Radio interferometry in astronomy: a view into the XXI century

Lecture 4

Space frontier of VLBI

Leonid Gurvits

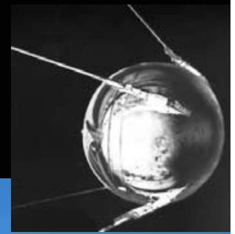
JOINT INSTITUTE FOR VLBI IN EUROPE

Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands

Delft University of Technology, Faculty of Aerospace Engineering, The Netherlands

Space exploration & radio astronomy: 52 years together

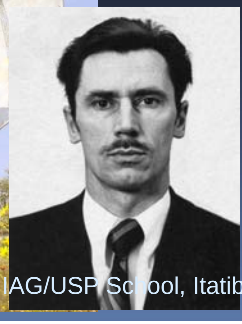
- Glorious start: Sputnik and 76-m Mk1 Jodrell Bank (now Lovell) telescope, 4 October 1957
- Parkes receives the first TV images of Appolo-11 on the Moon, 21 July 1969



Lovell 76 m, Jodrell Bank, UK

Parkes 70 m, NSW, Australia

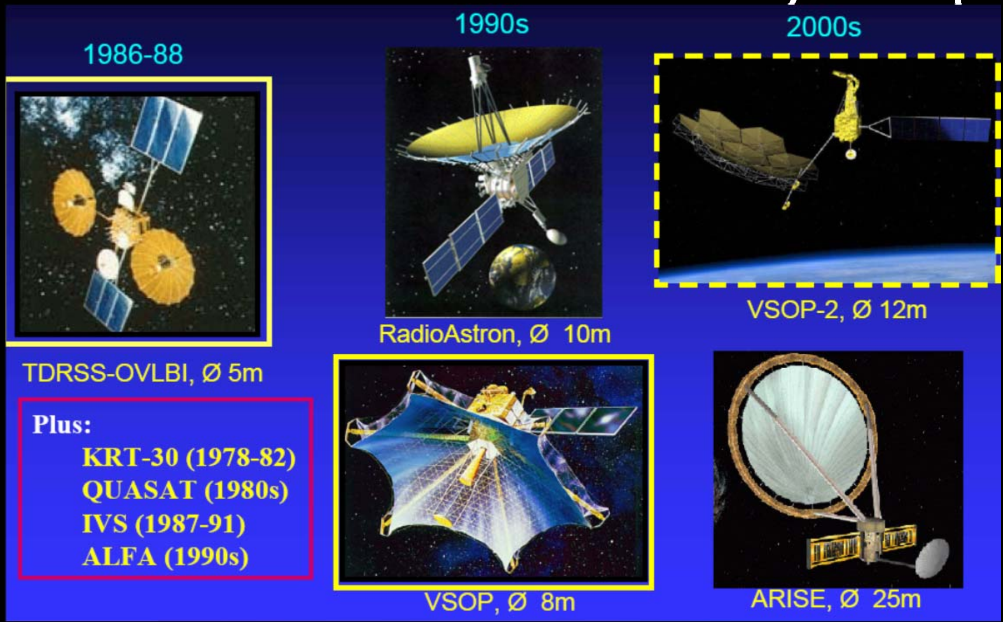
ADU-1000, Evpatoria, Ukraine

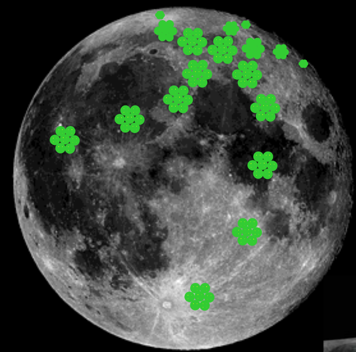


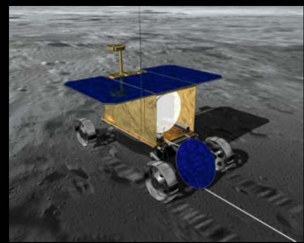
- Discovery of variability of extragalactic radio sources using deeps space communication antenna by G.B.Sholomitsky, 1965

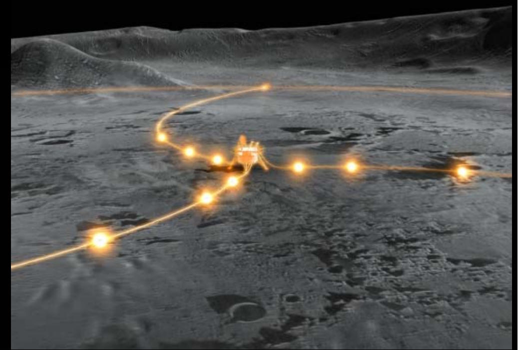
Radio interferometry and space science

- Radio interferometry in Space: Space VLBI









of

ft a

VLBI in Space

Why VLBI in Space?

- … Because THERE ARE celestial radio sources out there THAT DO NEED a sharper radio view!
- … and "we do this not because it is easy, but because it is hard…" (*J.F. Kennedy, announcing …., no, not the first Space VLBI mission, but rather the US intention to put a man on the Moon, 1961*)

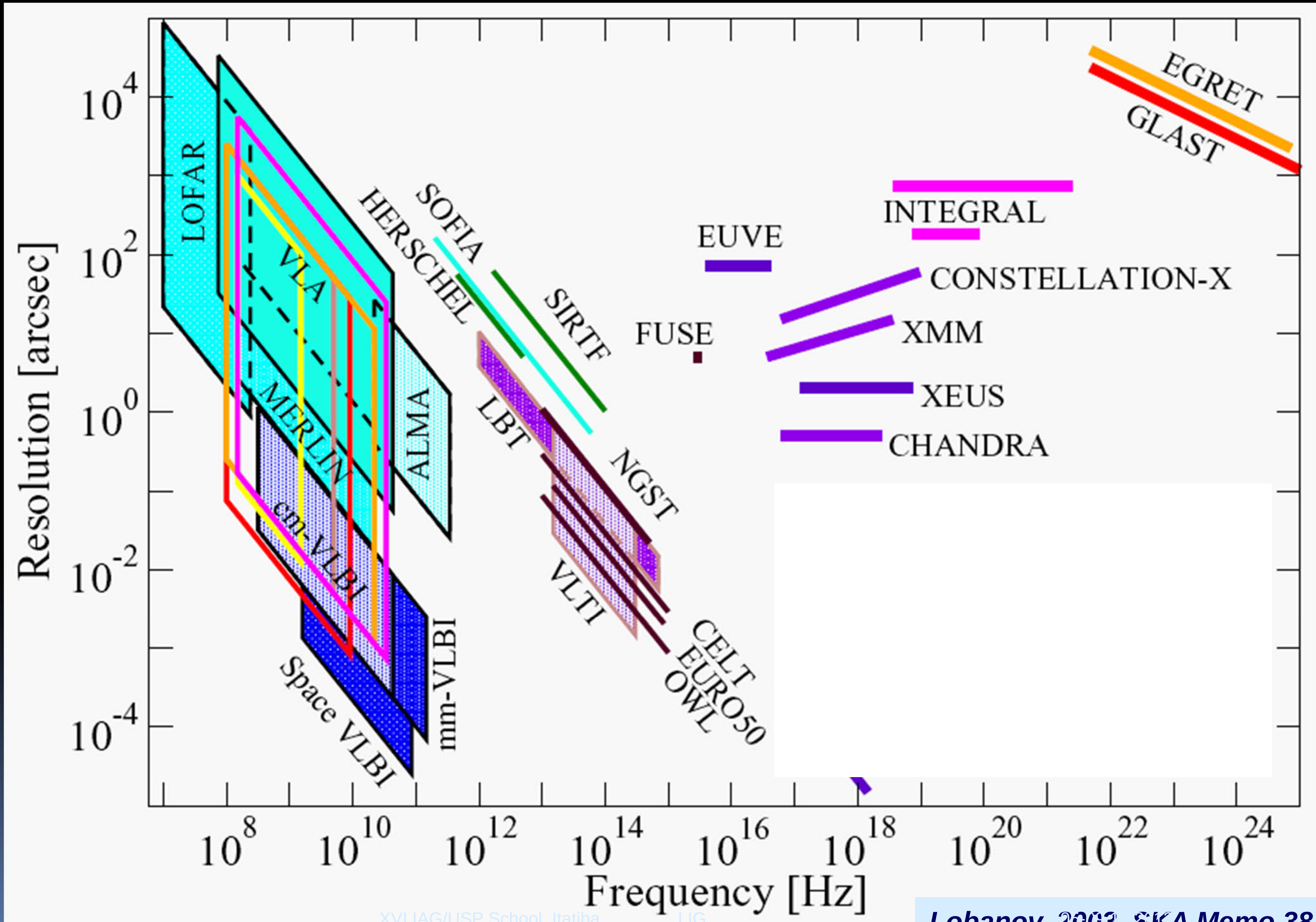
Half a century of Space VLBI

- The idea – 1963? *(Matveenko, Kardashev, Sholomitsky, 1965)*

- Evolving science case
  - Drive for extremely high resolution remains topical
  - Sociology of (Space) VLBI:
    - *~1000 professional radio astronomers in the world*
    - *~300 of them did/do VLBI*
    - *~100 of the latter ready to deal with SVLBI*
    - ***<u>Need to appeal to broad scientific community!</u>***

- Arguably, SVLBI is the most difficult space science activity...

