

VLBI observations of spacecraft

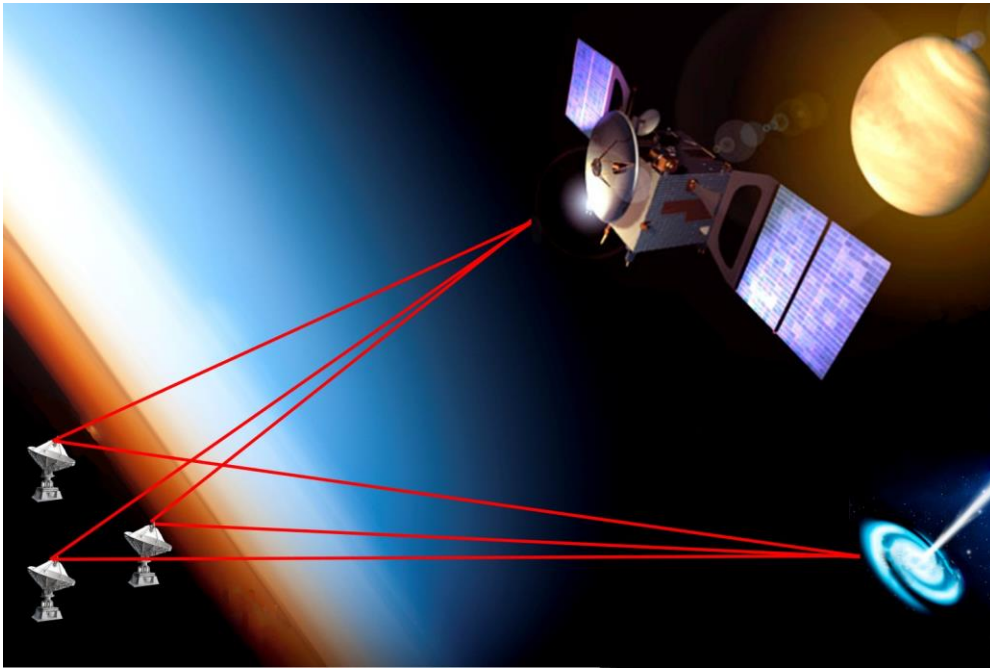
Joining space science and planetary data with “almost”
classical radio astronomy

Giuseppe Cimò

Joint Institute for VLBI - ERIC (JIVE)
Netherlands Institute for Radio Astronomy (ASTRON)

PRIDE: Space science and Radio Astronomy

Near-field VLBI:
“almost” classical radio astronomy



Planetary Radio
Interferometry and Doppler
Experiments (PRIDE)

A multi-purpose, multi
disciplinary enhancement
of mission science return,
based on Doppler tracking
and phase-referencing VLBI
technology and science

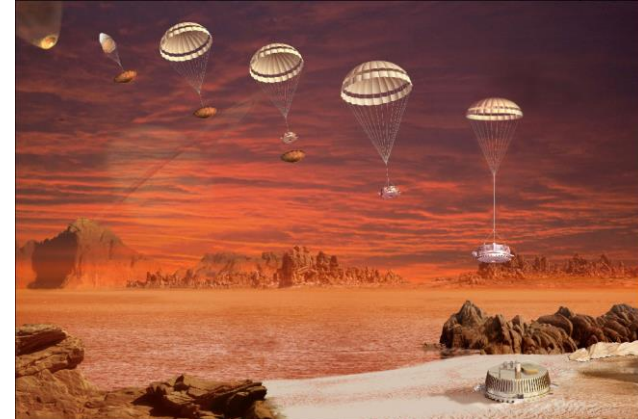
Why VLBI observations of Spacecraft ?

Planetary Radio Interferometry and Doppler Experiment (PRIDE) is able to provide highly accurate estimates of the state vectors for the orbiters and landers by means of Very Long Baseline Interferometry.

