Planetary probes as near-field VLBI targets

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Fist near-field VLBI workshop
Bonn, Germany
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Planetary Radio Interferometry and
Doppler Experiment (PRIDE)

PRIDE at glance

Ad hoc VLBI(-based) tracking of planetary probes

- Utilises radio transmission from S/C (*S-, X-, Ka-bands*)
- Usually deals with a single-harmonic signal
  - …but exploits many radio telescopes (aperture synthesis)
  - …and astrophysical VLBI approach ("images" vs. "delays")
  - Different way of dealing with the phase ambiguity
- Often – very weak signals (unlike LEO near-field VLBI)
- Typically – more sensitive than dedicated assets
  - *More larger antennas than DSN and ESTRACK combined*
  - Useful for critical time-limited operations
- Can operate in one-way (Huygens) or two-way modes
- SCHED, not SKED
- Flexible frequency/IF-bandwidth setup

Spacecraft as a celestial radio source

- Spacecraft tend to be radio loud… actually?
  - Transmitter power 1 W
  - Distance 5 AU (Jupiter)
  - On-board antenna gain 3 dB
  - Bandwidth 100 kHz

Flux density ≈ 0.5 mJy=0.5·10^{-29} Wm^{-2}Hz^{-1}

- Operate at frequencies radio astronomers love (or hate):

  UHF (400 and 800 MHz), S (2.3 GHz), X (8.4 GHz), Ka (32 GHz)

- Estimates of state-vectors of spacecraft:
  - Need for "higher-than-standard" accuracy in special cases
    - Geodynamics and planetology
    - Trajectory measurements in close vicinity of Solar System bodies (e.g. landings)
    - Fundamental physics
    - Space-borne astrometry missions (e.g. GAIA)
- Need for "eavesdropping" (sometimes, in desperation…)

Working in the near field with PRIDE

While praying λ/B , let's not forget $R_{nf} \propto \frac{B^2}{\lambda}$

Baseline	100 km	1000 km	10^4 km
Facility	MERLIN	EVN_{WE}	Global VLBI
λ = 3.6 cm *X-band*	2 AU	200 AU	0.1 pc
λ = 1 cm K_a-*band*	8 AU	750 AU	0.5 pc

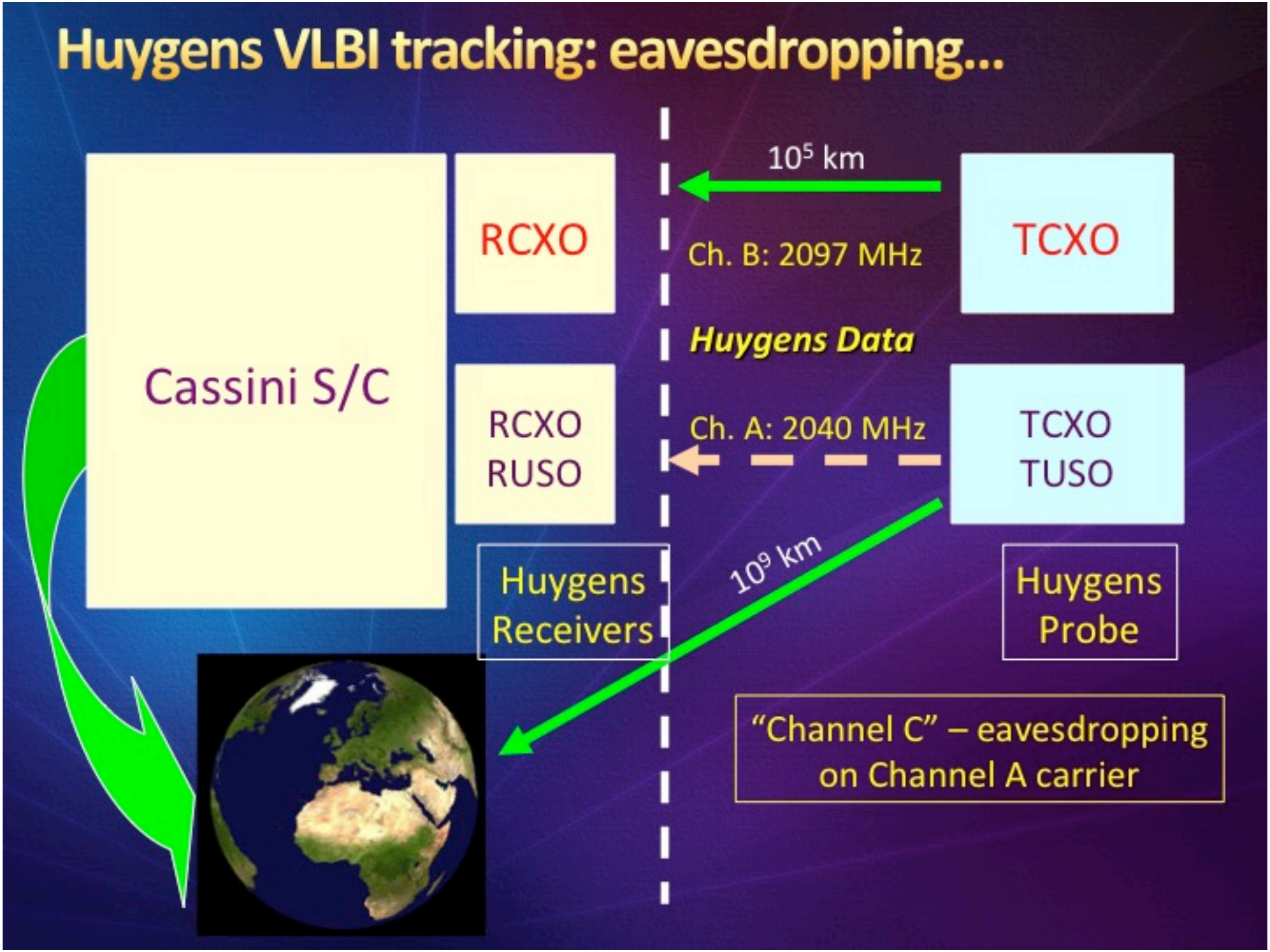
VEGA balloons VLBI tracking, 1986

f = 1.6 GHz, Δf = 2 MHz, 20 radio telescopes

σ_x = 10 km
σ_v = 1 m/s

Preston et al. 1986, Science, 231, 1414

Huygens VLBI tracking: eavesdropping...



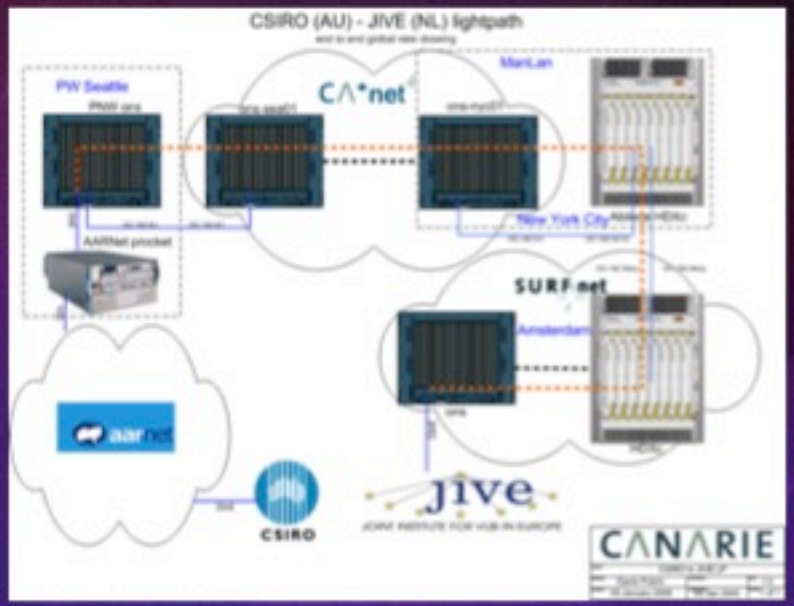
VLBI tracking of Huygens, 14 January 2005

