JIVE
Joint Institute for VLBI ERIC

ASTRON

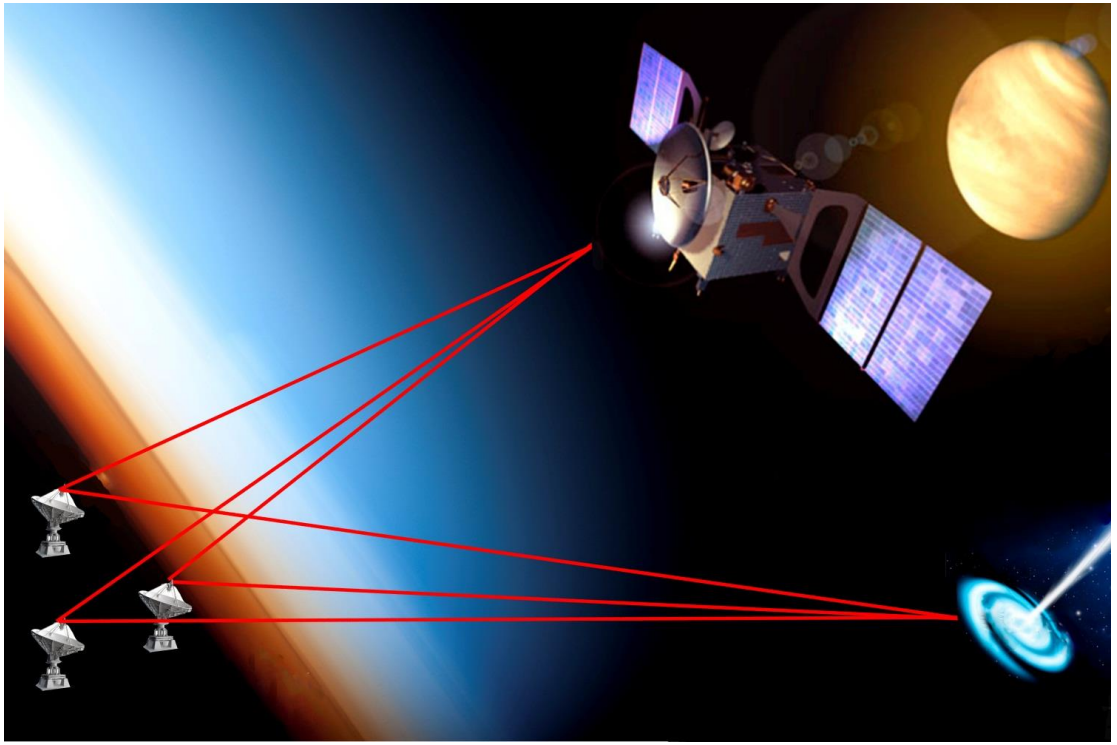
Radio Astronomy and Space Science

VLBI observations of orbiters and landers

Giuseppe Cimò

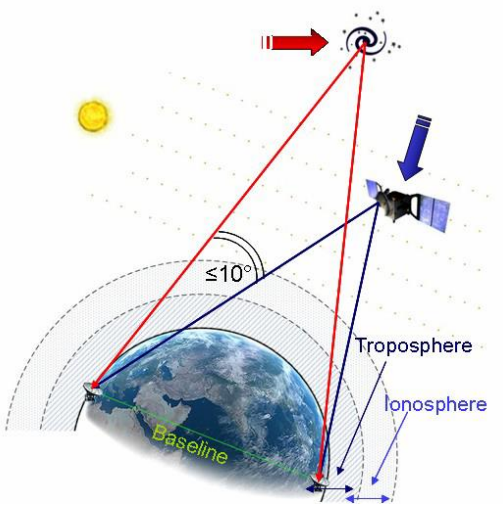
for the PRIDE collaboration

Planetary **R**adio **I**nterferometry and **D**oppler **E**xperiment



DeltaDOR and VLBI

DeltaDOR is a VLBI-like technique.
Phase-referencing:
• multi-station observations
• phases are calibrated using observations of “near-by” quasars
• far-field VLBI delay model for quasars
• near-field delay model for spacecraft.
Direct geometric measure of spacecraft angular position.



Differences with VLBI-PRIDE:
• number of telescopes
• required instrumentation
• visibility at the telescope and number of scans
• lateral accuracy
• possibility of ad-hoc observations:
simultaneous data transmission and positional measurements

PRIDE is science driven!

Why VLBI observations of Spacecraft ?

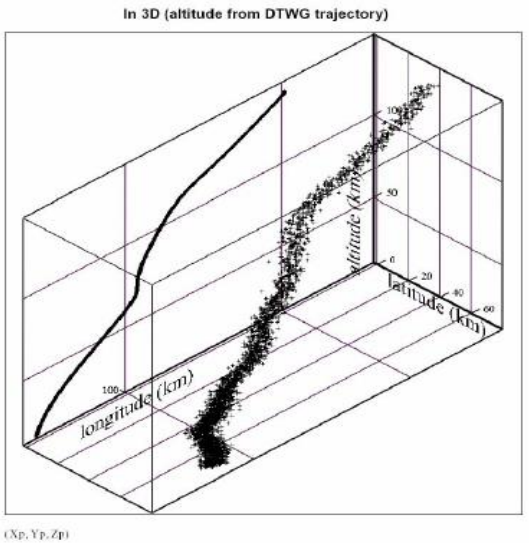
Planetary Radio Interferometry and Doppler Experiment is able to provide highly accurate estimates of the state vectors for the orbiters and landers by means of Very Long Baseline Interferometry.

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
- Improve ephemeris of moons → MEX & JUICE!
- Interplanetary Scintillation
- General relativity experiments → Gr. redshift
- Earth geodesy → GPS/GLONASS

Credits: NASA/ESA

A windy day on Titan!



Jupiter Icy Moon Explorer: JUICE

The Jupiter Icy Moon Explorer (JUICE) is the next ESA flagship unmanned space mission for the indepth exploration of the Jupiter system with a focus on Ganymede and Jupiter's magnetosphere. Investigations of Europa and Callisto would complete a comparative picture of the Galilean moons.

