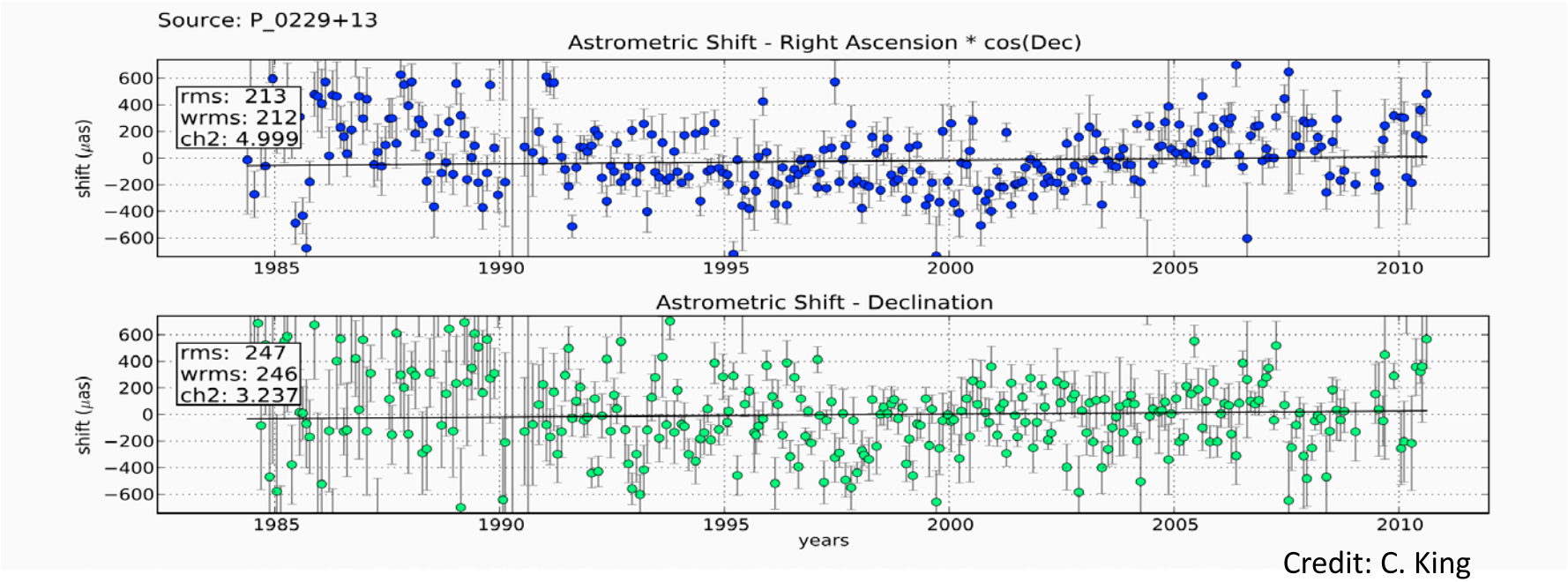
40 μas floor. ~1200 obj. well observed, ~2000 survey session only

Credit: Ma et al, eds. Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009

DSN CAT M&E programs to improve the Radio Reference Frame

(C. Jacobs, D. Bagri, C. King, A. Romero-Wolf, O. Sovers)

- 24 hours VLBI
- S-band (~ 200 MHz) & X-band (~ 500 MHz)
- Go-Ro and Go-Ti baselines one month.
- Each exp: 400 sources at 2.5 minutes → ~1200 for ~ 30 s
- Improvements over time (# bits,PCGs)
- → Mark6 recorders, JPL's DVP limit will soon be front-end bandpaths
- -> X/Ka

