# Precise VLBI tracking of planetary probes revisited

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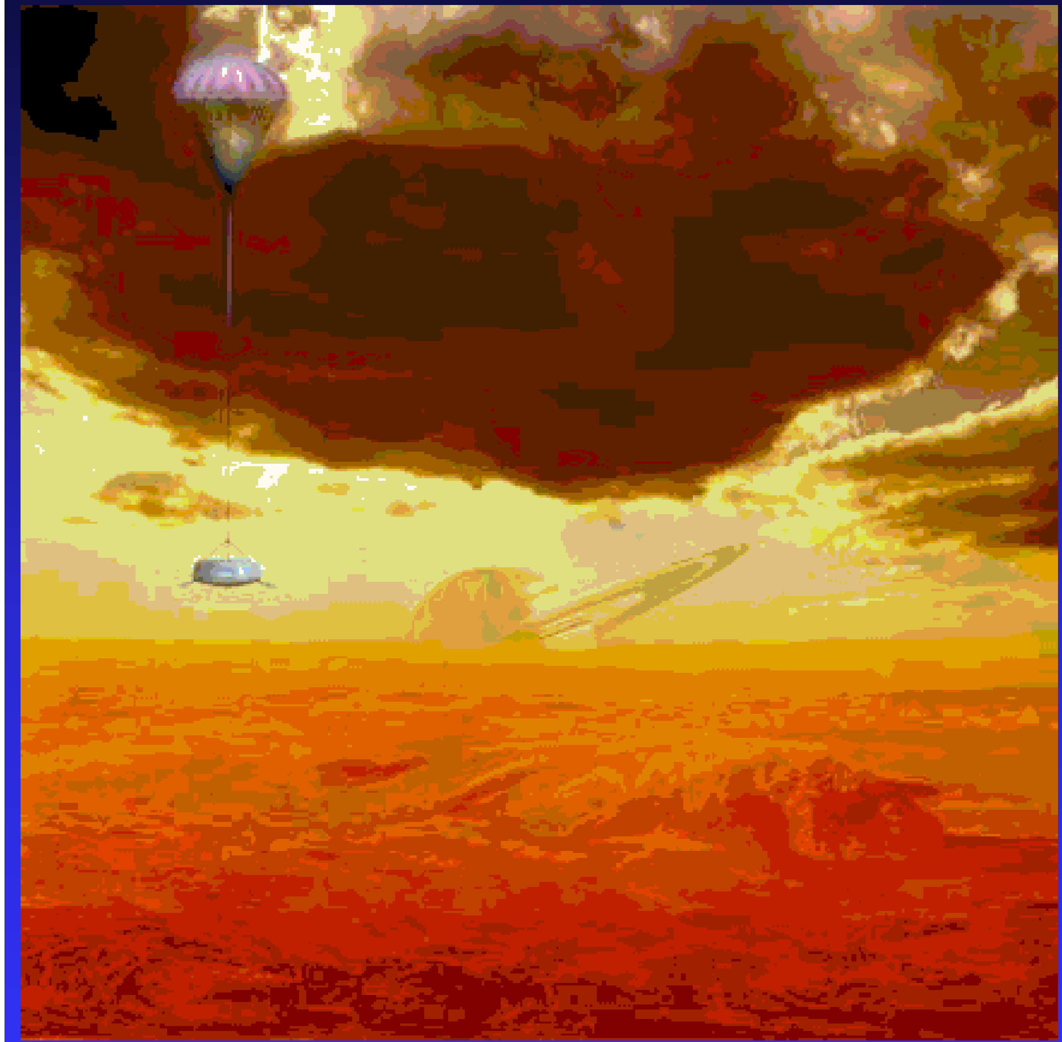
# *Radio Astronomy and Spacecraft Tracking*

- 4 October 1957: Jodrell Bank and Sputnik – accounts by Sir Bernard Lovel in "Astronomer by chance" (see also A.Gunn, in "RadioAstronomy from Karl Jansky to microjansky", 2005)
- 1963: VLBI with Jodrell Bank – Evpatoria? (B.Lovell's visit to Crimea)
- 1965: Detection of the variability of extragalctic  sources by G.Sholomitskii
- 20 July 1969: Parkes (J.Bolton and colleagues) sees N.Armstrong's "great step of mankind" (see "The Dish")
- 1984-86: VLBI tracking of the Venus  baloons (VEGA mission) and VEGA-Giotto Pathfinder experiment (Intercosmos-ESA-NASA)
- 1980s: VLA as a supersensitive deep space "downlink" station
- 1980s: NASA DSN stations (Goldstone, Robledo, Tidbinbilla) begin their VLBI duties
- 1990s: phase-referencing "satellite-3C279" demo (Asaki, Sasao et al.)
- 2000s: Selene project, Japan
- 2006: VLBI tracking for the Chinese mission to the Moon

# Cassini-Huygens: the mission



- Launched in Oct 1997;
- Joint ESA-NASA project;
- Arguably, the most complicated (and expensive) interplanetary mission so far;
- Targets:
  - Cassini – Saturn
  - Huygens – Titan
- The most distant controlled "landing" (~70 loght-minutes)
- S/C separation: 25 Dec 2004;
- Huygens atmosphere entry: 14 January 2005

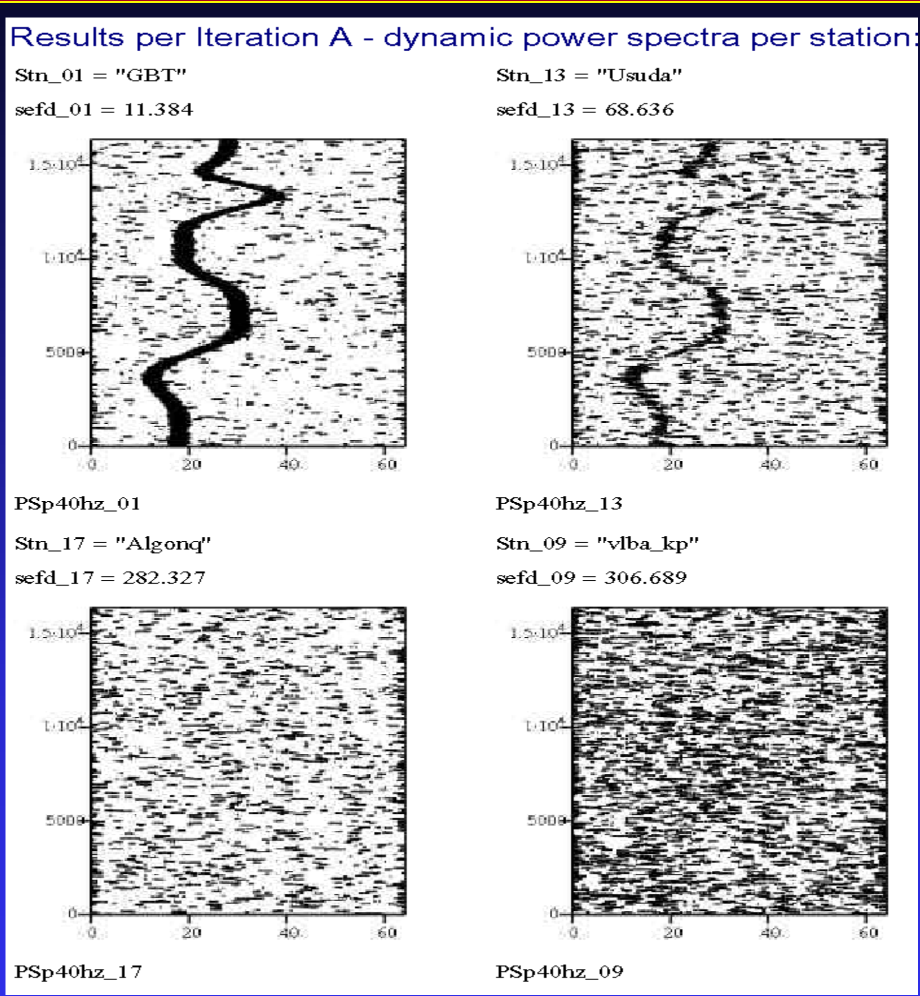
# Huygens VLBI tracking experiment at glance

