

Precise VLBI tracking of the Huygens probe

3rd International Planetary Probe Workshop
Anavyssos, Greece, 27 June - 1 July, 2005

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Huygens VLBI tracking team (abbreviated)



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**12 institutes and international
organizations in 7 countries**



Radio astronomy segment of the Huygens mission



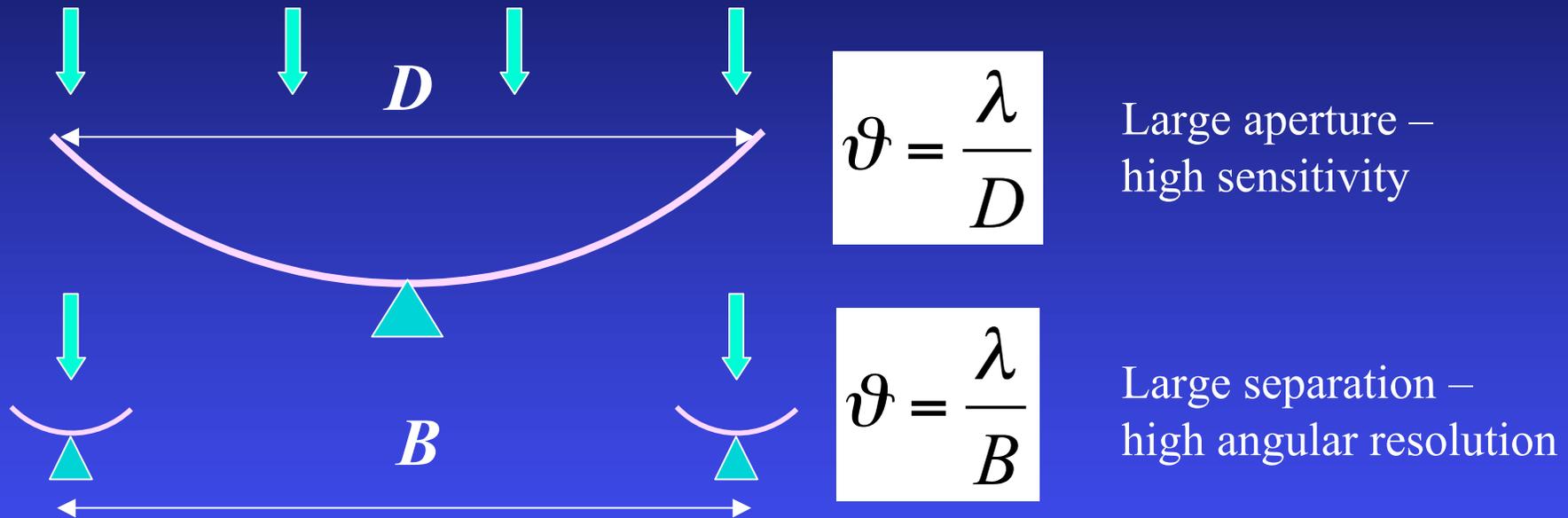
■ Radio astronomy segment of the mission

- ◆ Conceived as an Earth-based support to the Doppler Wind Experiment (DWE)
- ◆ Included
 - ◆ *Direct carrier signal detection with DSN-supplied Radio Sci Receiver (real time capability) at Green Bank and Parkes telescopes;*
 - ◆ *Direct Doppler measurements (JPL-led experiment) at four NRAO VLBA antennas;*
 - ◆ *Very Long Baseline Interferometry (VLBI) tracking of the probe from 17 radio telescopes;*
- ◆ Used (only!) the Channel A carrier signal at 2040 MHz only.

Interferometry: introduction



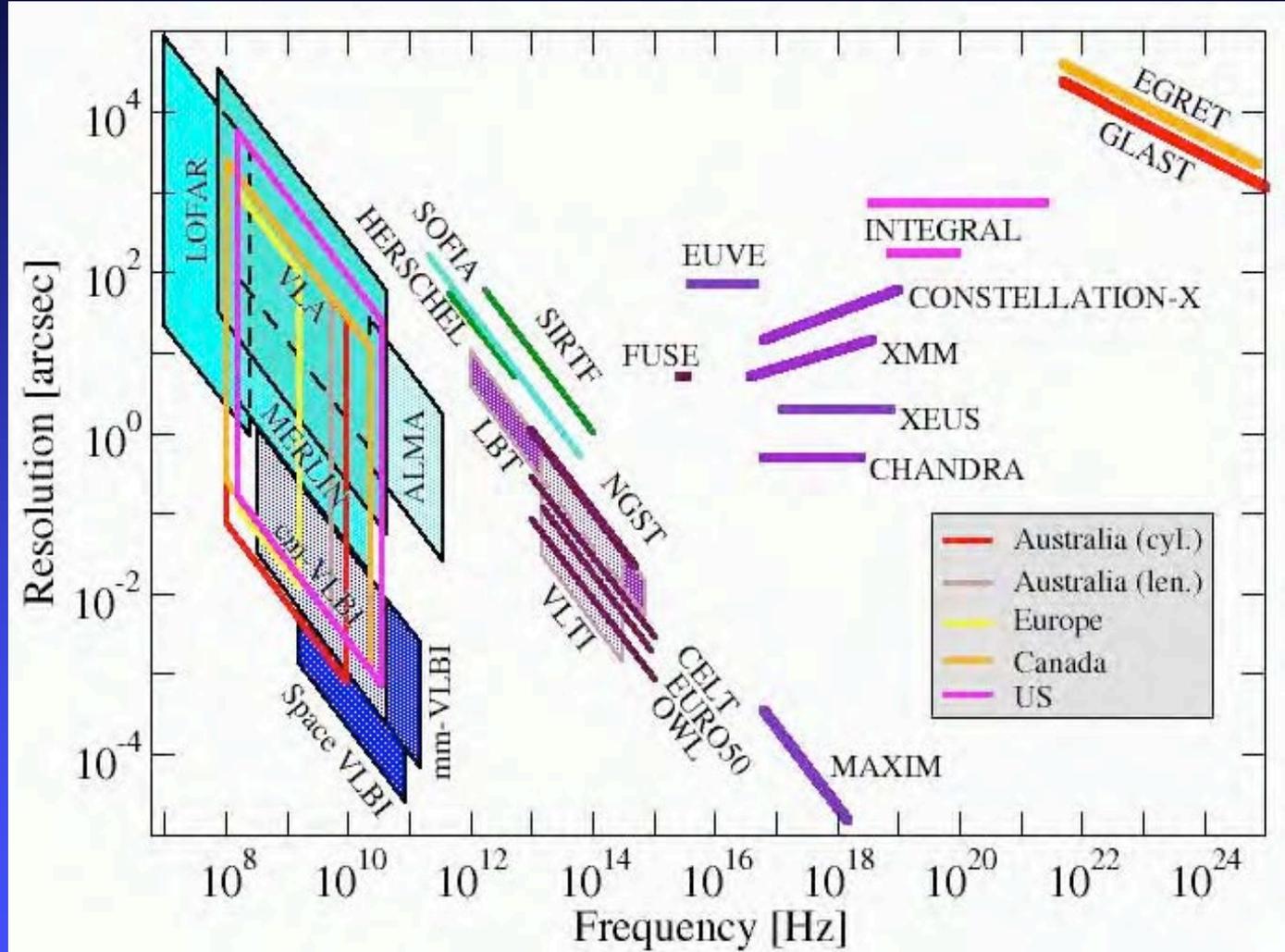
- **Michelson & Young, 1890s: measurements of stars' diameters**
- **Synthesis of large apertures: save money, trade sensitivity for resolution.**



- **At present, interferometry in astrophysics covers wavelengths from 10^3 cm (~ 30 MHz) to 10^{-4} cm (~ 300 THz), except sub-mm & far IR**
- **Very Long Baseline Interferometry (VLBI) – the ultimate angular resolution in astrophysics**

$$\vartheta = \frac{\lambda}{B}$$

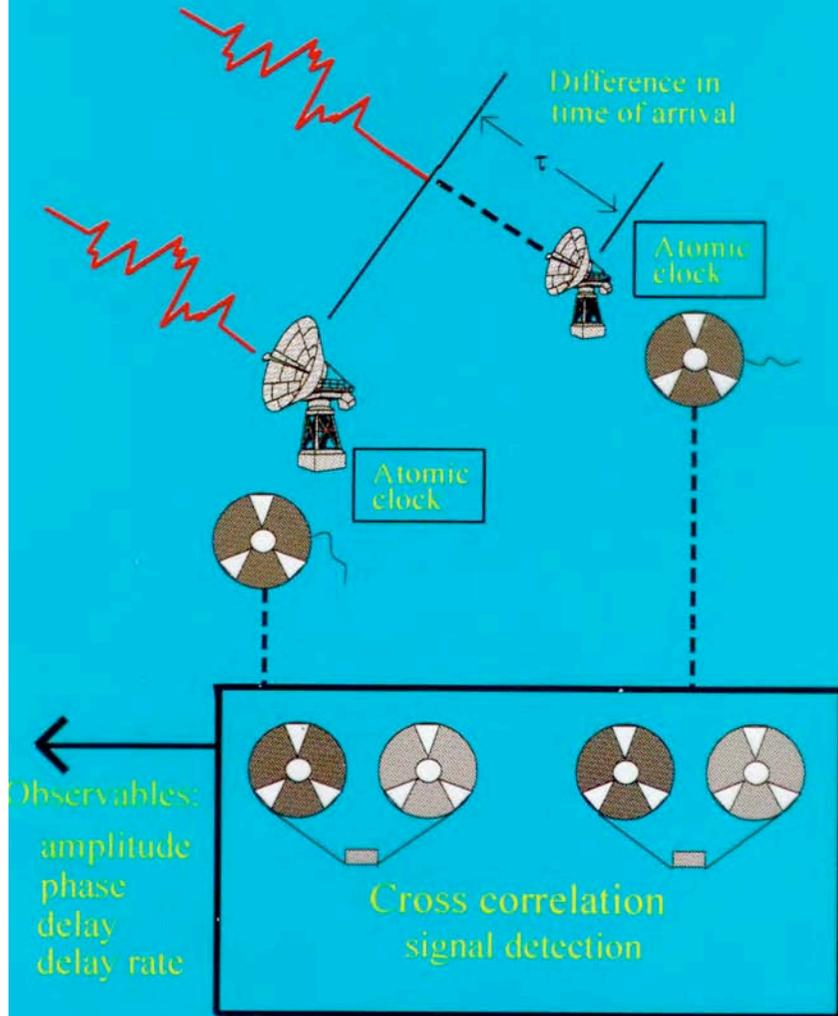
Why VLBI?



← 3 cm 3 μm 3 Å Lobanov 2002 & poster #52



VLBI Configuration



How interferometry works?