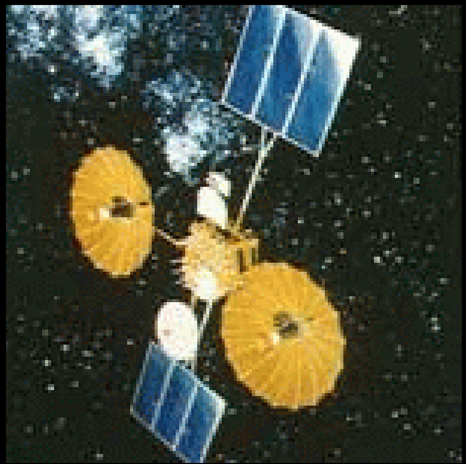
Best (imaging) angular resolution across EM spectrum



Lobanov. 2003, SKA Memo 38

Three generations of VLBI in Space

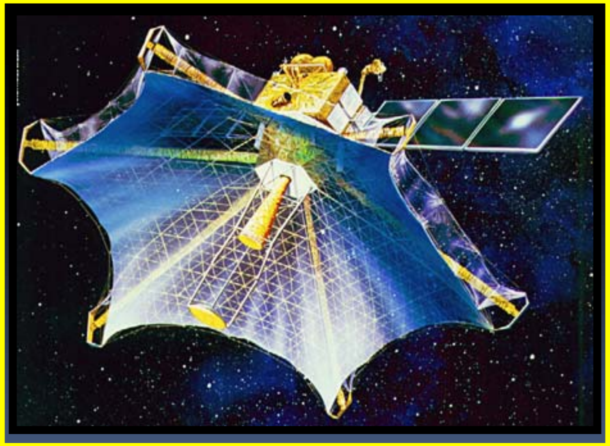
1986-88



TDRSS-OVLBI, Ø 5m

1990s

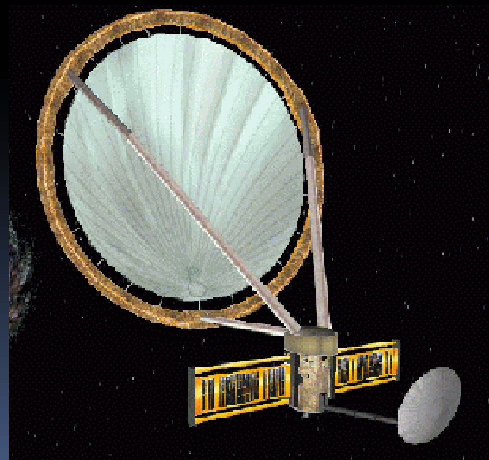
RadioAstron, Ø 10m



VSOP, Ø 8m

2000s

VSOP-2, Ø 12m

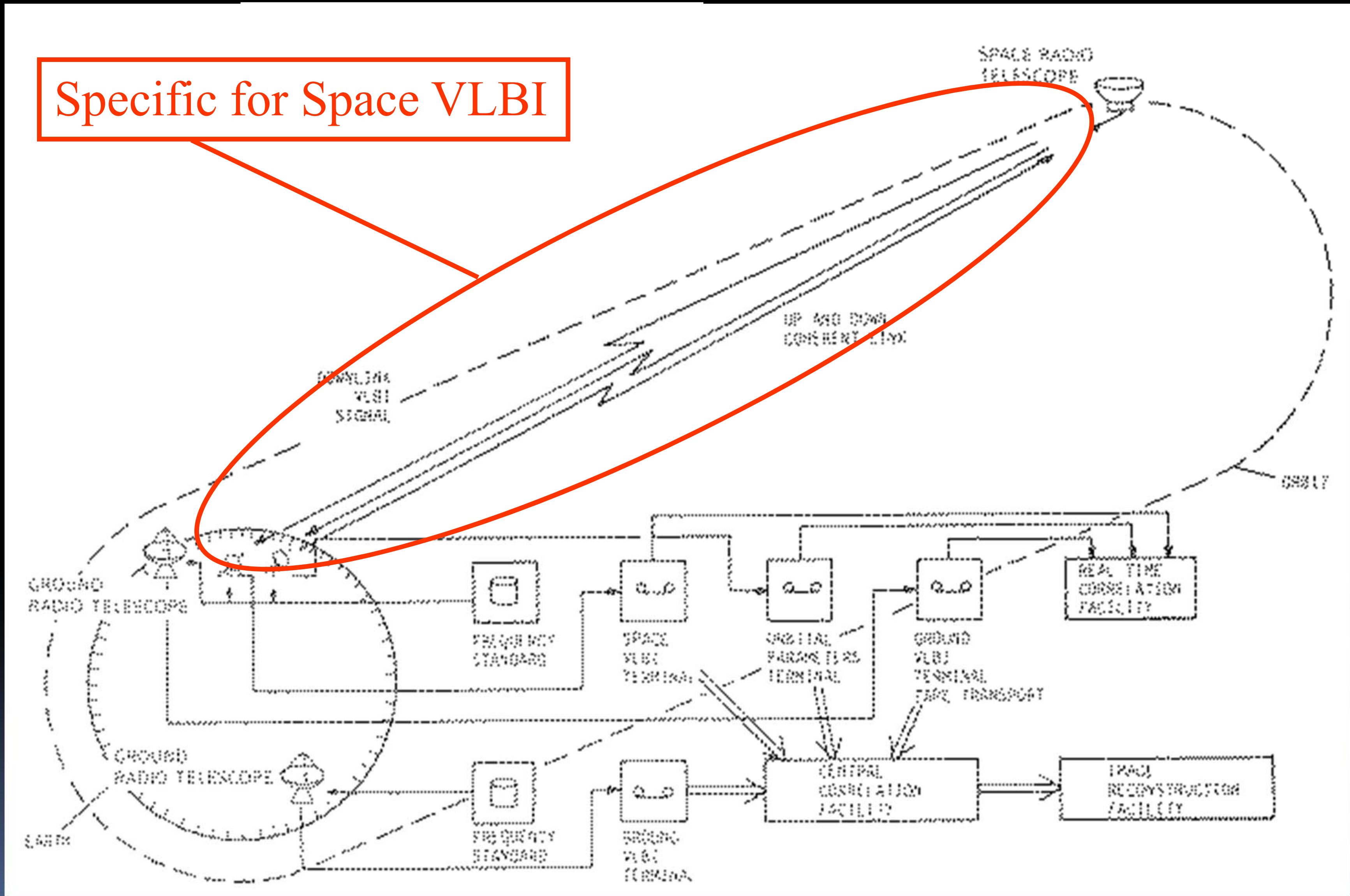


ARISE, Ø 25m

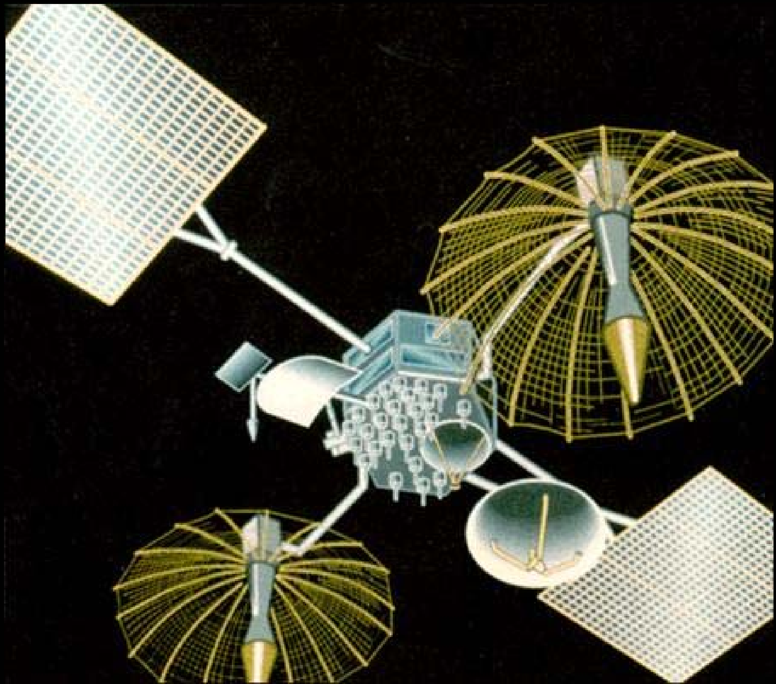
Plus:

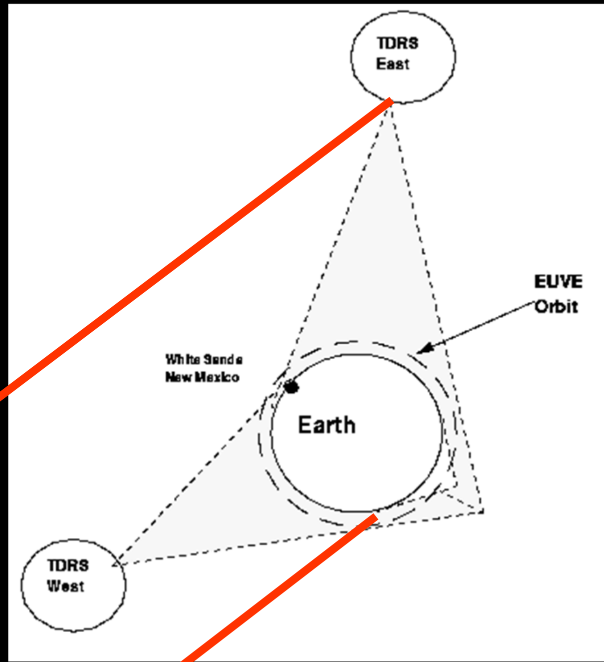
KRT-30 (1978-82)
QUASAT (1980s)
IVS (1987-91)
ALFA (1990s)