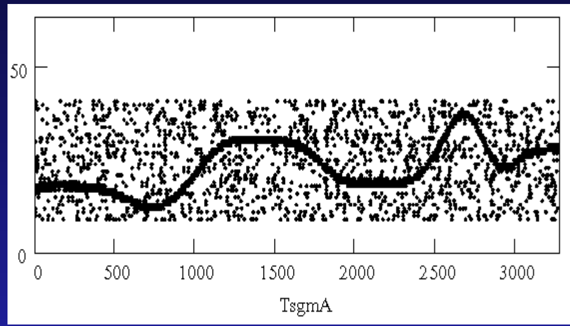
- **Very Long Baseline Interferometry (VLBI) as a S/C navigation tool?**
- **The study commenced in February 2003, complementary to the Huygens Doppler Wind Experiment; not foreseen in the original mission scenario**
- **Aimed at direct detection of the Huygens probe S-band signal by Earth-based radio telescopes;**
- **Based on the expertise, available at JIVE, in particular in the following areas:**
  - Development of state-of-the-art VLBI instrumentation and its use in radio astronomy studies;
  - Practical experience in conducting the most sensitive radio astronomy observations;
  - VLBI support of VEGA (Venus – Halley Comet) and Giotto/Pathfinder experiments (1984-1986);
- **Paves the way for future advanced applications for interplanetary navigation**

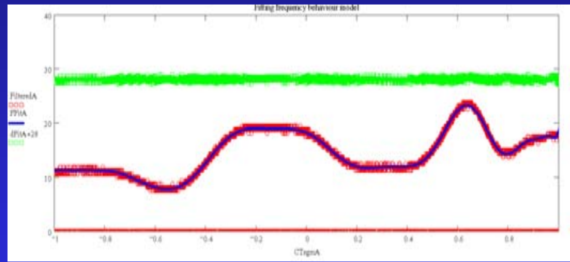
# *Huygens VLBI tracking: challenges*

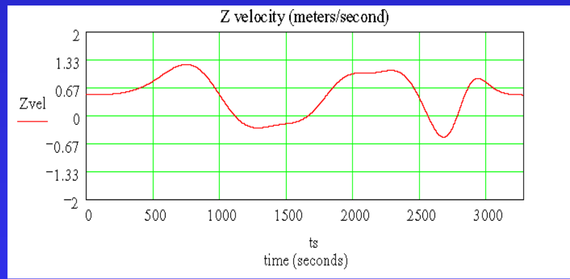
- **VLBI tracking was not foreseen as a mission component:**
  - Ad-hoc use of the Huygens→ Cassini S-band up-link
    - *Signal is very weak (1.2 billion km versus 30,000 km);*
    - *Up-link frequency (2040 MHz) is outside radio astronomy spectrum allocation*
- ***Task 1*: Availability of radio telescopes**
  - Potential participants identified;
  - Receiver/electronics modifications under discussion (as necessary);
  - Number/configuration of telescopes assessed;
- ***Task 2*: Radio astronomy reconnaissance of the Huygens Field:**
  - Observations at frequencies from 0.9 to 8.4 GHz;
  - Results promising; ongoing effort;
- ***Task 3*: Data recording, transport and processing**
  - Disk-based Mk5 VLBI system as the project recording medium;
  - Data processing algorithms developed;
  - Instrumental (EVN) and "live" (Beagle-2) tests performed;

# *Feasibility of the Huygens VLBI tracking experiment*



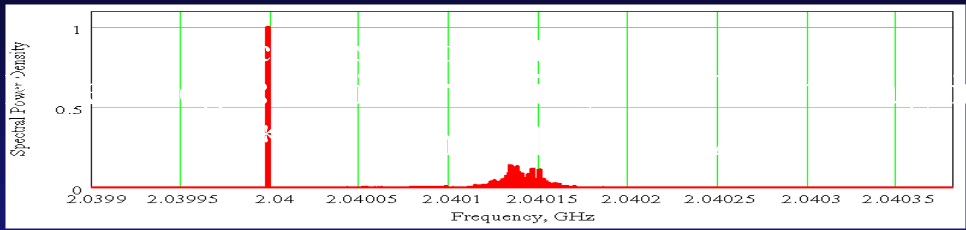



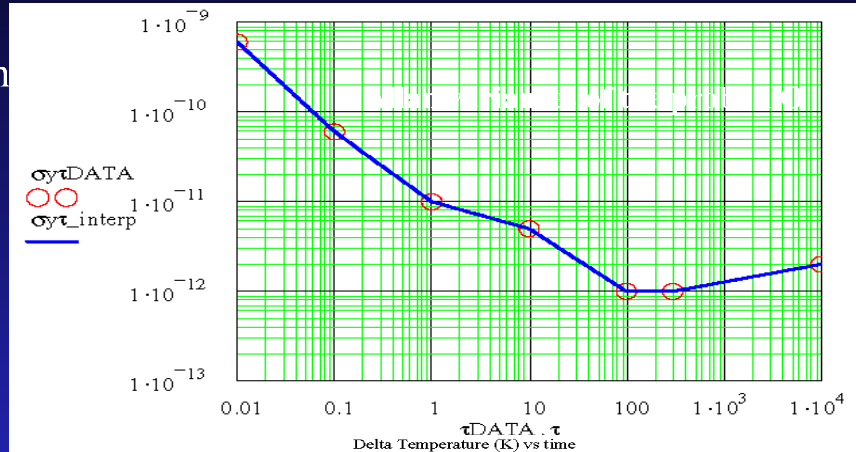


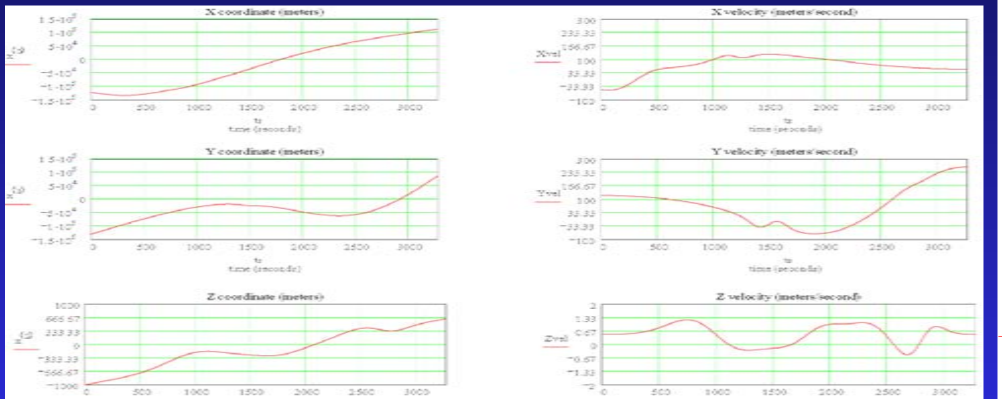

Simulated ynamic spectra for 4 stations, resolution 1.25 Hz

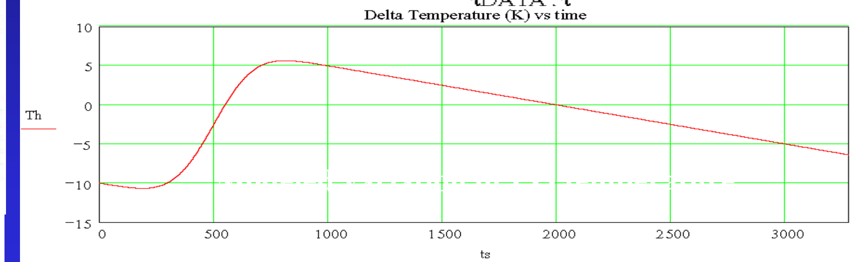
1. Common Mode – Image enhanced average dynamic spectrum,
2. polynomial fit to recreate the frequency drift model and
3. Input Doppler velocity model for comparison