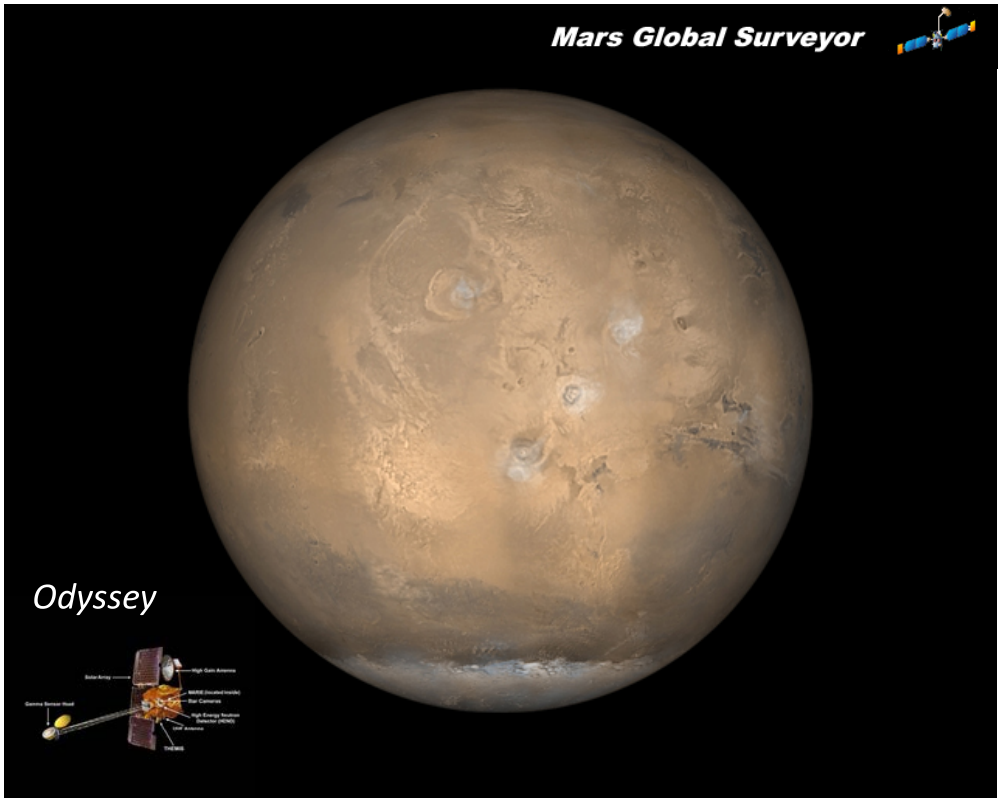


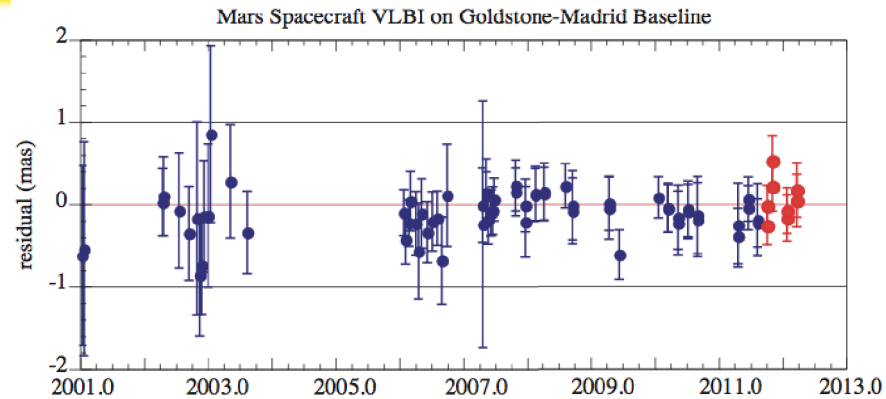
Credit: C. King

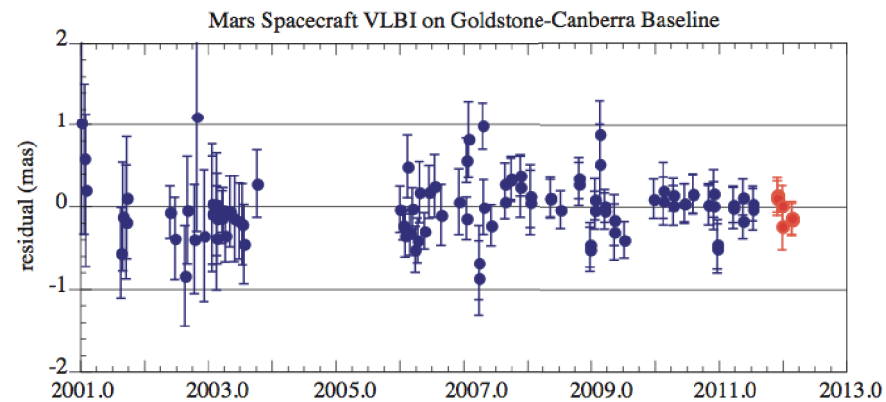
Planetary Ephemeris to ICRF Frame Tie

- ΔVLBI measurements of spacecraft around a planet obtains position in the ICRF frame

- Doppler and range measures spacecraft in planet center Frame.







Folkner et al, IAU. 2012
200 µas (1. nrad) residuals

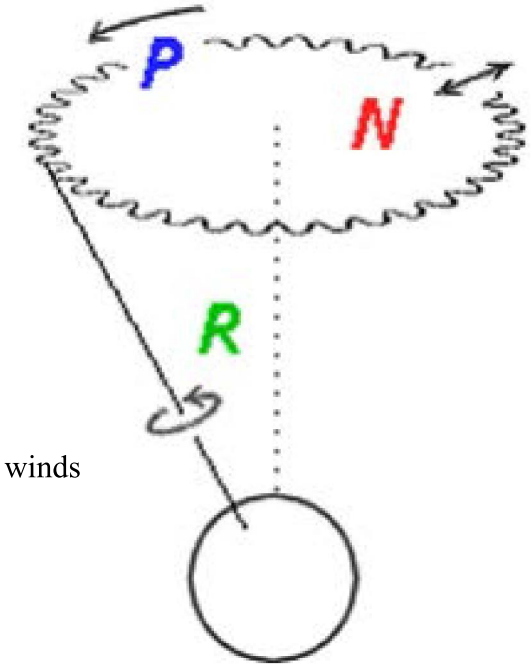
http://referencesystems.info/uploads/3/0/3/0/3030024/folkner.pdf

The DSN's VLBI TEMPO

Accurate navigation of interplanetary spacecraft requires accurate knowledge of Earth's orientation

- Must know Earth's orientation in space to know spacecraft's position in space from Earth-based tracking measurements
- Error in UT1 of 0.1 ms (4.6 cm) -> a position error at Mars of 1.6 km

- Earth's orientation in space given by 5 parameters:
  - 2 precession-nutation parameters (Dy, De)
    - Specifies location of spin axis in *celestial* reference frame
  - 2 polar motion parameters (PMX, PMY)
    - Specifies location of spin axis in *terrestrial* reference frame
  - 1 spin parameter (UT1)
    - Specifies angle through which Earth has rotated about spin axis



- Earth's orientation varies rapidly and unpredictably
  - UT1 variations are particularly difficult to predict
    - Rapid UT1 variations caused mainly by changes in angular momentum of winds
    - Predicting UT1 is as challenging as predicting the weather
  - Precession-nutation is particularly easy to predict
    - Caused by gravitational effect of Sun, Moon, and planets on Earth
    - Can be modeled and predicted to within 3 cm up to a year in advance
    - Model predictions rely on past measurements

- Measurements of UT1 and polar motion must be taken frequently and processed rapidly to maintain a real-time knowledge of the Earth's orientation

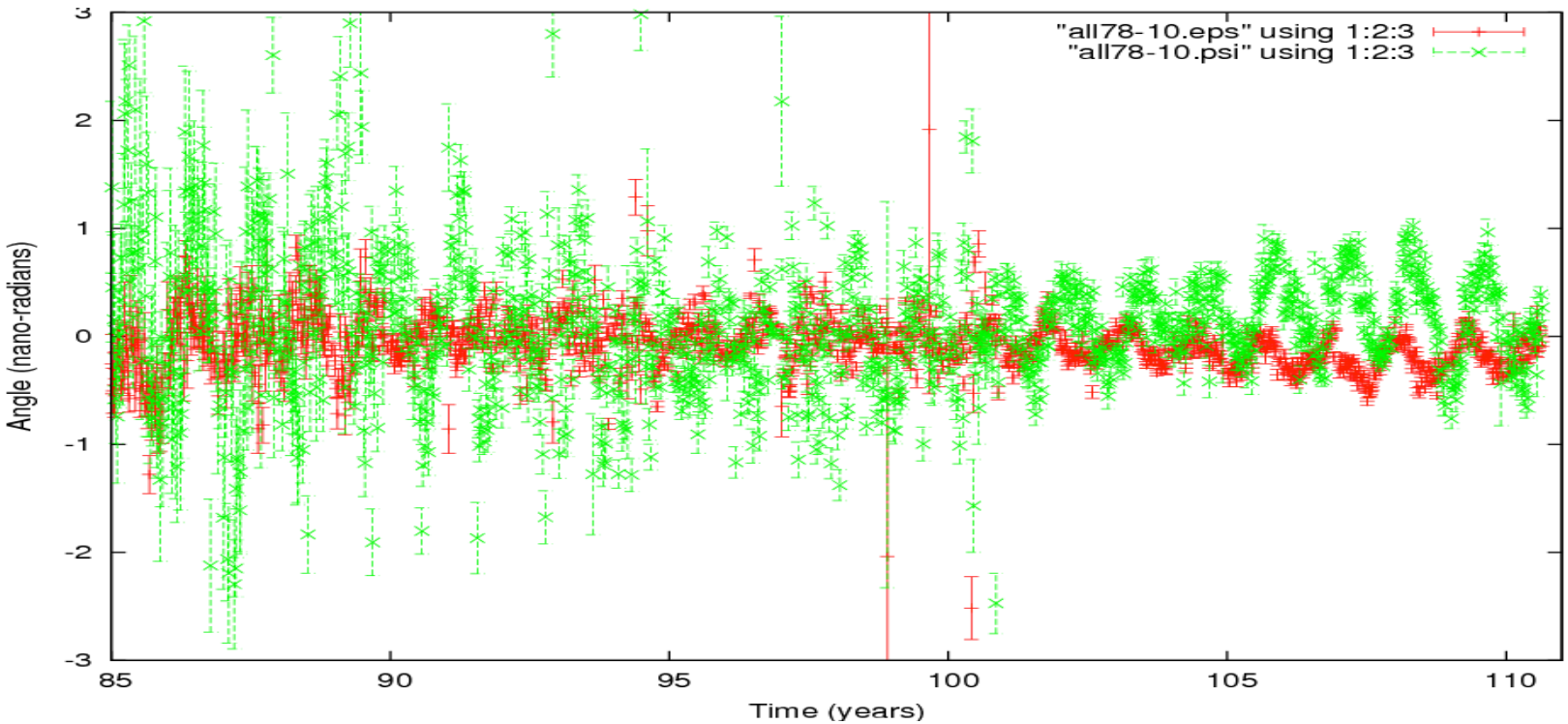
- JPL optimizes EOP by combining JPL GPS and JPL VLBI-TEMPO data with external data via a Kalman filter.