Space VLBI block-diagram



TDRSS-OVLBI: proof of SVLBI concept



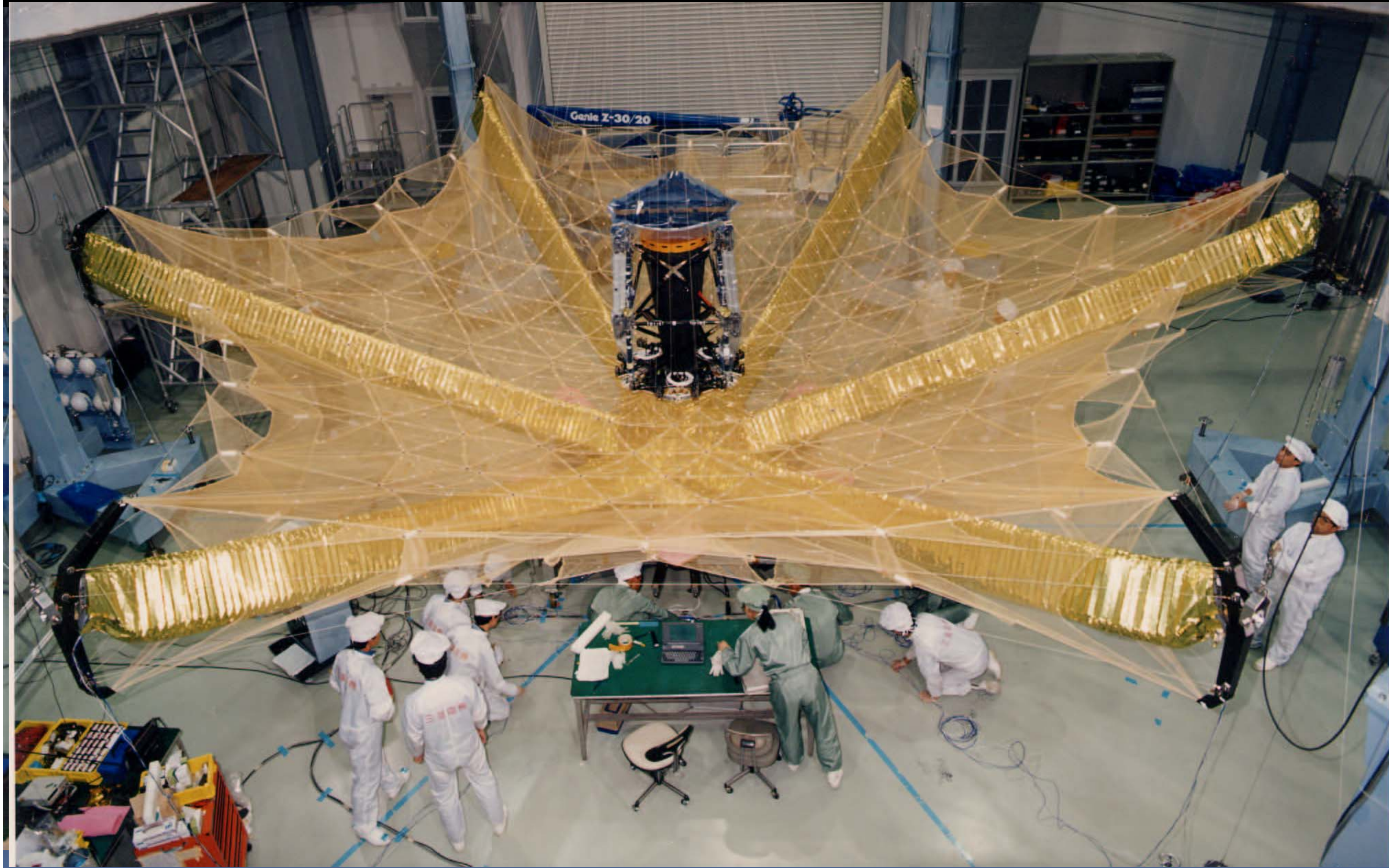


$B = 2.2 D_{Earth}$

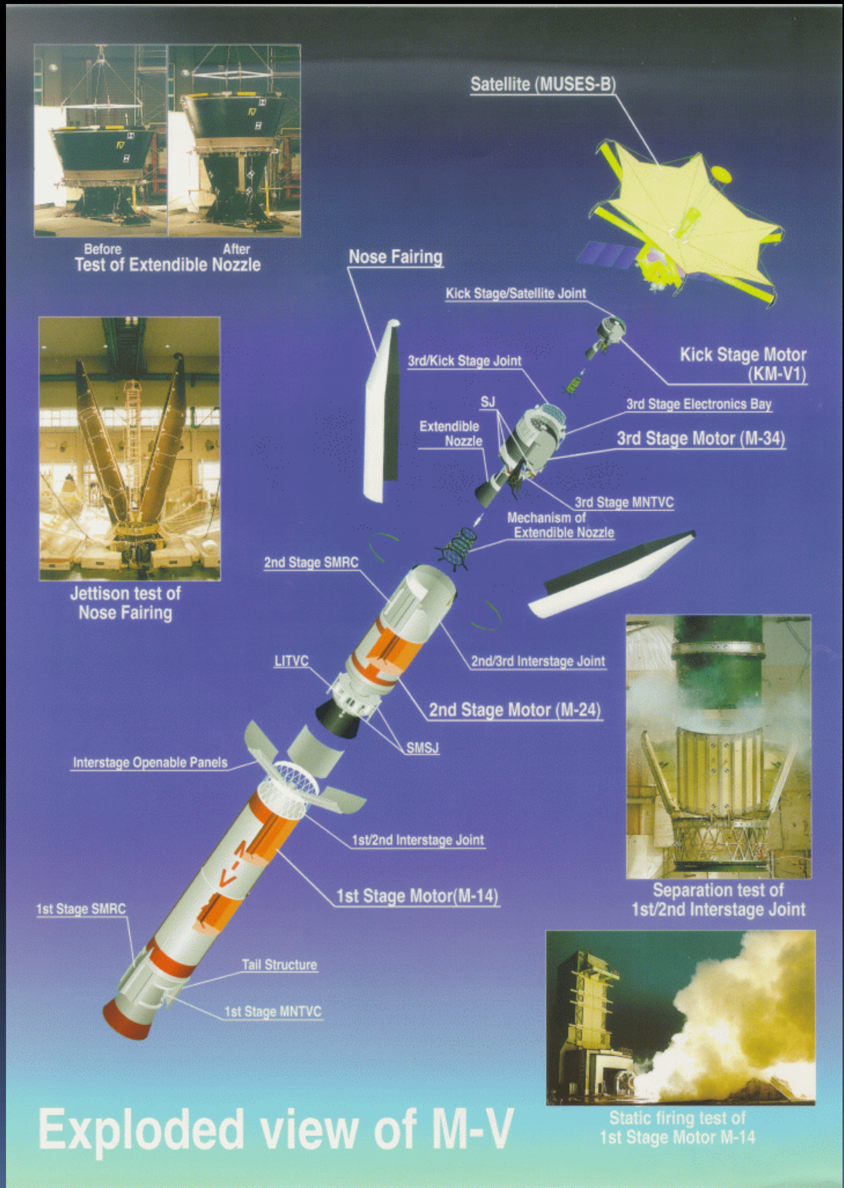
- First Space-Earth VLBI fringes in 1986
- 2.3 and 15 GHz, 3/4 ground-based telescopes, Mk3 (28 MHz /width)
- A dozen of strong quasars detected