By determining spacecraft state vectors we are given the ability to study a wide variety of phenomena:

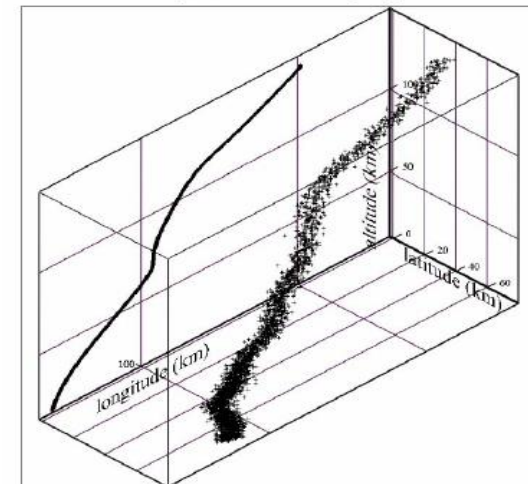
- Wind on other planets or moons
- Internal structure and composition
- Atmosphere dynamics → ESA's VEX drag
- Improve ephemeris of moons → JUICE!
- Interplanetary Scintillation
- General relativity experiments

Credits: NASA/ESA



A windy day on Titan!

In 3D (altitude from DTWG trajectory)



(Xp, Yp, Zp)

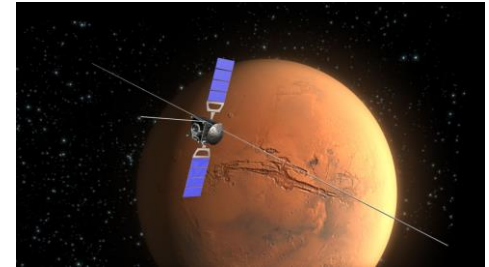
Our data products

Several levels of data

- Raw data: the actual data recorded at each telescope
Huge amount → Mostly noise!
- Cross-correlation: VLBI data after correlation
What astronomers get → still uncalibrated
- Frequency: radio signal emitted by onboard communication system

- Processed data
 - Images are made from the VLBI data → Real position of spacecraft in the sky
 - Doppler Shifts after correcting for a number of effects → Spacecraft velocity

- Scientific data products
 - ephemerides
 - gravity field measurements
 - space weather
 - orbit determination
 - ...