⇐ telescopes in different locations (countries, continents)

⇐ data relayed or recorded on tape and transported to a central facility

⇐ data processed (“correlated”)

Data rate: ~1 Gbps per RT;

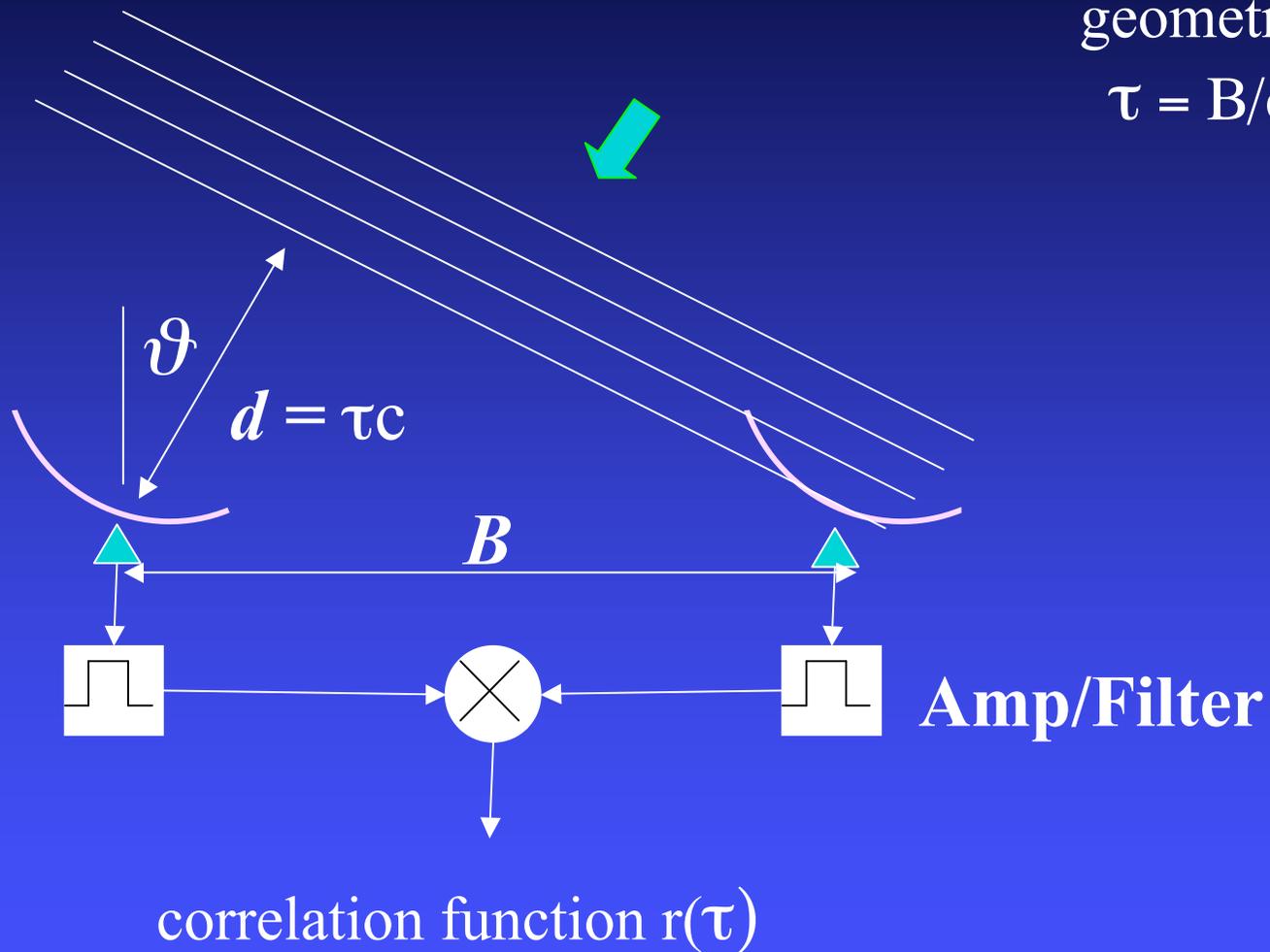
Total: ~ 1-100 TB per exp.

Interferometry: introduction



geometric delay

$$\tau = B/c \sin \vartheta$$

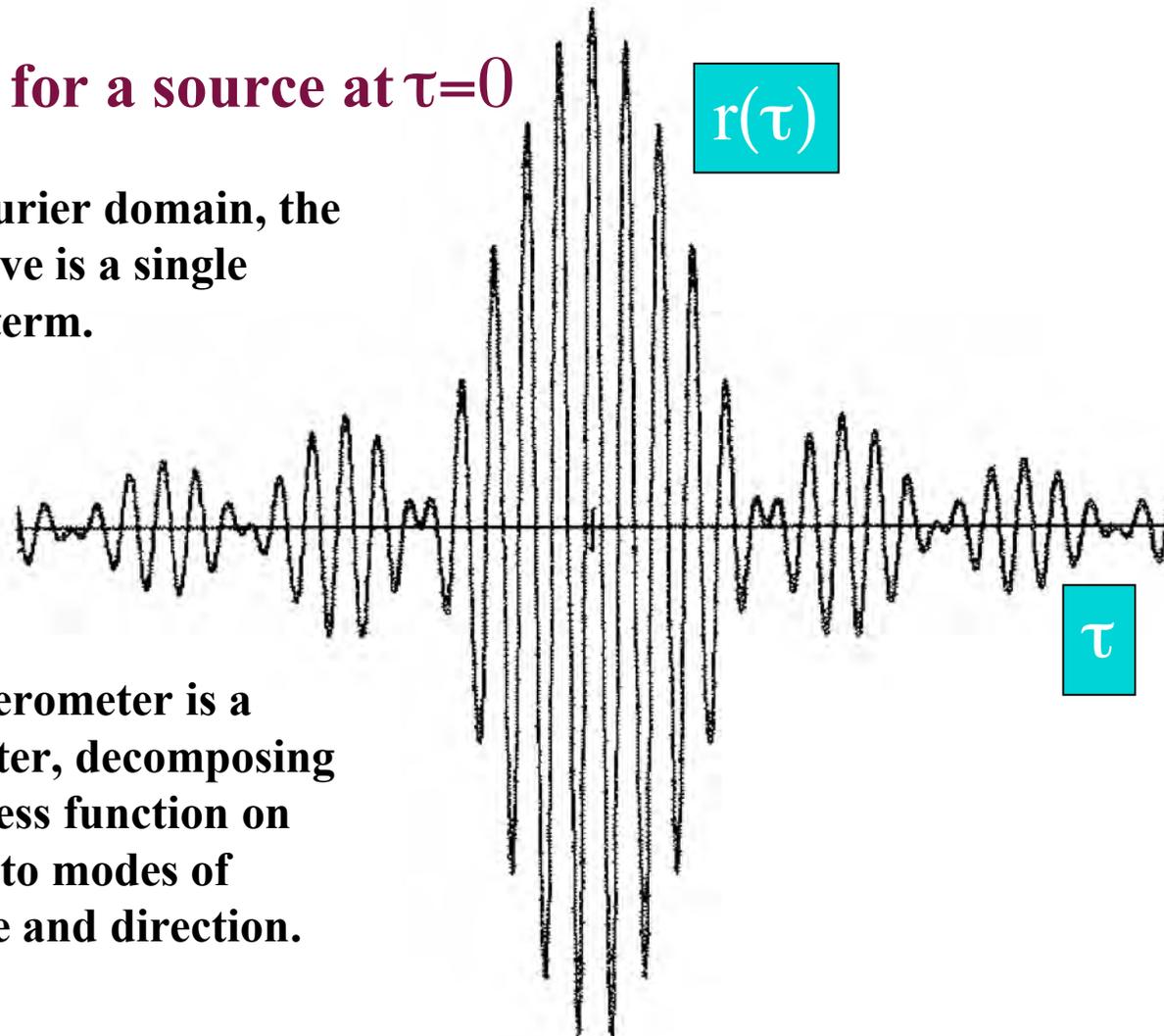


Interferometric Fringes



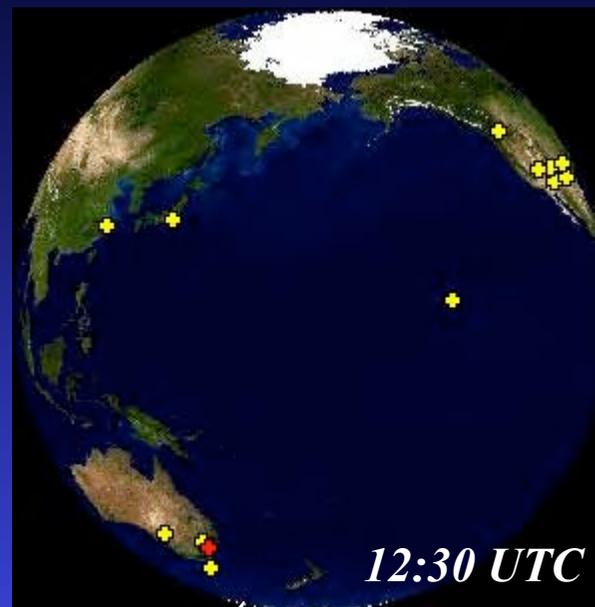
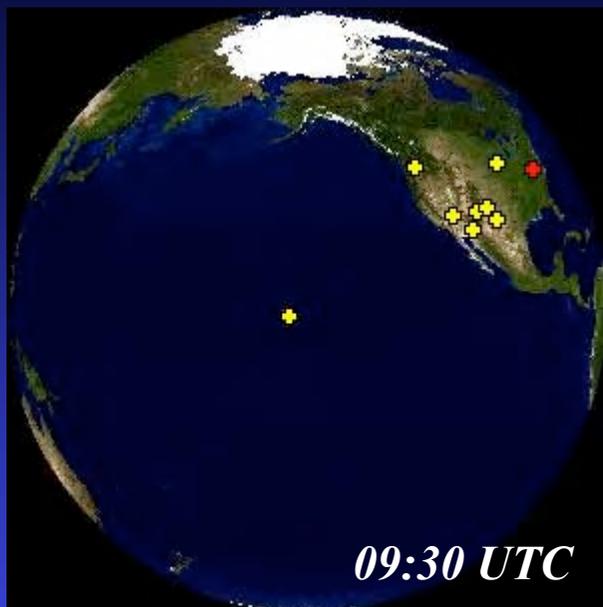
- **Fringes for a source at $\tau=0$**

- **In the Fourier domain, the cosine wave is a single complex term.**



- **An interferometer is a spatial filter, decomposing a brightness function on the sky into modes of amplitude and direction.**

Our Telescope Array



cece

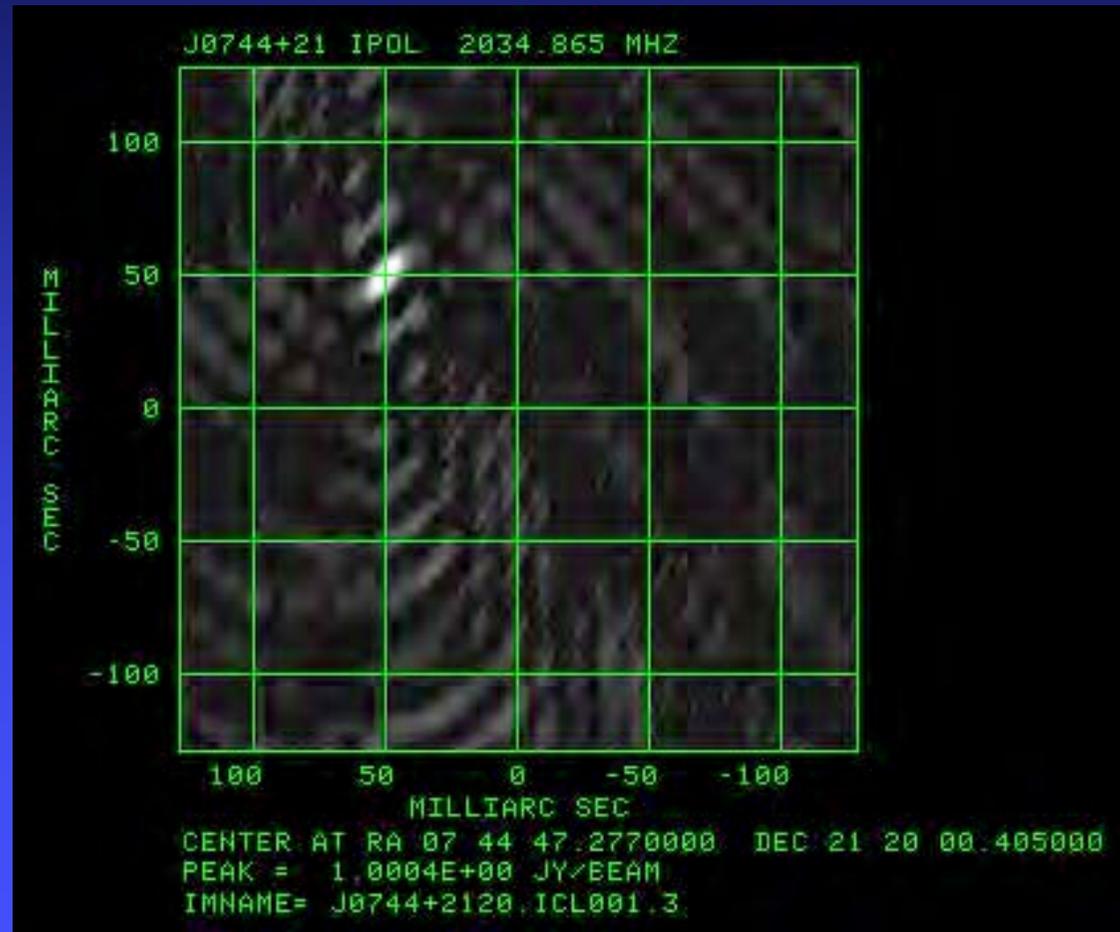
27

Global Interferometer: Model Source



Model: point source offset from phase tracking center

Instrument:
Huygens Tracking array.