Levy et al. 1986, Science 234, 187

VSOP/HALCA antenna deployment test



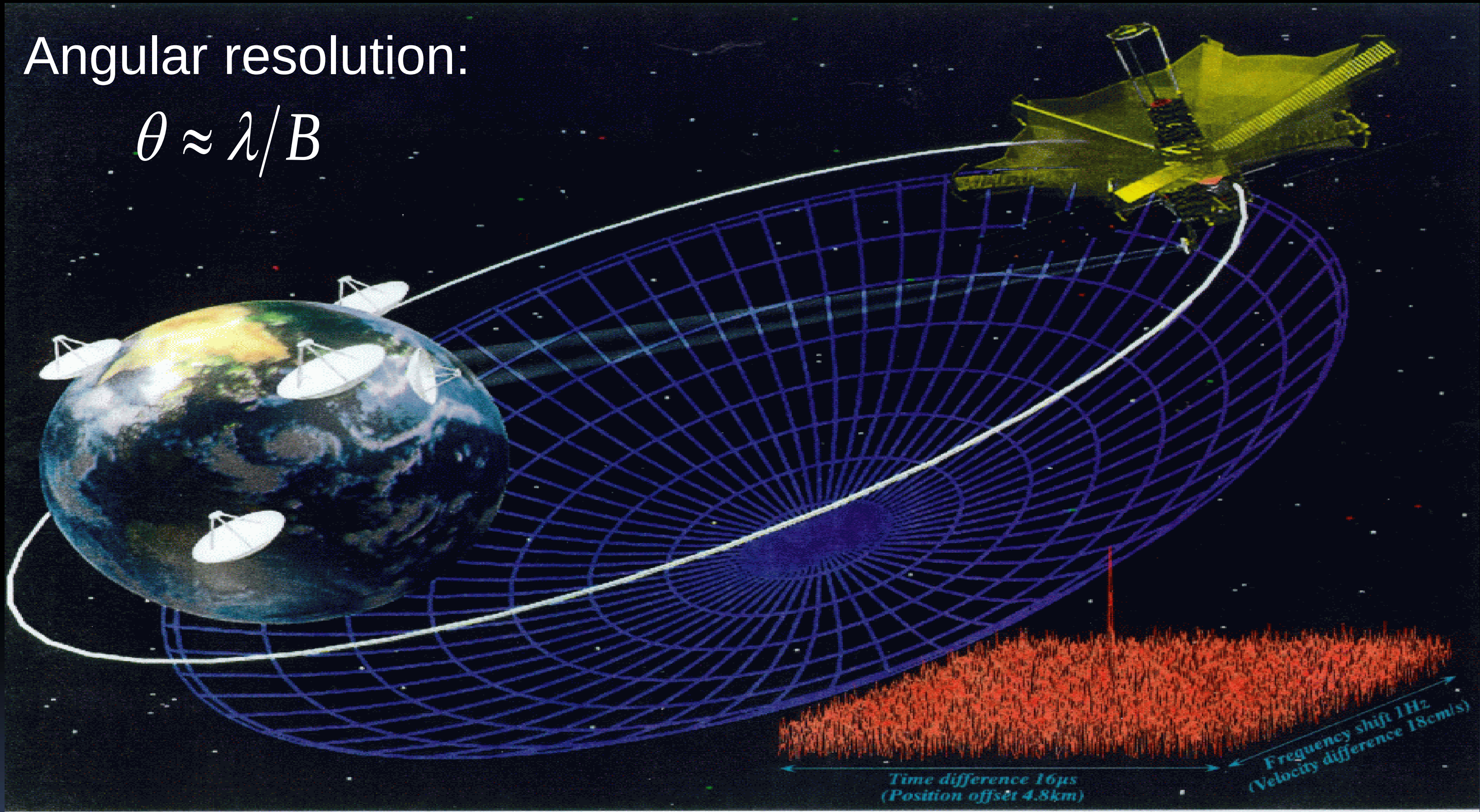
VSOP/HALCA launch 12 February 1997



VLBI beyond the Earth diameter: VSOP mission
ISAS, Japan + world-wide collaboration (1997 – 2005)

Angular resolution:

$$\theta \approx \lambda / B$$



Ground-based VLBI: $\lambda = 6\ \mathrm{cm};\ B = 10000\ \mathrm{km} \Rightarrow \theta \approx 1.5\ \mathrm{mas}$

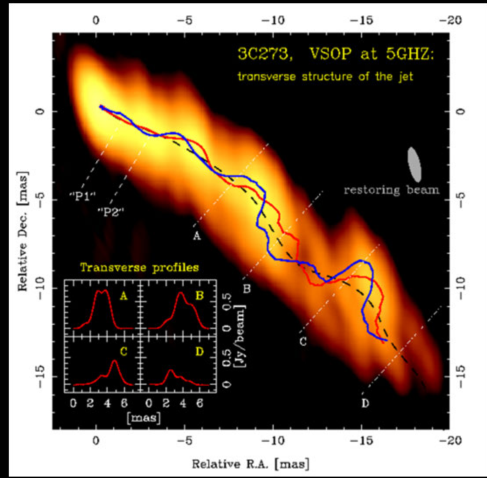
VSOP: $\lambda = 6\ \mathrm{cm};\ B = 30000\ \mathrm{km} \Rightarrow \theta \approx 0.5\ \mathrm{mas}$

1986, Rome: Space-VLBI WG formed by IACG (Inter-Agency Consultative Group of Space Science)

VSOP/HALCA mission summary

- VLBI Space Observatory Programme (VSOP, ISAS, Japan):
  - 8-m parabolic telescope on board HALCA satellite;
  - Launched on the maiden flight (!) of M-V rocket 12 Feb 1997;
  - Unified a “truly” global VLBI network of ground RT;
  - Operated at frequencies 1.6 and 5 GHz (18 and 6 cm);
  - Recording data rate 128 Mbit/s (bandwidth 32 MHz);
  - Baselines up to ~ 30,000 km (three-fold increase of angular resolution over ground-based VLBI);
  - 50% of operational time were open for the world community;
  - 25% -- VSOP Survey (led by the mission, ISAS).
- More info: http:\\www.vsop.isas.ac.jp\

VSOP mission legacy



- High quality, high resolution images of several "famous" sources (*e.g. 3C273, Lobanov & Zensus, 2001*)
- Several surprisingly compact galactic OH masers *(Slysh et al. 1999)*
- Correlation between structural and other properties of flat-spectrum AGN (*Lister et al. 2001)*
- The highest lower limit of $T_B = 5.8 \times 10^{13}$ *K (Frey et al. 2000)*
- Statistics of sub-mas structures in AGN based on the VSOP Survey *(Horiuchi et al. 2004)*