# Simulation of the Huygens signal processing : Signal Model

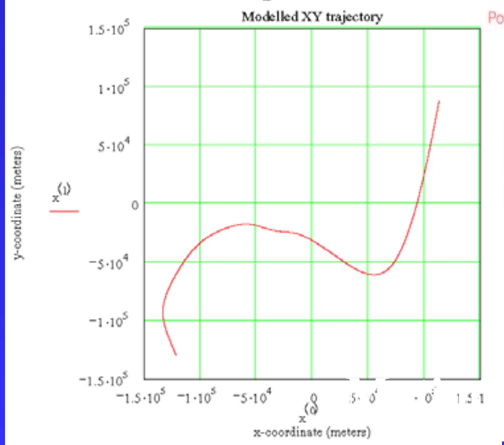


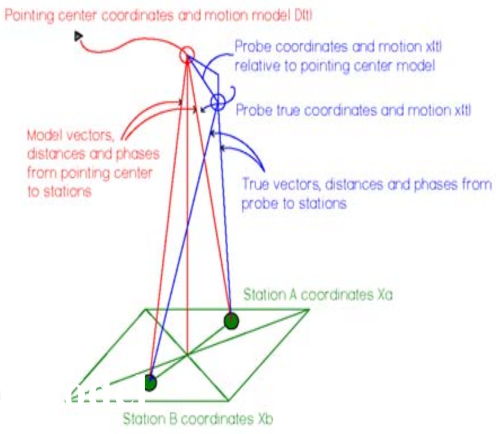



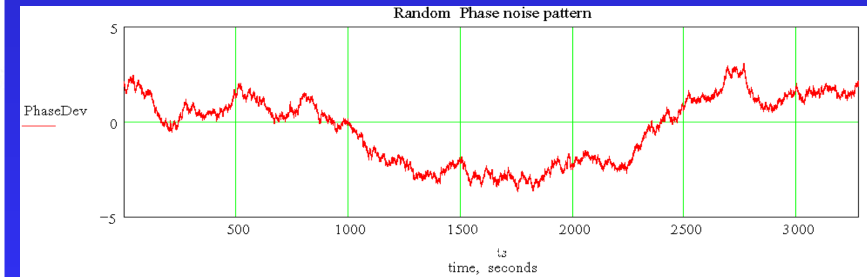




Ref: Huygens: Science, Payload and Mission, ESA SP-1177, 1997



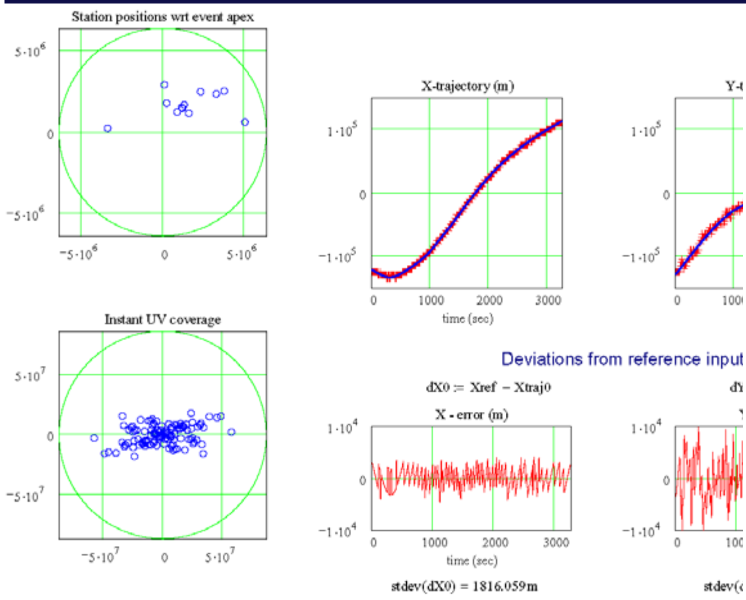



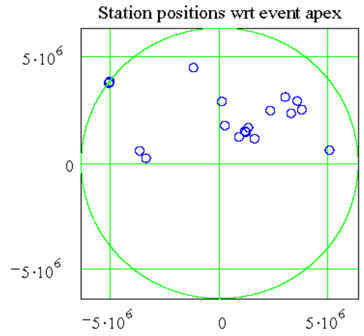



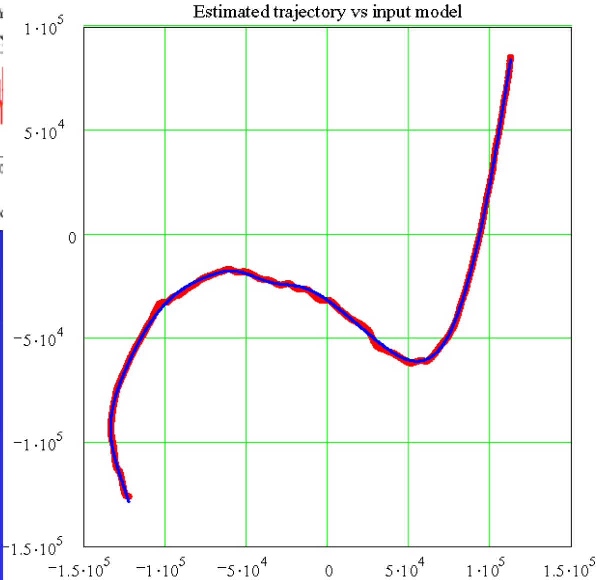

Ref: Rogers & Moran, IEEE TIM 30:4:283, 1981

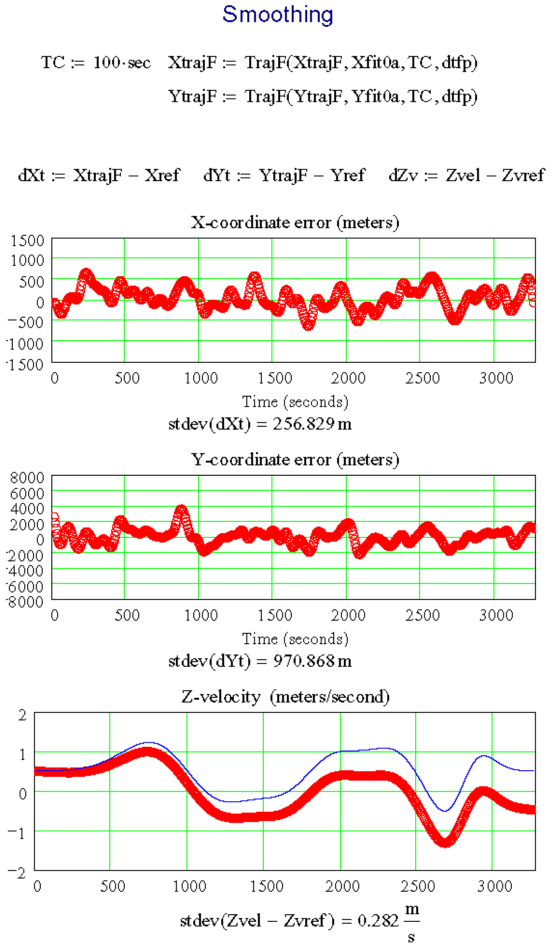
# *Simulation of the Huygens VLBI signal processing : trajectory reconstruction*

First iteration of the probe motion mapping, 12 stations, RMS 2 km (X) and 4 km (Y)



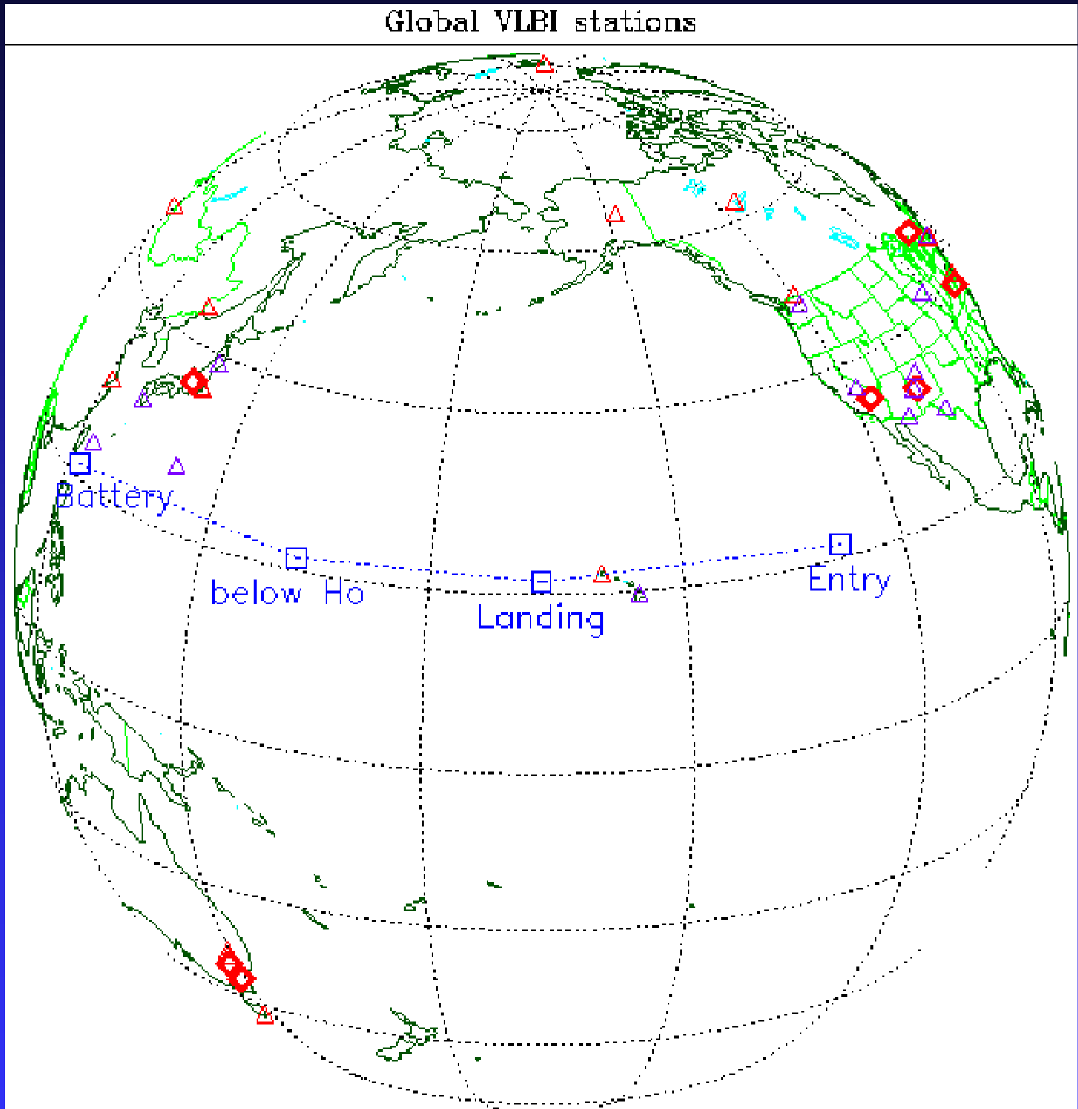




Simulation results
of the Huygens probe trajectory
reconstruction:

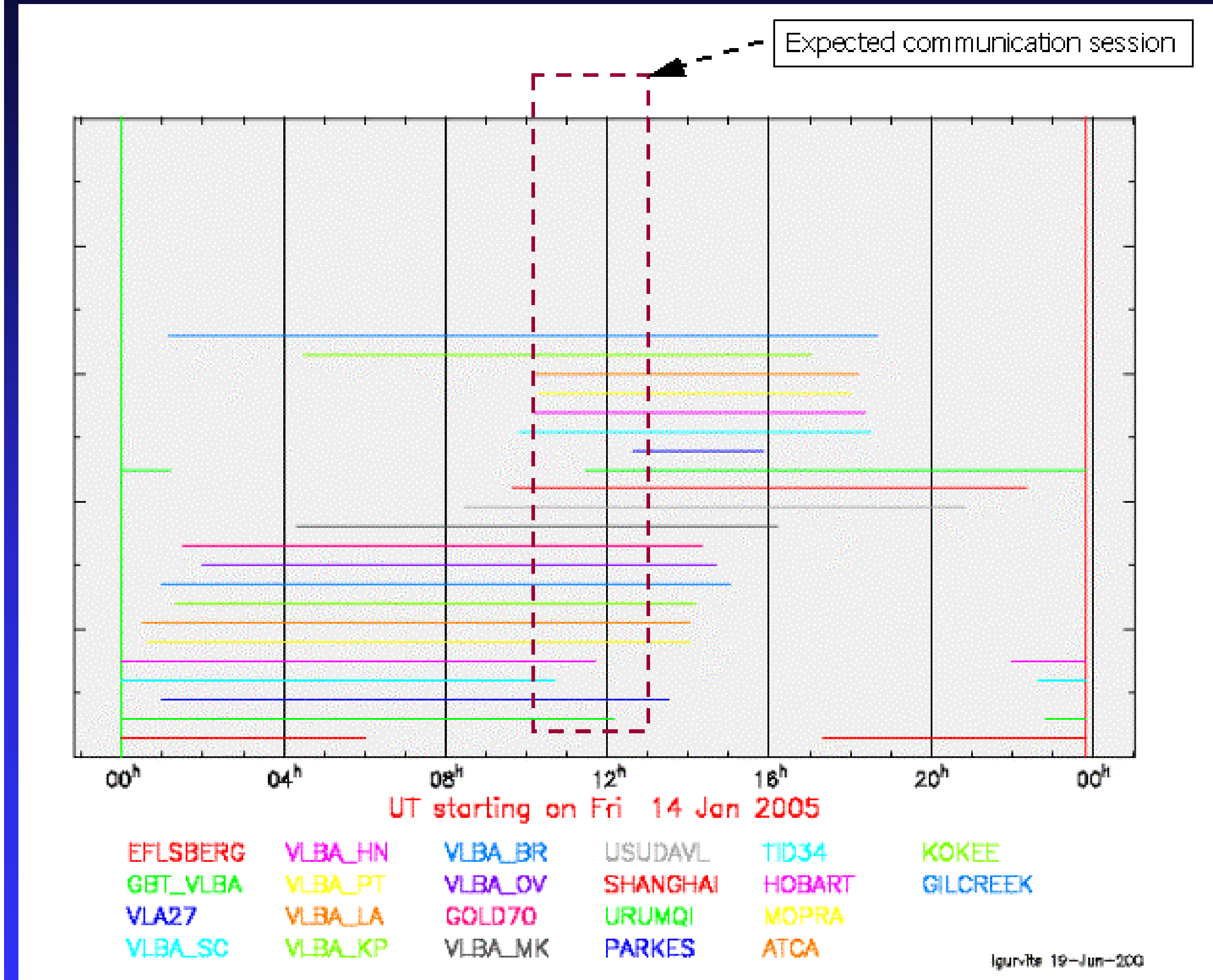
**20 VLBI stations,**
**100 seconds smoothed sampling**
**RMS = 260 m (X) and 970 m (Y)**

# *Task 1: Availability of radio telescopes*




14 Jan 2005
Entry: ~10:00UT

# *Task 1: Availability of radio telescopes*




GBT 100m
VLBA 8x10m
Mopra 22m
Sheshan 25 m
Kashima 34m
Parkes 70m
Hobart 26m
Ceduna 30m
Urumqi 25m

Usuda 70m ?

# Task 1: availability of radio telescopes

| | Telescope | Country | Diameter [m] | $T_{sys}$ [K] | Eff | Status | |
|---|---|---|---|---|---|---|---|
| | | | | | | S-band Rx | Mk5 |
| 1. | GBT | USA | 100 | 23 | 0.71 | OK | Need |
| 2. | VLBA_SC | USA | 25 | 40 | 0.48 | OK | Need |
| 3. | VLBA_HN | USA | 25 | 32 | 0.48 | OK | Need |
| 4. | VLBA_NL | USA | 25 | 30 | 0.49 | OK | Need |
| 5. | VLBA_FD | USA | 25 | 30 | 0.55 | OK | Need |
| 6. | VLBA_LA | USA | 25 | 30 | 0.50 | OK | Need |
| 7. | VLBA_PT | USA | 25 | 30 | 0.52 | OK | Need |
| 8. | VLBA_KP | USA | 25 | 30 | 0.55 | OK | Need |
| 9. | VLBA_OV | USA | 25 | 25 | 0.47 | OK | Need |
| 10. | VLBA_BR | USA | 25 | 30 | 0.50 | OK | Need |
| 11. | VLBA_MK | USA | 25 | 27 | 0.45 | OK | Need |
| 12. | Algonquin | Canada | 46 | | | Need upgrade | Need |
| 13. | Usuda | Japan | 70 | | | Need upgrade | Need |
| 14. | Kashima | Japan | 34 | | | Need upgrade | OK |
| 15. | Nanshan | China | 25 | | | Need upgrade | OK |
| 16. | Sheshan | China | 25 | | | Need upgrade | OK |
| 17. | Mopra | Australia | 22 | 36 | 0.60 | OK | Need |
| 18. | Parkes | Australia | 64 | | | Need upgrade | Need |
| 19. | Hobart | Australia | 26 | | | Need upgrade | Need |
| 20. | Ceduna | Australia | 30 | | | Need upgrade | Need |

# *Task 2: "Reconnaissance" of the Huygens Field*

- **VLBI technique in its "phase-referencing" incarnation**

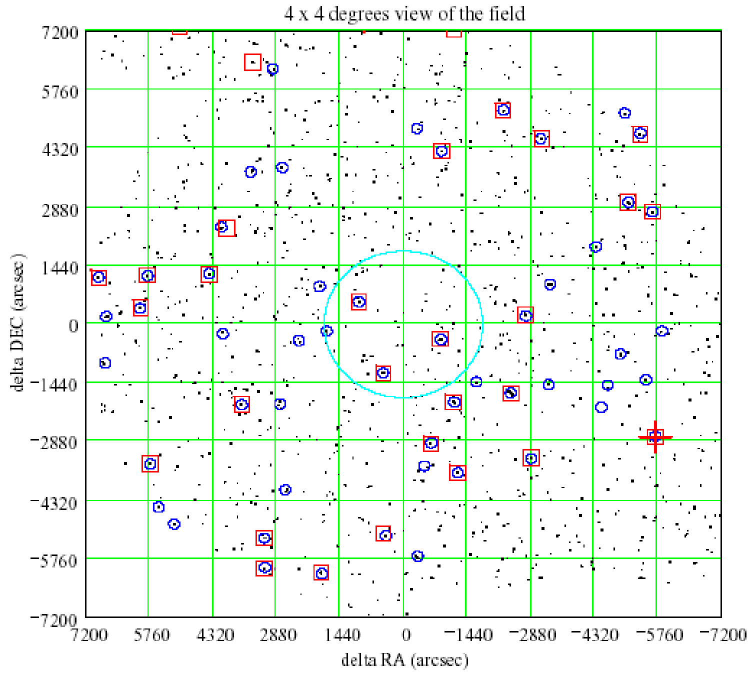
- **Observations:**

    - *Australia Telescope Compact Array (S-band), one epoch completed;*
    - *Westerbork Synthesis Array Telescope, first epoch completed;*
    - *VLA, observed 20-21 Dec 2003, completed;*
    - *MERLIN, observations underway 20 Nov 2003 – 15 Jan 2004;*
    - *EVN, observed in Feb 2004, data processing nearly completed*

- **Preliminary results: no miracles (i.e. no strong compact calibrators within the GBT primary beam), but the experiment is "doable".**

# Celestial radio background in the Huygens Field

Combined plot of the FIRST sources and GBT (circles), TEX (boxes) and JVAS (+) detections around the target center.