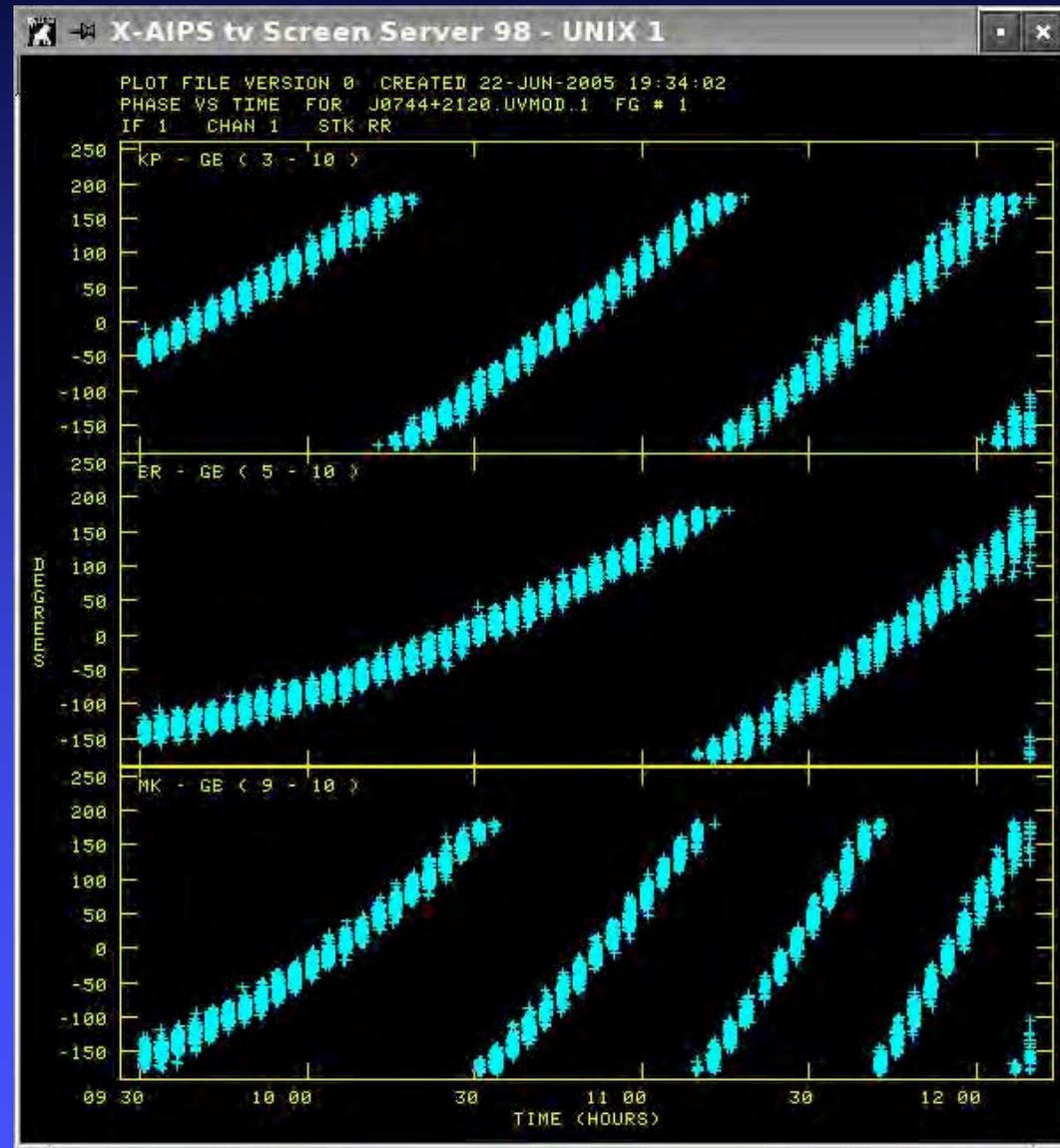
Global Interferometer: Model Phases



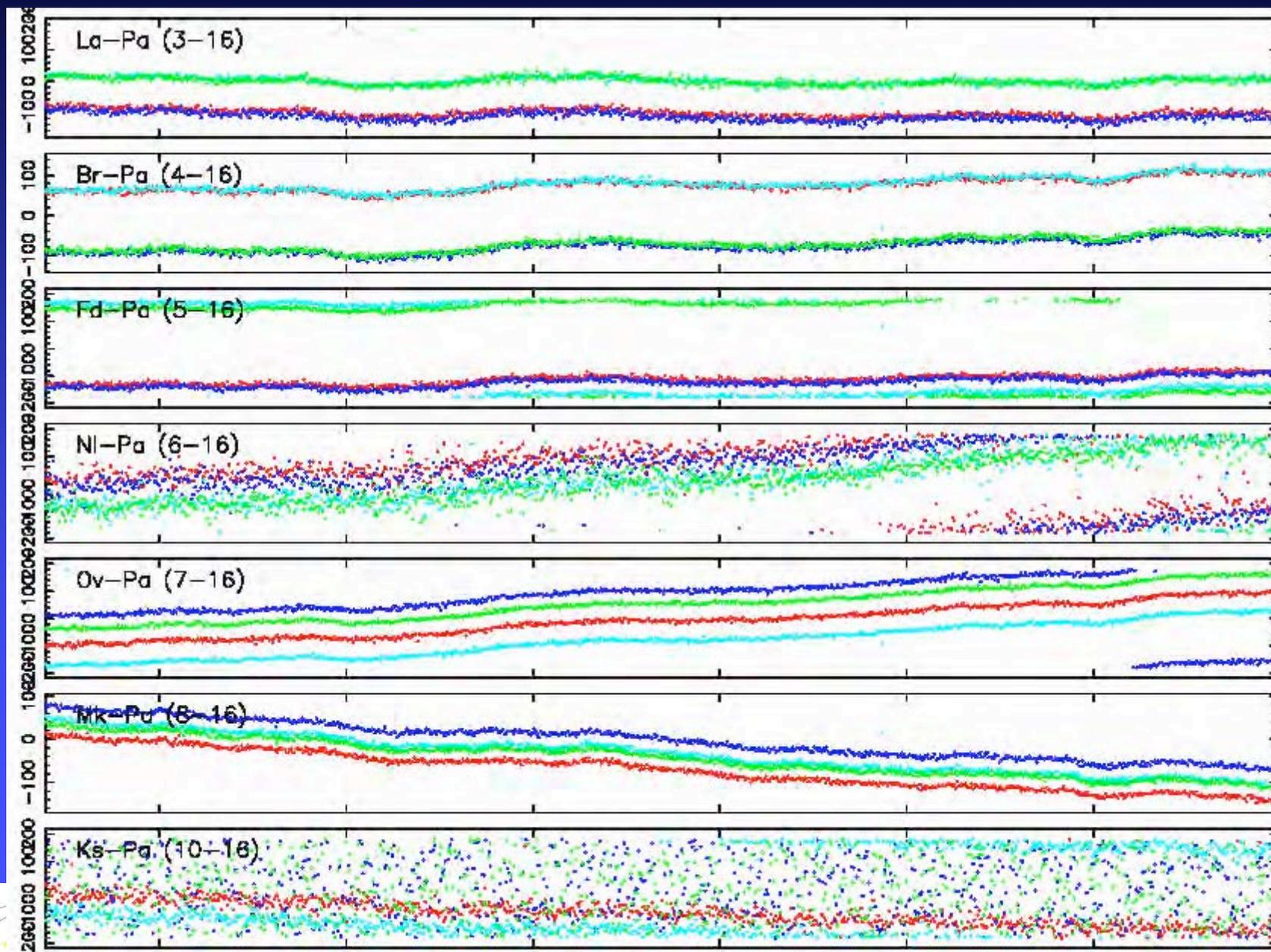
Baselines have nonzero phase because source is not at reference position.

Phase changes because geometric delay changes as Earth rotates.

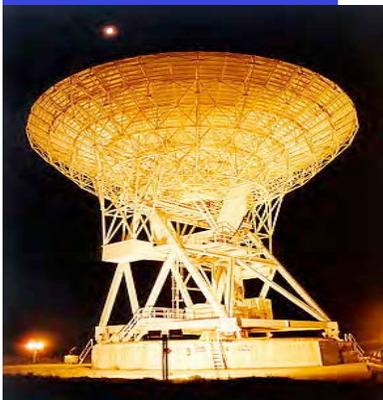
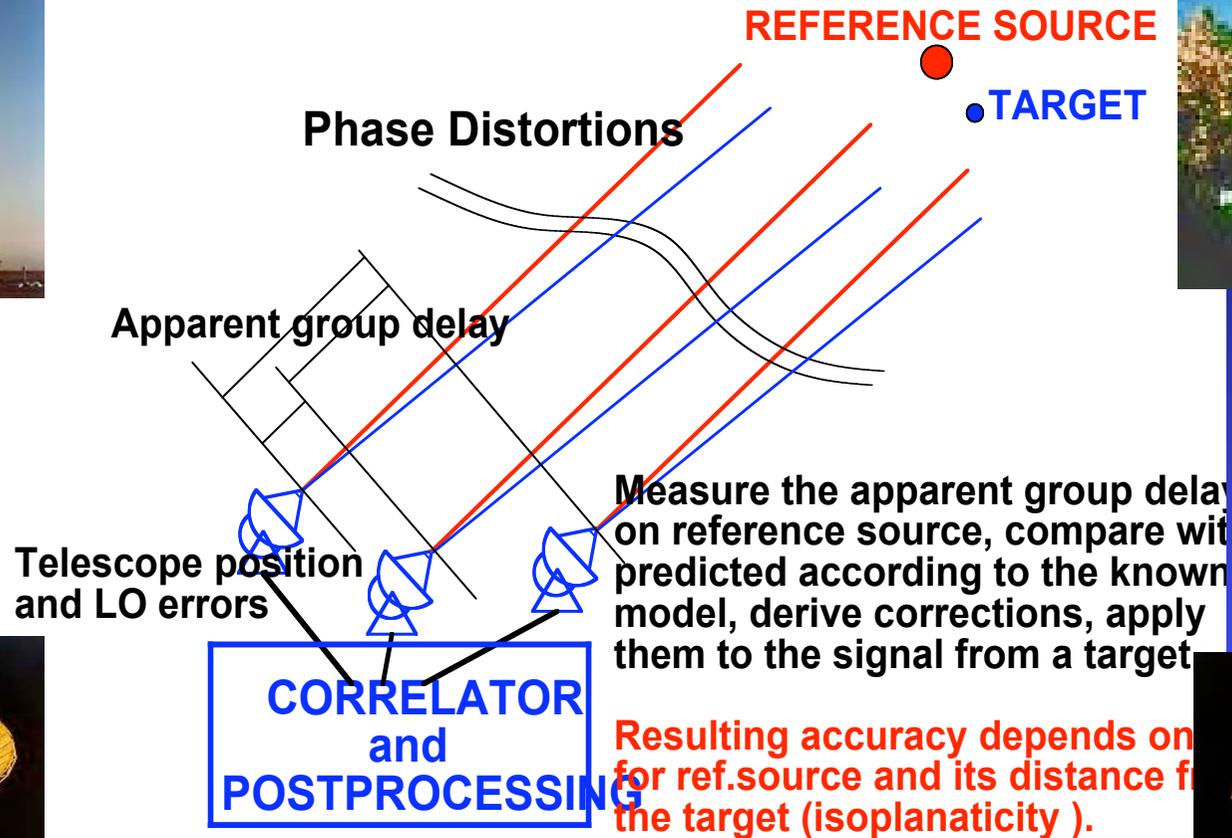
The difference of these measured phases from zero gives the position of the source on the sky.