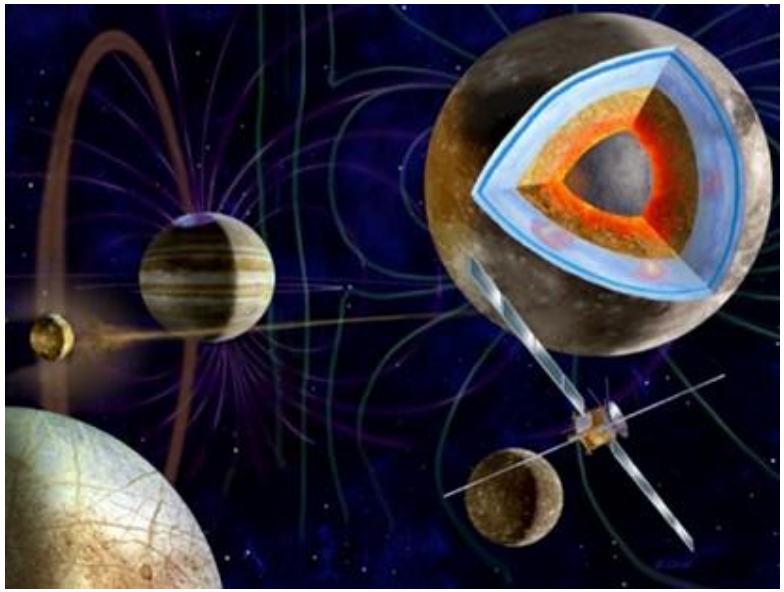
Does the Jupiter system harbour habitable worlds?

Mission	Distance (AU)	Transmitter power/gain	Band (GHz)	Time Resolution (s)	Delay Noise (ps)	Lateral Accuracy (m)
Huygens	8	3W/3 dBi	2.2 (S)	500	15	1000
JUICE	5	70W/6 dBi	8.4 (X)	10	5	60
			32 (Ka)	10	3*	20

*Limited by the propagation effects in the Earth troposphere

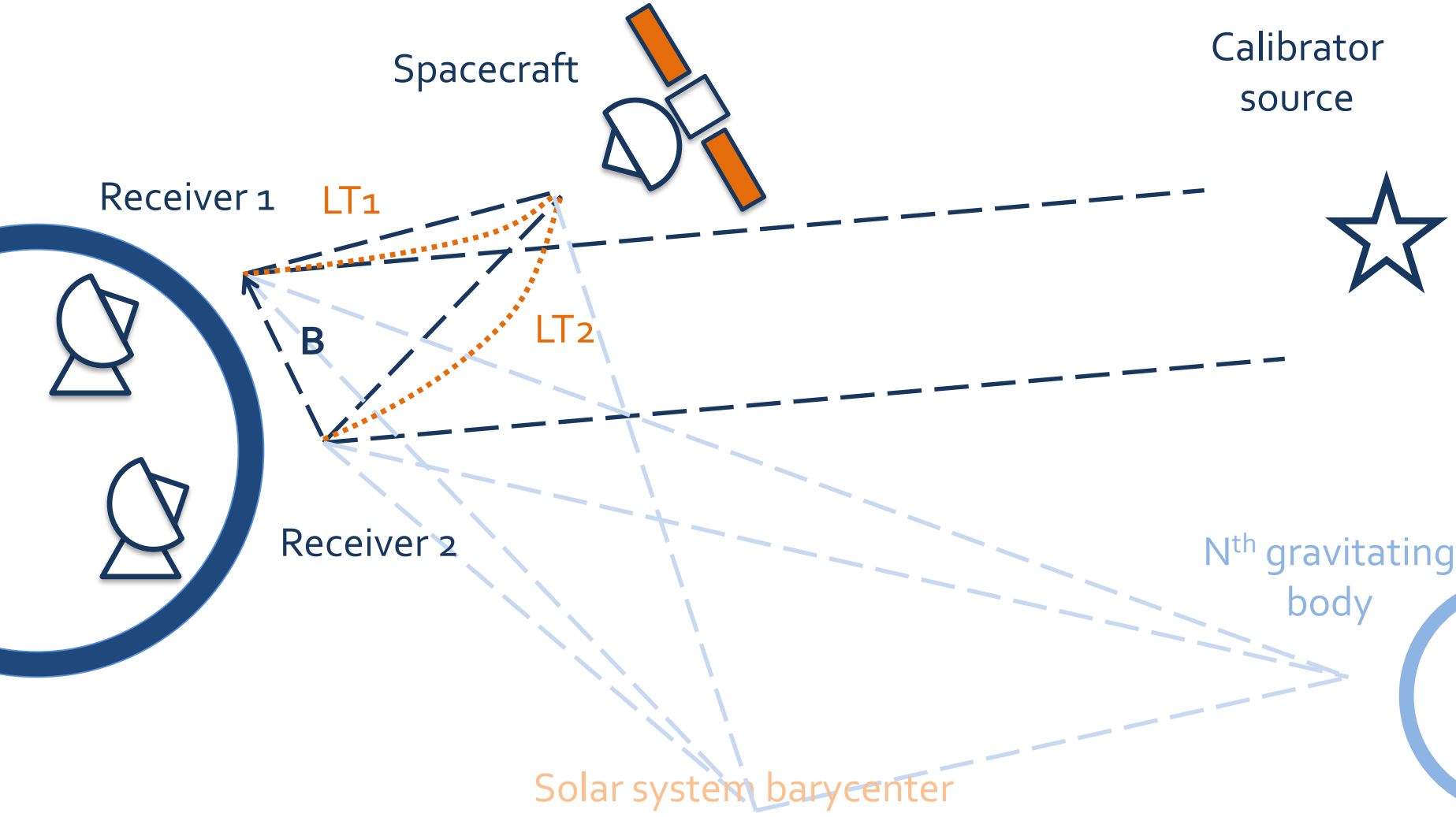
The main science objectives are:

- sub-surface oceans;
- ice shells and any subsurface water;
- internal structure for Ganymede and the intrinsic magnetic field the exospheres, plasma environments, and magnetospheric interactions;
- studying structure and dynamics of the Jovian atmosphere;
- Jovian magnetosphere;
- interactions occurring in the Jovian system;
- origin of the Jupiter system.



PRIDE is a selected JUICE experiment!