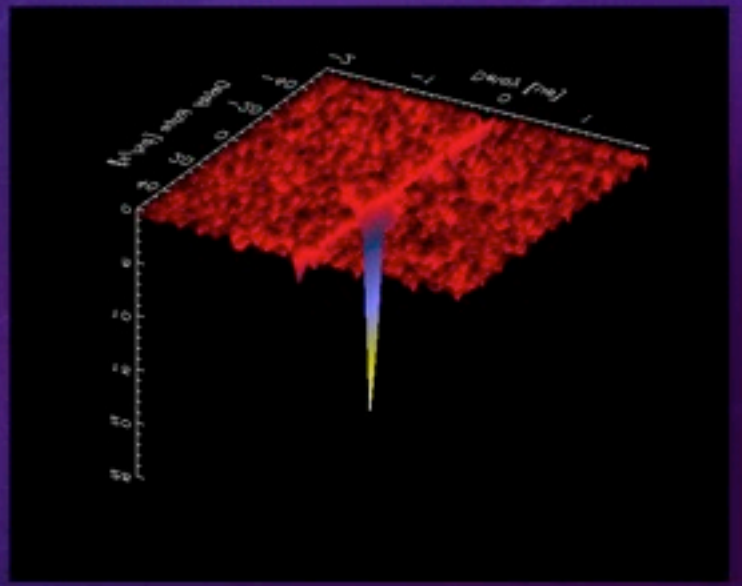
09:30 UTC

16:00 UTC

~20 radio photons per 25-m telescope per second…

e-VLBI & "Night Flight": 14 – 15 January 2005

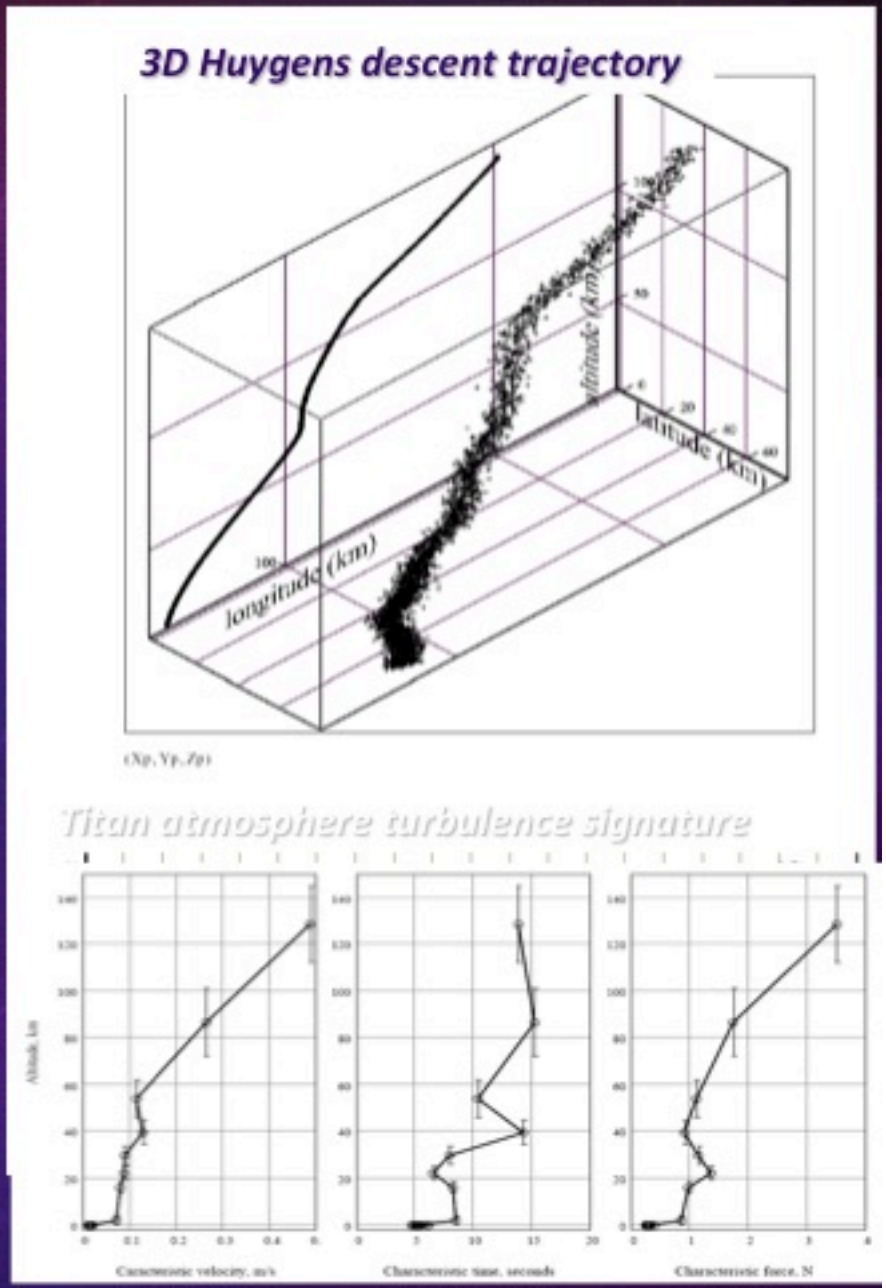




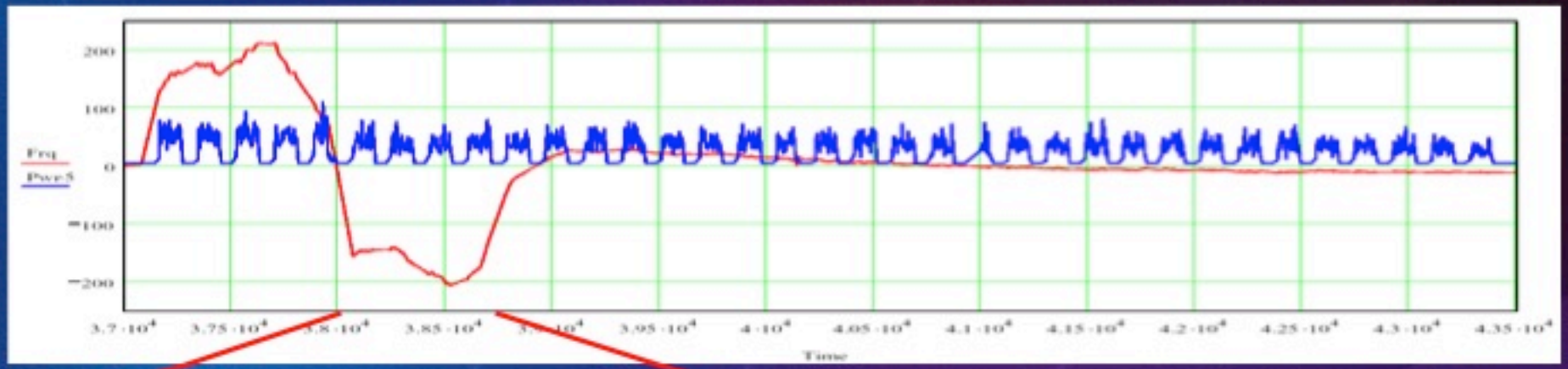
A.Tzioumis & C.Phillips, ATNF,
acting in near-RT mode

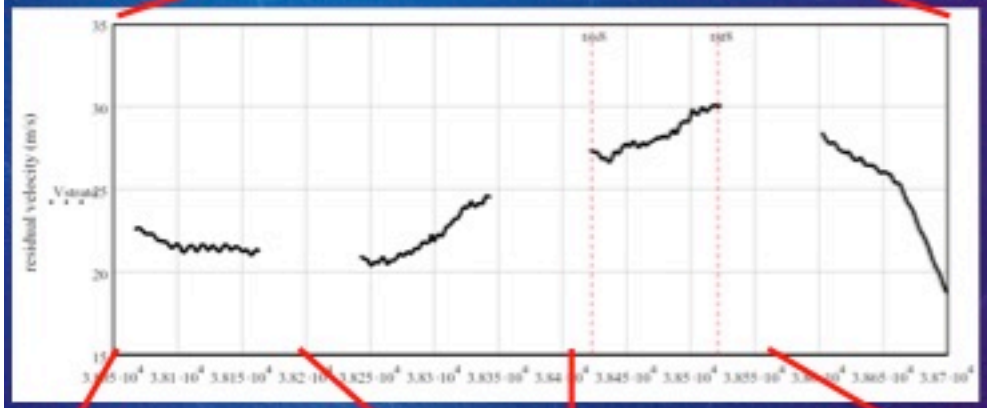
Huygens VLBI heritage: 20 photons/dish/s

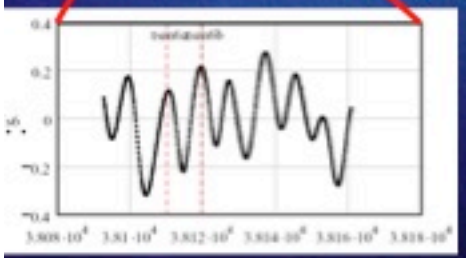
- Ad hoc use of the Huygens "uplink" carrier signal at 2040 MHz
- Utilised 17 Earth-based radio telescopes
- Non-optimal parameters of the experiment (not planned originally)
- Achieved 1 km accuracy of Probe's descent trajectory determination
- Assisted in achieving one of main science goals of the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