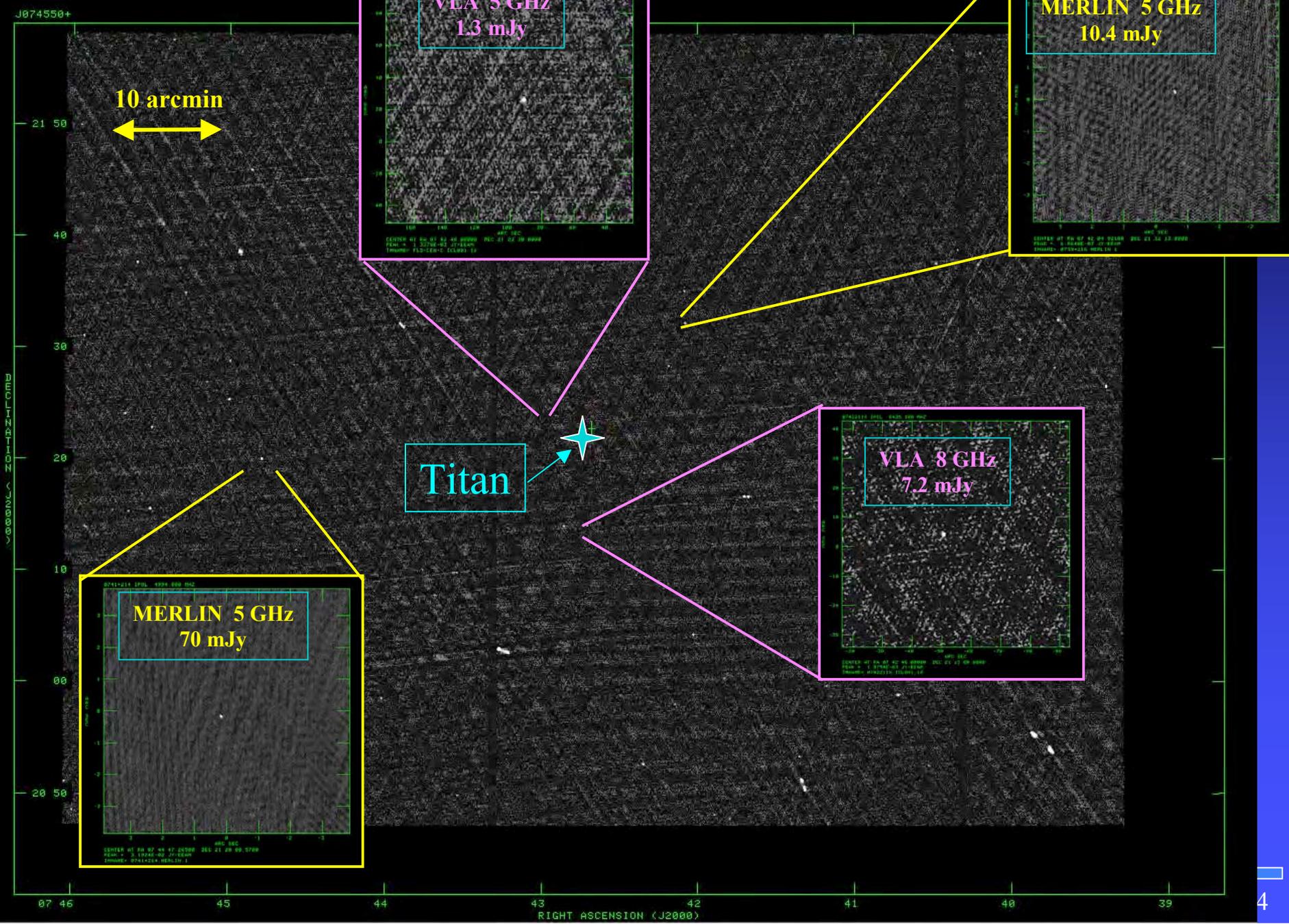
VLBI fringes (to Parkes), “Fringe Finder” Source



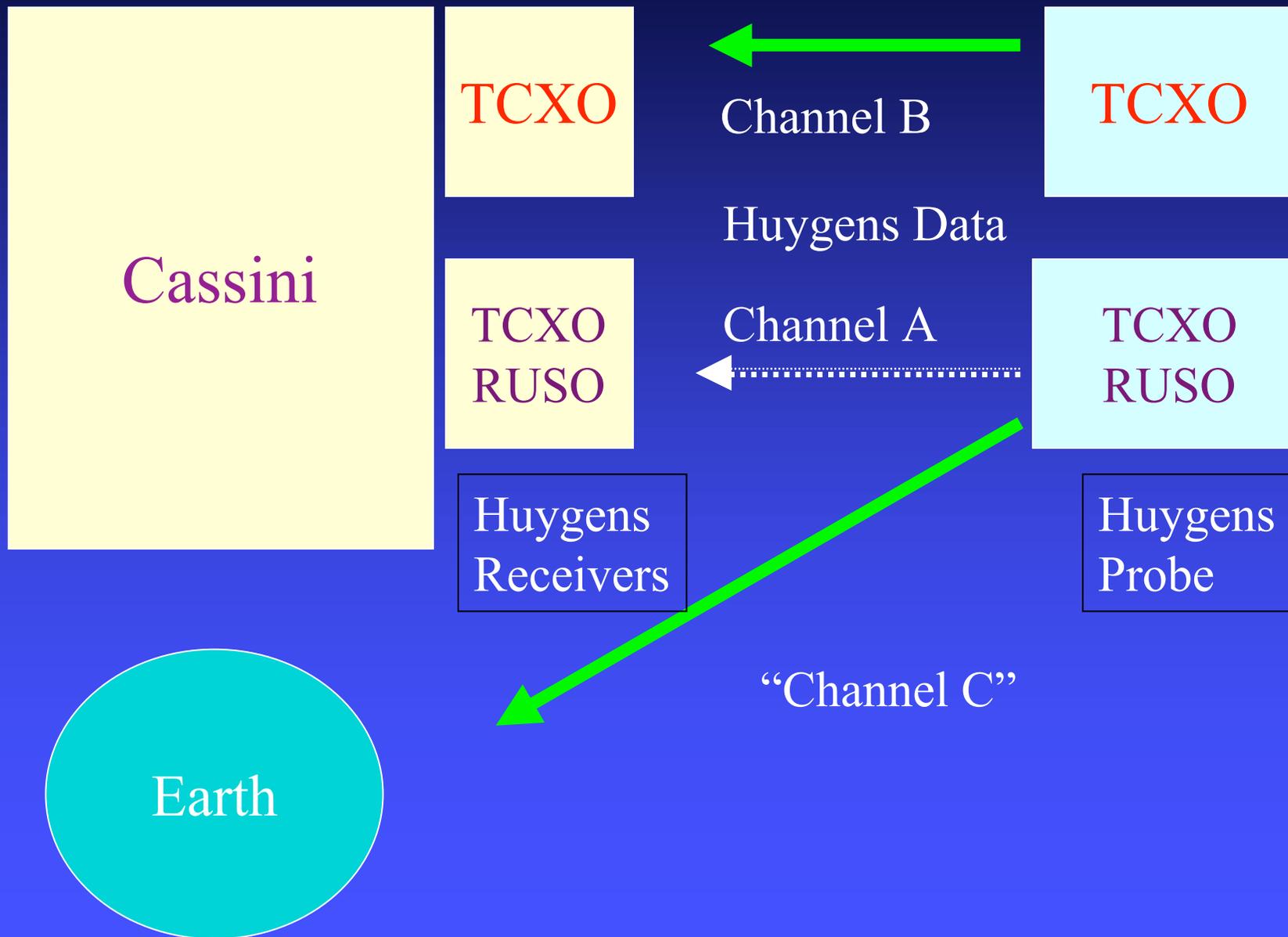
Basics of phase-referencing VLBI



Huygens Field



Huygens signal paths



How long did we hear Huygens?

340 min



	Start (2005-14) UTC	Stop (2005-14) UTC	Comment
GBT	09:31:10	12:15:00	Real time RSR detection
VLBA Fort Davis	09:31:10	13:45:00	
VLBA North Liberty	09:31:10	13:15:00	
VLBA Pie Town	09:30:11	14:15:04	No nodding – on Titan continuously
VLBA Los Alamos	09:31:10	14:00:00	
VLBA Kitt Peak	09:31:10	14:15:00	
VLBA Brewster	09:31:10	14:48:00	
VLBA Owens Valley	09:30:09	14:49:14	No nodding – on Titan continuously
VLBA Mauna Kea	09:31:10	16:00:00	
Parkes	12:26:23	16:00:00	Real time RSR detection
Hobart	11:13:10	16:00:00	
Ceduna	10:13:10	16:00:00	
Mopra	10:10:10	16:00:00	
Kashima	09:31:10	16:00:00	
Shanghai	10:01:10	16:00:00	
Urumqi	11:31:10	16:00:00	Calibration only, no Huygens signal at 2040 MHz
ATCA	10:01:10	16:00:00	Calibration only, no Huygens signal at 2040 MHz
Onsala	19:01:10	22:15:00	
Wettzell	21:46:10	22:15:00	

“Standard” broad-band VLBI correlation on calibrators



Imaging of calibrators and calibration definition



Extraction of narrow-band probe’s Signal from Mk5 to HSC



Application of calibration corrections to the narrow-band data



Iterative search for monochromatic (carrier) signal; Common Mode defined

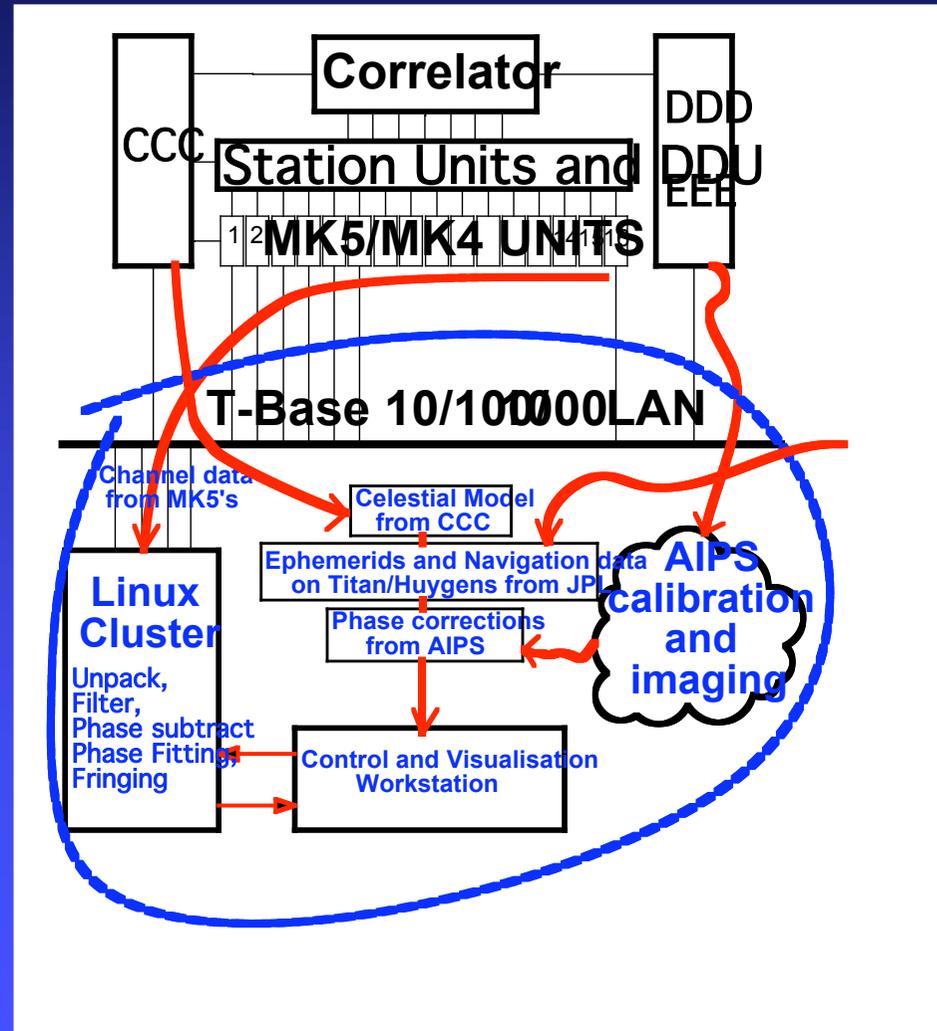


Phase-lock to Common Mode, inarrowing down search window



Iterative imaging (trajectory reconstruction)

Algorithm of VLBI processing



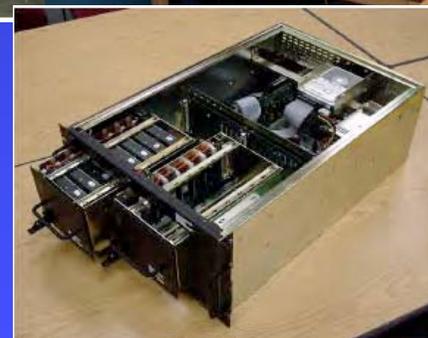
EVN MK4/MK5 Data Processor @ JIVE: the most powerful VLBI processor on Earth



The Mark 5 system is being developed at Haystack Observatory.