Near-field delay model

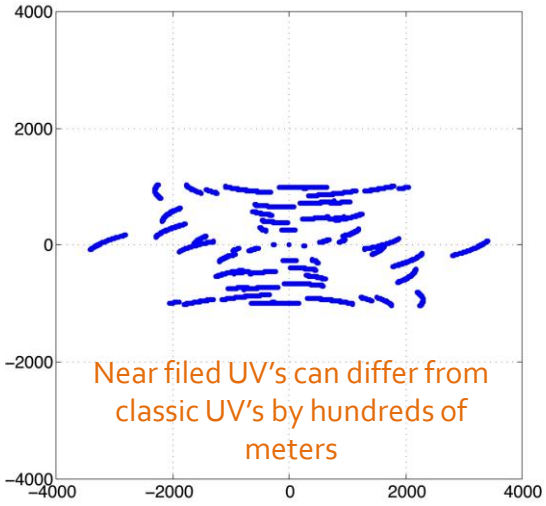


Imaging and *uv*-coverage for near-field VLBI

Van Cittert – Zernike theorem:

$$I_t(l,m) = \int S(u,v)\cdot V(u,v)\cdot \Re(e^{-2\pi i\cdot(ul+vm)})\,\mathrm{d}u\,\mathrm{d}v\,\Big|_t$$

Traditional
«uv»-projections of baselines



Elements of the Jacobian
for the near-field VLBI case

Derivatives of differential delays with respect
to the geocentric spherical coordinates of the source

$$J_{ij}|_t = \begin{pmatrix} \frac{\partial(\tau_1-\tau_2)}{\partial\varphi} & \frac{\partial(\tau_1-\tau_2)}{\partial\theta} \\ \vdots & \vdots \\ \frac{\partial(\tau_1-\tau_N)}{\partial\varphi} & \frac{\partial(\tau_1-\tau_N)}{\partial\theta} \\ \vdots & \vdots \\ \frac{\partial(\tau_{N-1}-\tau_N)}{\partial\varphi} & \frac{\partial(\tau_{N-1}-\tau_N)}{\partial\theta} \end{pmatrix}$$

Spacecraft imaging and state vector estimation

$$\overrightarrow{\Delta\phi}\,\Big|_t = \left(J_{ij}\cdot\overrightarrow{\Delta\alpha}\right)\Big|_t$$

- measurement equation

$$\overrightarrow{\Delta\phi} = \begin{pmatrix} \phi_{12} \\ \vdots \\ \phi_{1N} \\ \vdots \\ \phi_{N-1,N} \end{pmatrix},\quad \overrightarrow{\Delta\alpha} = \begin{pmatrix} \Delta\phi \\ \Delta\theta \end{pmatrix}$$

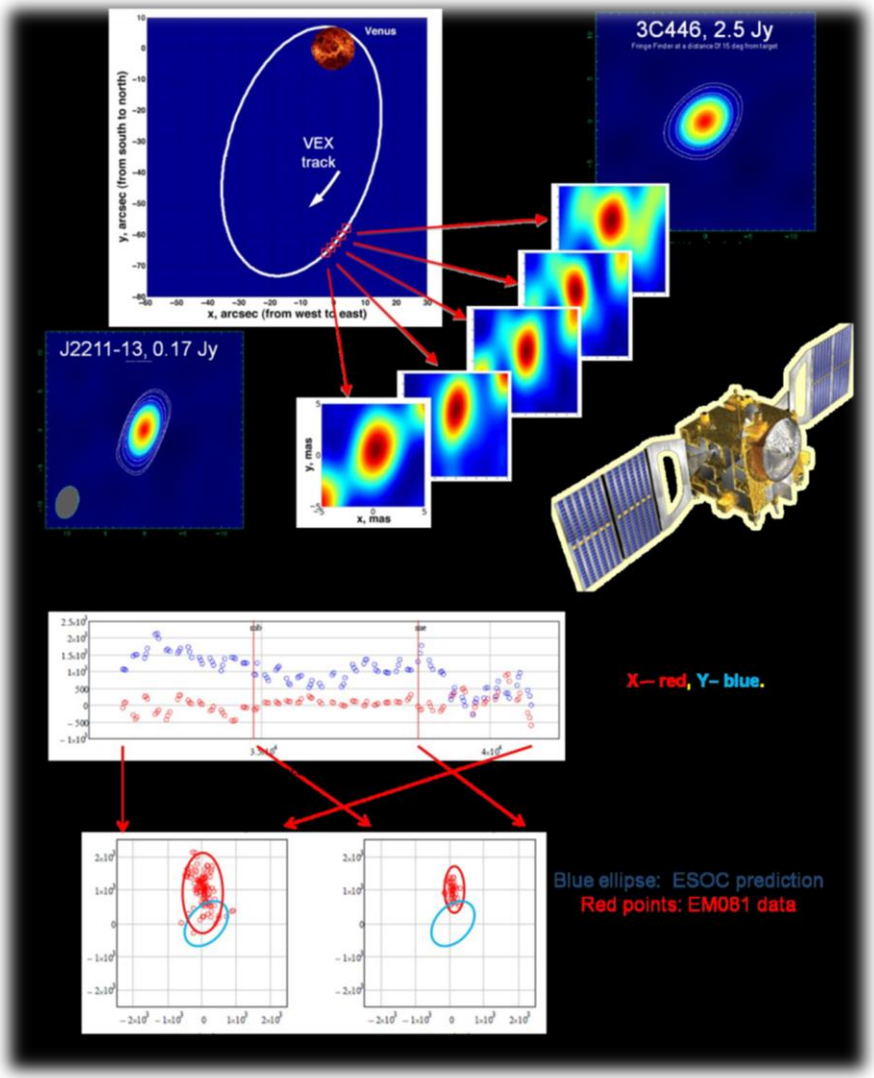
- differential phases
- vector of corrections

Duev et al 2012

To get corrections to the S/C a priori lateral position, solve measurement equation for **Δα**

…or correlate using Near-Field model and use **AIPS!**

Venus Express and EVN



Instantaneous reconstructed image of VEX (point-like source). The averaging time for each image is 20 min

VLBI and Doppler tracking experiment observed with 11 radio telescopes on 2011.03.28:

- 7 Europe
- 2 Russia
- 1 Africa
- 1 North-America

The radio telescopes alternated observing the natural reference source and VEX spacecraft.