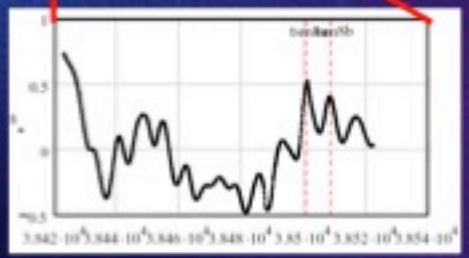


VLBI processing by-product: Doppler data (probe's motion)





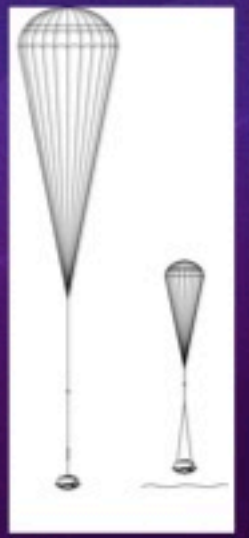


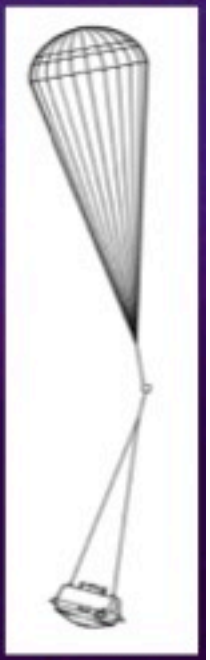


$T = 8 \div 10$ s

$\Delta V = 0.22$ m/s

$A \approx 0.6$ m





Data available for analysis!

PRIDE-2013 vs Huygens VLBI tracking

Mission	Distance	Transmitter power/gain	Band	Time resolution	Delay noise	Positional accuracy (lateral)
	[AU]		*[GHz]*	*[s]*	*[ps]*	*[m]*
Huygens VLBI	8	3 W / 3 dBi	2.0 (S)	500	15	1000
PRIDE-JUICE	5	10 W / 6 dBi	2.3 (S)	100	5	120
			8.4 (X)	10	3	70
			32 (Ka)	10	1	23

Tom-Tom accuracy anywhere in Solar System

- **Conservative estimate, today's technology**
- **Minimal special requirements for the on-board instrumentation**
- **Helps to address the key science of EJSM-Laplace – search for undersurface liquid water by means of Europa tidal deformation monitoring**

ESA: Jupiter Icy Satellites Explorer (JUICE)

Progressing from exploration to characterisation of habitable worlds

JUICE Science Themes

- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*

Emphasis on studies of Ganymede and Europa:

