Precise VLBI tracking of planetary probes revisited

L.I. Gurvits on behalf of the Huygens VLBI Tracking Team:

JIVE
I.M. Avruch
H. Bignall
A. Brunthaler
R.M. Campbell
M.A. Garrett
S.V. Pogrebenko

ESA-ESTEC
C. van’t Klooster
J.-P. Lebreton

NASA-JPL
S. Asmar
W. Folkner
R.A. Preston

NRAO
W. Brisken
F. Ghigo
G. Langston
J. Romney

ASTRON
A.R. Foley

U Bonn
M. Bird

ATNF
J. Lovell
C. Phillips
J. Reynolds
R. Sault
T. Tzioumis

U Tasmania
G. Cimo
S. Elingsen
B. Reid

NICT(CRL)
T. Kondo

NAO China
T. An (ShAO)
X. Hong (ShAO)
S. Huang (ShAO)
D. Jiang (ShAO)
X. Liu (UAO)

Helsinki University
A. Mujunen
J. Ritakari

ISAS
R. Dodson
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 extragalactic 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 light-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

Results per Iteration A - dynamic power spectra per station:

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

Simulated dynamic spectra for 4 stations, resolution 1.25 Hz
Simulation of the Huygens signal processing: Signal Model

Allan variances of the probe LO

Typical spectrum of BPSK modulated signal

Random phase noise pattern for given Allan variances

Modeled variation of LO temperature


Power budget:

3W in carrier line, 3 dB TX antenna gain

= 5*10^-25 W/m^2 @ Earth (8.5 AU)


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

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**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

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

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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, inarowing 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 units 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