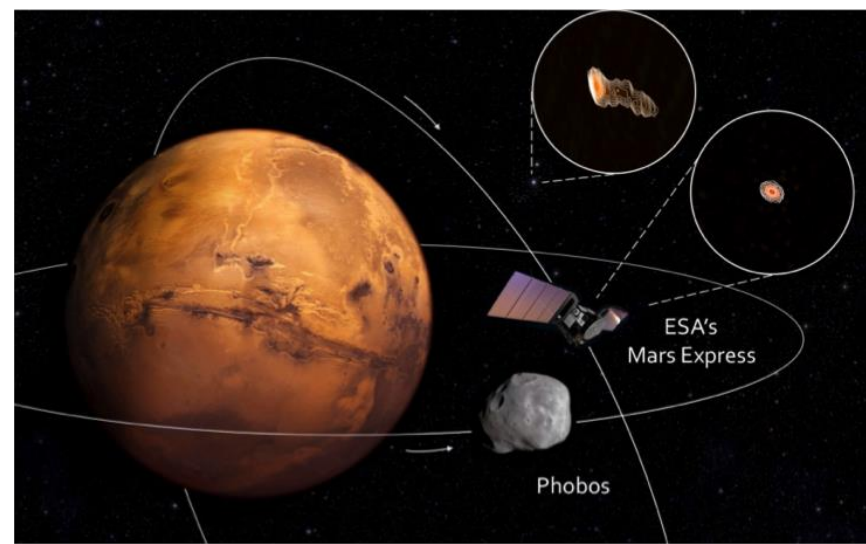


Credits: ESA

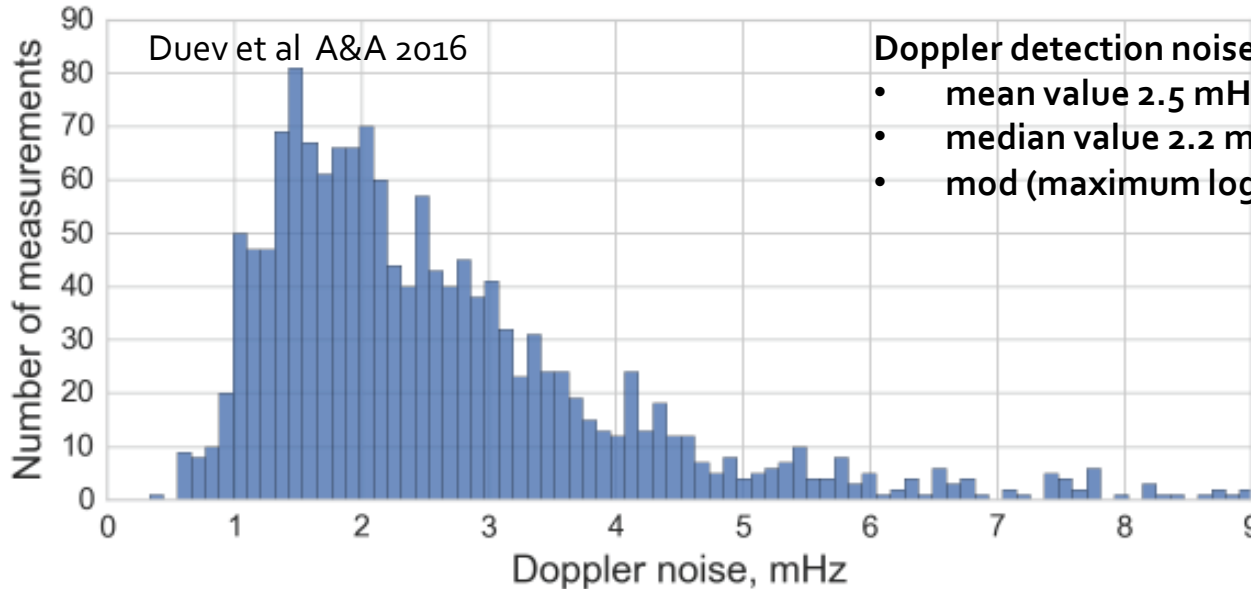


MEX Phobos flyby

28 – 29 December 2013
Closest flyby of MEX ~50km
More than 30 radio telescopes globally
~26 hours of continuous observation time
3 consecutive Mars revolutions (7 hours long)