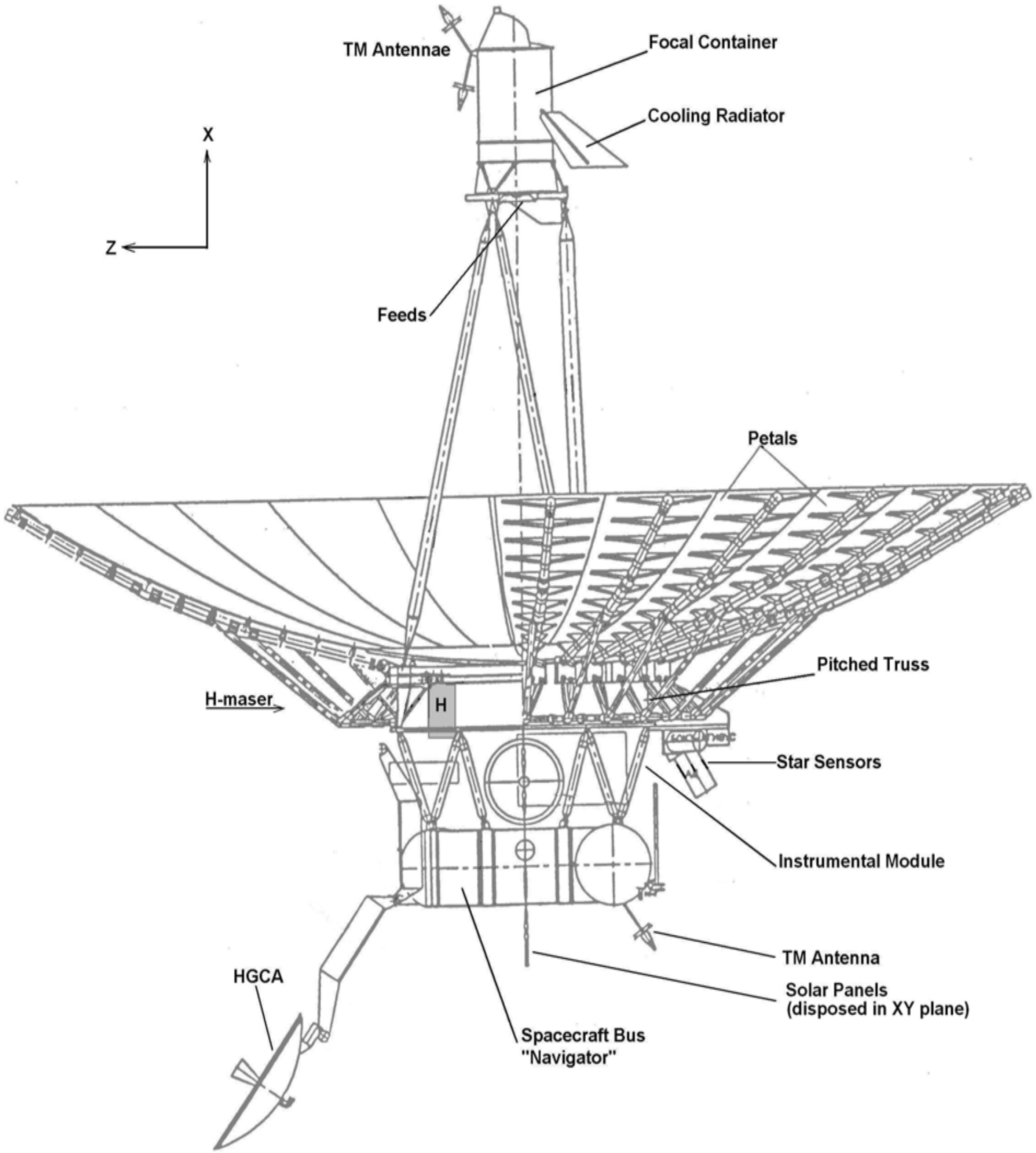
Total of ~700 observations conducted

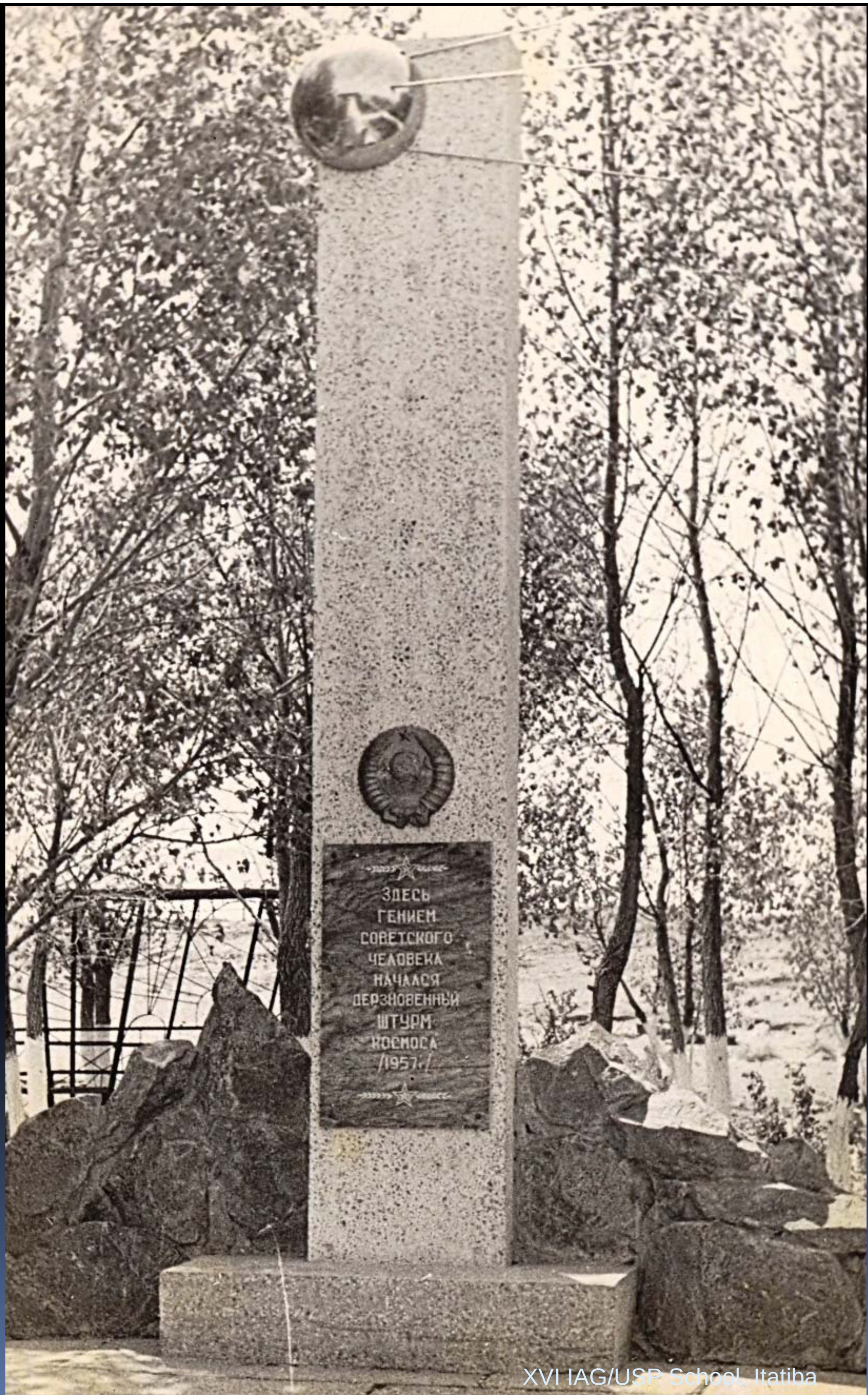
Link to results: http:\\www.vsop.isas.ac.jp

RadioAstron – Spektr-R

- 10-m antenna
- 0327, 1.6, 5 and 22 GHz
- Dual-polarization
- 128 Mbps
- 2 on-board H-masers
- Apogee (initial) – 343,000 km
- Data reception - Pushchino

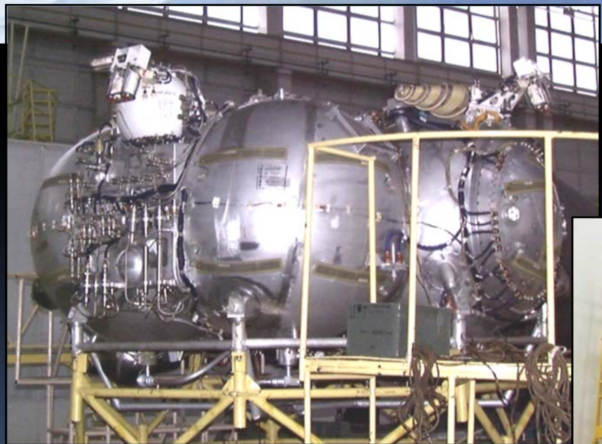
In preparation since 1978


TM Antennae
Focal Container
Cooling Radiator
X
Z
Feeds
Petals
Pitched Truss
H-maser
H
Star Sensors
Instrumental Module
TM Antenna
Solar Panels
(disposed in XY plane)
HGCA
Spacecraft Bus
"Navigator"


ЗДЕСЬ
ГЕНИЕМ
СОВЕТСКОГО
ЧЕЛОВЕКА
НАЧАЛСЯ
ДЕРЗНОВЕННЫЙ
ШТУРМ
КОСМОСА
/1957г./


СССР
ЗДЕСЬ
ГЕНИЕМ
СОВЕТСКОГО
ЧЕЛОВЕКА
НАЧАЛСЯ
ДЕРЗНОВЕННЫЙ
ШТУРМ
КОСМОСА
/1957г./


"FREGAT" UPPER STAGE



"FREGAT" CHARACTERISTICS:

Altitude (m)………………. 1.5

Diameter (m)……………… 3.35

Lift-off mass (kg)……. up to 6535

Fuel mass (kg)…….. up to 5440

Fuel ………………… UDMH/N_2O_4

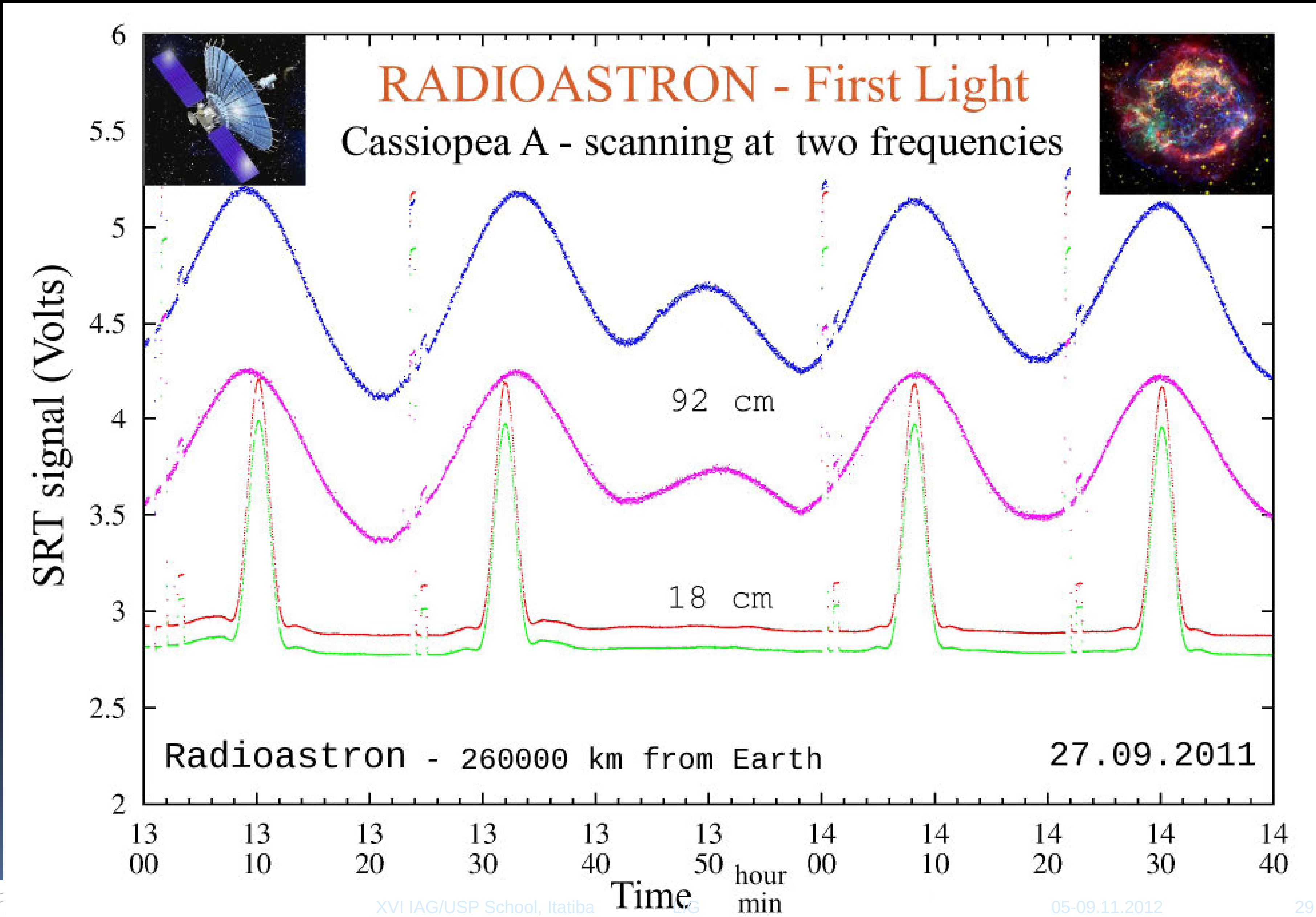
Main engine thrust (кН)…….19.6

Number of ignition……….. up to 20

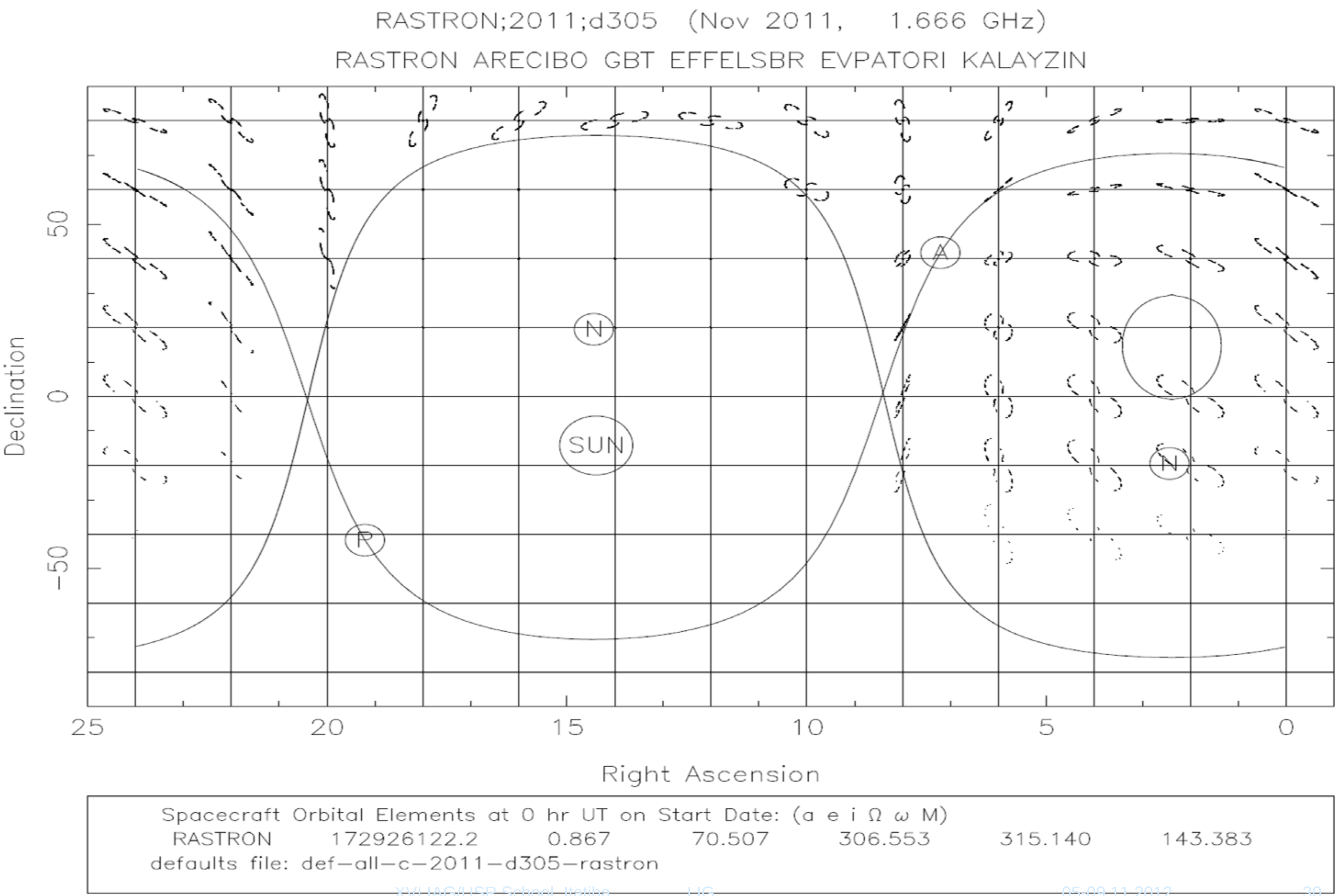