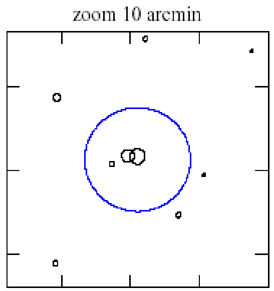



| | |
|---|---|
| Number of FIRST sources within the 1 degree area of interest | Nf1d = 68 |
| The brightest source among them has a flux of (mJy) | max(FF1d) = 146.58 |
| Total 21 cm flux (mJy) within the area of interest | TF1d = 877.47 |

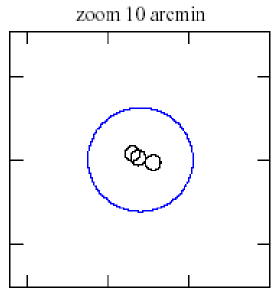
Figure 1. Known sources in the Huygens-Titan encounter field, with multiple detections noted.

Zoomed view at the FIRST sources within 1 degree patch for which the multiple detections were found

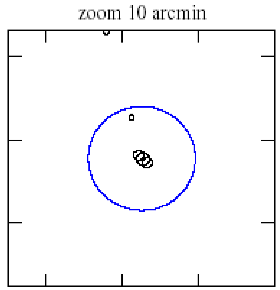
NVSS and FIRST fluxes are the totals of all components within an equivalent of 6 cm GBT beam (blue circle)



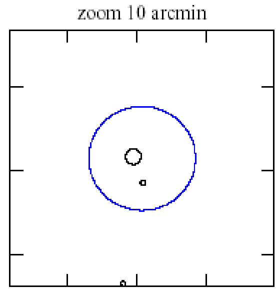

| Seq 23 | | | flux |
|---|---|---|---|
| TEX | 07 41 41.2 | +21 16 40 | 318 |
| NVSS | 07 41 41.7 | +21 16 27 | 115 |
| FIRST | 07 41 41.7 | +21 16 27 | 118 |
| BWE | 07 41 41.7 | +21 16 27 | 42 |
| 87G | 07 41 41.2 | +21 16 22 | 43 |
| GB6 | 07 41 40.6 | +21 16 33 | 40 |




| Seq 29 | | | flux |
|---|---|---|---|
| TEX | 07 43 14.6 | +21 02 51 | 1147 |
| NVSS | 07 43 14.8 | +21 02 48 | 401 |
| FIRST | 07 43 14.8 | +21 02 48 | 378 |
| MGI | 07 43 16.8 | +21 03 11 | 91 |
| BWE | 07 43 14.3 | +21 02 44 | 110 |
| 87G | 07 43 14.1 | +21 02 44 | 112 |
| GB6 | 07 43 14.8 | +21 02 48 | 118 |

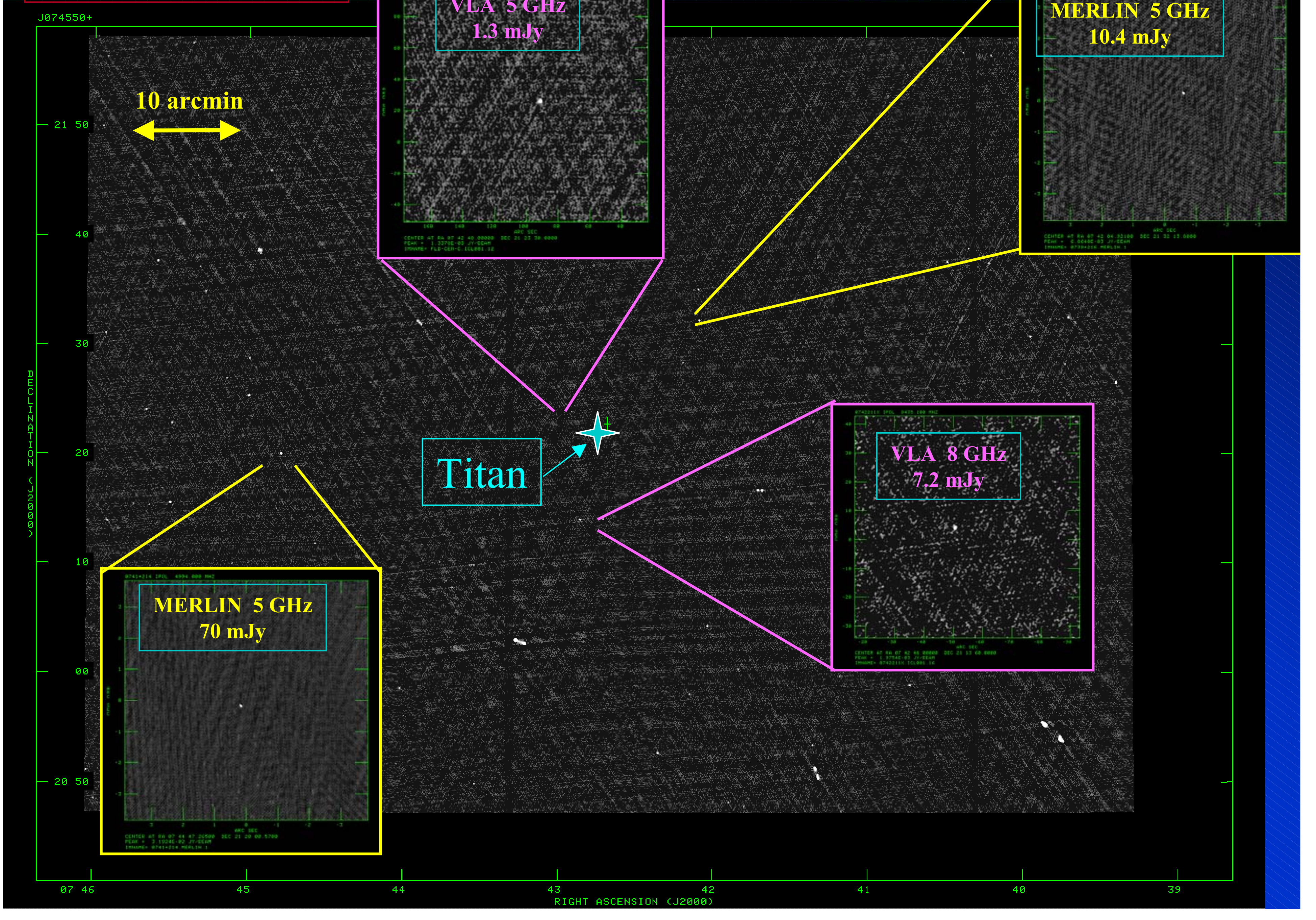



| Seq 30 | | | flux |
|---|---|---|---|
| TEX | 07 43 53.9 | +21 32 02 | 268 |
| NVSS | 07 43 53.9 | +21 32 02 | 58 |
| FIRST | 07 43 53.9 | +21 32 02 | 57 |
| GBT | - no detection - | | |




| Seq 31 | | | flux |
|---|---|---|---|
| TEX | - no detection - | | |
| NVSS | 07 44 47.2 | +21 20 01 | 72 |
| FIRST | 07 44 47.2 | +21 20 00 | 80 |
| BWE | 07 44 46.2 | +21 20 00 | 44 |
| 87G | 07 44 45.8 | +21 20 08 | 46 |
| GB6 | 07 44 45.8 | +21 19 56 | 51 |