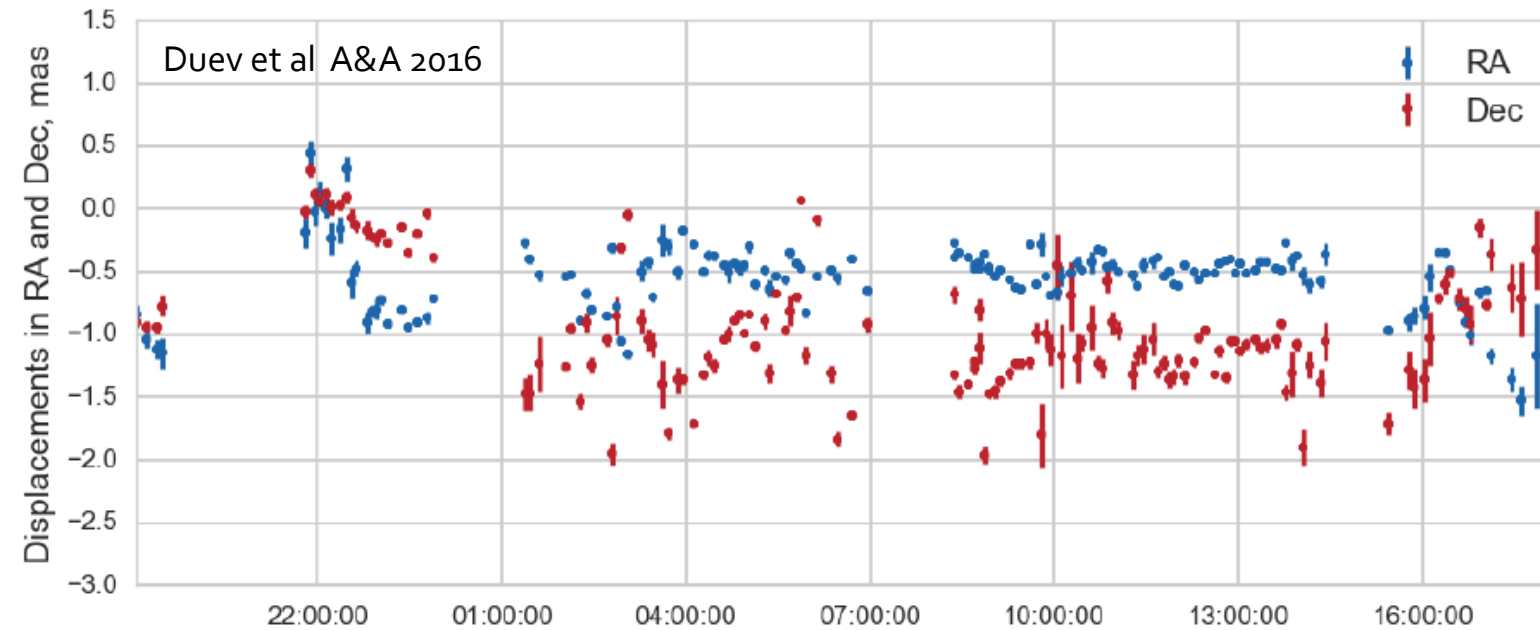
Credits: ESA (for Mars, Phobos and MEX)



Doppler detection noise, 10 s integration:

- mean value 2.5 mHz
- median value 2.2 mHz
- mod (maximum log-normal fit) value 1.7 mHz → 30 $\mu\text{m/s}$

Spacecraft astrometry

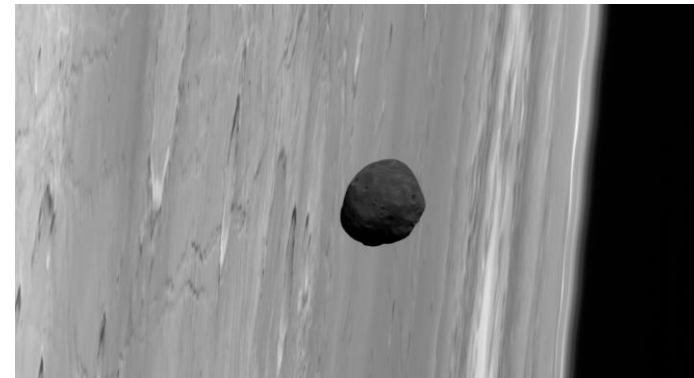


Displacements between measured and predicted MEX celestial position, 2 min per point

Credits: ESA

Median 3σ formal error for the full range are:

RA $34 \mu\text{as} \rightarrow 35 \text{ m}$
Dec $58 \mu\text{as} \rightarrow 60 \text{ m}$



Our data

Raw data for the Phobos flyby → 100+ TeraBytes

- Data are recorded in hard disks and shipped to JIVE for the cross-correlation
- After correlation, the disks are recycled: no archive for raw data
- Miscommunication with other communities: ESA requires archiving of raw data

www.jive.eu

Cross-correlation

- JIVE archive of FITS files
- Proprietary time for PIs

Doppler shift

- ASCII table with times and frequencies
- Complementary to Radio Science
 - agreement on formats
 - agreement on repositories
 - agreement on data policies

Processed data

- Images and maps created with AIPS (on my hard drive!)
- Table with lateral positions: formats depend on experiment
- Complementary to onboard experiments
 - agreement on formats, repositories, policies,...