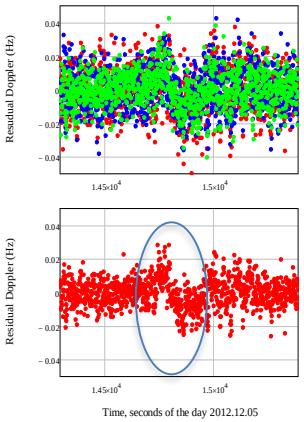
VEX drag campaign

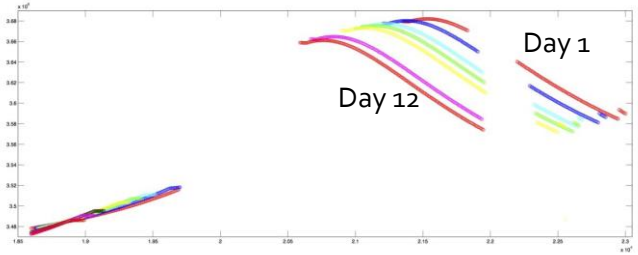
The orbit of the spacecraft is modified to pass near the periapsis.

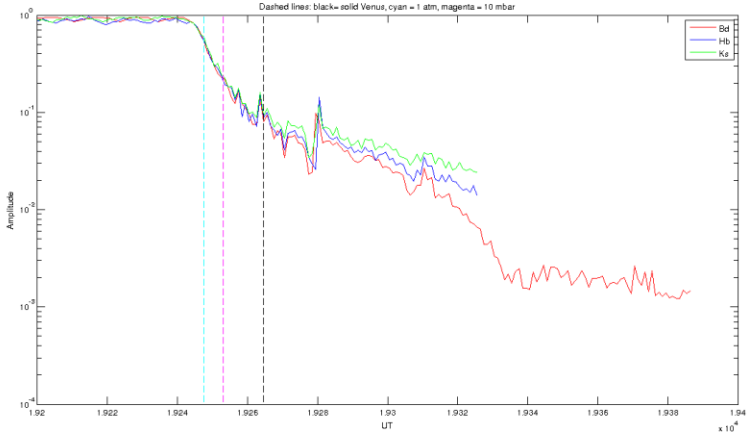
The campaign was carried out between 25 of April and 6 of May2012: In total , we observed 12 days of observations with an average of 3 telescopes per day.

12 radio telescopes were arranged to conduct the observations.

VEXaDE: (in collaboration with P. Rosenblatt)
Doppler detection noise at 1 second integration per point:
HartRAO-12m: 12mHz, Kashima-12m: 11mHz,
Badary-32m: 9mHz.
Averaged (RED dots) : 6mHz.
Doppler frequency drop ~40 mHz, or ~1.5 mm per second in velocity.

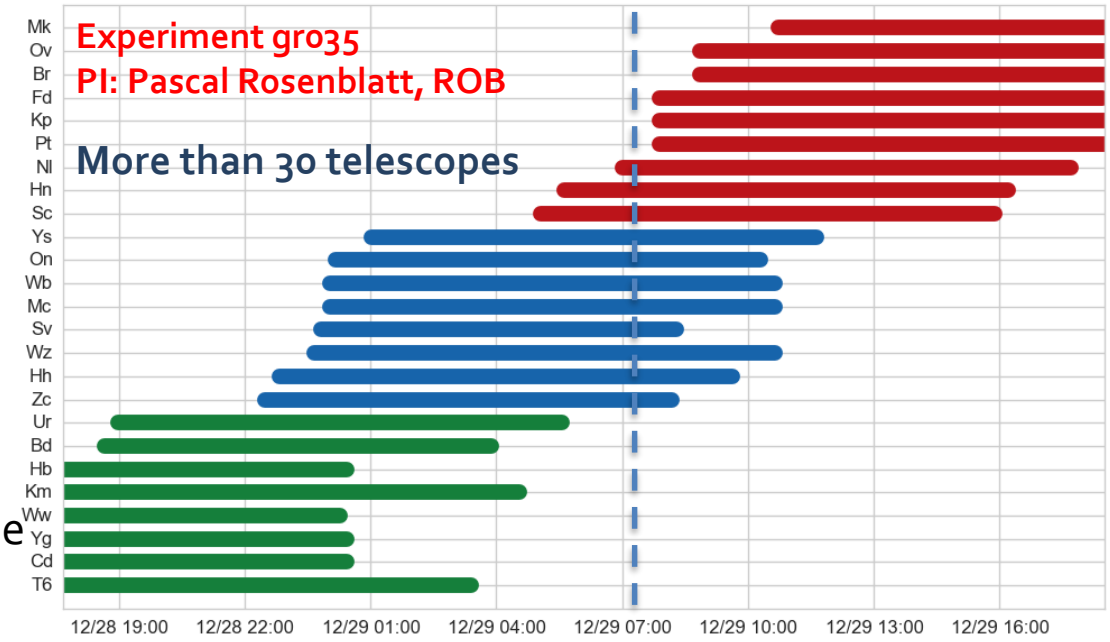






ESA's Mars Express Phobos fly-by

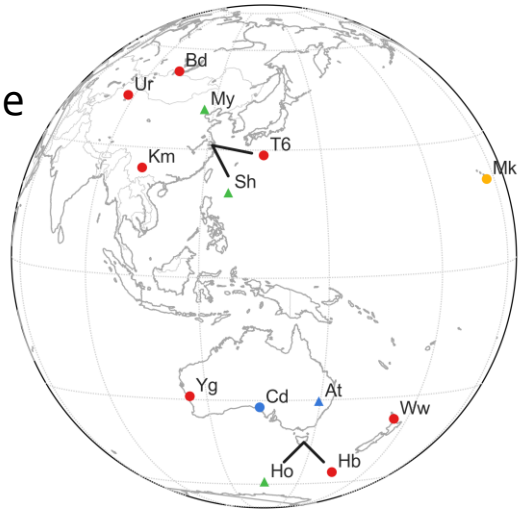
28 – 29 December 2013
Closest flyby of MEX 45km

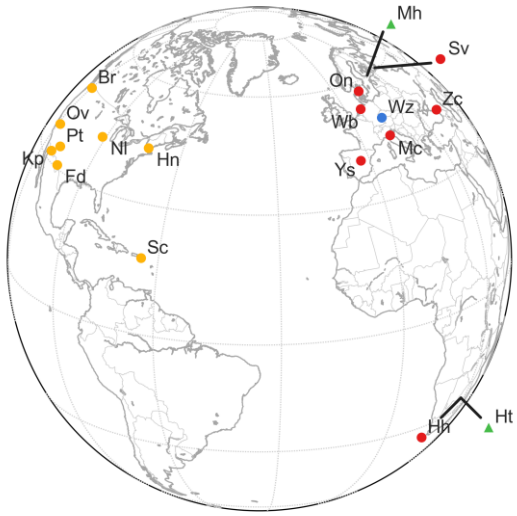


Goal: High precision positional and Doppler measurements

- Study of the Interior of Phobos
- Improving models on the origin of the Mars system
- Ephemerides