# Huygens Field

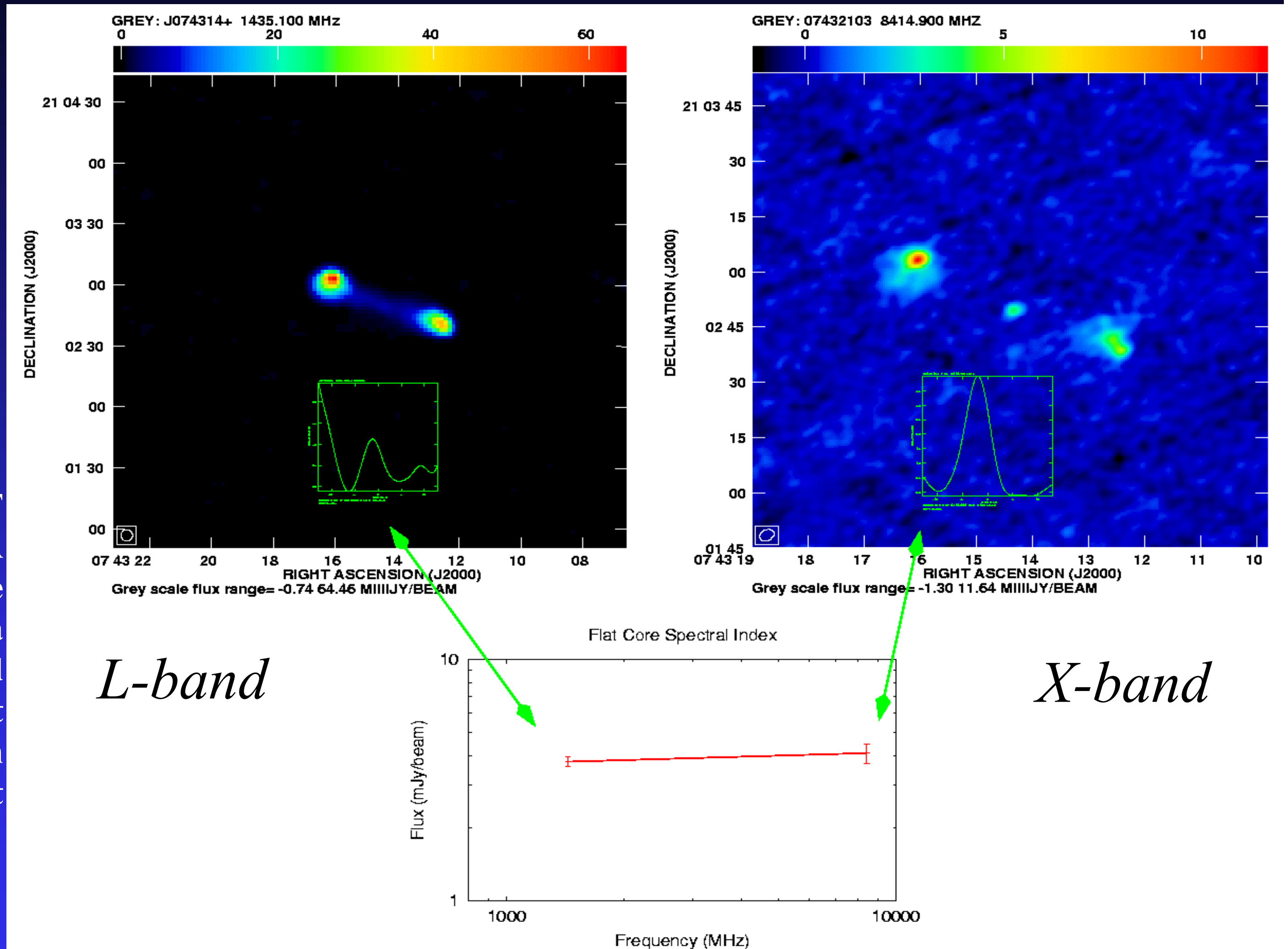


# *Celestial background in the Huygens Field - closer look at potential calibrators*

**Source: J074314+210245**
**Catalog data**

| | frq(GHz) | FlD (mJy) |
|---|---|---|
| TEX | 0.4 | 1147 |
| NVSS | 1.4 | 401 |
| FIRST | 1.4 | 378 |
| MGI | 4.8 | 91 |
| BWE | 4.8 | 110 |
| 87G | 4.8 | 112 |
| GB6 | 4.8 | 118 |

**Comparison of the FIRST 1.4GHz image (left) and VLA project AC406 8.4 GHz image shows a compact core with a flat or possibly peaked spectrum, which indicates that it can be a VLBI source with expected flux of a compact component at 3-5 mJy level.**




**Multi-frequency survey of 1 square degree around the target point is initialized in order to identify flat spectrum VLBI compact radio sources at detection limit < 1 mJy.**

# "Faint" celestial environment of the Huygens Field

| | Source name | RA (J2000) | DEC(J2000) | Δ [arcmin] | S_1.5 [mJy] |
|---|---|---|---|---|---|
| B1 | J074254+212411 | 07 42 54.2 | +21 24 11 | 3.4 | 3.0 |
| B2 | J074242+211358 | 07 42 42.5 | +21 13 59 | 8.8 | 6.1 |
| B3 | J074211+212823 | 07 42 11.2 | +21 28 24 | 8.9 | 5.7 |
| B4 | J074251+211401 | 07 42 51.0 | +21 14 02 | 9.1 | 10.9 |
| B5 | J074204+213213 | 07 42 04.8 | +21 32 13 | 12.6 | 15.2 |
| B6 | J074223+210934 | 07 42 23.4 | +21 09 35 | 13.8 | 3.5 |
| B7 | J074204+213505 | 07 42 05.0 | +21 35 05 | 14.8 | 5.2 |

Need for pre-interface deep VLBI observation of the field is obvious!!!

## *Algorithm of VLBI processing*

"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

↓

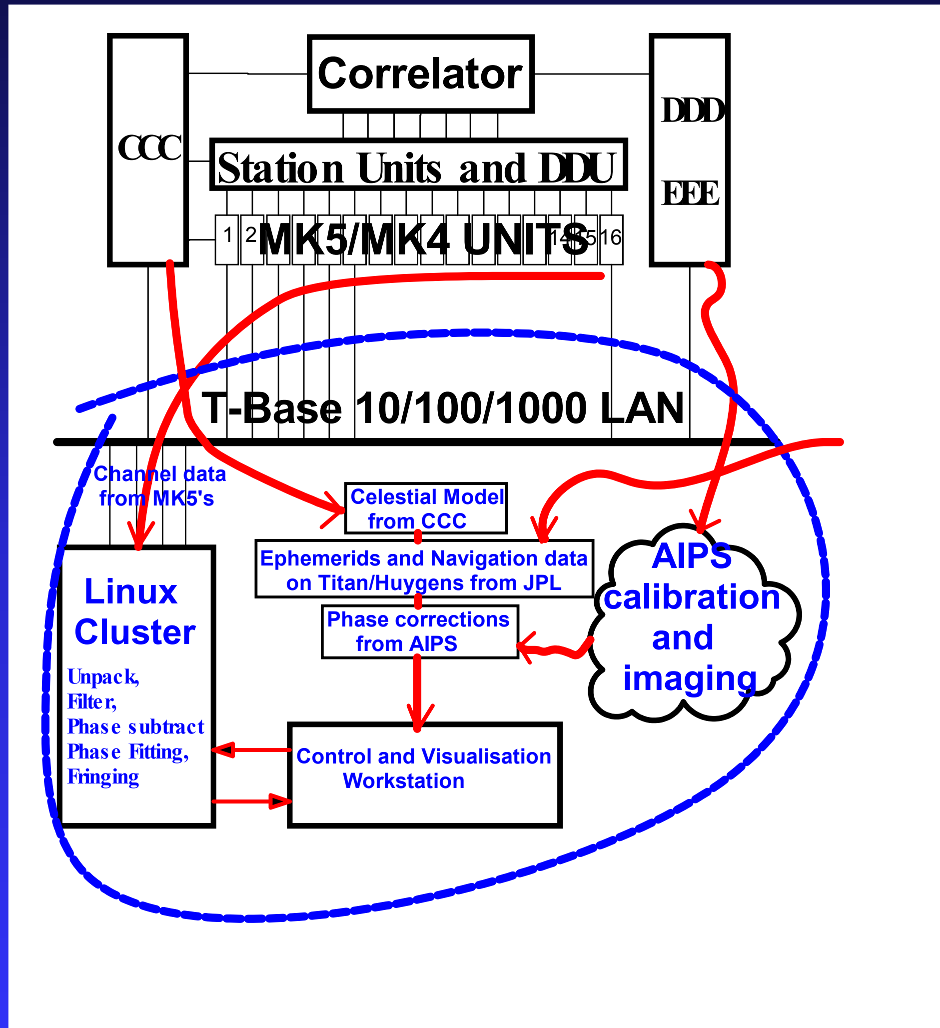
Iterative search for monocromatic (carrier) signal; Common Mode defined

↓

Phase-lock to Common Mode, inarrowing down search window

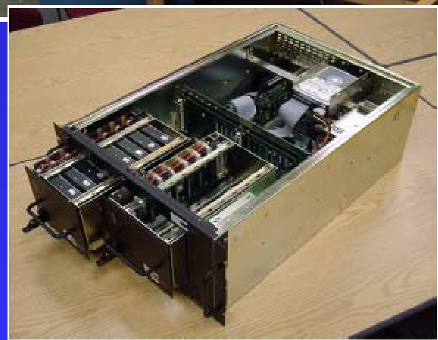
↓

Iterative imaging (trajectory reconstruction)



# *EVN MkIV/Mk5 Data Processor @ JIVE: the most powerful VLBI processor on Earth*


EVN Data Processor at JIVE equipped with 16 Mk5 units !