Scientific data products

- Collaborations with space agencies
- Collaboration with other groups (planetary and space science)

The screenshot shows the JIVE website interface. At the top, there is a navigation bar with links for Home, Contact Us, EVN, Intranet, Wiki, and Daily Image. Below this is a header image with binary code and a network diagram. The main content area is divided into several sections:

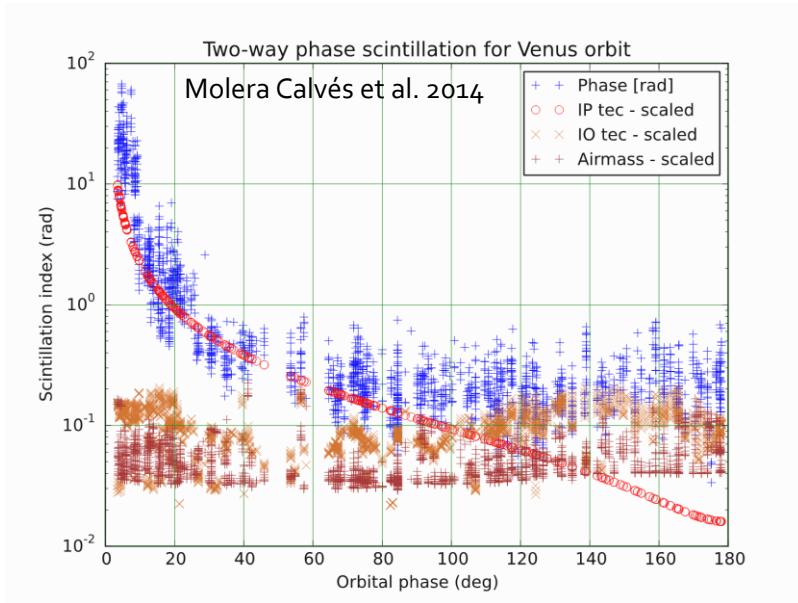
- JIVE**: A sidebar menu with links to About JIVE, Media, Employment, JIVE Board, ERIC Council, JIVE Management Team, Meetings, News, Reports, Research, User support, and Visit.
- EVN Correlator**: A sidebar menu with links to Correlator overview, e-VLBI, Operations, Software, and Status.
- EVN Data Archive**: A sidebar menu with links to Archive home, Archive introduction, Search archive, and ParseITongue.
- Select experiment**: A section titled "EVN Data Archive at JIVE" with a dropdown menu set to "N16C1". Below it, there is a table titled "Access to EVN archive" with a link to "Show experiment N16C1".
- Access to VO archives**: A section with a table of source positions from EVN experiment N16C1. The table has columns for Ra, Dec, Source, Image, and Image. The source positions are:

| Ra | Dec | Source | Image | Image |
|---------|---------|------------|-------|-------|
| 49.9507 | 41.5117 | 3C84 | sdss | |
| 64.5887 | 38.0266 | J0418+3801 | sdss | |

 Below the table, there is a section titled "Access to VO archives" with two links: "Aladin Sky Atlas" and "Sloan Digital Sky Survey". A red circle highlights these links, and a red arrow points from the circle to the text "VO".
- Info**: A section with links to "Increase of data since 2000" and "Web statistics since June 2004".
- Fits Archive EVN Correlator at JIVE**: A section with a table of source positions. The table has columns for P. Investigator, Experiment, Source name, RA, DEC, Equinox, and Total Width. The source positions are:

| P. Investigator | Experiment | Source name | RA | DEC | Equinox | Total Width |
|-----------------|------------|-------------|-----|-----|---------|-------------|
| Any | Any | Any | Any | Any | Any | Any |

Space weather



Two-way phase scintillation for ESA's Venus Express. Data show the phase scintillation index measured with VLBI radio telescopes.