Credit:Richard Gross JPL Talk, 5/7/2005

THE DSN's TEMPO

To meet Tracking and Navigation Service Requirements (ut1 30 cm (1 sigma) in real time) JPL's TEMPO (Time and Earth Motion Precision Observations) conducts one six hour VLBI experiment on the Goldstone-Madrid baseline every two weeks. Currently over 150 quasar source over the full sky are examined and the global solution is optimized for Earth orientation parameter extraction.

TEMPO Team: D. Bagri, A. Steppe, C. Jacobs



A typical TEMPO type solution for the precession and nutation angles for the Global data set.

Fast Radio Transients

- Known
  - Giant Pulses from Pulsars
    - Only ~ 10 known GP emitters -->

PSR B0531+21	Staelin, Refenstein (1968) Crab pulsar
PSR B1937+21	Wolszcan, Cordes & Stinebring (1984)
PSR B1821-24	Romani & Johnston (2001)
PSR B1112+50	Ershov & Kuzmin (2003)
PSR B0540-69	Johnston & Romani (2003)
PSR B0031-07	Kuzmin, Ershov & Losovsky (2004)
PSR J0218+42	Joshi, Kramer, Lyne et al. (2004)
PSR B1957+20	Joshi , Kramer, Lyne et al. (2004)
PSR J1823-3021	Knight, Bailes, Manchester et al (2005)
PSR J1752+2359	Ershov & Kuzmin (2005)

  - RRATS (Rotating Radio Transients)
    - (McLaughlin et, al, Nature, 439,817,2006)
- Possibles
  - Lorimer burst, (Science, 318,777, 2007)
- Exotics ?
  - Magnetars (J1810-197 pulse of 10 Jy and .15 sec widths, Camilo Nature, 442, 892, 2006)
  - Compact Objects Mergers (Hanson & Lyutikov 2001)
  - GRB Prompt Emission (Paesold & Benz)
  - Cosmic Strings (Vachaspati 2008)
  - Primordial black holes (Rees 1977)
- Good Summaries
  - CRAFT: The Commensal Real-time ASKAP Fast Transients Survey, http://arxiv.org/abs/1001.2958
  - The Transient Sky, E. Keane ISBN 978-3-642-19626-19627-0
  - Detection of Fast Radio Transients with Multipole Stations, arXiv:1104.4900v1

Surveys

- Transients programs growing leaps and bounds
- Past Surveys (see details in VLBA paper arXiv:1104.4900v1)
  - ATA Fly's Eye (von Korff et al. 2009)
  - LWA transients study (Taylor et al. 2006),
  - LOFAR transient campaign (Hessels et al. 2009),
- Current Efforts: (via CRAFT paper)

–	Freq	Time Res	Sensitivity (1σ)	Baseline	Starting
• Parkes	1.4 GHz	64 μs	1.5 mJy	NA	9/2009
• VLBA	.6-.9 GHz	2-10 μs	5.6 mJy	200 - 8600 km; Continental	2/2010
• GMRT	.3-.6 GHz	32 ms	22 mJy	NA	done
• LOFAR	.12 GHz	50 μs	40 mJy	1000 km	2010
• ***JPL***	***2.2 GHz & 8.3 GHz***	***1ms ->50 μs***	***xxxx***	***10000 km; Intercontinental***	2012

New surveys coming on line will set the bounds on rates !

- CRAFT (Johnston et al. 2008), Murchison Widefield Array (MWA) (Lonsdale et al.2009), and MeerKAT (Jonas 2009)
- Nice VLBA paper: V-FASTR limits arXiv:1205.5840v1 1300 hours from 327 Mz -86 GHz.
  - No single-pulse events found

- All transient surveys must show events are not of terrestrial origin and all are very sensitive to impulsive RFI
- RFI migitation is a challenge for all teams.

- JPL will only contribute in a small niche:
  - S and X-band transients (> 100 Hours per year for many years) at high time resolution.
  - Address single-pulse detection challenge in noisy data

JPL's Transient History

- **GLUE:** Goldstone Lunar Ultra-High Energy neutrino experiment

  P. W. Gorham, C. L. Hebert, K. M. Liewer, C. J. Naudet, D. Saltzberg, and D. Williams
- From 1999-2003 a series of experiments were conducted
- Coincidence experiment of two antennas (DSS14 and DSS13) 22 km apart at Goldstone
- Dual S-band with L-band off-axis veto capability with ~ 120 observation time
- 50ns local gate and 150 μsec dual antenna gate (set by years range of moon's geom-delay),
- 250 μsec data record at 1 Gsam/sec
- Synthesized IF pulse signal calibration, back-end timing ~ 1ns; pulse transmitter and Limb of the moon for total cross-polarization timing ~ 1 ns. 3c273 for dual antenna timing (~10ns)
- > 95% livetime, .003 Hz trigger rate

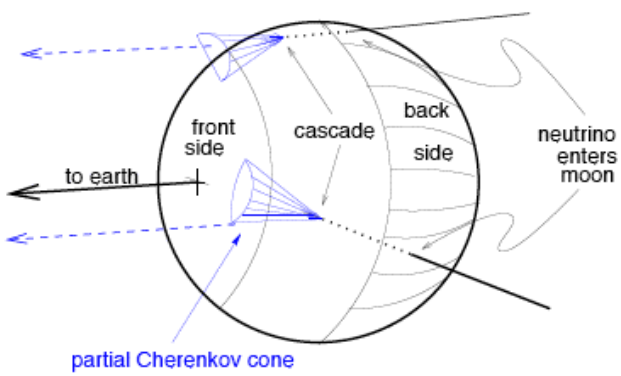


FIG. 1: Geometry of lunar neutrino cascade event detection.