<http://web.haystack.mit.edu/mark5/Mark5.htm>

Shown at the right are MK5 recorder/playback unit and 1.5 TB disk pack



Huygens detection (Green Bank)



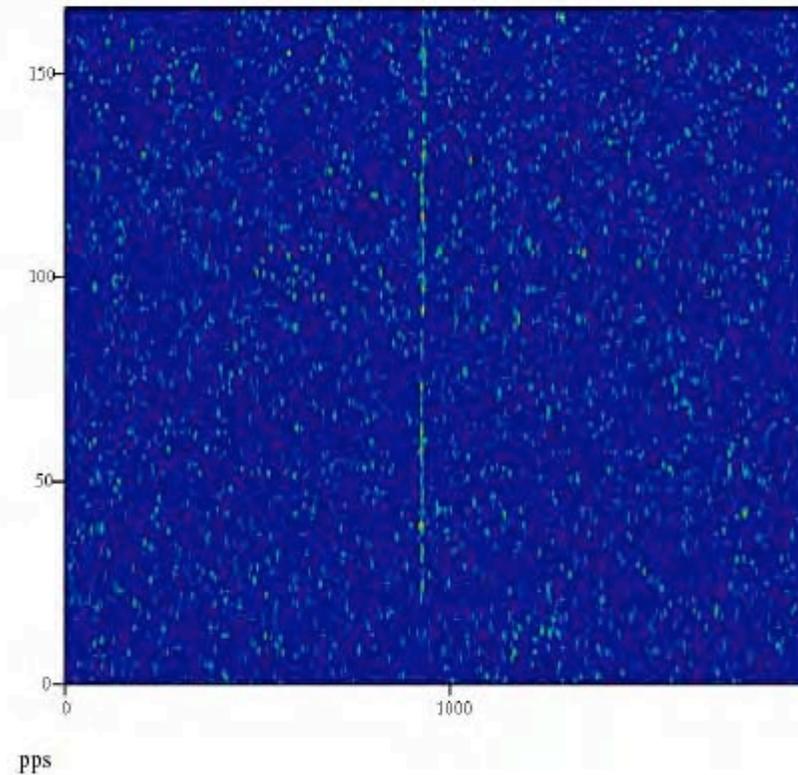
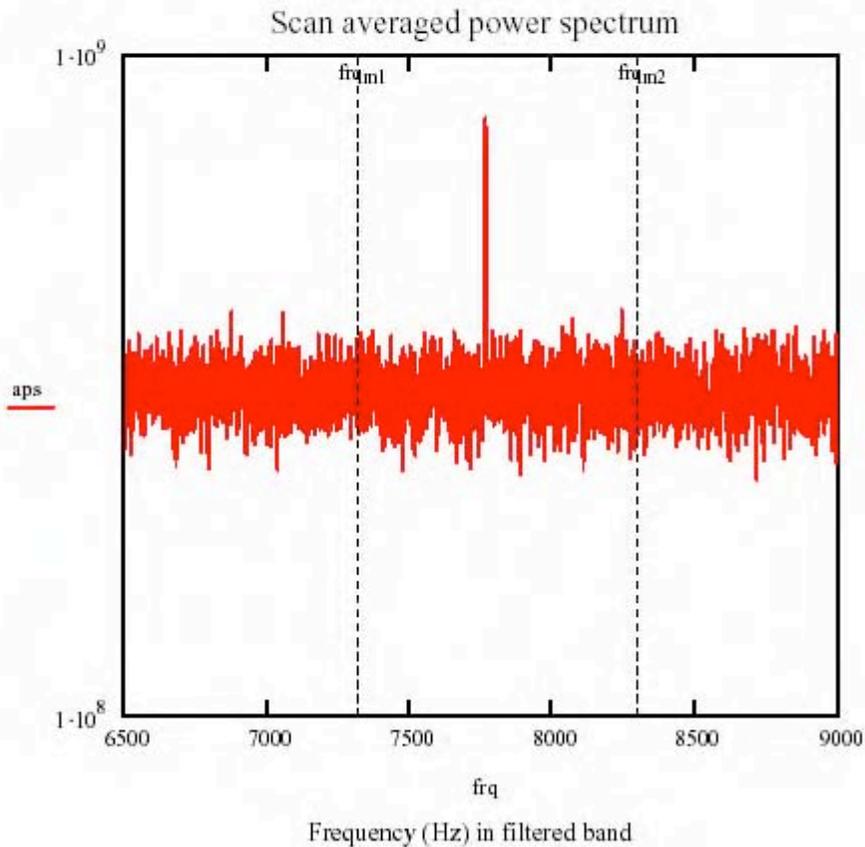
GG057C Preview

Station := "GB" Scan := 91

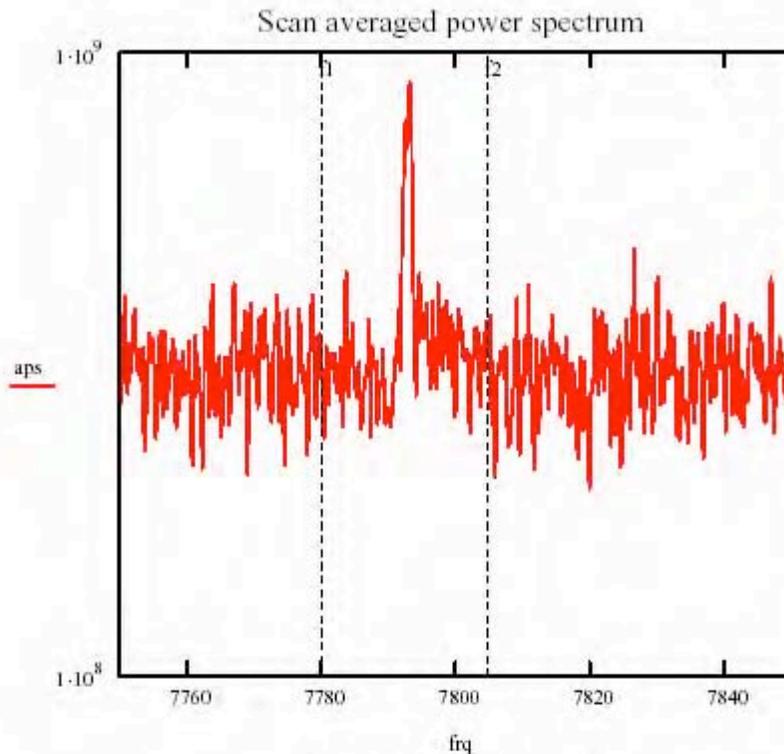
Resolution 0.9 Hz, Scan duration 110 sec

Huygens carrier at Green Bank, Mk5 VLBI

Dynamic spectrum



Huygens detection (Parkes)

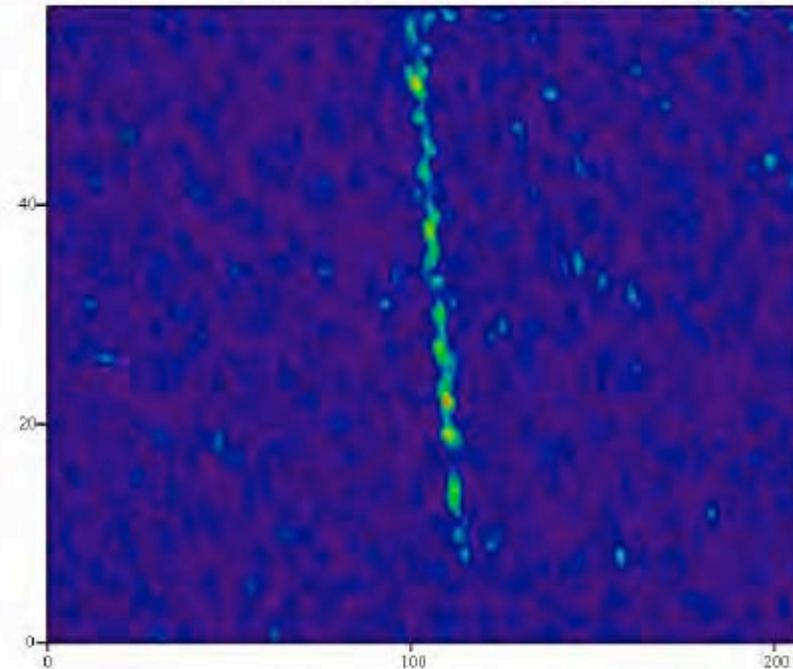


Frequency (Hz) in filtered band

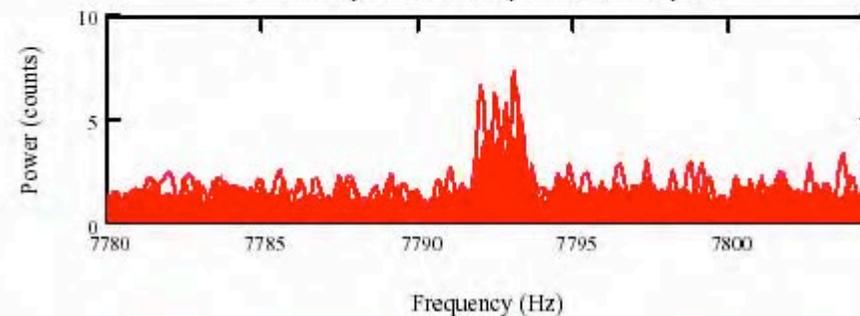
Integration time per spectrum $T_{int} = 4.194303999999998 \text{ s}$
FFT Resolution (with padding), Hz $df = 0.11920928955078125$

GG057C Preview, Station Parkes,
scan start: 13h 19m 0s, duration 127 seconds

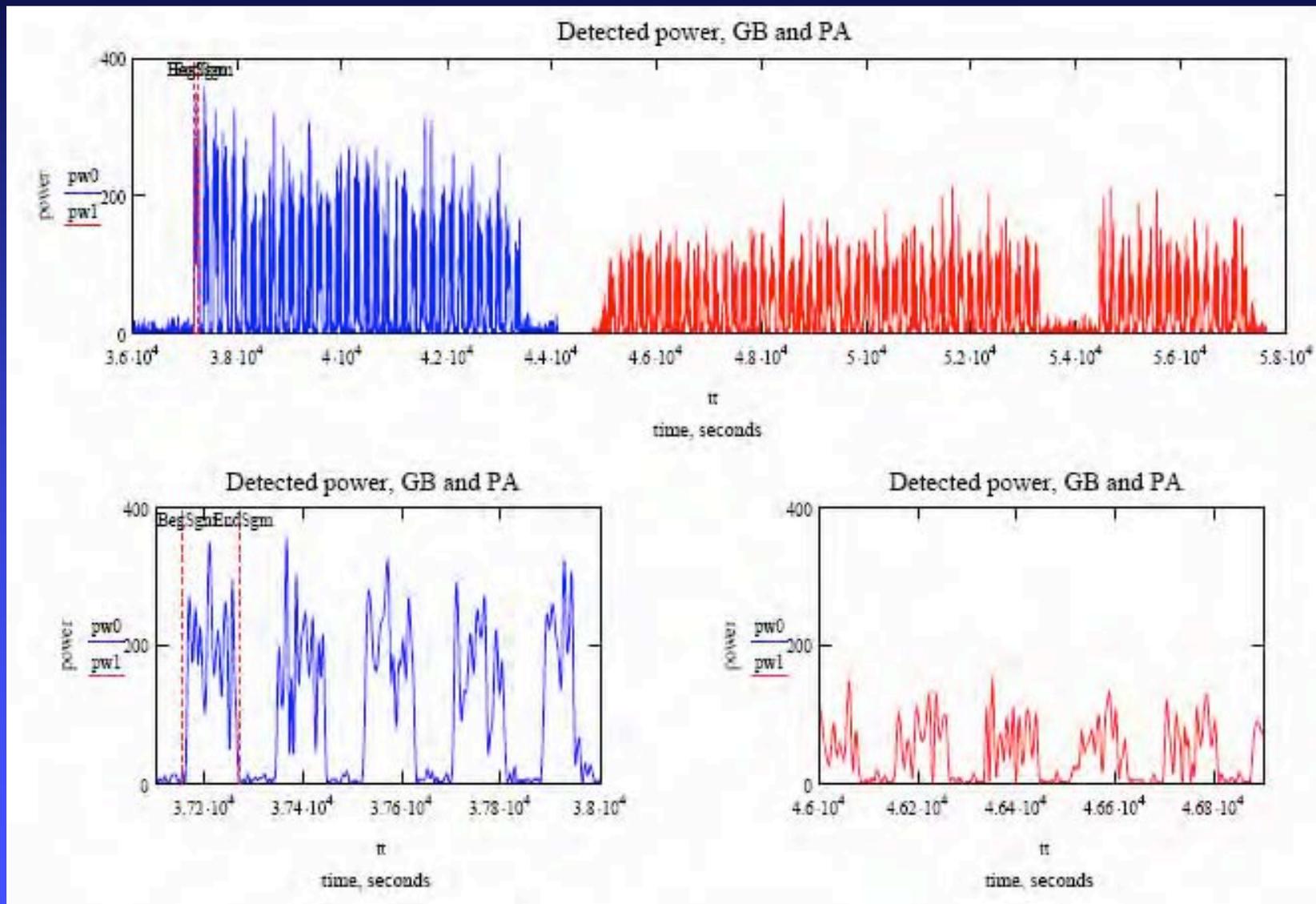
Dynamic spectrum,
horizontal axis - frequency bins, 110 MHz per bin
vertical axis - time bins, 4.2 s per bin (50% overlap)