- search of "hidden" bodies of water
  - *by tidal deformations*

plus

- *ephemerides of Jovian system*

Tasks for PRIDE

1610
Discovery

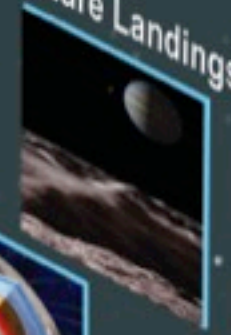
1974
Insight

1985
Deep habitats on Earth

1995
Exploration

2004
First extra-solar waterworld

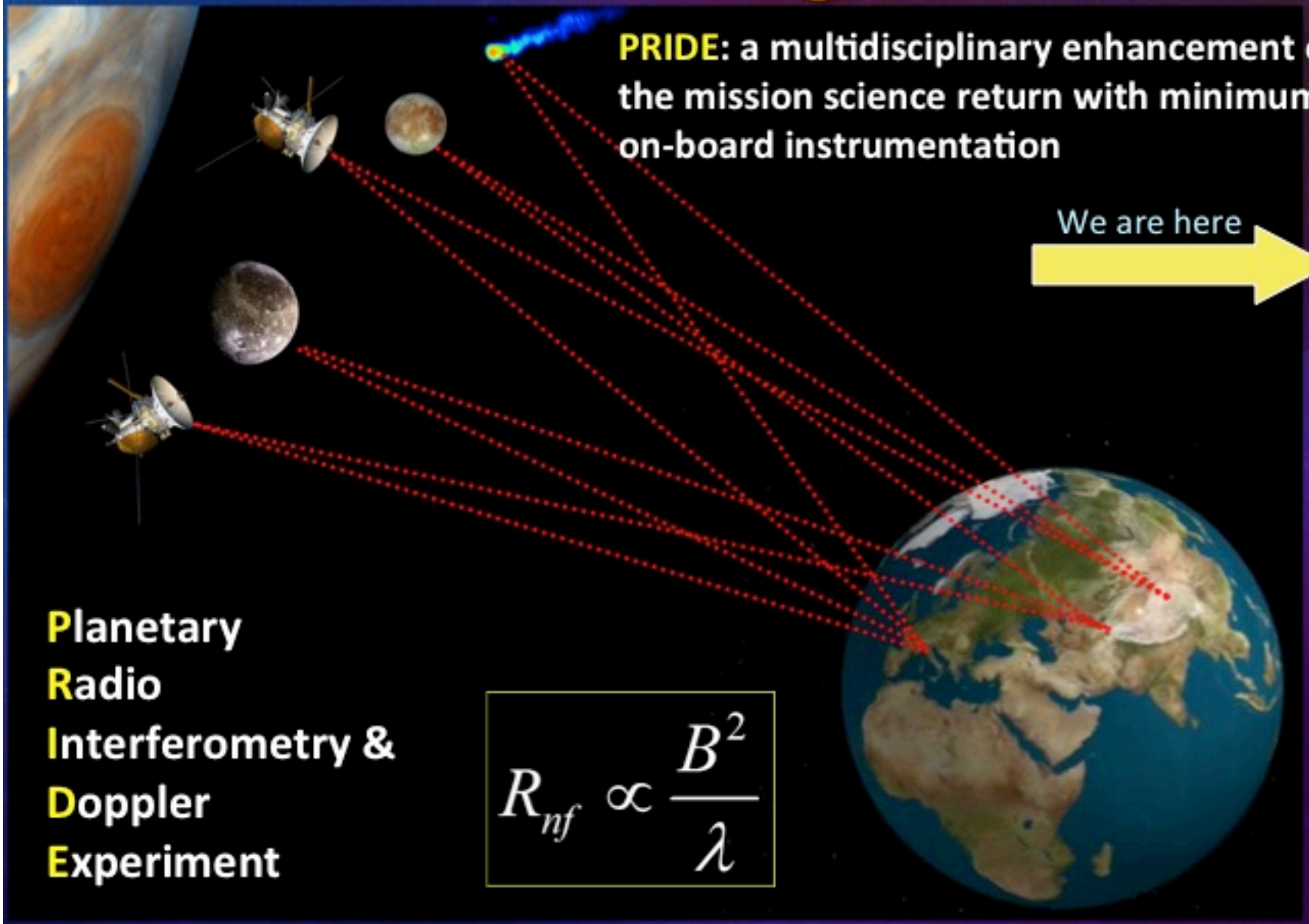
2012
Characterisation



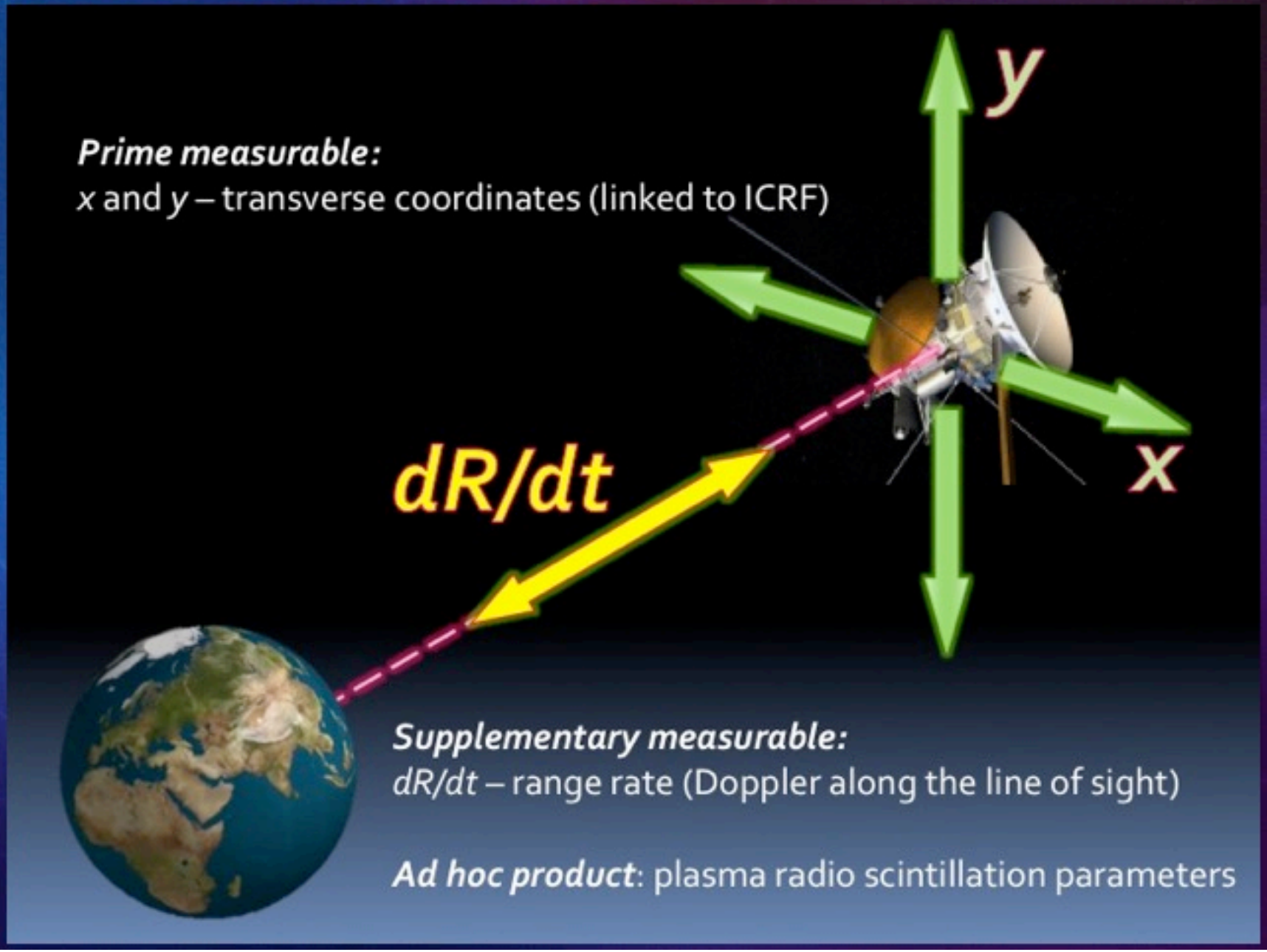
2030
Future Landings

Launch: 2022
Arrival to Jovian system: Dec 2029
Nominal mission: 3 years

Generic PRIDE configuration



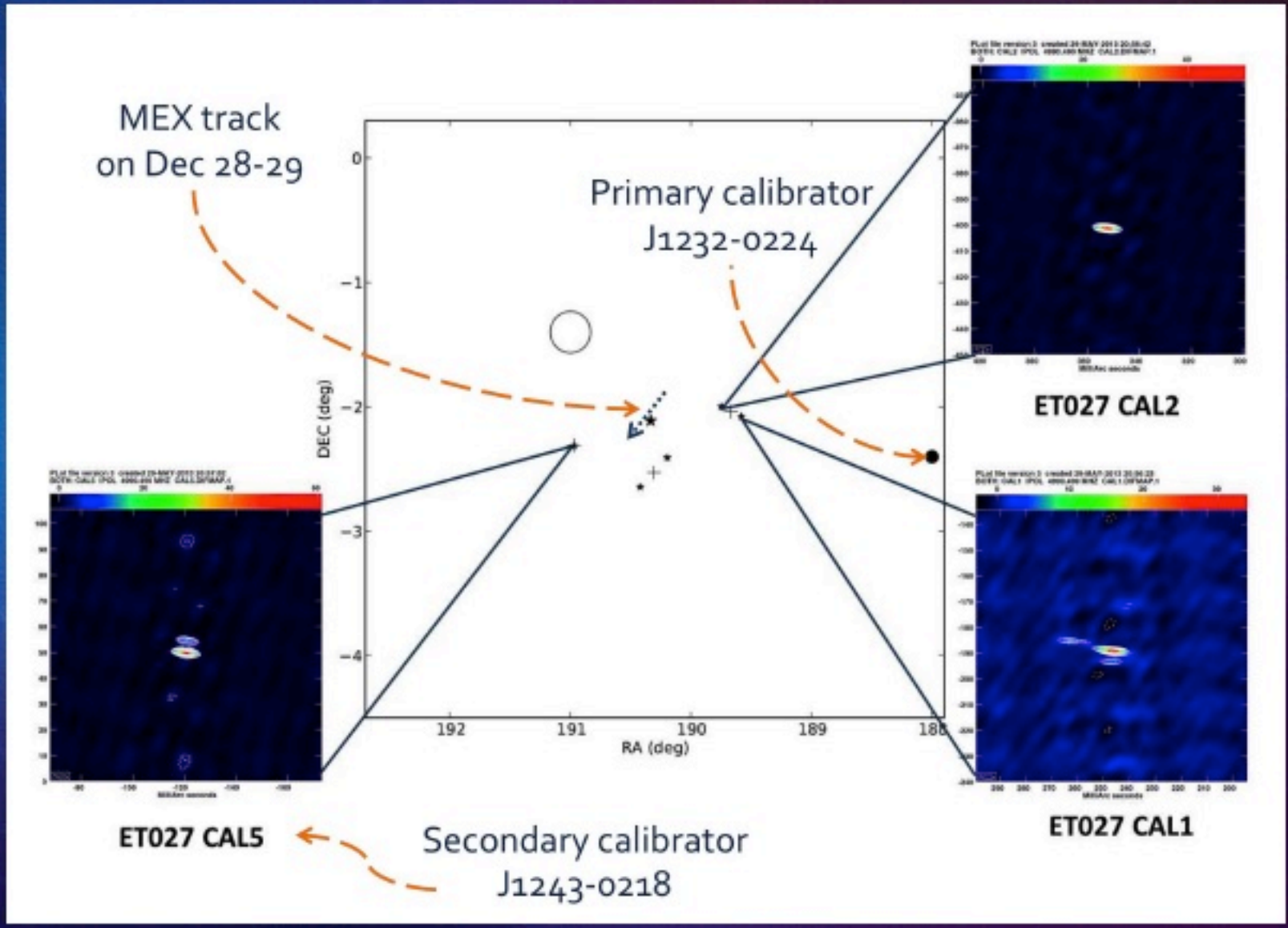
PRIDE measurables



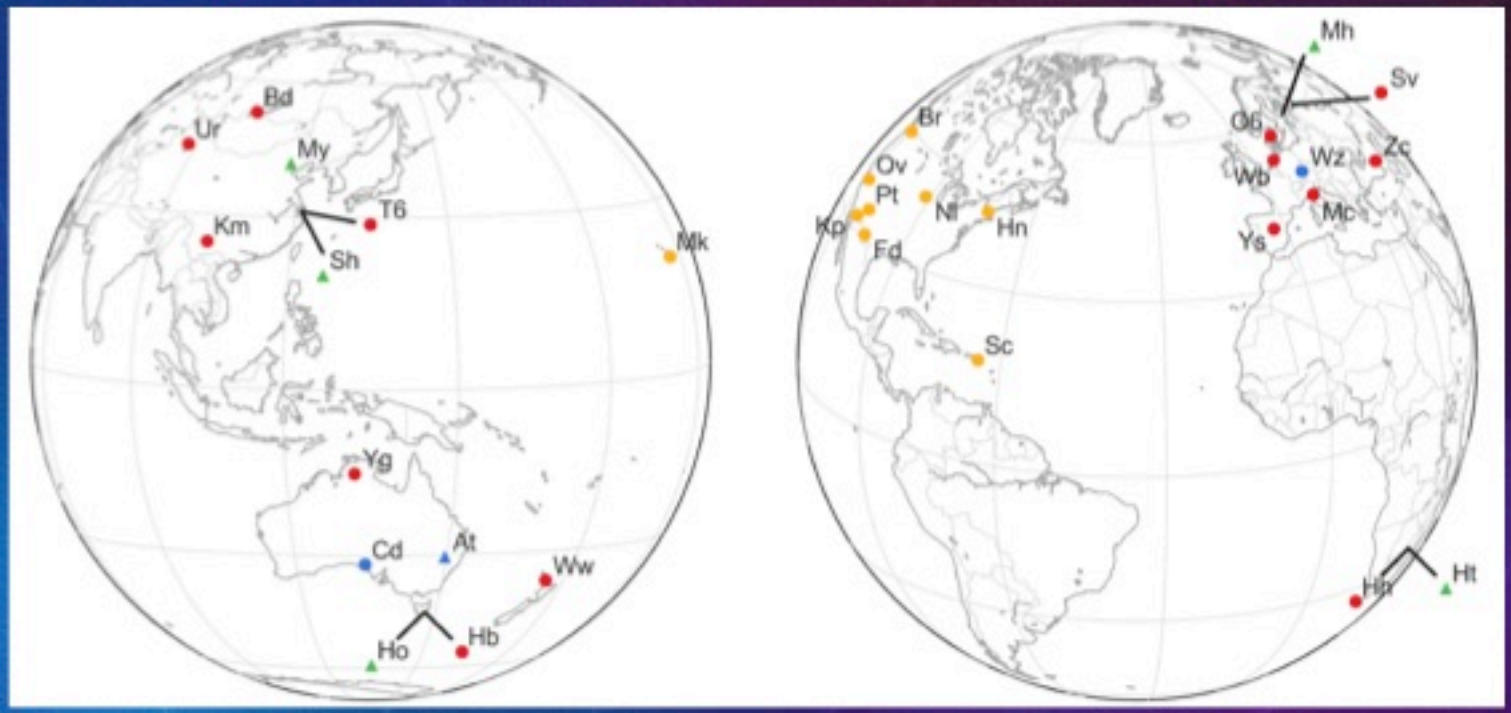
MEX/Phobos flyby as a test case

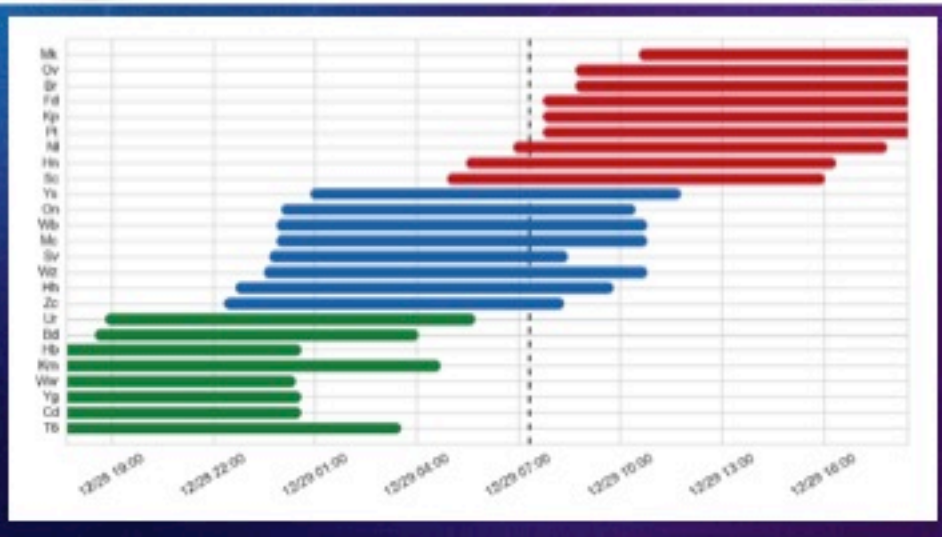
- Uniquely close (58 km) Phobos flyby by MEX