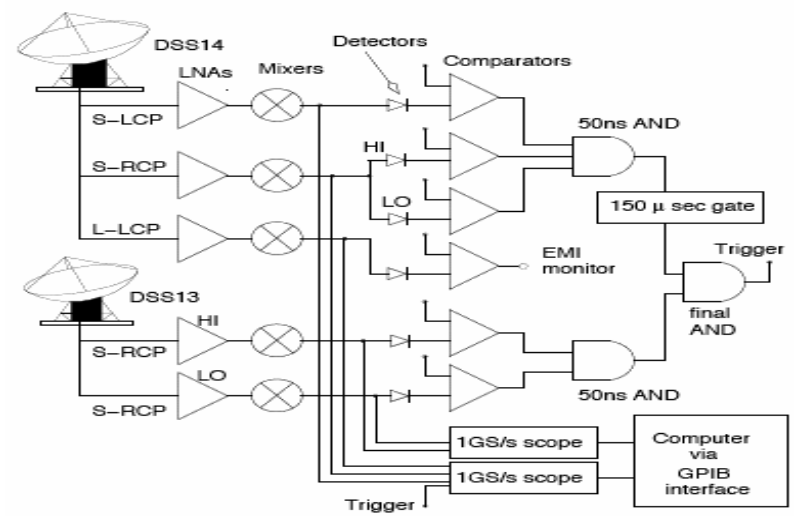


FIG. 2: GLUE trigger and data recording system.

GLUE

- RFI Noise is critical issue, 70m very sensitive
  - local trigger is easy with a Bic lighter
- Lessons learned:
  - Requires multi-antennas, veto
  - multi-bands,
  - dual polarization
  - Use open-loop recording,
- Goldstone is a on a military base and the impulsive noise can be overwhelming. Even with 22 km separation several days the entire experiment was loss,
  - ~ 100 deadtimes due to RFI
- Big gates allowed for offline analysis of in and out of time events (study background)
- No events above background

- P. Gorham, K. Liewer, C. Naudet, D. Saltzberg, and D. Williams, (GLUE Collaboration) "Experimental Limit on the Cosmic Diffuse Ultra-High Energy Neutrino Flux", Phys. Rev. Lett., **93**, 041101 (2004).

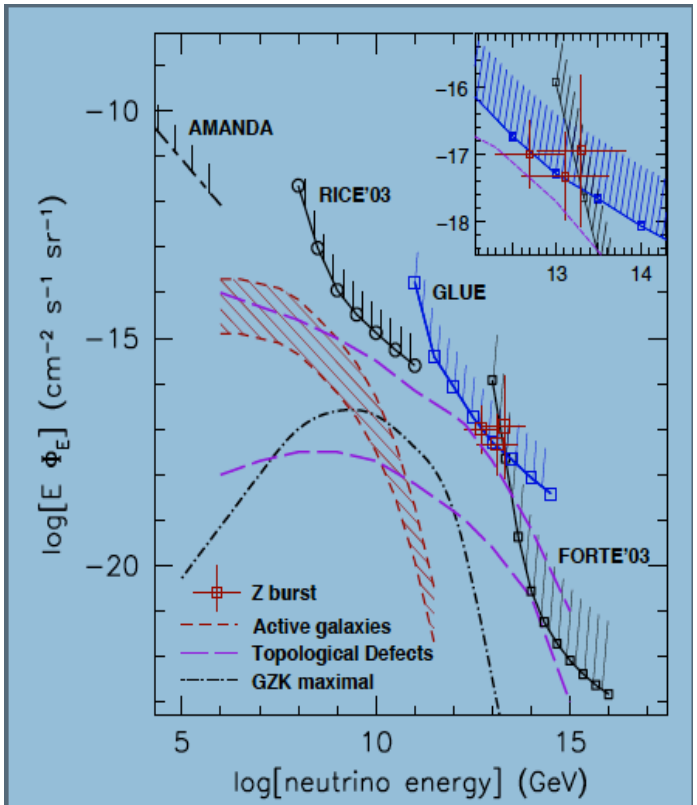


FIG. 4: Model neutrino fluxes & limits from the present work and other current experiments. The inset expands the region near the Zburst predictions.

JPL's Giant Pulse Search

- 2008 A small JPL team was formed to search for CGPs
  - (W. Majid, T. Kuiper, S. Lowe, C. Naudet)

- Why GPs ?
  - Only way to detect extragalactic pulsars
  - Important for understanding the magnetospheres of Pulsars
  - Emission mechanism is not well understood
  - How high energy emission might be linked with radio Emission
  - Conflicting claims on few detections
  - Are GPs restricted to small group of pulsars or many waiting to be discovered
  - Galactic pulsar population may be larger than we thought
  - Wide range of single pulse properties apparent
  - Algorithms relevant to transient detection phenomenon

JPL's Giant Pulsar Search

- Source of GP emission currently unknown
  - Changes in coherence of radio emission
  - Changes in pair creation rate in the pulsar magnetosphere
  - Changes in beaming direction

- Correlation studies with high energy emission is one way to pin-point the origin of GP emission
  - Look for increase in high-energy flux during GP emission
  - Look for frequency dependence of GP emission and coincidence with high energy emission

JPL's Giant Pulsar Search

70m at DSS14 / DSS63
L-band : 90 MHz of bandwidth, single pol, Tsys ~30K
S-band: 100 MHz, dual pol, Tsys ~35K
X-band: 400 MHz, dual pol, Tsys ~35K