# *Test correlation of MK5 data on Ultra-High Spectral Resolution Software Correlator ("Huygens software correlator")*

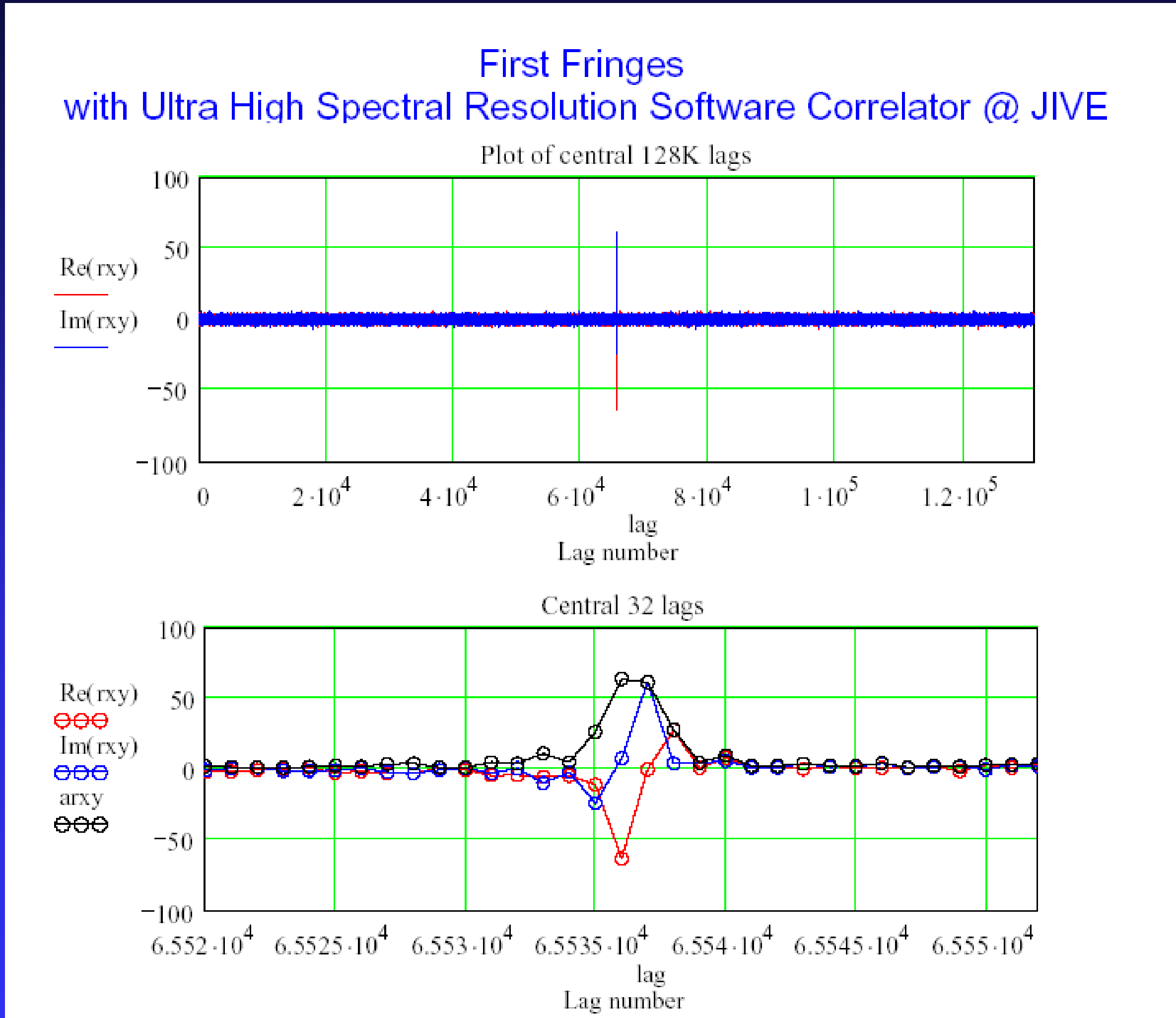
This test was performed in order to check data consistency when transferring raw VLBI data from MK5 unit and control parameters from CCC into a general purpose computer.

Achieved spectral resolution matches that required for probe's signal detection.

Source – DA193, 5 Jy at 5 GHz
Baseline – Effelsberg-Medicina
Bandwidth: 8 MHz
Recording: MK5 256 Mbps
Obs.date: 2003.06.05
Proc.date:2003.09.27

Spectral resolution:
1 M spectral bins, 8 Hz per bin
Equivalent of 2 M lag correlation