Observations of ESA's spacecraft at different solar elongation from 2009 to 2016

- Interplanetary scintillation
- Solar wind studies
- Analysis of Coronal Mass Ejection
- Scintillation effects on communication signal
- Spacecraft observations and experiment strategies
- VLBI phase referencing cycle determination

Strict communication with ESOC for transmission windows
Ad hoc observing arrangement with the radio telescopes
PI driven experiments

Our data

Raw data from VLBI disk packs

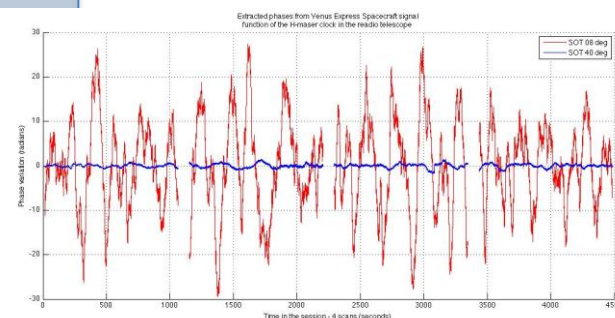
- Data are recorded in hard disks and shipped to JIVE for the cross-correlation
- Single dish only: No cross-correlation
- After correlation, the disks are recycled: no archive for raw data

Doppler shift

- ASCII table with times and frequencies
- Local archiving at JIVE

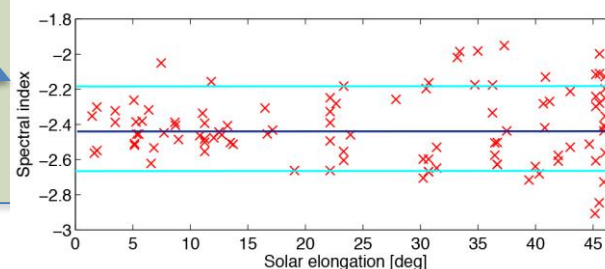
Processed data

- Binary files with measured frequencies and frequency shifts
- Phase variations due to scintillation
- Complementary to space weather experiments
 - agreement on formats, repositories, policies,...



Scientific data product

- Phase scintillation index
- turbulence parameters in the interplanetary medium
- parametrization of solar wind, ionosphere and troposphere
- Collaborations with space agencies
 - ESA Space Situational Awareness
 - Compatibility with ESA Space Weather network



Conclusions and feedback

PRIDE has proven to be beneficial for a wide range of scientific applications.

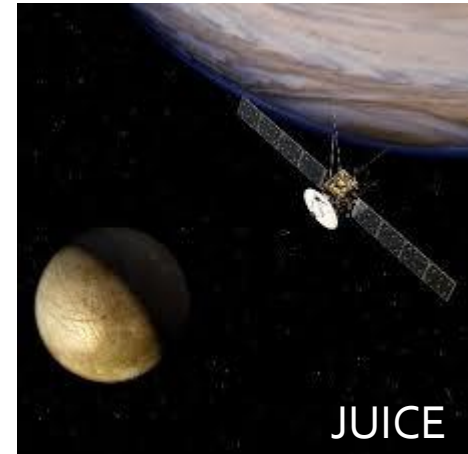
PRIDE is an experiment of ESA's JUICE mission

Challenges: ← Help from VO experience

- Different formats
 - Automatic format generation/conversion?
- Different repositories
- Different policies
 - Proprietary windows
 - Archiving
- Different communities and backgrounds
 - Space agencies
 - Pls of onboard experiments
 - Planetary and space scientists

Feedback and suggestions:

- Interactions with EUROPLANET-VESPA
- VLBI and VO? → EVN FITSfinder and Italian model (Cristina's talk)
- Interdisciplinary events → ASTERICS! (of course!) 😊



Credits: ESA