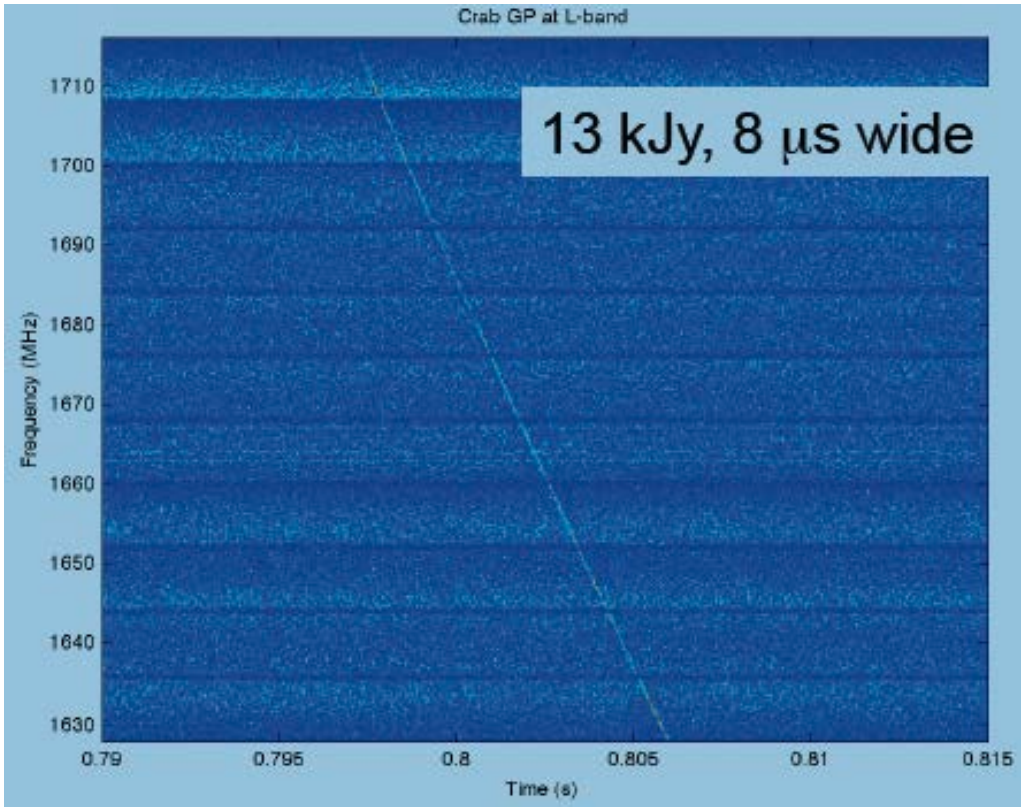
12 IF channels, 4 MHz wide

Baseband I and Q data recorded on VLBI recorders

Automated analysis pipeline:

- coherent dedispersion (straight-up then sum)
- matched filter algorithm
  Widths *= 1,2,4…2048

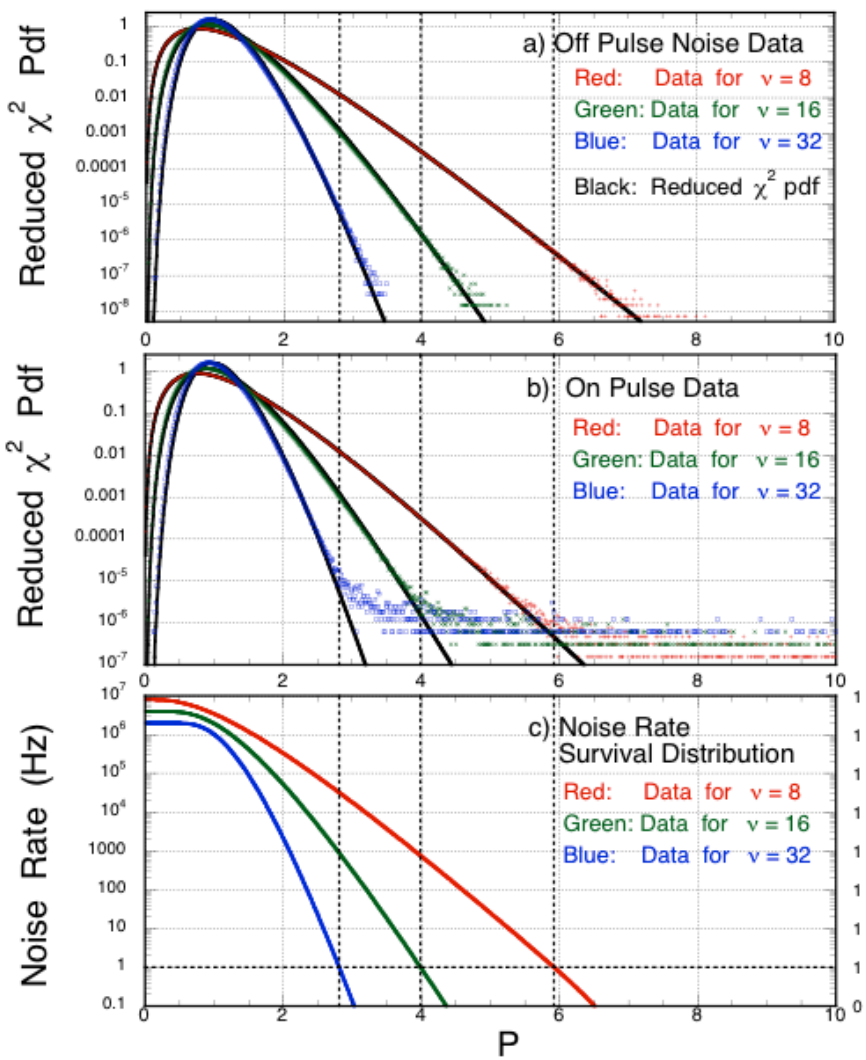
High time resolution reaching ~100 ns



Frequency-Time Plot

Noise Statistics

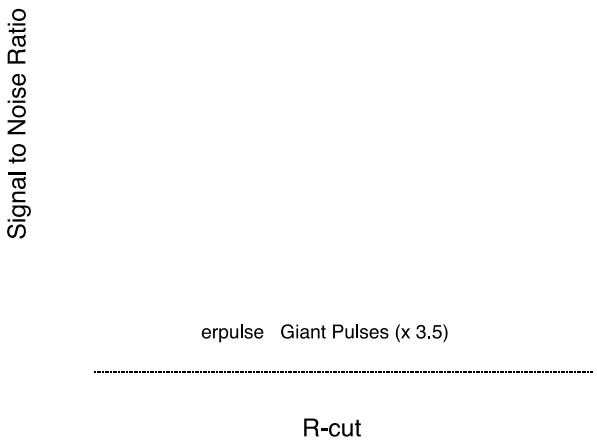
- Model noise as Chi-squared distribution with proper ndf
- Automated accounting of ndf with varying sub-bands and time resolutions
- Excellent agreement over 8 orders of Magnitude. Nice white noise!
- Define R to be false alarm rate to pass threshold cut equivalent to choosing a constant event confidence level independent of pulse width