Life-time …………………… up to 48 hours

Launch vehicle…………….Soyuz
Zenit
Angara
Arian-5

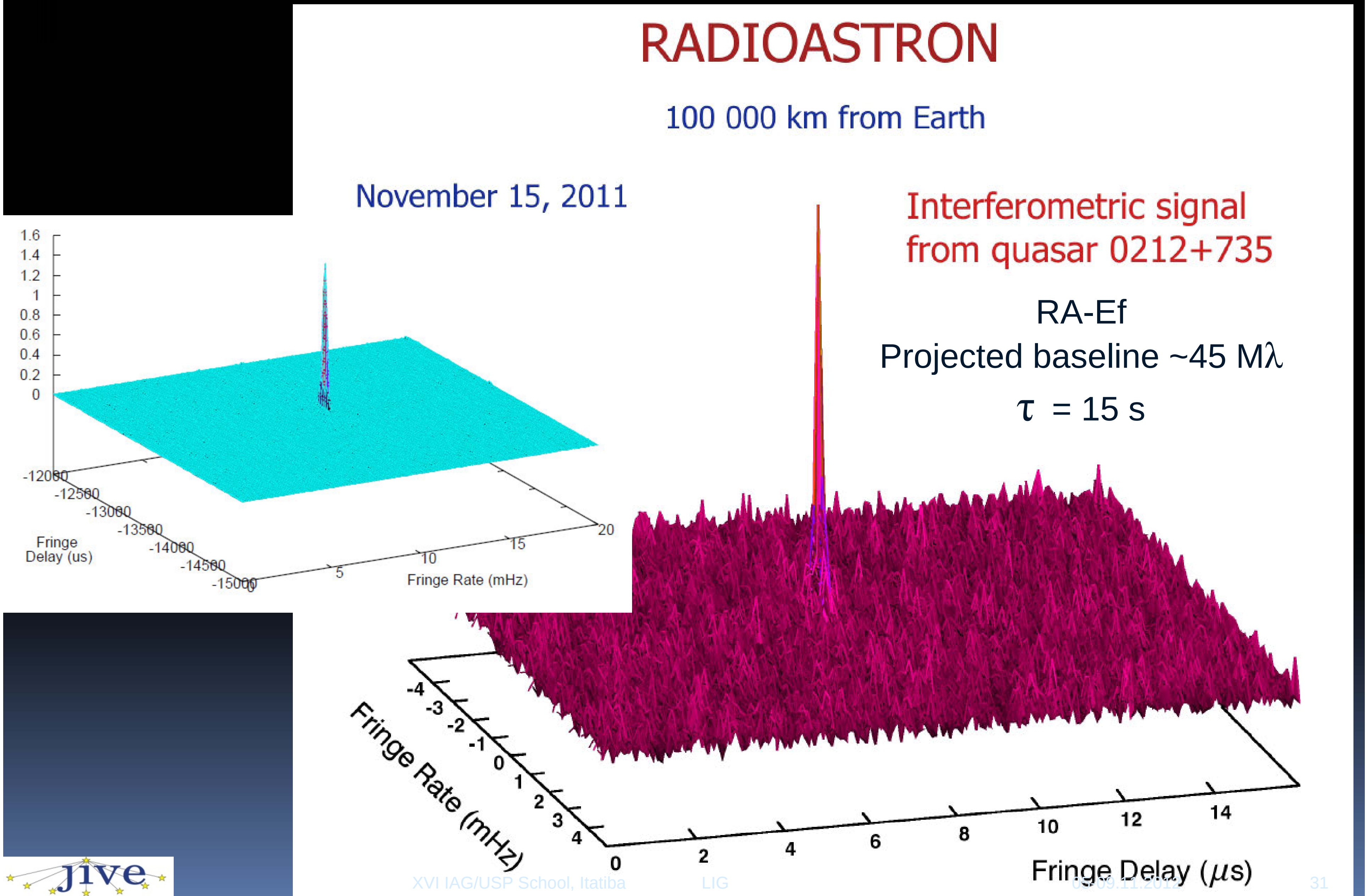
RadioAstron first noise



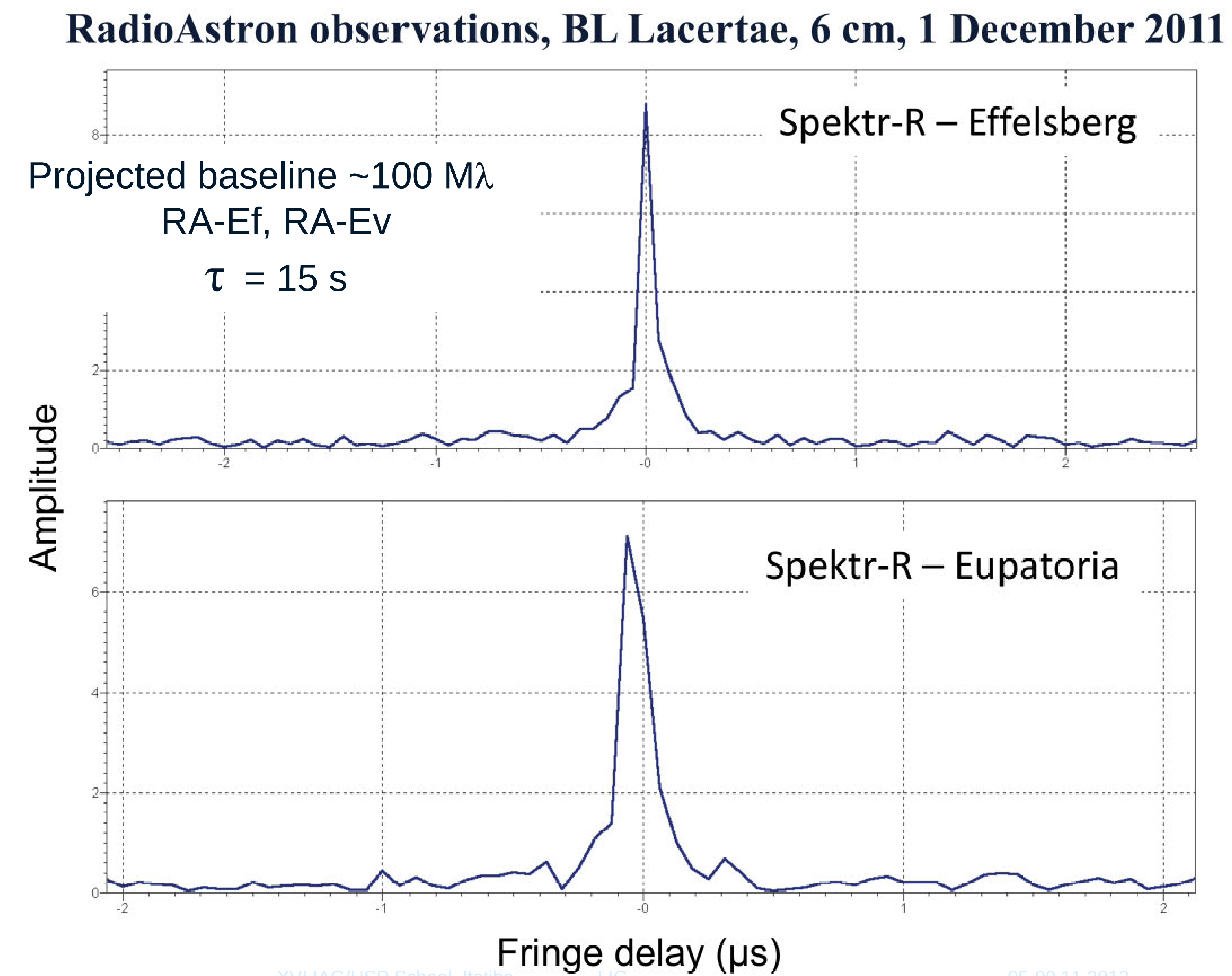
Sky coverage: pointing restrictions

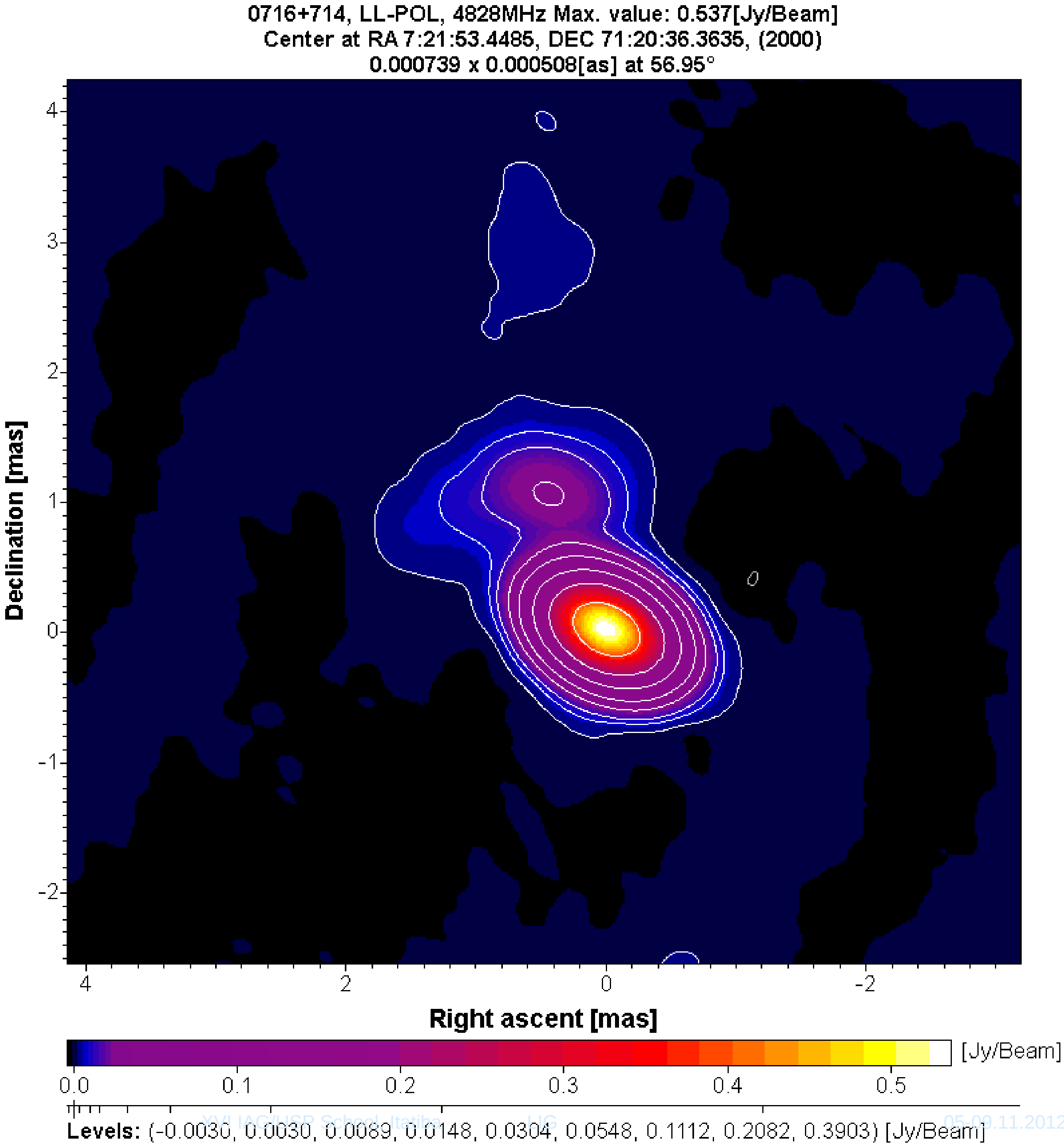


Fringes!

