VLBI Observations of Spacecraft with EVN Radio Telescopes

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YERAC-2011, Jodrell Bank Observatory, University of Manchester, UK
18-20 July 2011
Overview

• PRIDE overview
• Results of VLBI observations of ESA’s Venus Express (VEX) spacecraft and GNSS satellites
• Conclusions and outlook
**Generic PRIDE configuration**

**Planetary Radio Interferometry and Doppler Experiment**

Background sources

Orbiter(s)

VLBI network and 2-way tracking stations

Celestial body – target

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

Dmitry Duev. YERAC-2011, University of Manchester/Jodrell Bank Observatory, UK. 19.07.2011
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

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• 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.

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PRIDE (prospective) customers:

Mercury: ESA-JAXA BepiColombo, 2014
Venus: VEX, CNES EVE and RSA Venera-D, >2018?
Moon: ESA NEXT and Chinese Chang’E-2
Jupiter + Europa, Ganymede, Callisto
   ESA-NASA Europa-Jupiter System Mission (EJSM), 2020?
Saturn + Titan, Enceladus
   ESA-NASA-JAXA Titan Saturn System Mission (TSSM), 2022?

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

Direct to Earth (DtE) radio link

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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
- 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
- A priori state vectors of the S/C
- Reconstruction of the apparent state vectors of the S/C

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Near-field delay model

Geometry of VLBI observations of spacecraft in the Barycentric celestial reference frame

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Gravitating Body

Solar System Barycentre

+ Don’t forget about clock offsets/rates, charged media and troposphere!

Spacecraft S (T_0, X_0)

Receiver 1 R_1 (T_1, X_1)

Receiver 2 R_2 (T_2, X_2)

B
Why phase-referencing?

VEX phase behaviour on the baseline Onsala – Metsahovi, 25.03.2011, no phase referencing

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Why phase-referencing?

![Graph showing spectral power density vs. frequency]

- **Red** – detected phase fluctuations
- **Blue** – scintillation slope fit
- **Light blue** – with system noise added

Kolmogorov spectrum of phase scintillations, Onsala, 25.03.2011

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Why phase-referencing?

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Kolmogorov spectrum of phase scintillations, Onsala, 25.03.2011

Nodding: $\tau = 180$ s, $f_0 = 1/\tau \approx 5.5$ mHz

Scintillation phase:

$$\left[ \int_{f_0}^{f_{\text{max}}} D(f_0) \cdot \left( \frac{f}{f_0} \right)^{\text{slope}} \, df \right]^{1/2}$$
Why phase-referencing?

Nodding: $\tau = 180$ s, $f_0 = 1/\tau \approx 5.5$ mHz

Kolmogorov spectrum of phase scintillations, Onsala, 25.03.2011
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
Phases of the fringe finder, calibrator and VEX + calibrated delay of the VEX spacecraft. Baseline Onsala - Metsahovi, em081c, 28.03.2011

Dmitry Duev. YERAC-2011, University of Manchester/Jodrell Bank Observatory, UK. 19.07.2011
Phases of the fringe finder, calibrator and VEX + calibrated delay of the VEX spacecraft. Baseline Onsala - Metsahovi, em081c, 28.03.2011

\[
\tau_{tropo} = \tau_{\text{zenith}} \cdot mf(zd) \approx \frac{\tau_{\text{zenith}}}{\cos(zd)}
\]

\[
-\frac{\sin(zd_c)}{\cos^2(zd_c)} \Delta zd_{c-v}
\]

Dmitry Duev. YERAC-2011, University of Manchester/Jodrell Bank Observatory, UK. 19.07.2011
Post-fit delay. Baseline Onsala - Metsahovi, em081c, 28.03.2011

Standard deviation: 11 ps
Lateral VEX a-priori coordinate deviations, baselines On-Mh, On-Pu, Mh-Pu. 25.03.2011. No phase referencing.
Test Experiment g100816

- Telescopes
  - *Onsala (SE), Medicina (IT)*
- GLONASS satellites, 16 August 2010
  - *PR21, 12.45 - 13.00 UT*
  - *PR13, 13.30 - 13.45 UT*
- Mark5A, 16 MHz bandwidth @ L-band
- PIs – V. Tornatore (Politecnico di Milano, IT), R. Haas (Chalmers University, SE)
Corrections to the GLONASS PR21 satellite ITRF position,
Baseline Onsala - Medicina, 16.08.2010

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Conclusions and Outlook

• Spacecraft positioning with a very high accuracy is achievable with PRIDE

• We attract new users to EVN and JIVE

• 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!