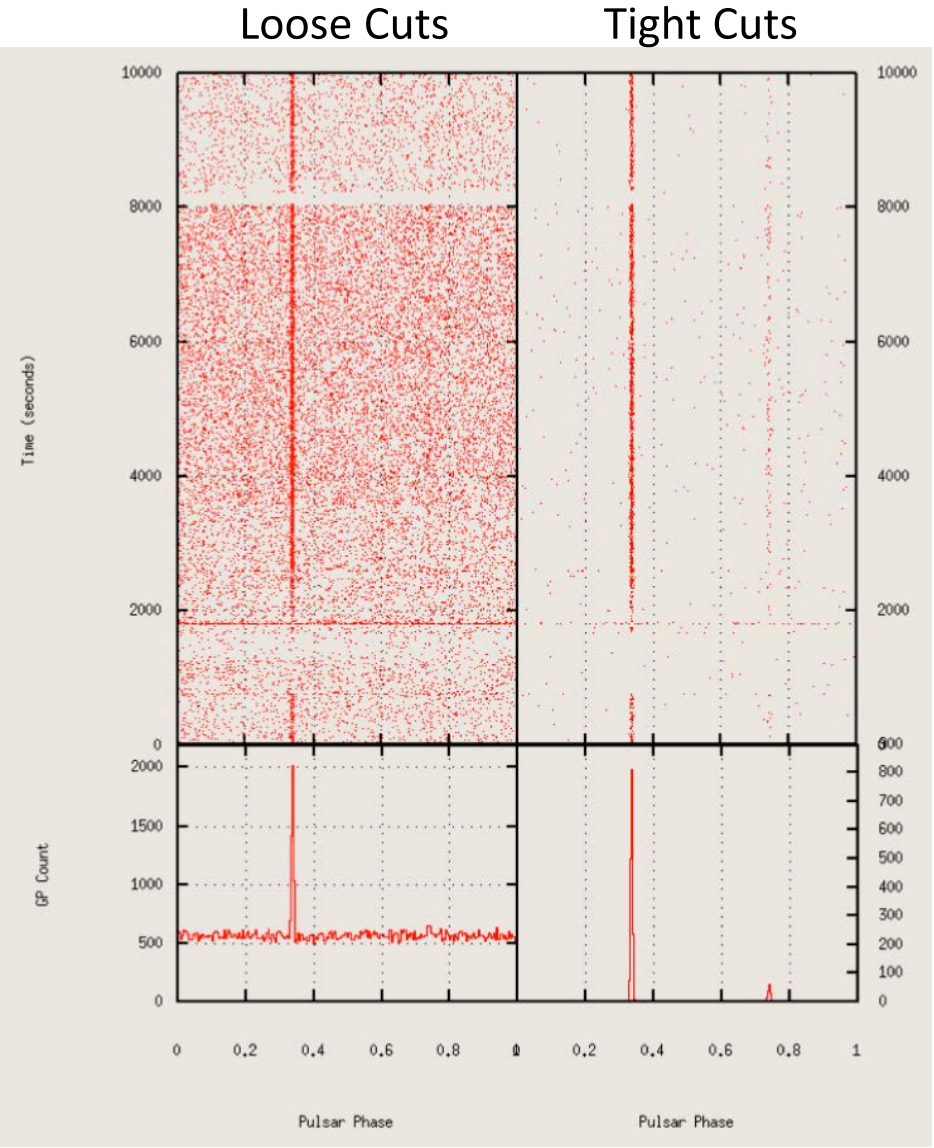
Crab Phase-Time Plots

The false alarm noise level (R)
Strongly impacts the number of GPs and GP SNR.

Tight cuts (R=.0006 Hz): SNR= ~38
Loose cuts (R=.6 Hz): SNR= ~25



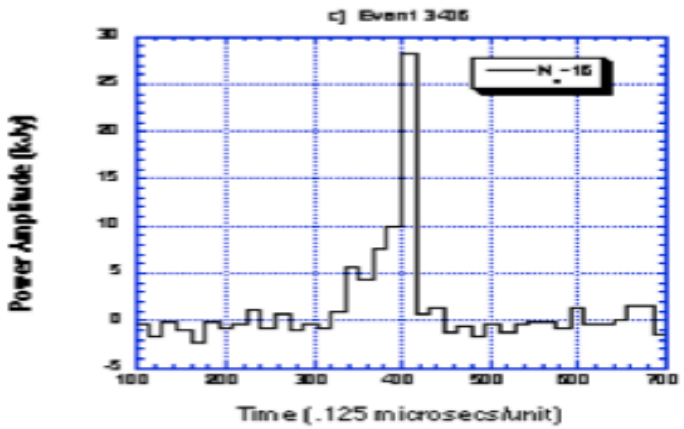
In/out phase Pulsar GPs essential tool
For transients studies

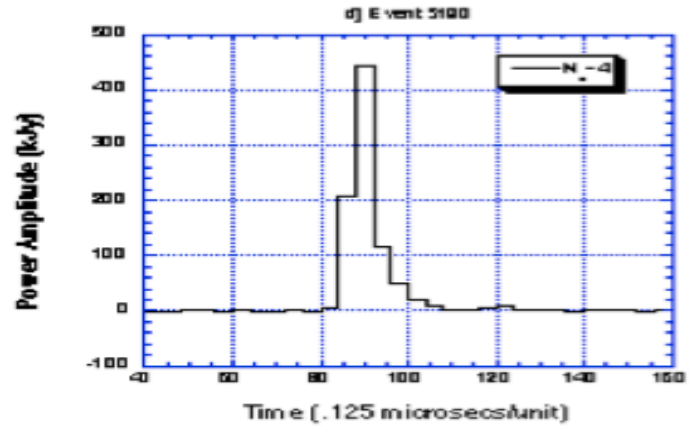


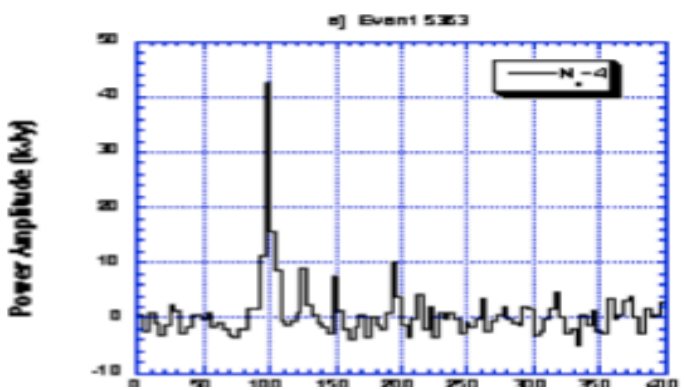
Pulse Morphology

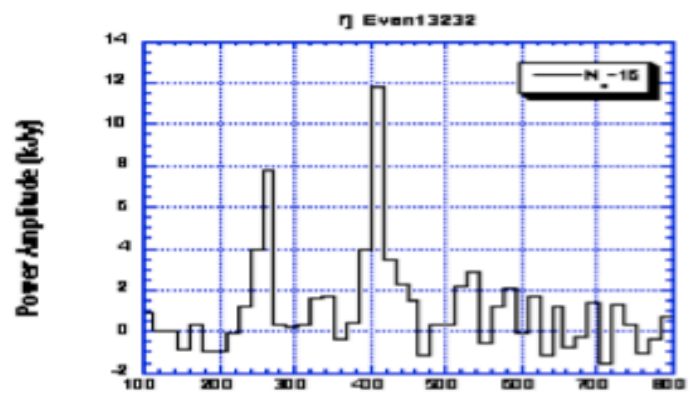
Wide variety of pulse shapes and sub-structure.
Examination of in-phase to out-phase