Instant spectra, 4 s input time samples



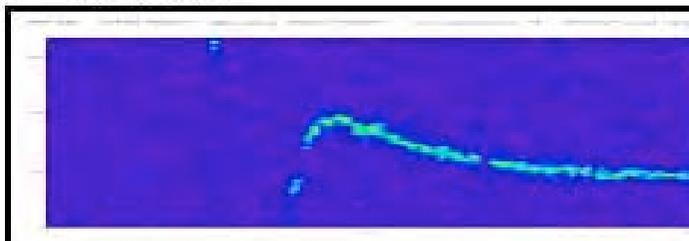
Huygens Signal Detections



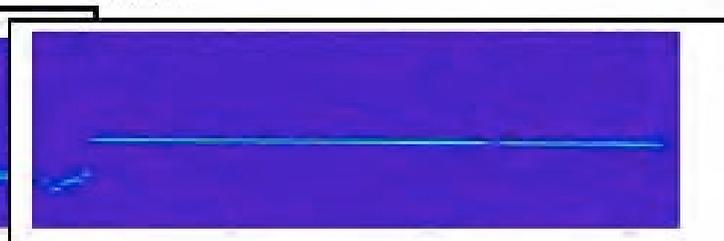
Huygens ch. A detections with 25-m antennas



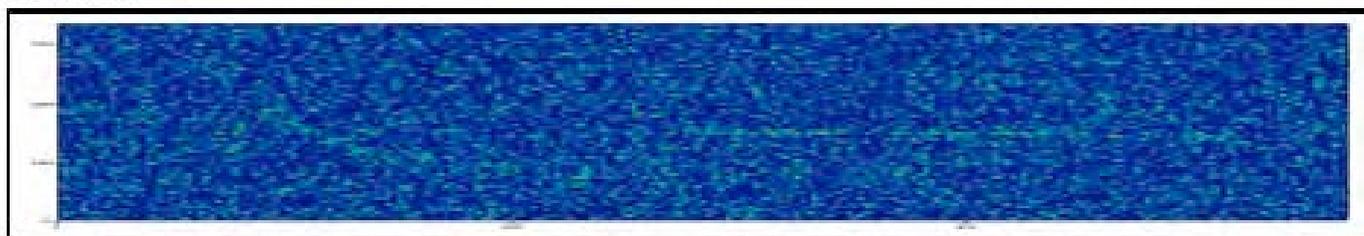
Green Bank



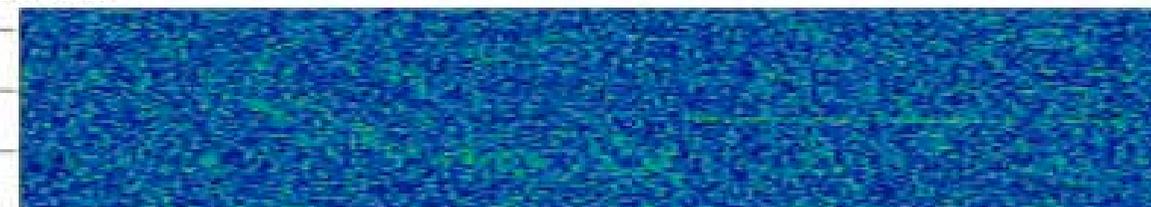
Parkes



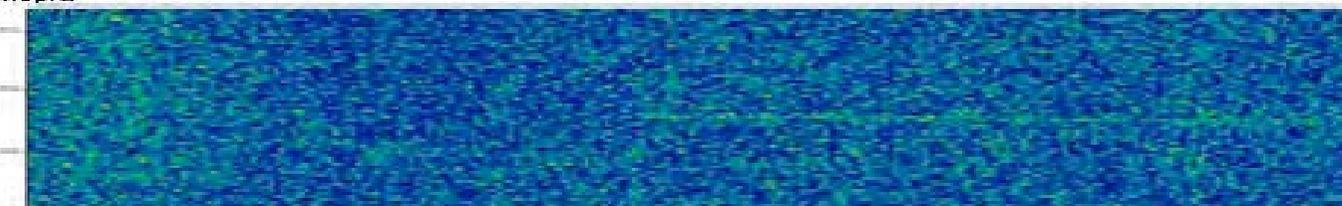
Mauna Kea



Brewster



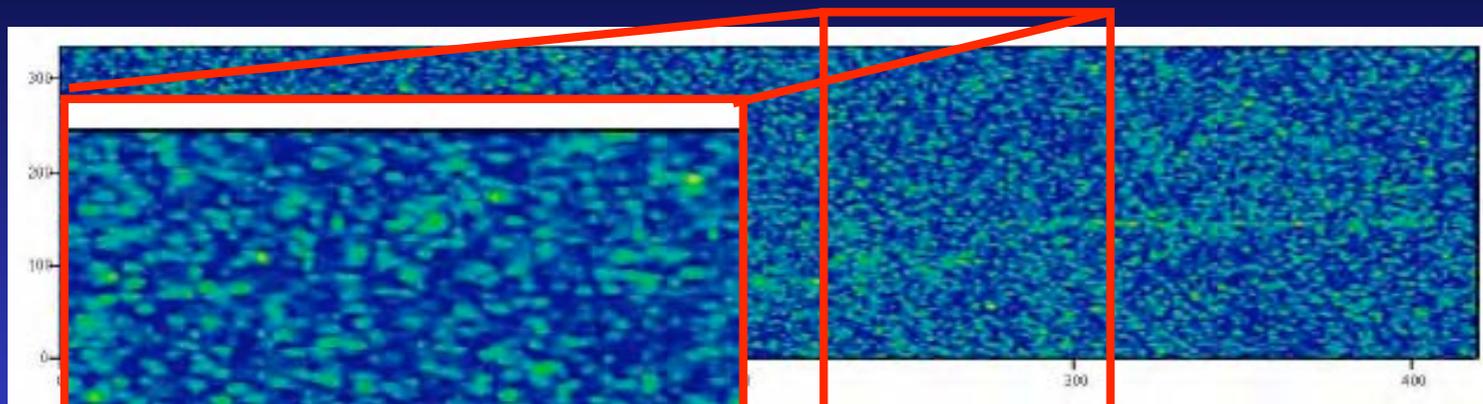
Mopra



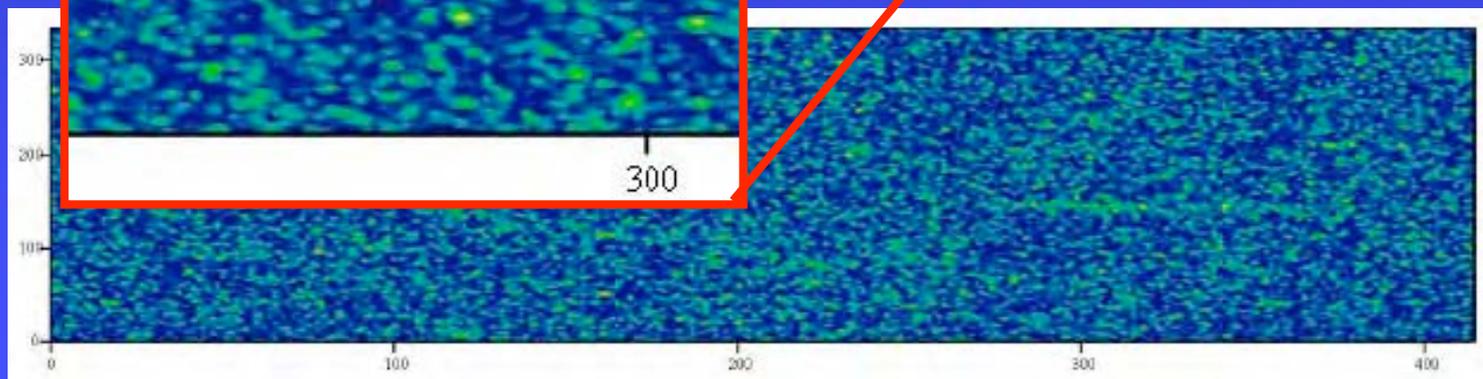
Statistics