  - 29 December 2013 (Sunday)
  - Prime science: MaRS (MEX radio science), not PRIDE
- Implemented under ESPaCE-MaRS agreement
  - as a PI-led EVN/Global experiment GR035
    - *PI – Pascal Rosenblatt, Royal Observatory Belgium*
  - conducted by PRIDE team as a technical test
    - *no autonomous science evaluation by PRIDE team*
- Involved more than 30 radio telescopes globally
- Lasted for 26.5 hours continuously, ~3 MEX orbits
  - PRIDE data processing at JIVE, “operational” pipeline

GR035 finding chart

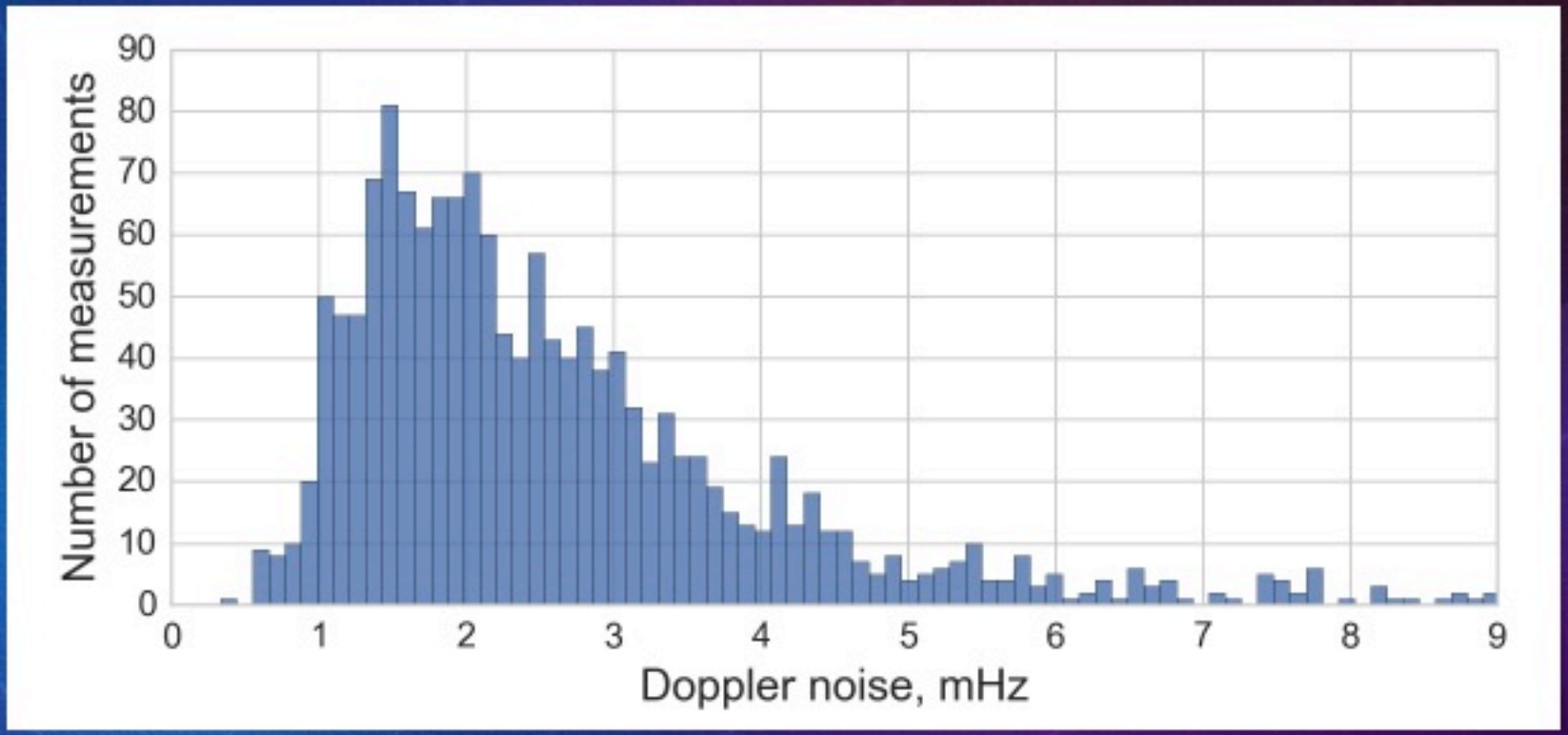


GR035, VLBI network configuration





GR035, Doppler detections



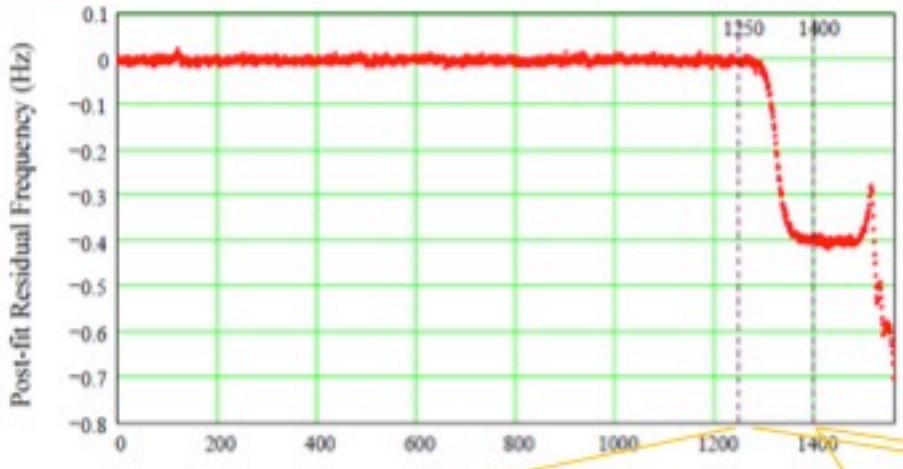
Doppler detection noise, 10 s integration:

- mean value 2.5 mHz
- median value 2.2 mHz
- mod (maximum log-normal fit) value 1.7 mHz → 30 µm/s

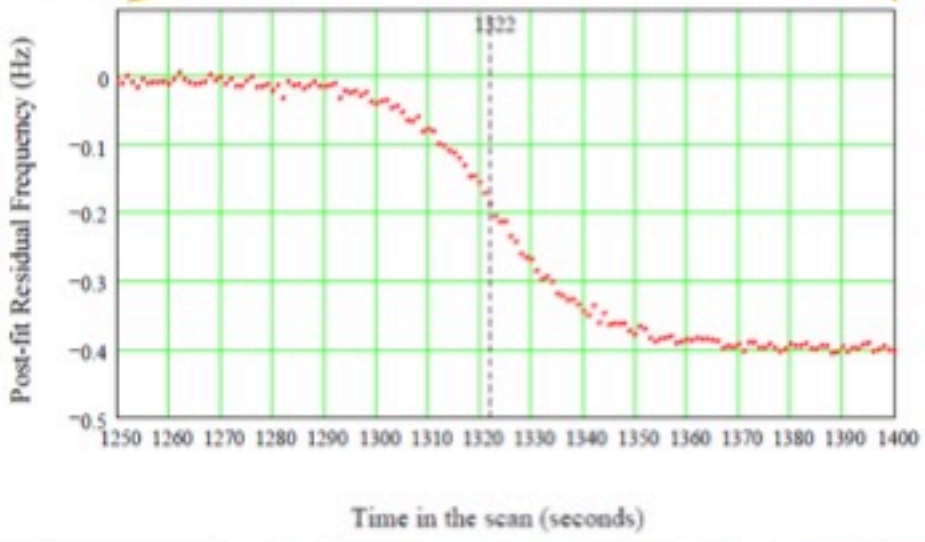
Ht-15m flyby CA scan

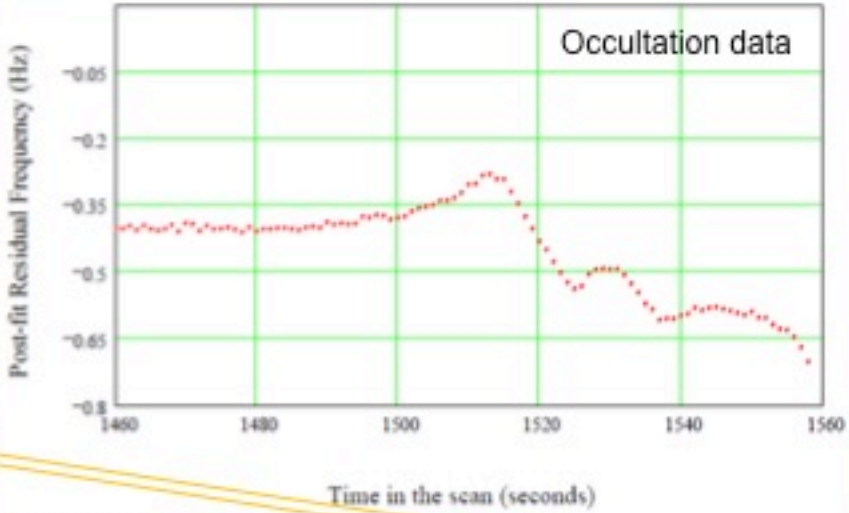
Doppler noise 5 mHz in 1 s

Post-fit residuals

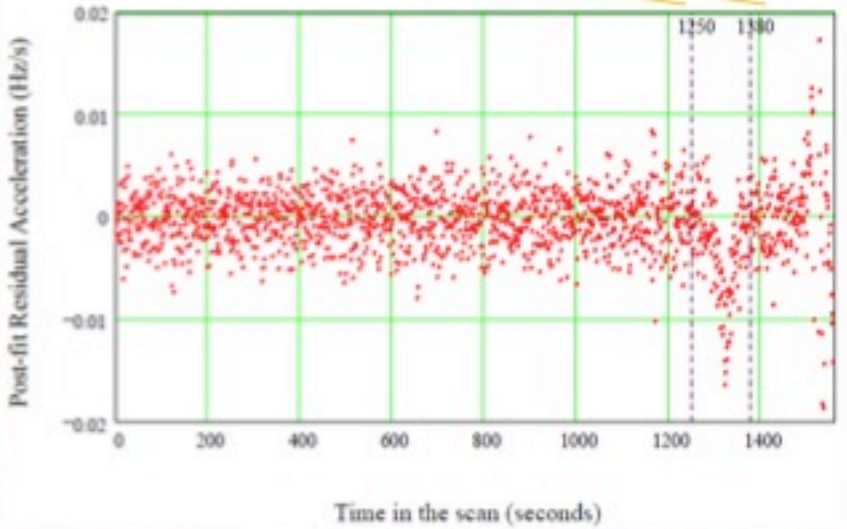


Flyby