- White noise pulses and GPs almost indistinquishable
- Small Kurtosis differences seen

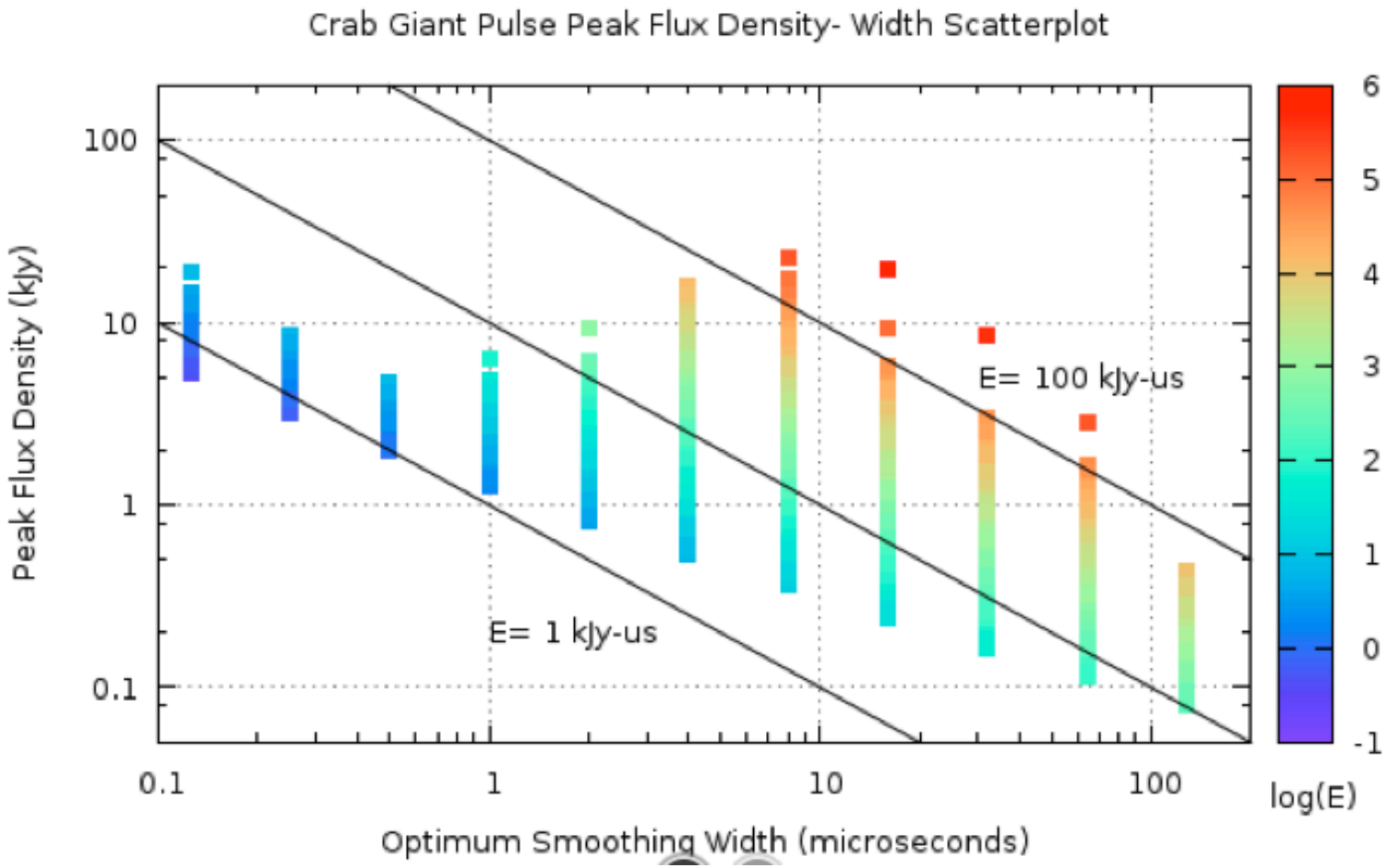








Crab GP Energy Isotherms



Crab GP cover 3 orders in Pulse width and Flux Density

Crab GPs

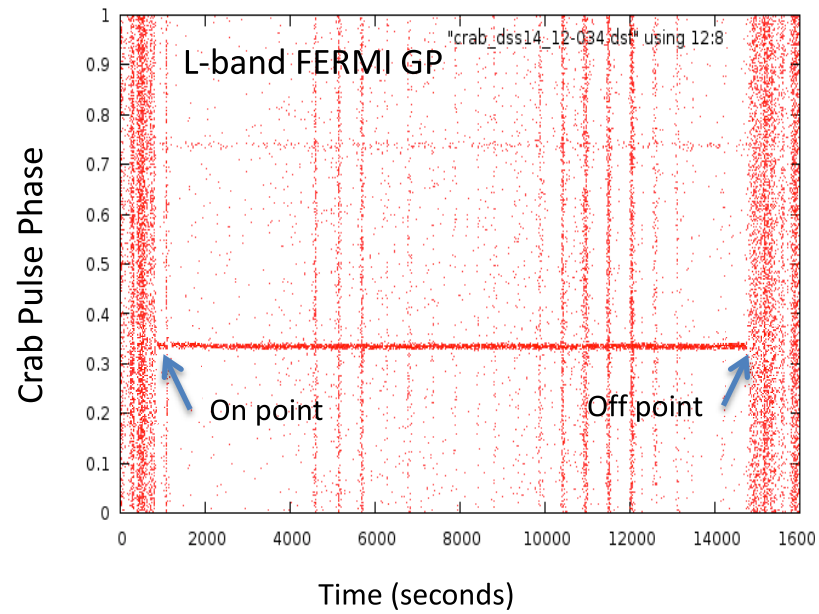
- To date
- L-band: 15 exp: 42 hours, ~ 45K GPs, ~.29 per sec
- S-band: 1 exp: 3.75 hours, ~ 1800 GPs, ~.13 per sec
- X-band: 4 exp: 16 hours, ~ 383 GPs, ~.006 per sec

- ~60 hours of data → ~ 50 Tbytes of disk space
- Total reprocessing time on current machine (16 threads) ~ 2 week
- Current Rule of Thumb: 1 hr of data needs 1 TB and 6 hrs of cpu for 1 DM
- RFI : Only a handful of seconds per experiment need to be removed
  - Near antenna on / off source.
  - DM of 56 solves most of RFI problems
  - Caution in calibration: modulated diodes, Phase Calibration Tones