~26 hours of continuous observation time
3 consecutive Mars revolutions
7 hours long



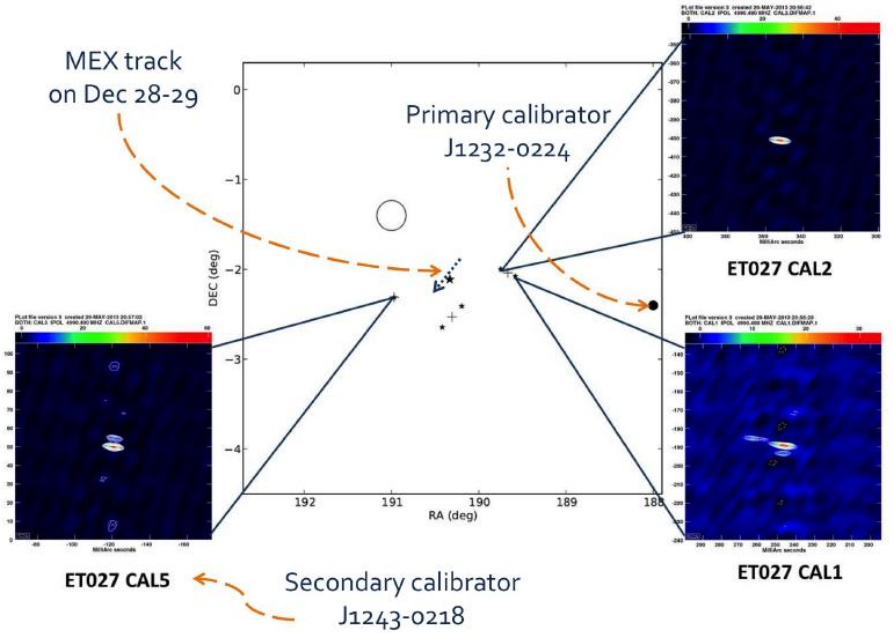


In preparation for ESA's **JUICE**

ESA's Mars Express Phobos fly-by

VLBI phase-referencing

- Primary: J1232-0224 (0.717 Jy @ X-band)
- Secondary: J1243-0218 (85 mJy)
- 2min scans



Standard VLBI recording equipment

Mark5 data acquisition system, mixed bandwidth setup:

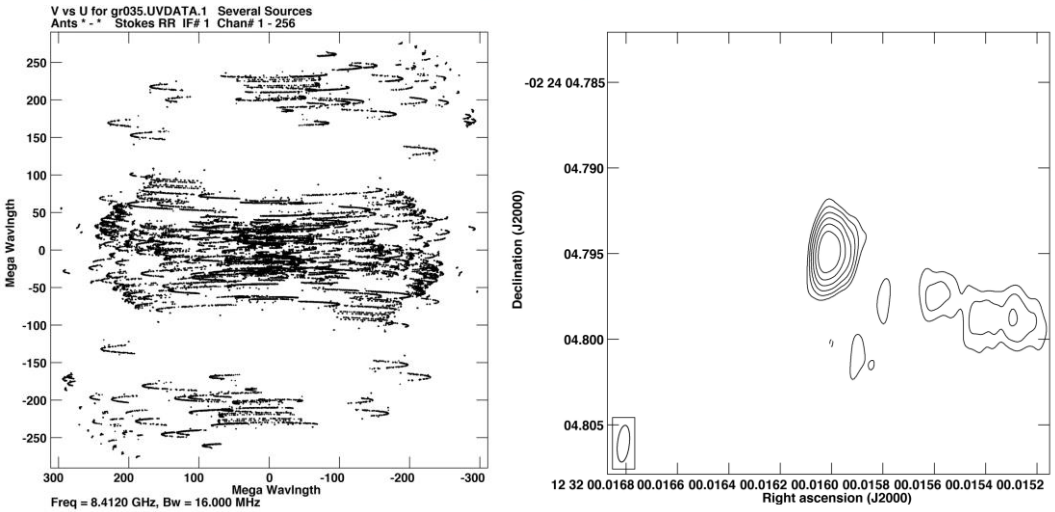
8x16 MHz most of the VLBI stations
4x16MHz Wz and VLBA

4x16 MHz S/X for Doppler stations

Standard VLBI data reduction

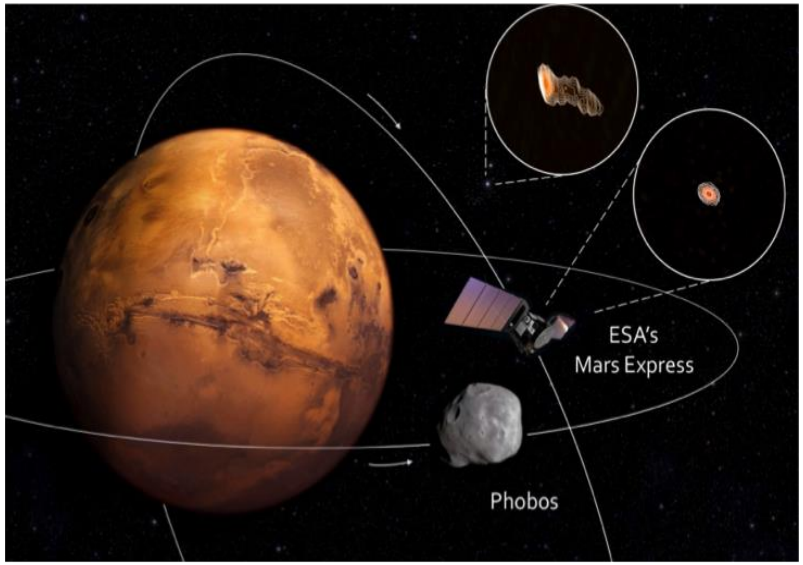
AIPS

Too many scans → Parseltongue!



