Status of the Planetary Radio Interferometry and Doppler Experiment (PRIDE): Applications for the Phobos-Soil and Other Planetary Missions

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Overview

- VEGA and Huygens VLBI tracking heritage
- PRIDE overview
- (Test) VLBI observations of ESA’s Venus Express (VEX) spacecraft
- PRIDE – Phobos
- Conclusions and outlook
VEGA balloons VLBI tracking, 1986

\[ f = 1.6 \text{ GHz}, \Delta f = 2 \text{ MHz}, 20 \text{ radio telescopes} \]

\[ \sigma_x = 10 \text{ km}, \sigma_v = 1 \text{ m/s} \]
Huygens VLBI heritage: 20 photons/dish/s

- Ad hoc use of the Huygens “uplink” carrier signal at 2040 MHz
- Utilised 17 Earth-based radio telescopes
- Non-optimal parameters of the experiment (not planned originally)
- Achieved 1 km accuracy of Probe’s descent trajectory determination
- Assisted in achieving one of main science goals of the mission – vertical wind profile

Titan, 14 January 2005

$\sigma_x = 1 \text{ km}$
$\sigma_v = 3 \text{ cm/s}$

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Generic PRIDE configuration

Planetary Radio Interferometry and Doppler Experiment

Background sources

Orbiter(s)

Landers/Balloons

Celestial body – target

VLBI network and 2-way tracking stations

Earth

PRIDE: a multi-purpose, multi-disciplinary enhancement of mission science return, based on the phase-referencing VLBI technology and science

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Science with PRIDE

**VLBI estimates of the S/C state vector**

- Ultra-precise celestial mechanics of planetary systems;
  - measurements of tidal accelerations of the satellites may be possible

- Geodynamics, internal structure and composition;
  - Powerful constraints on the interior structure of the moons can be obtained from the joint analysis of topography and gravity field data.

- Shape and gravimetry;
  - multiple flybys can be used to define the low order gravity field parameters.

- Electric properties of icy satellite surfaces and their environments;
  - PRIDE will bring in multi-antenna detections enabling “stereoscopic” view on the phenomena under study.

- Anomalous accelerations of deep space probes and other *fundamental physics effects*.

+ “Cruise” science plus mission diagnostics (“health check”)

**Direct to Earth (DtE) radio link**
Science with PRIDE

VLBI estimates of the S/C state vector

PRIDE (prospective) customers:

- **Mercury**: ESA-JAXA BepiColombo, 2014
- **Venus**: ESA VEX, CNES EVE and RSA Venera-D, >2018?
- **Moon**: Luna-Resource and Luna-Globe, >2012
- **Mars + Phobos**: ESA MEX; RSA Phobos-Soil, 2011; ESA ExoMars, 2018?
- **Asteroid sample return**: ESA MarcoPolo-R, 2020?
- **Jupiter + Europa, Ganymede, Callisto**: ESA Jupiter Icy Satellites Explorer (JUICE), 2022?
- **Saturn + Titan, Enceladus**: ESA-NASA-JAXA Titan Saturn System Mission (TSSM), >2024?

“Cruise” science plus mission diagnostics ("health check")

Direct to Earth (DtE) radio link
Block-diagram of data processing and analysis

Raw observational data

Reference Source coordinates

Broad-band correlation of the reference source with the far-field delay model

Residual group delay and phase

Delay/phase corrections

Group and phase delay of the S/C signal with resolved $2\pi$ ambiguity

Reconstruction of the apparent state vectors of the S/C

A priori state vectors of the S/C

Broad-band correlation of the S/C data band with the near-field delay model

Residual group delay and phase

Narrow-band correlation of the S/C carrier and ranging tones with the near-field delay model

Residual phases of the carrier and ranging tones

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Near-field delay model

Geometry of VLBI observations of spacecraft in the Barycentric celestial reference frame
Near-field delay model

Additional contribution to the signal delay due to clock offsets/rates @ stations, charged media (IPM and ionosphere) and troposphere!

Geometry of VLBI observations of spacecraft in the Barycentric celestial reference frame
Propagation effects: Ionosphere

IGS Total Electron Content Maps

- Provide vertical TECs on a global grid
- Single thin layer model

\[
TEC = \frac{vTEC}{\cos z'}
\]

\[
\sin z' = \frac{R}{R + H} \cdot \sin z
\]

\[
\tau_{iono} = \frac{5.308018 \cdot TEC}{4 \cdot \pi^2 \cdot f^2}
\]

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Options for Troposphere mitigation

Ready-to-use (empirical) models:

- Zenith delay + Mapping Function
- Niell Mapping Functions
- Vienna Mapping functions

On-demand (dynamic) models:

- Ray-tracing through Numerical Weather Models
Ray-tracing option for troposphere mitigation

- 4D meteo data from NWM $(p, T, RH)$
- refractive index $n(r, \lambda, \varphi)$ distribution
- solve Eikonal equation $|\nabla L_i|^2 = n(r_i)^2$
- ray path
- troposphere delay

\[
\tau_{tropo} = \int (n(r, \lambda, \varphi) - 1) \cdot ds + (L - S)
\]
Phase-Referencing VLBI Experiment em081c

• Telescopes:
  • Onsala (SE)
  • Metsähovi (FI)
  • Hartebeesthoek (ZA)
  • Svetloe, Zelenchuk (RU)
  • Wettzell (DE)
  • Medicina, Matera (IT)
  • Yebes (ES)
  • St. Croix (US)

• ESA VEX Spacecraft fringe finder - J2225-0457, calibrator - J2211-1328

• 8.45 - 11.30 UT, 28 March 2011

• Mark5A, 16 MHz bandwidth @ X-band

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VEX orbit around Venus, as seen from the GC

Preliminary imaging result. Corresponding lateral position deviation – better than 1 km
PRIDE with Phobos-Soil

- Gravimetry of
  - Mars
  - Phobos

- Need for precise S/C state-vector determination

- Phobos-Grunt equipped with USO – crucial for PRIDE

- X-band (8.4 GHz) signal

- Origin of Phobos (by means of gravimetry)?
VLBI observing proposals

- **EVN, Phobos cruise phase, EG055**
  - 3-4 observing runs in Jan-July 2012, ~3 hrs each
  - Essentially - tests
  - Accepted with qualifications

- **LBA (Australia), Phobos cruise phase**
  - Exactly as above

- **CVA (Chinese VLBI network)**
  - De facto unlimited access

- **EVN, Ecliptic plane survey (reference sources)**
  - Sources within 2 deg belt around PhS orbit
  - Flux(8GHz) > 50 mJy and spectral index flatter than -0.5
  - 99 hrs, Expected accuracy 0.2 mas

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Conclusions and Outlook

- Spacecraft positioning with a very high accuracy is achievable with PRIDE
- Preparatory work towards PRIDE-Phobos is ongoing
- A lot of work in the pipeline fine-tuning (including scheduling, tracking, processing and analysis) is still required
We would like to express a sincere gratitude to the personnel of the telescopes which took part in the observations.
Thank you for your attention!