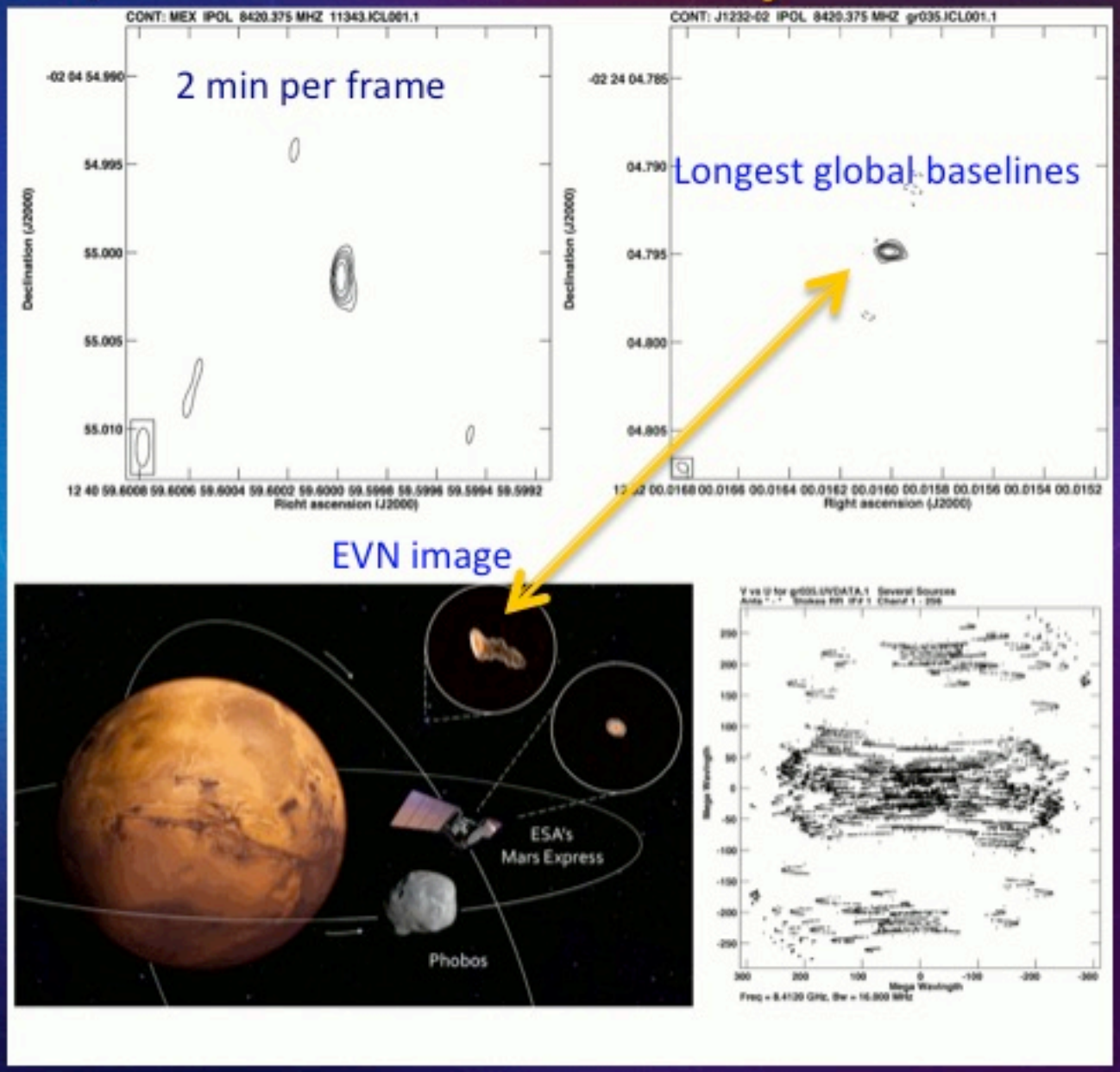




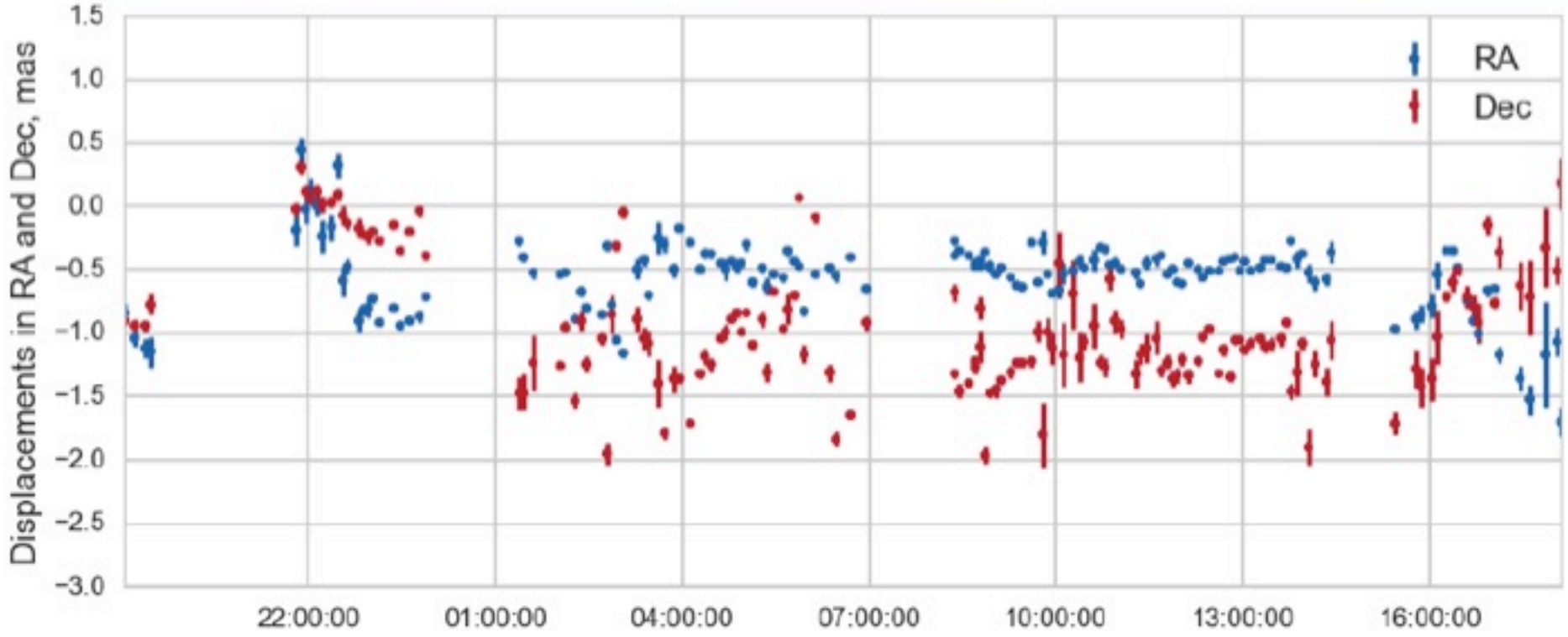
Acceleration



GR035, VLBI astrometry



GR035, VLBI astrometry

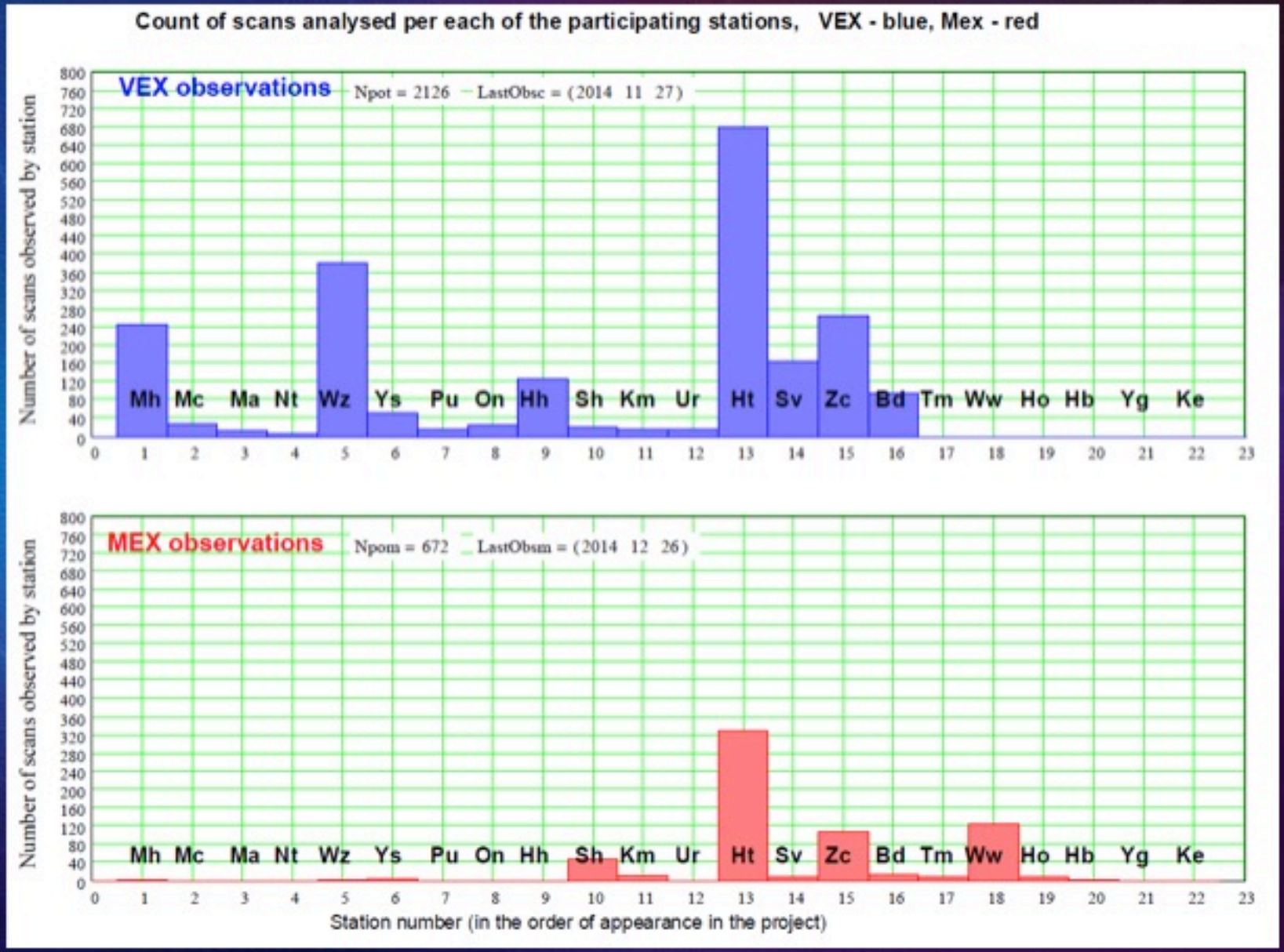


Displacement between measured and predicted MEX celestial position, 2 min per point (imaging approach).