Pie Town



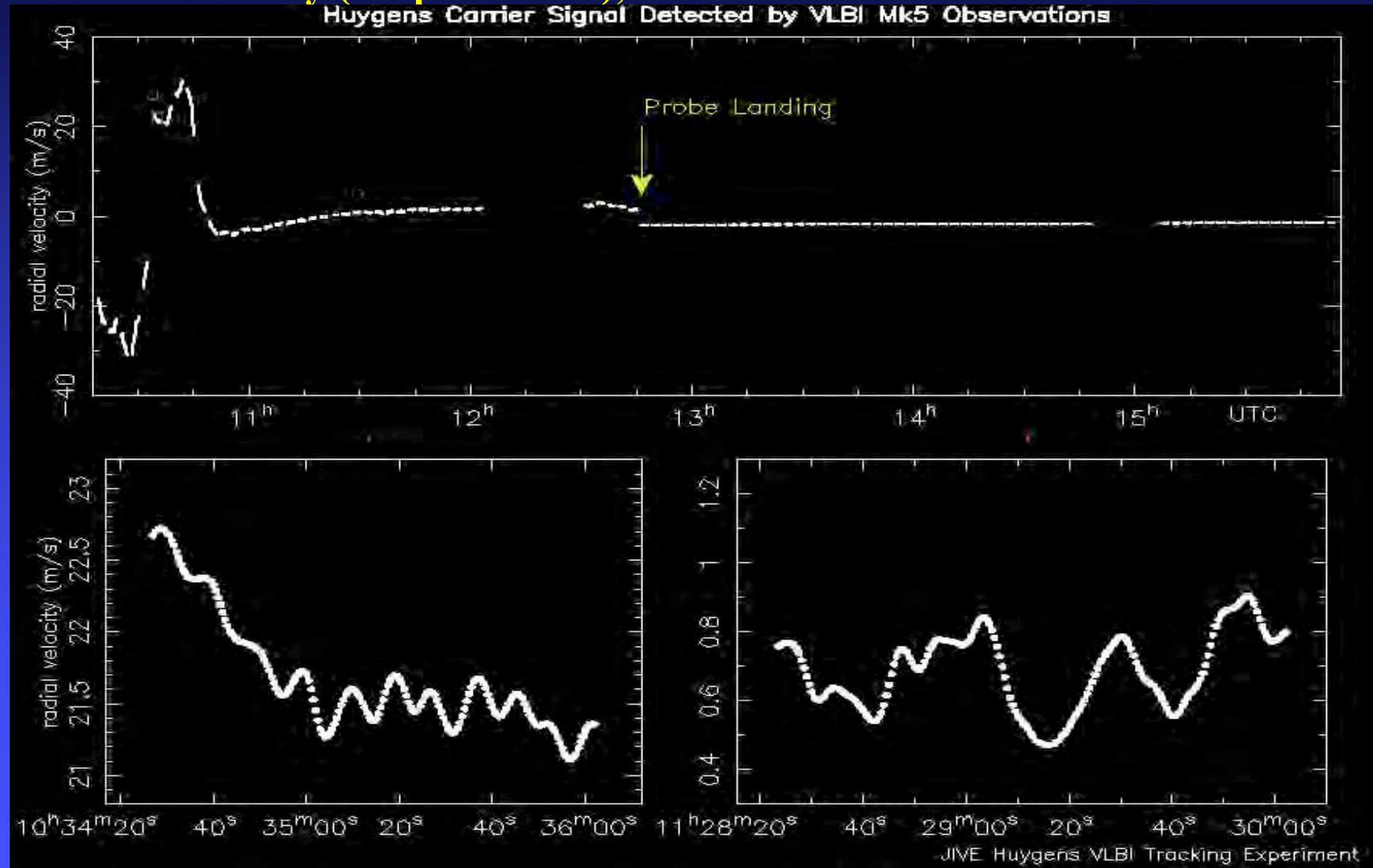
Kitt Peak



Huygens Doppler Measurements



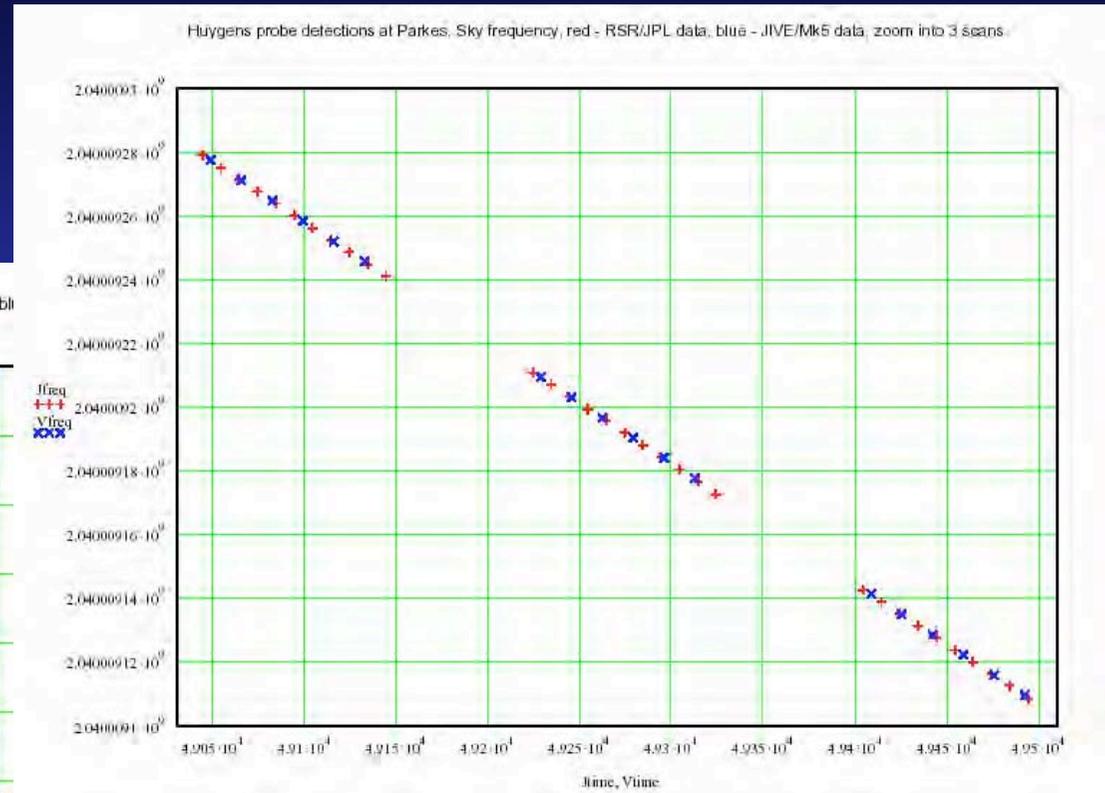
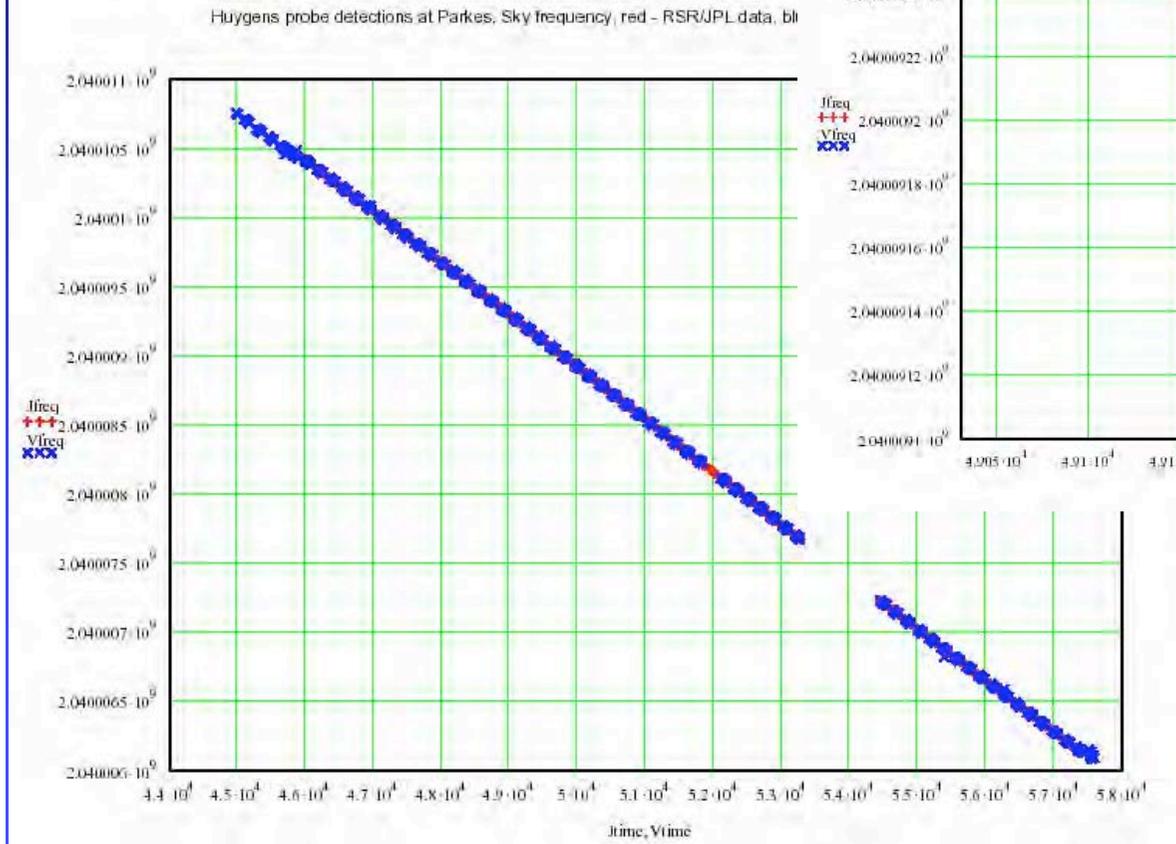
- Radial velocity (freq deviation), measured.



Verification of the RSR and VLBI Doppler measurements



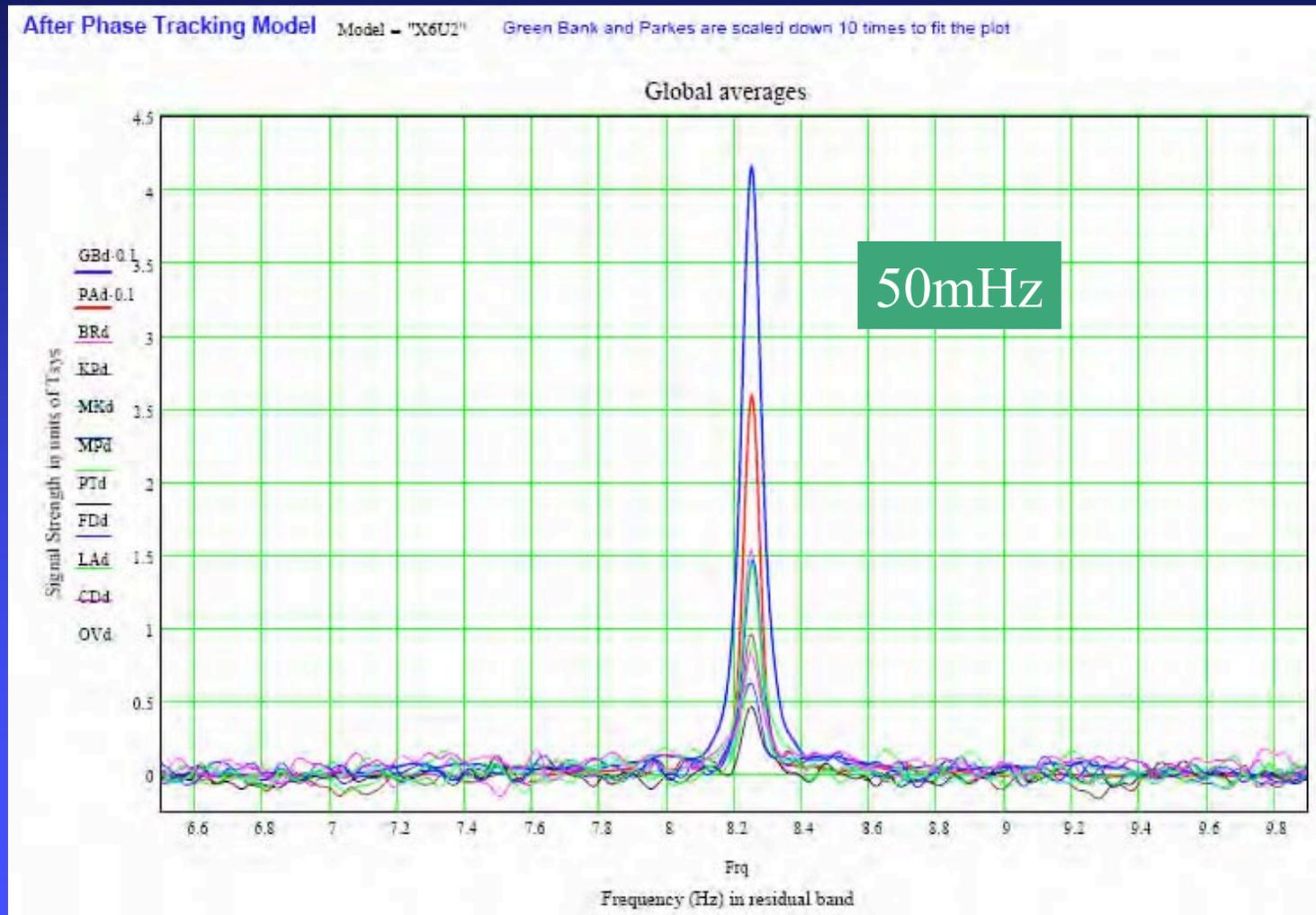
Parkes data



Stopping Huygens Fringes



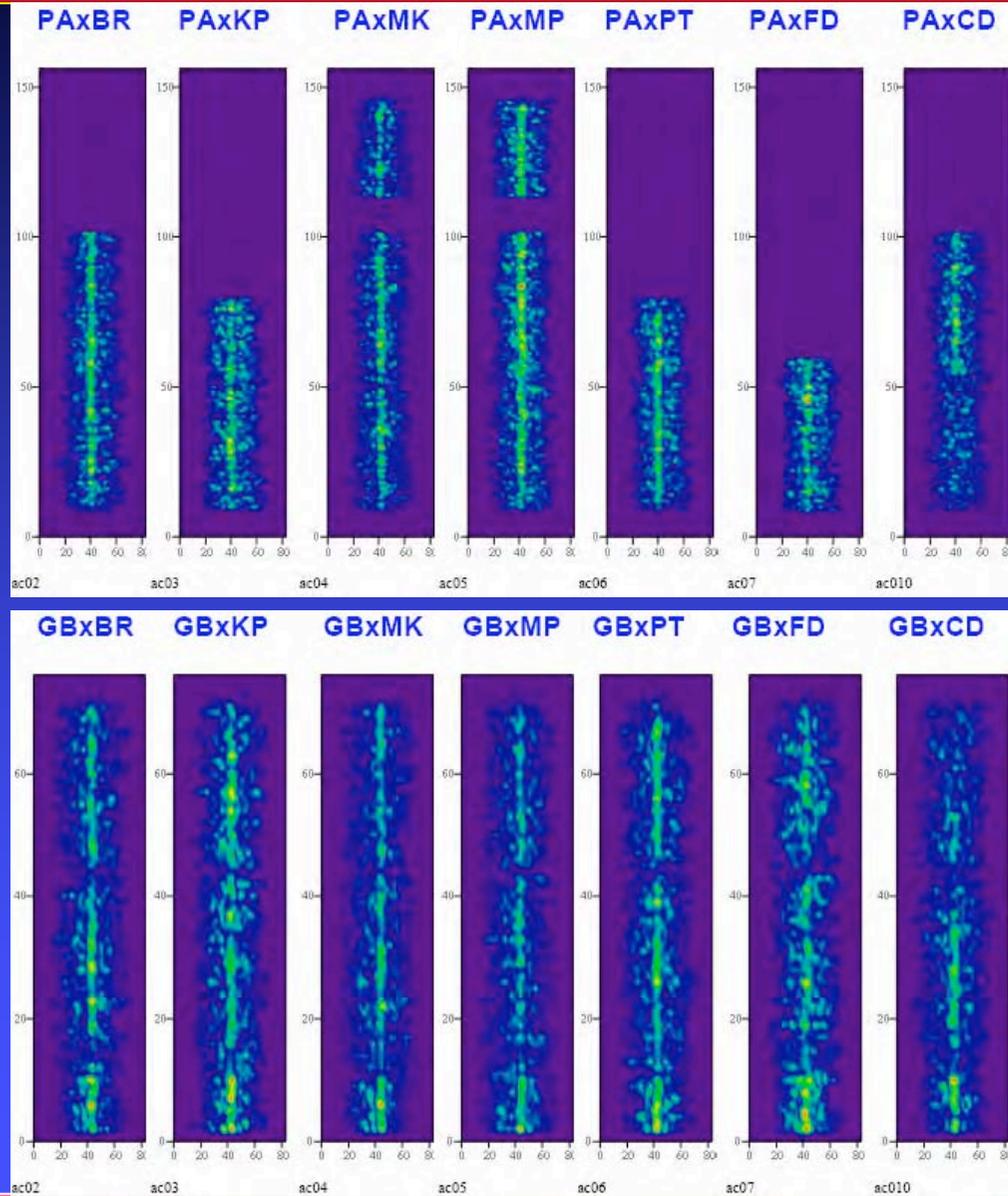
- We detect and remove a Doppler model from the data.