MEX Phobos flyby

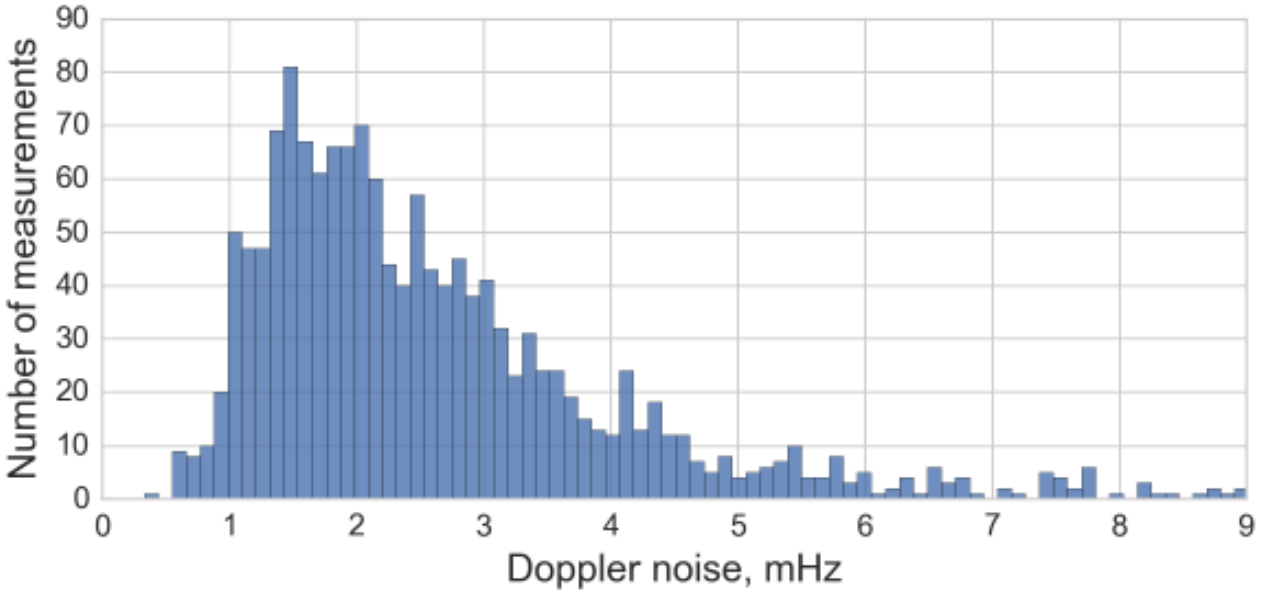
Doppler results



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 µm/s**

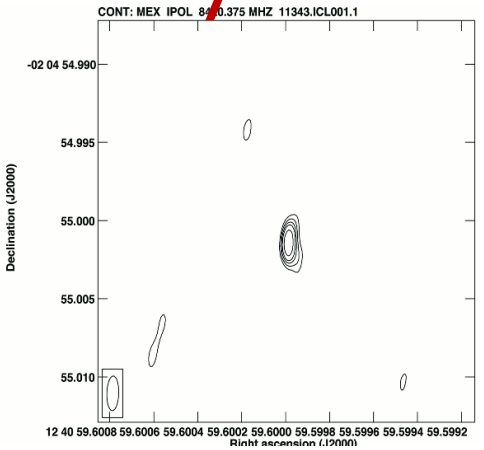


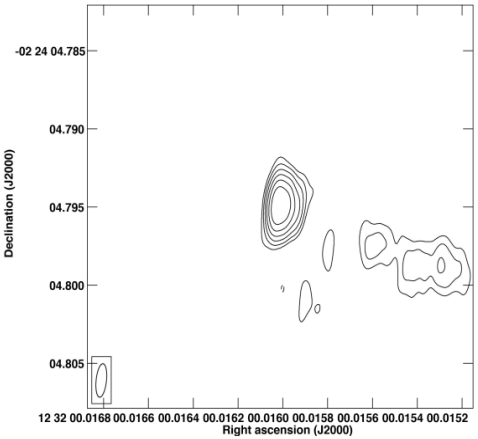
Duev et al 2016

Spacecraft astrometry

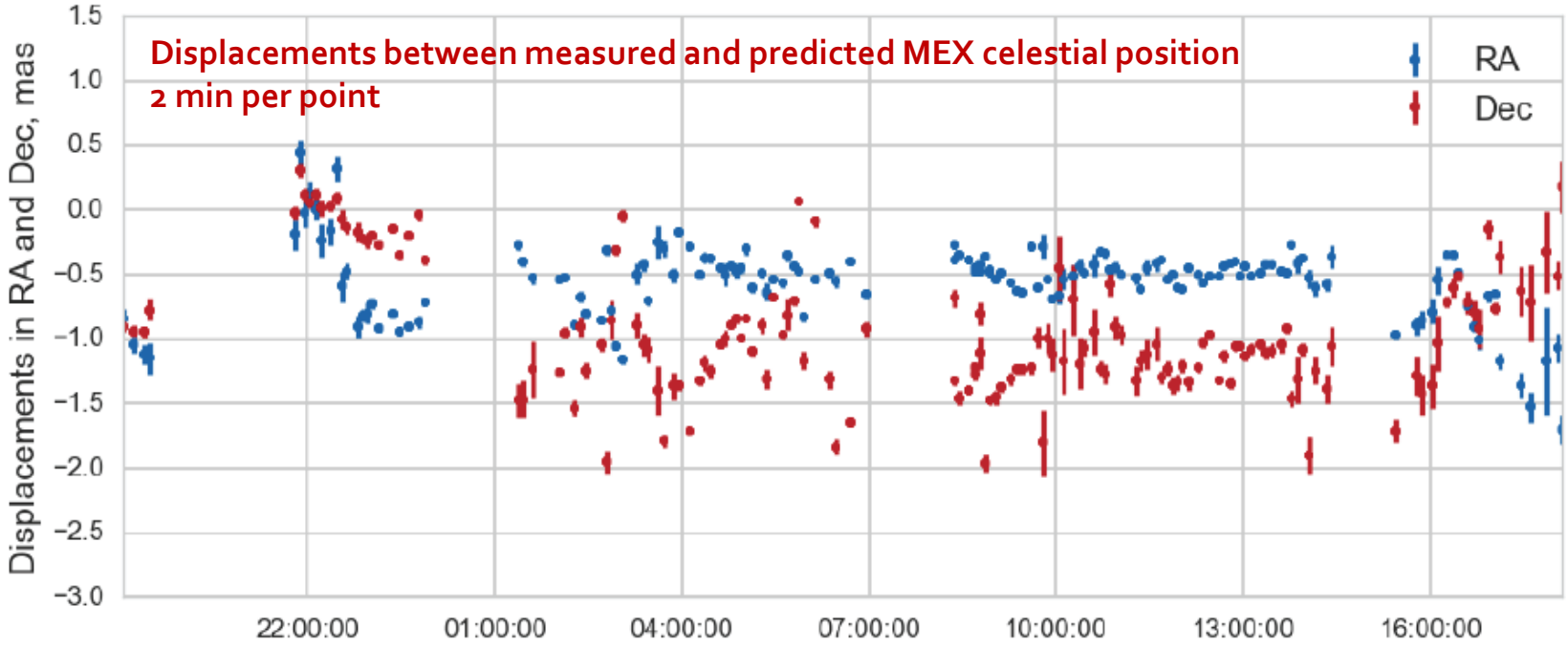
Median 3σ formal error for the full range are:

RA 34 μas → 35 m
Dec 58 μas → 60 m





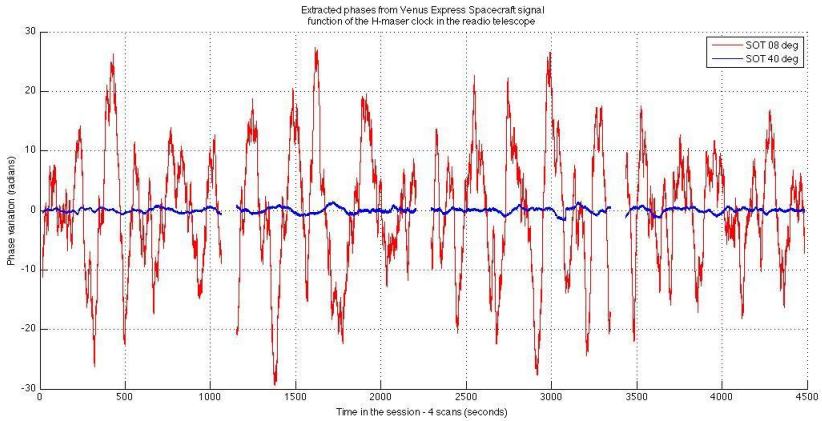
Duev et al 2016



Space weather

Several times per month from 2009 to 2016, we have observed a number of ESA's spacecraft at different solar elongation.

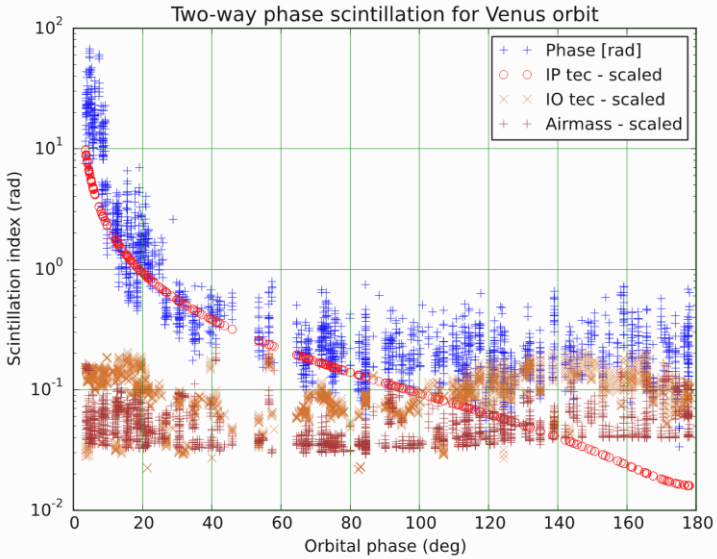
Strict communication with ESOC for transmission windows
Ad hoc observing arrangement with the radio telescopes
PI driven experiments



Molera Calvés et al. 2014

What can we do with this data?

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



Coronal Mass Ejection

Coronal Mass Ejection on 06/04/2015 detected on single-dish observations of ESA's Mars Express

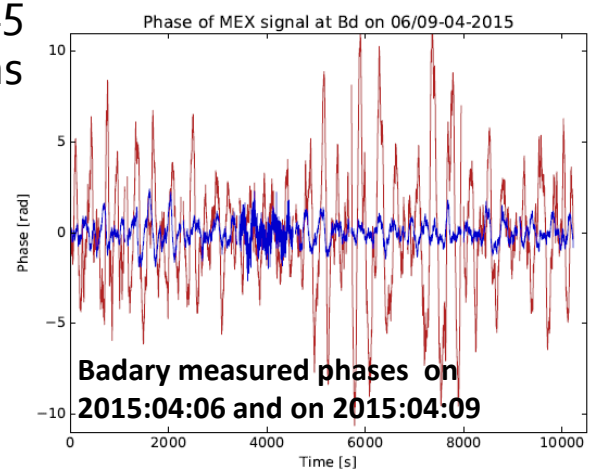
Solar Elongation → 18 degrees

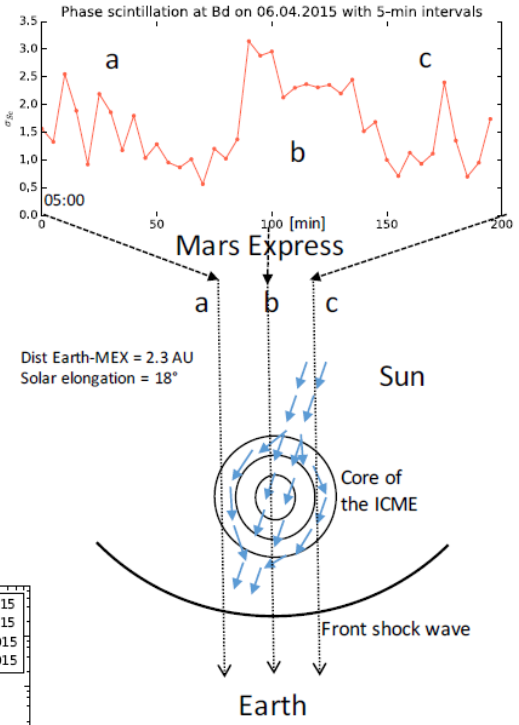
In one day, phase scintillation index increased of a factor of 3