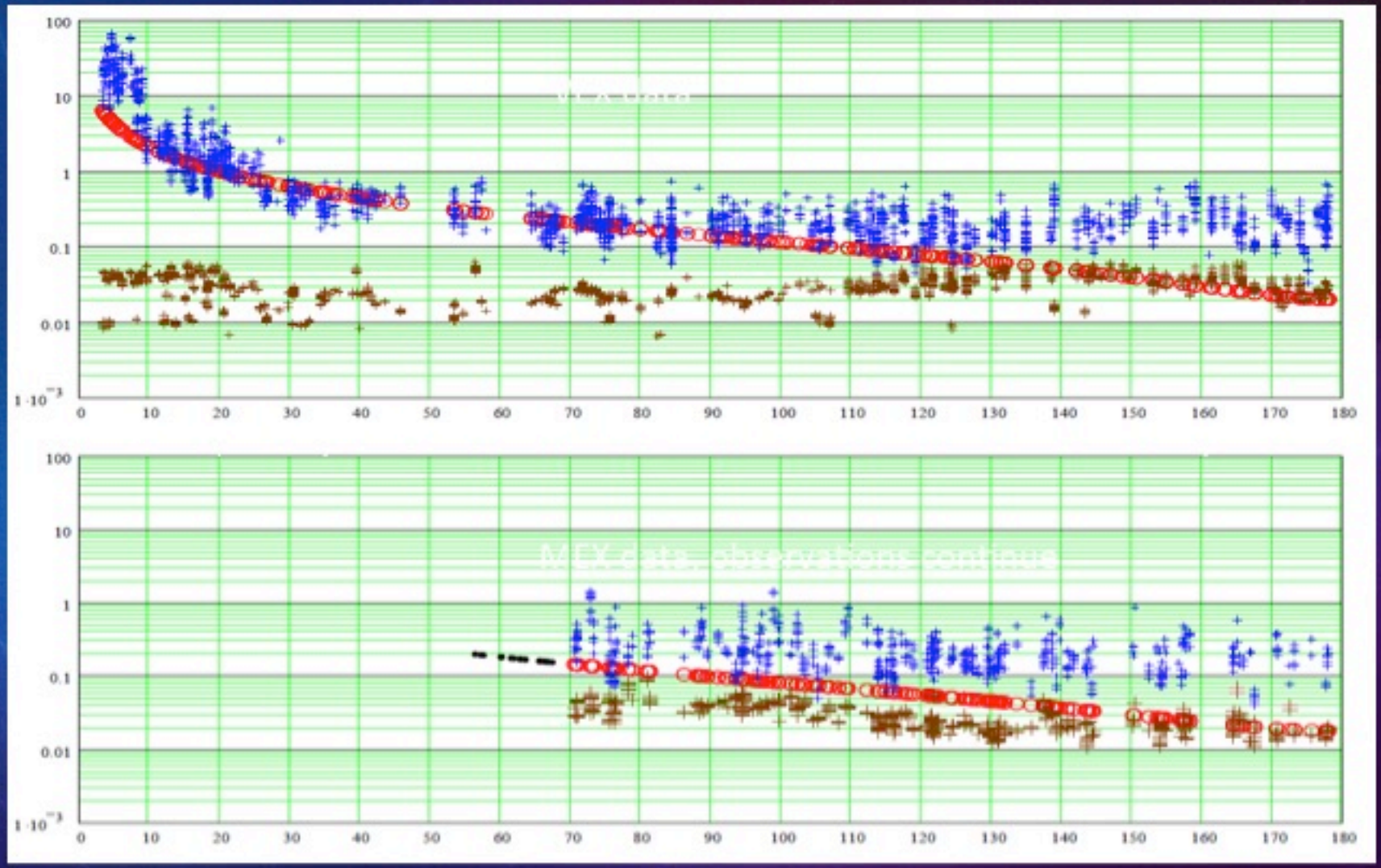
Formal precision (3σ):

RA	**34 µas**	**35 m**	**~0.17 nrad**
Dec	**58 µas**	**60 m**	**~0.30 nrad**

VEX and MEX observations *by Jan 2015*



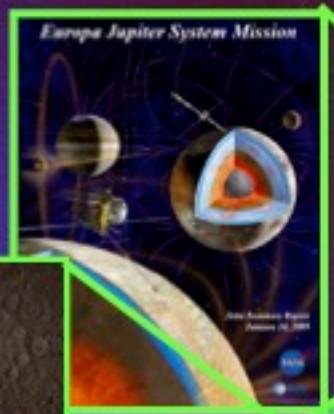
Scintillation index from PRIDE on VEX & MEX



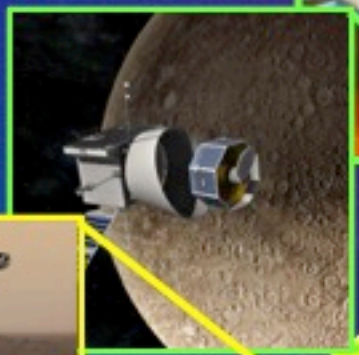
Measured scintillation index or phase RMS in 300 s integration (radians) – blue +'s
Two-way interplanetary TEC – red circles, two-way ionospheric TEC – brown +'s,
scaled for a best fit with the phase scintillation measurements

Planetary science missions – PRIDE "customers"

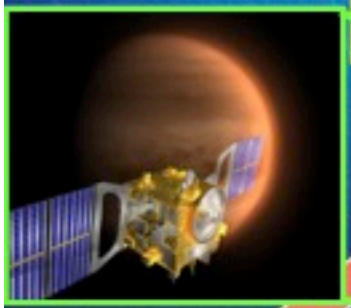
JUICE-Laplace



BepiColombo
MMO



ExoMars



Adopted by ESA
launch in 2022

2025

ESA & JAXA
launch in 2017

2020

LaRA under consideration by
ESA & RFSA

2015

Operational

2010

VenusExpress &
MarsExpress

PRIDE in the planetary sci agenda

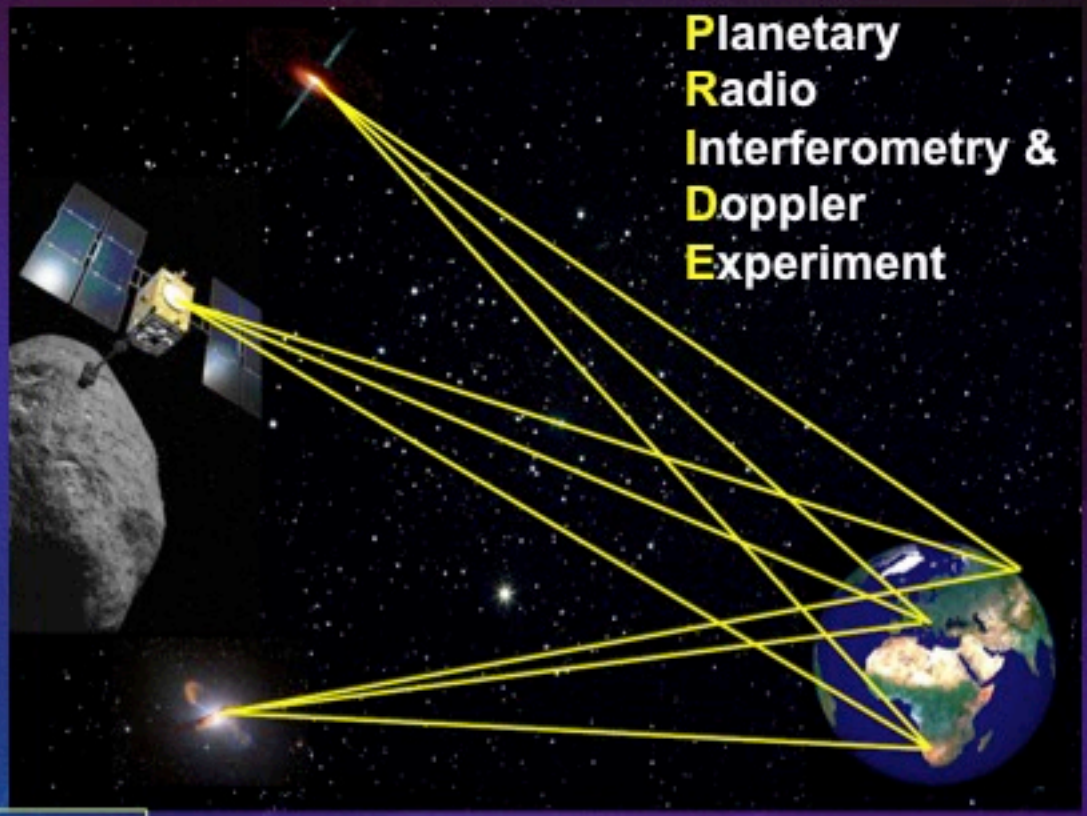
- Already developed to a mature state ("high TRL")
- Leading and recognised position in Europe and beyond
  - attractive issue for collaboration with China, potentially - India
- Bridge between radio astronomy and planetary science
  - Long-term strategic "cornerstone"
  - on the SKA agenda
    - *also as an ad hoc DtE facility*
- Requires very modest investment
  - but offers high "value per €" in science output
    - *even potential for industry's involvement and spin-off*
- Time to capitalise on it!

Near field VLBI

$$R \approx B^2/\lambda$$

3D astrometry of high T_B objects

$T_B > 10^{18}$ K?



Kardashev, Parijskij & Umarbaeva, 1973

Baseline	**100 km**	**1000 km**	**10^4 km**	**10^5 km**	**10^6 km**	**10^7 km**	**10^8 km**
Facility	MERLIN	EVN *WE*	EVN	R-Astron	L2	-	~1 AU
λ = 3 cm	2 AU	200 AU	0.1 pc	10 pc	1 kpc	100 kpc	10 Mpc
λ= 30 cm	3x10^7km	20 AU	2x10^3AU	1 pc	100 pc	10 kpc	1 Mpc

Astrometry of extragalactic pulsars?