Noise

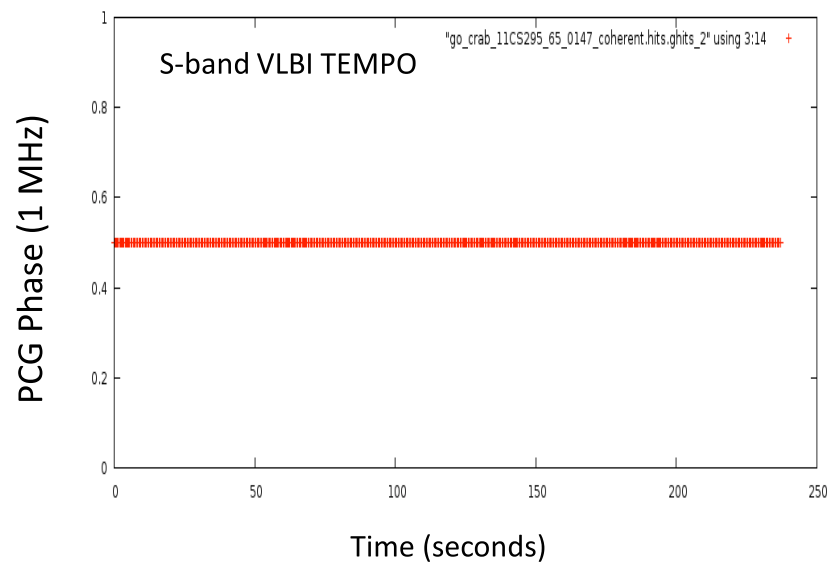
At L-band a 550 sec period RFI Noise was seen.

- Easily removed by dropping a 4 MHz Channel
- All seen ad DM=0
- DM smeared out
- All pulses very wide (> ~.25 msec)
- Seen at DSS14 and DSS63
- Source unknown (Satellite or common equip?)



Calibration Issues:

- Phase calibration tones yield nice pulses in time domain but are problematic
- Modulated Noise diodes similar
- Both can be filtered, currently work in progress.
- Calibration during precal is ideal



Looking for Transients in VLBI Data

- Use JPL Operational VLBI for Transients searches (no $$$)
  - 34m ant, S/X-band, Over 100 hr a year, Multi-year future
  - Full sky, ~500 sources, repetitive
  - Apply GP matched-filter at both antennas individually.
  - Apply VLBI clock offsets and total geometry delay corrections

  But
  - Must be NIB (non-interferenc basis) → Must Filter PCGs
  - Quasars will contribute correlated noise.

  Problems
  - Data logistics
  - CPU intensive
  - Non-thermal Noise

Phase 1: Shake out

- Incoherent dedispersion (min pulse width ~ .1ms)
- Limit DM search from 0 to 500
- Incrementing DM with ΔDM
- Set SNR cut high enough to inspect all Candidates manually (~ 1 candidate hit/scan)
- Require clean and clear Frequency-Time plots

Status

Phase 1: Completed

~ 40 hrs of VLBI Full Sky

~ 50 candidates:

One 1 pair $\Delta t < 1$ sec

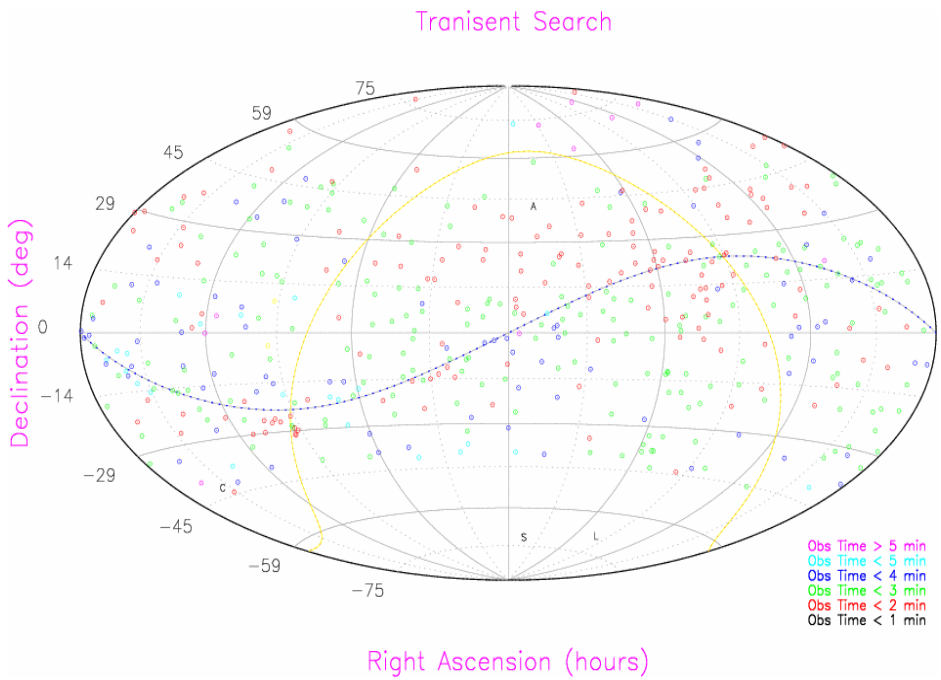
DSS15 SNR=18 DM= 0.14

DSS65 SNR=12 DM= 2.4

$\Delta t > .3$sec & $\Delta DM > 2.3$

Low DM

No VLBI Transient Candidate yet.



- Phase 2 (starting now)
  - Install new CPU with 75 Tbytes disk space
  - Reduce SNR thresholds in incoherent dedispersion searches
  - Increase DM search range 0 to 1000
  - Save all dual hit candidates and reproprocess with coherent dedispersion
  - Use new VLBI DVP recorder (allow full bandwidth, 200 MHz at S-band)
  - Negotiate adding in a Giant Pulsar cal source once per track
  - RFI Mitgation improvements. *Algorithms development*

Related JPL Efforts

- Study of Electrical Activity in Martian Dust Storms with the Deep Space Network antennas
  - Martinez, S.; Kuiper, T. B. H.; Majid, W. A.; Garcia-Miro, C.; Tamppari, L. K.; Renno, N. O.; Ruf, C.; Trinh, J. T.
  - http://adsabs.harvard.edu/abs/2012espc.conf..937M

- Current effort is being made to implement a real time transient detector for all the IFs and antennas in the DSN

- The DSN Transient Radio Observatory
  - Kuiper, T. B.; Lazio, T. J.; Majid, W. A.; Navarro, R.; Teitelbaum, L. P.; Trinh, J. T.
  - http://adsabs.harvard.edu/abs/2013AAS...22143914K