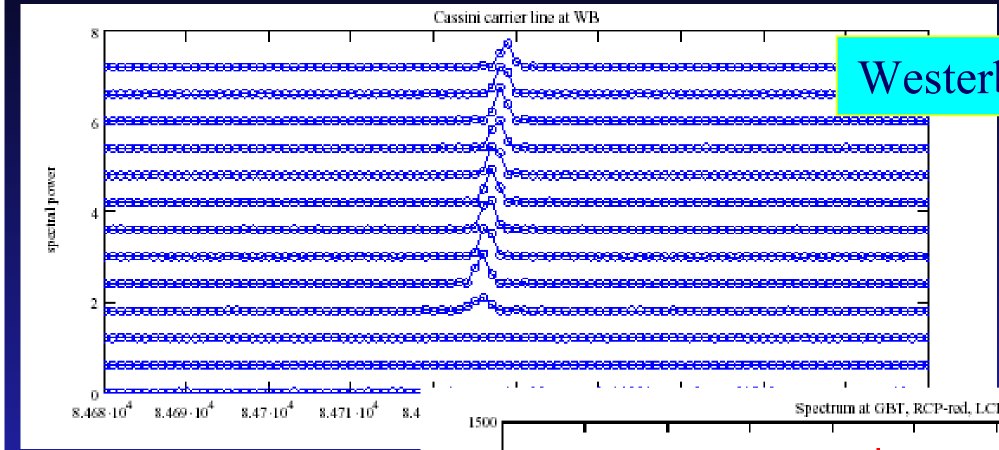
SNR = 70 at 0.131 sec integration

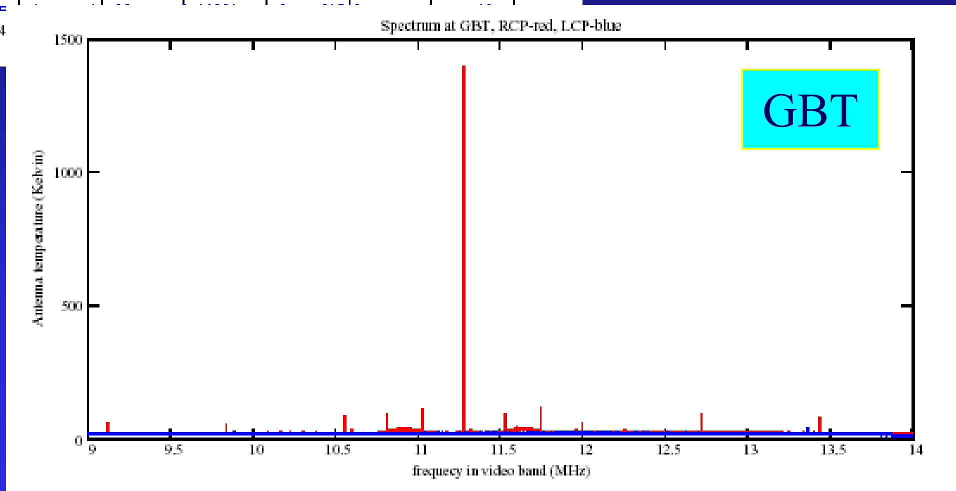


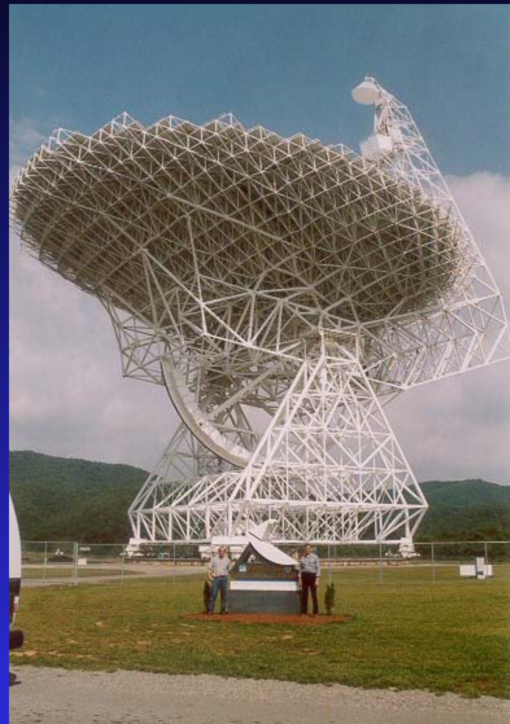
# *Huygens VLBI tracking project: current status*

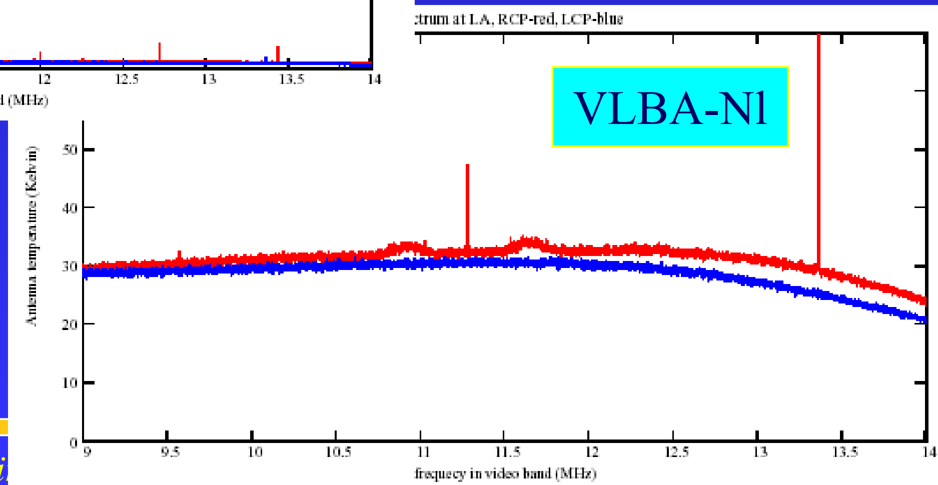
- **16 radio telescopes in the “circum-pacific” area are being prepared;**
- **RF hardware being procured/installed;**
- **Digital hardware (Mk5 units for NRAO and JIVE, PCEVN-Mk5 compatibility kits) under preparation in Australia);**
- **MkIV Data Processor at JIVE upgraded to Mk5 level; 18 play-back unitrs available;**
- **Software correlator at JIVE under development/tests;**
- **First global Huygens tracking test conducted on 27 Aug 2004:**
  - First ever fringes with Mk5 at GBT;
  - First ever 1 Gbps fringes on transatlantic baselines at JIVE;
  - First full-scale use of Mk5 at NRAO
  - Bottlenecks, bugs, etc. found (a lot!)
- **Series of local test during October 2004**
- **Major global general rehearsal on 17 November 2004**
- **Live event on 14 January 2005**

# *Test results – autocorrelation*



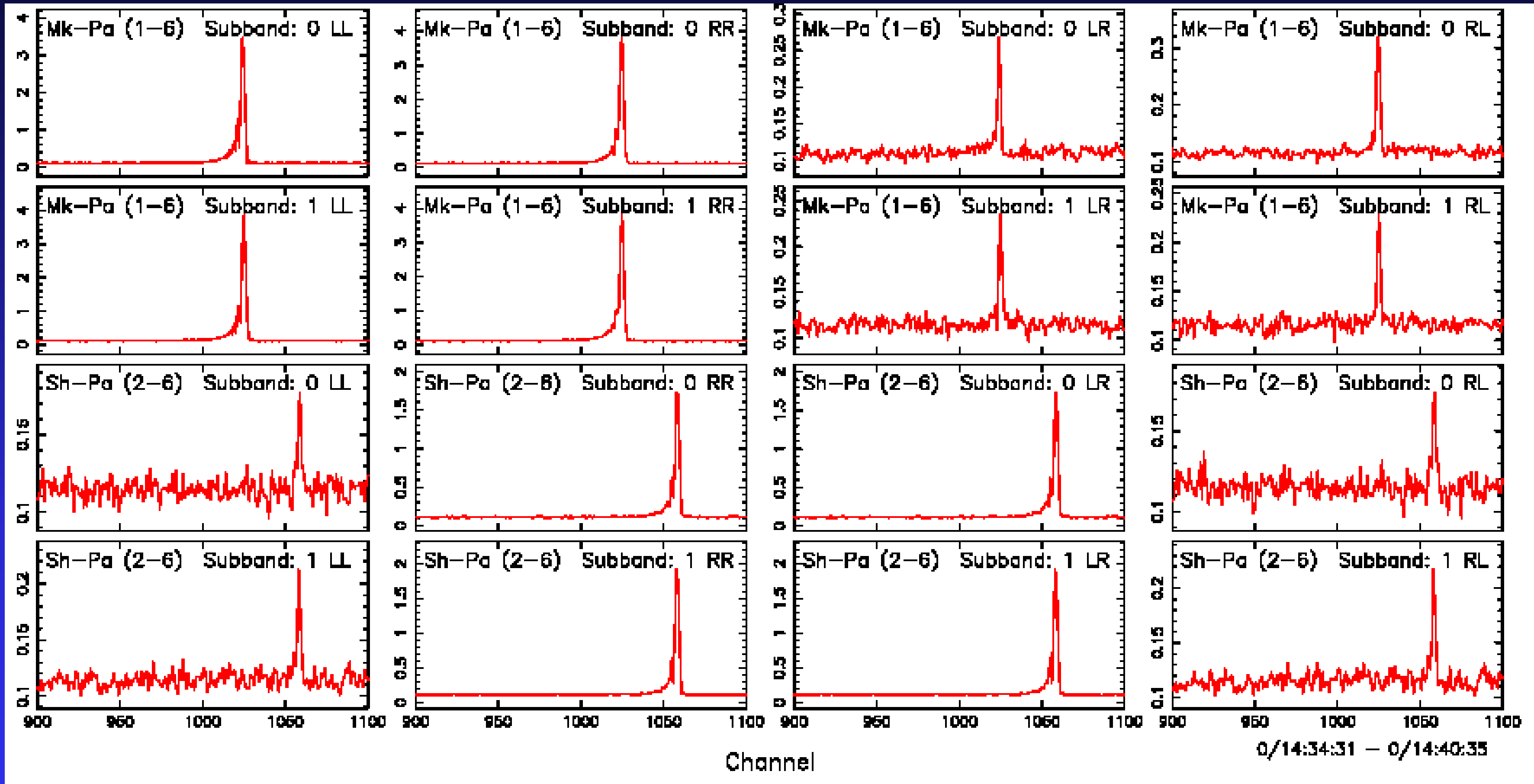






27 Aug 2004:
Cassini X-band spectra

# *Test results – mixed-mode cross-correlation*




27 Aug 2004: First circum-Pacific Mk5-PCEVN-VLBA fringes

# *Conclusions and actions*

- **VLBI referencing technique allows us to detect the Huygens S-band signal using a network of Earth-based radio telescopes**
- **Pinpointing the probe's position with ~1 km accuracy in the atmosphere of Titan is feasible**
- **An excellent a priori knowledge of the background celestial field (the "Huygens Field") is essential**
- **Huygens VLBI tracking as an example for future missions/applications**
- **More info: www.jive.nl/docs/resnotes/resnotes.html**

# *Huygens – VLBI: a two-way road*

- **Huygens VLBI tracking project helped to complete the "quiet upgrade" of the EVN Data Processor at JIVE – 16 Mk5 playback units operational**
- **Huygens "Software-Machine" proved to be a powerful diagnostics tool for the network; could become a platform for further software correlator development**
- **Help in upgrading NRAO facilities to Mk5 (GBT !)**
- **Bridge to the S2-PCEVN-dominated Southern Hemisphere**
- **A road toward closer collaboration EVN-ESA**