Huygens Fringe Amplitudes vs. Frequency



time

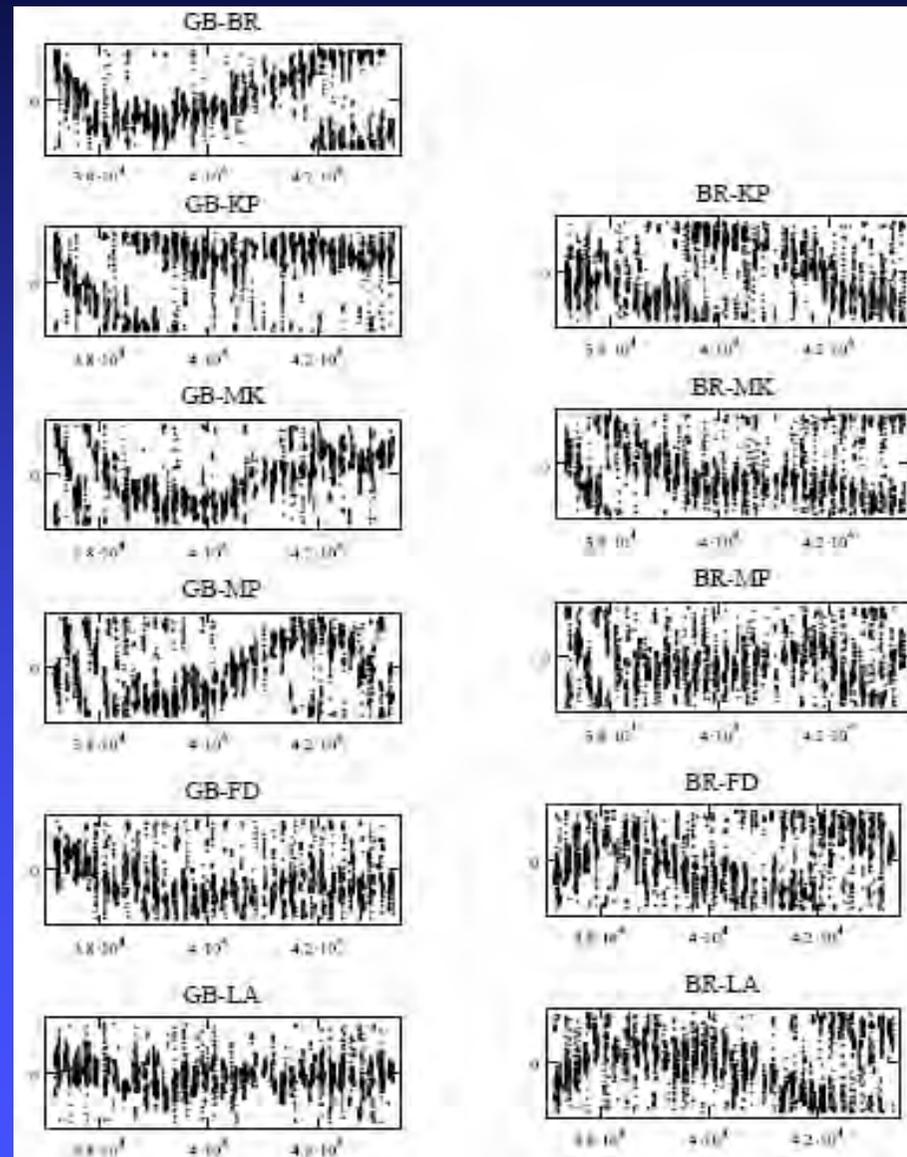


Huygens Fringe Phases vs. Time

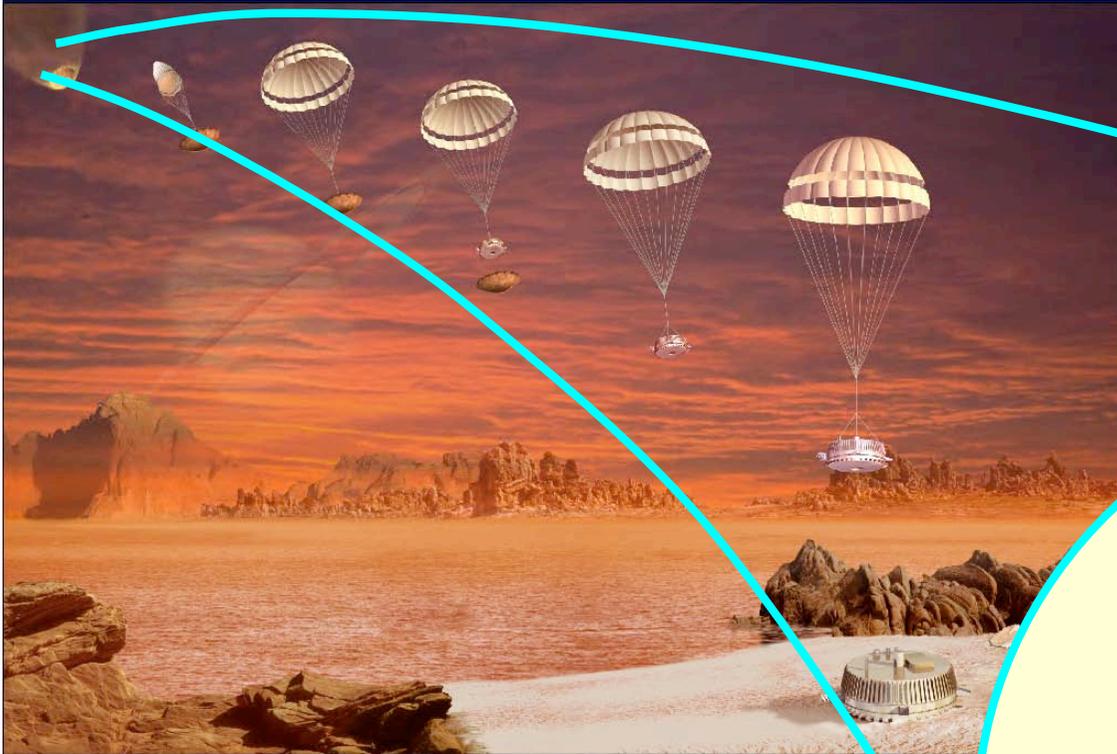


Good detections on
25m-25m baselines.

These phases measure
Huygen's position in
the radio coordinate
frame.



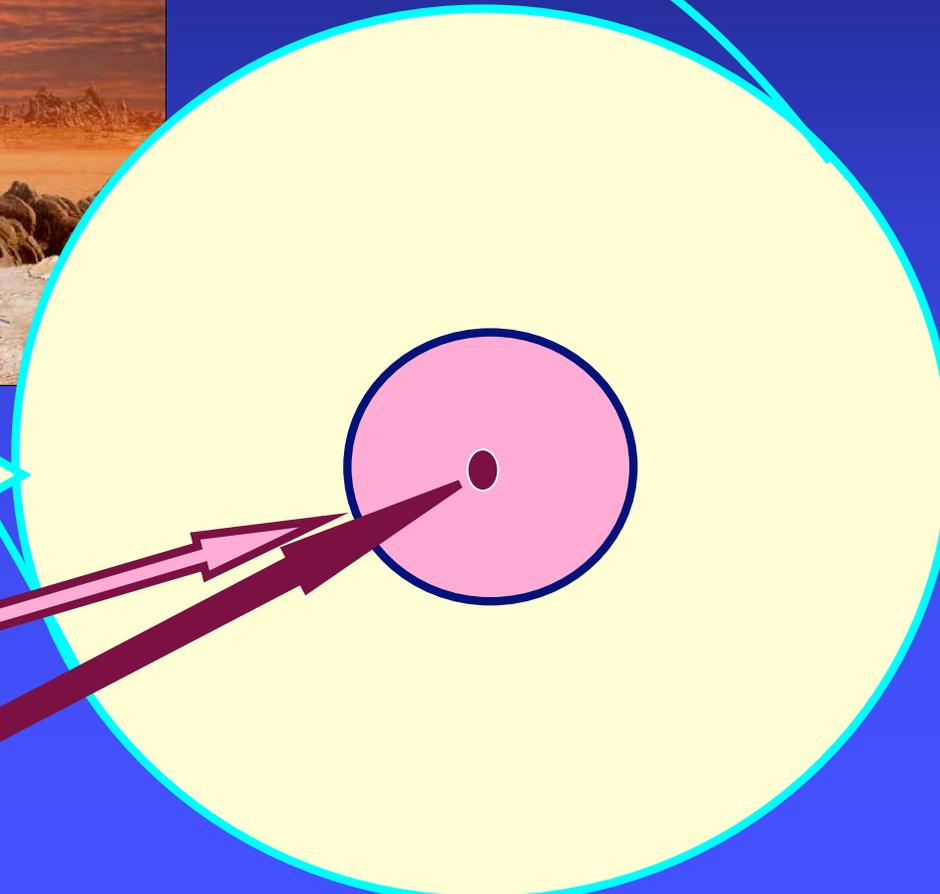
VLBI determination of the Huygens descent trajectory



A priori accuracy: ~100 km

Doppler interferometry: ~25 km

Full VLBI accuracy: ~1 km



Status of the Huygens (VLBI) Tracking Project (a)



- **17 radio telescopes recorded the data (all scheduled + 2):** **27 TByte**
- **Quality of the data:**
 - ◆ perfect at several stations (e.g. GBT, Mauna Kea, Parkes, Mopra)
 - ◆ Problematic:
 - ◆ *Los Alamos, Owens Valley, North Liberty (?) – RFI*
 - ◆ *Hobart, Kashima – data recording (but mostly recovered)*
 - ◆ *Shanghai, Urumqi, Kashima – high noise*
 - ◆ Others – reasonable (as expected)
- **“Production correlation” – completed (pre-processing complete – good results)**
- **Current status** **Huygens signal fringes to all telescopes!**
- **(Positive) deviations from the original experiment plan (e.g. Doppler data extraction, post-landing data analysis)**

Status of the Huygens VLBI Experiment (b)



- **Doppler-tracking filtering continues. Global SNR up with each iteration.**
- **Huygens has produced fringes in preliminary correlation.**
 - ◆ A calibration of atmospheric and instrumental contributions to the correlator output has been derived from our 'reference source' observations.
 - ◆ Investigating systematic errors: reference frames, algorithmic choices such as detection thresholds.
- **Results round-up in mid-July, at a JIVE-hosted meeting in Dwingeloo.**
- **More can and will be done with fine timescale and post-landing analysis**
- **VLBI tracking of the Huygens probe became possible due to progress of technology over last ~3-5 years**
 - ◆ High bandwidth networks and RAIDs allow random access to the digital data.
 - ◆ Software & Hardware capability developed for the Huygens VLBI expt. can be applied to other spacecraft/probes.
 - ◆ *Precise timing/positioning relative to fundamental frame or other spacecraft.*