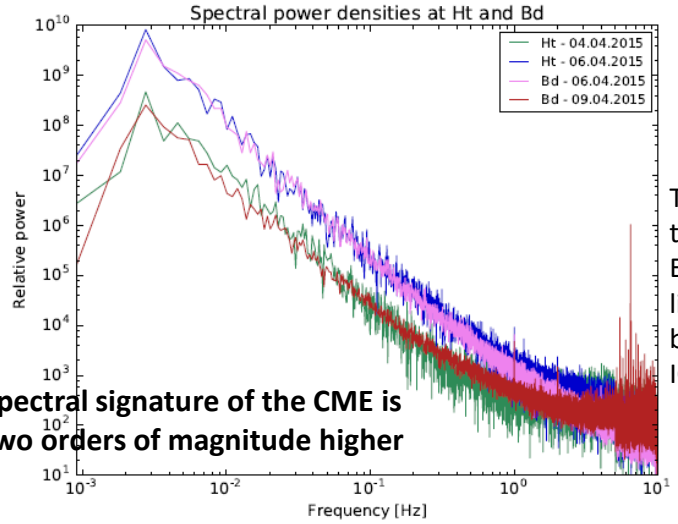
At the same time, the Total Electron Content increased of a similar factor

Study of CME structure

size: 3×10^6 Km (0.02AU)







The three vertical black lines illustrate the propagation of radio signals in the Earth frame when the ICME crossed the line of sight of the Earth and Mars. The blue arrows illustrate the flow of the ICME.

Talking to the Space community

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

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

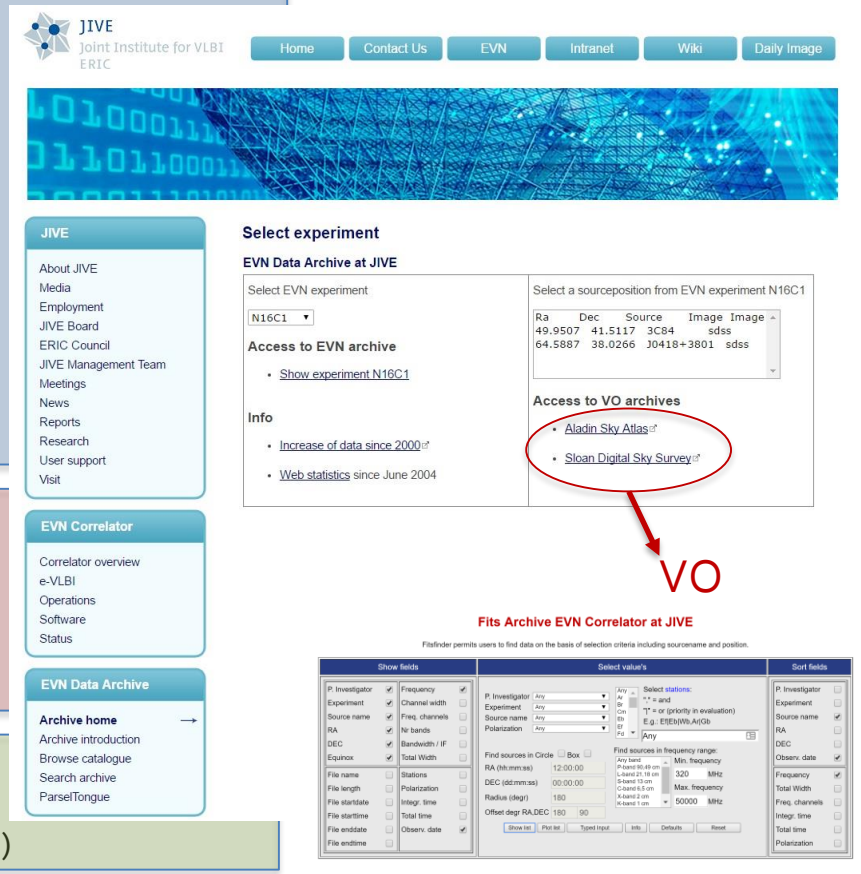
Processed data

- 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)

www.jive.eu



Talking to the Space community

Raw data from VLBI disk packs

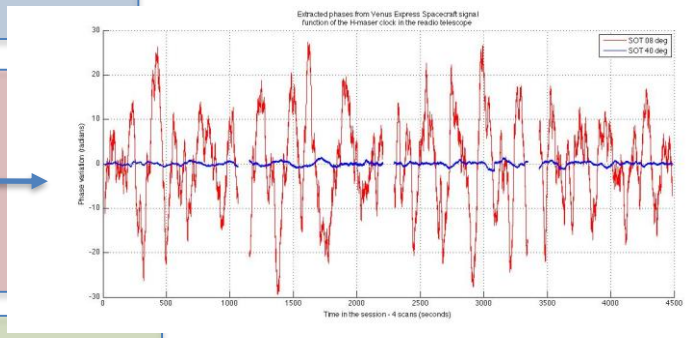
- Data are recorded in hard disks and shipped to JIVE for the cross-correlation
- Single dish only: No cross-correlation
- After correlation, the disks are recycled: no archive for raw data

Doppler shift

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

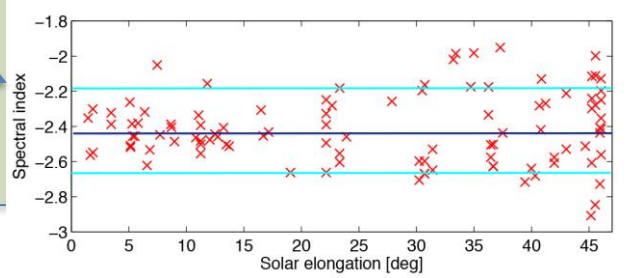
Processed data

- 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



Radio Astronomy and Radio Science

Interactions with the Space community

Challenges:

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

Credits: ESA

Feedback and suggestions:

- Interactions with EUROPLANET-VESPA
- VLBI and VO?
- Interdisciplinary events → ASTERICS! (of course!) ☺

Conclusions

Planetary Radio Interferometry and Doppler Experiment - PRIDE - has proven to be beneficial for a wide range of scientific applications.

Near-field model for VLBI

Addition to JIVE SFXC correlator

(Spectral masking and compression)

We have observed the ESA's MEX spacecraft flying by Phobos using 30+ radio telescopes for 26 hours.

Radial Doppler precision: 30 μm/s

Lateral position precision: ~50 m

Improving ephemeris of Mars system

Helping to constrain dynamical models of Mars system

Geophysical parameters to understand the nature of Phobos

The experiment helped to improve our pipeline for VLBI observations of spacecraft. In preparation for ESA's flagship mission JUice ICy moons Explorer (**JUICE**).