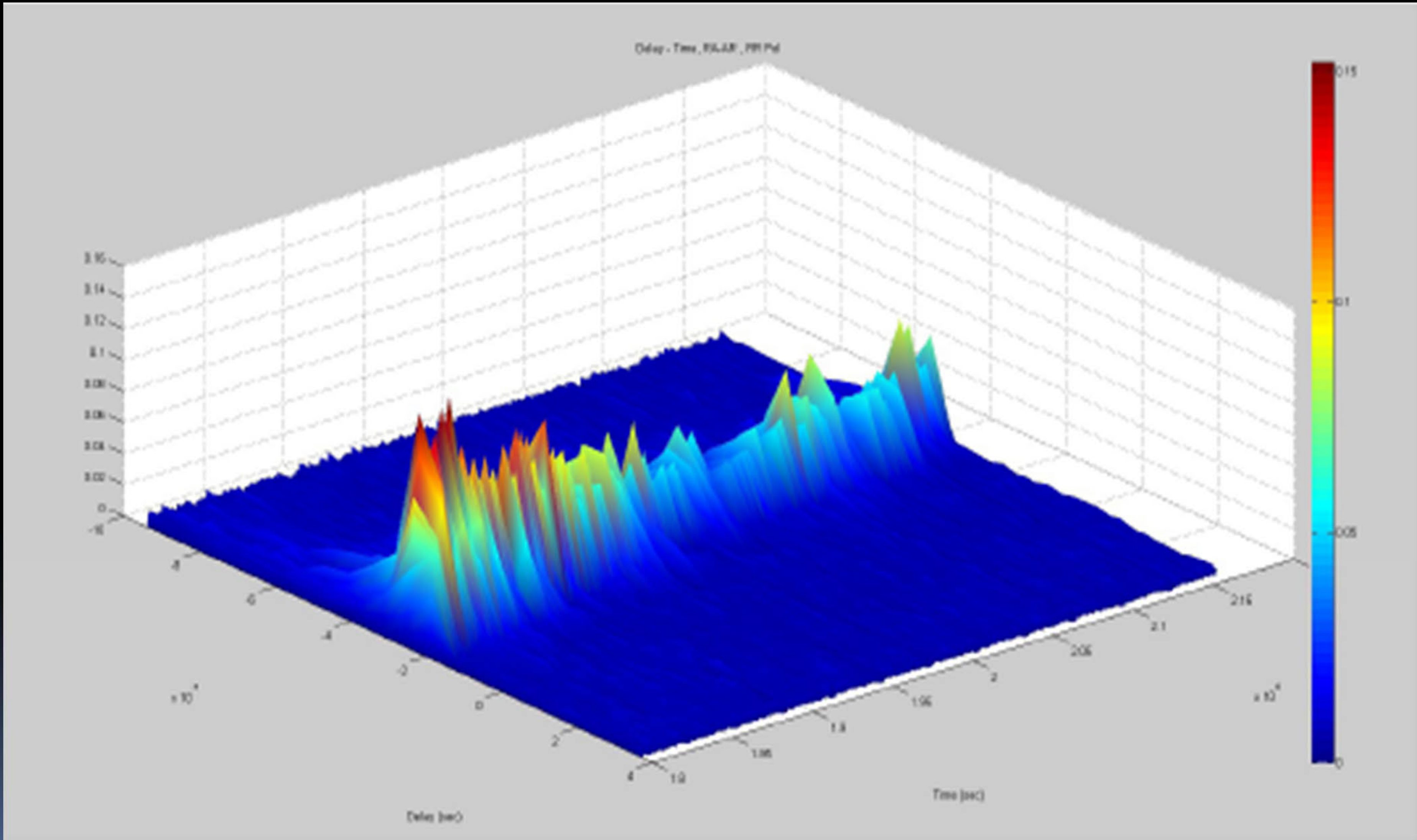

RADIOASTRON
100 000 km from Earth
November 15, 2011
Interferometric signal from quasar 0212+735
RA-Ef
Projected baseline ~45 Mλ
τ = 15 s
Fringe Delay (us)
Fringe Rate (mHz)
Fringe Rate (mHz)
Fringe Delay (μs)

First fringes at 5 GHz



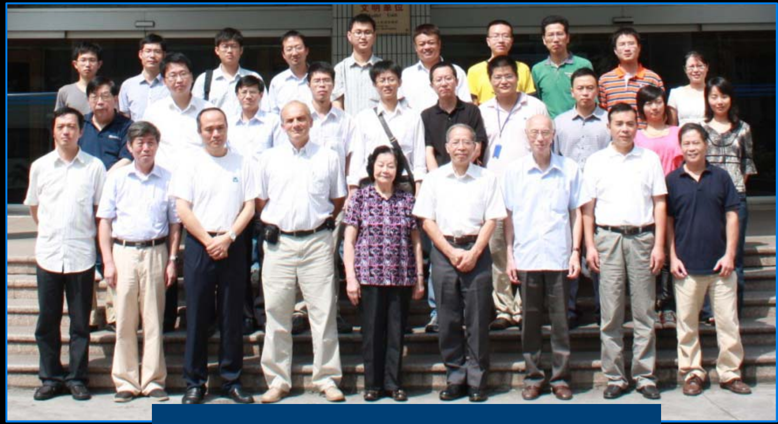

0716+714, LL-POL, 4828MHz Max. value: 0.537[Jy/Beam]
Center at RA 7:21:53.4485, DEC 71:20:36.3635, (2000)
0.000739 x 0.000508[as] at 56.95°
Declination [mas]
Right ascent [mas]
[Jy/Beam]
0.0
0.1
0.2
0.3
0.4
0.5
Levels: (-0.0030, 0.0030, 0.0089, 0.0148, 0.0304, 0.0548, 0.1112, 0.2082, 0.3903) [Jy/Beam]

PSR0950+08, 92 cm, RA-Ar, 25.01.2012



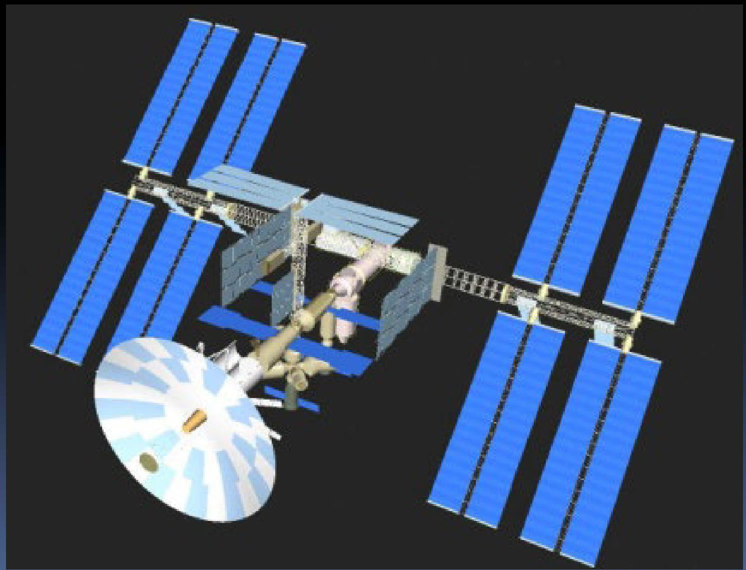
Н.С. Кардашев[1], В.В. Хартов[2], В.В. Абрамов[3], В.Ю. Авдеев[1], А.В. Алакоз[1], Ю.А. Александров[1],
С. Анантакришнан[4], В.В. Андреянов[1], А.С. Андрианов[1], Н.М. Антонов[1], М.И. Артюхов[2],
В. Баан[5], Н.Г. Бабакин[1], В.Е. Бабышкин[2], К.Г. Белоусов[1], А.А. Беляев[6], Б.Ф. Бёрк[7],
А.В. Бирюков[1], А.Е. Бубнов[8], М.С. Бургин[1], Дж. Буска[9], А.А. Быкадоров[10], В.С. Бычкова[1],
В.И. Васильков[1], К. Веллингтон[11], И.С. Виноградов[1], П.А. Войцик[1], А.С. Гвамичава[1],
И.А. Гирин[1], Л.И. Гурвиц[5], Р.Д. Дагкесаманский[1], Л. Д'Аддарио[13], Г. Джиованини[14],
Д. Джонси[11], А.А. Дьяков[15], Р. Екерс[11], В.Е. Жаров[16], В.И. Журавлёв[1], Г.С. Заславский[17],
М.В. Захваткин[17], А.Н. Зиновьев[1], А.В. Ипатов[15], Б.З. Каневский[1], И.А. Кнорин[1],
К.И. Келлерманн[18], Ю.А. Ковалев[1], Ю.Ю. Ковалев[1], А.В. Коваленко[1], Б.Л. Коган[19],
Р.В. Комаев [2], А.А. Коноваленко[20], Г.Д. Копелянский[1], Ю.А. Корнеев[1], В.И. Костенко[1],
Б.Б. Крейсман[1], А.Ю. Кукушкин[8], В.Ф. Кулишенко[20], А.М. Кутькин[1], В.Х. Кэннон[21],
М.Г. Ларионов[1], М.М. Лисаков[1], Л.Н. Литвиненко[20], С.Ф. Лихачев[1], Л.Н. Лихачева[1],
А.П. Лобанов[12], С.В. Логвиненко[1], Г. Лэнгстон[18], С.Ю. Медведев[6], М.В. Мелёхин[2], Д. Мерфи[13],
Т.А. Мизякина[1], Н.Я. Николаев[1], Б.С. Новиков[1,8], И.Д. Новиков[1], В.В. Орешко[1],
Ю.К. Павленко[6], И.Н. Пащенко[1], Ю.Н. Пономарёв[1], М.В. Попов[1], А. Правин-Кумар[4],
Р. Престон[13], В.Н. Пышнов[1], И.А. Рахимов[15], В.М. Рожков[22], Дж.Д. Ромни[18], П. Роша[9],
В.А. Рудаков[1], А. Рэйзенен[23], С.В. Сазанков[1], Б.А. Сахаров[6], С.К. Семенов[2],
В.А. Серебренников[2], Р.Т. Скилици[5], Д.П. Скулачев[8], В.И. Слыш[1], А.И. Смирнов[1],
Дж. Смит[13], В.А. Согласнов[1], К.В. Соколовский[1], Л. Сондаар[5], В.А. Степаньянц[17],
М.С. Турыгин[3], С.Ю. Турыгин[3], А.Г. Тучин[17], С. Урпо[23], С.Д. Федорчук[1],
А.М. Финкельштейн[15], Э.Б. Фомалонт[18], И. Фэйеш[24], А.Н. Фомина[25], Ю.Б. Хапин[8],
Г.С. Царевский[1], Дж.А. Цэнзус[12], А.А. Чуприков[1], М.В. Шацкая[1], Н.Я. Шапировская[1],
А.И. Шейхет[2], А.Е. Ширшаков[2], А. Шмидт[12], Л.А. Шнырева[1], В.В. Шпилевский[15],
В.Е. Якимов[1]

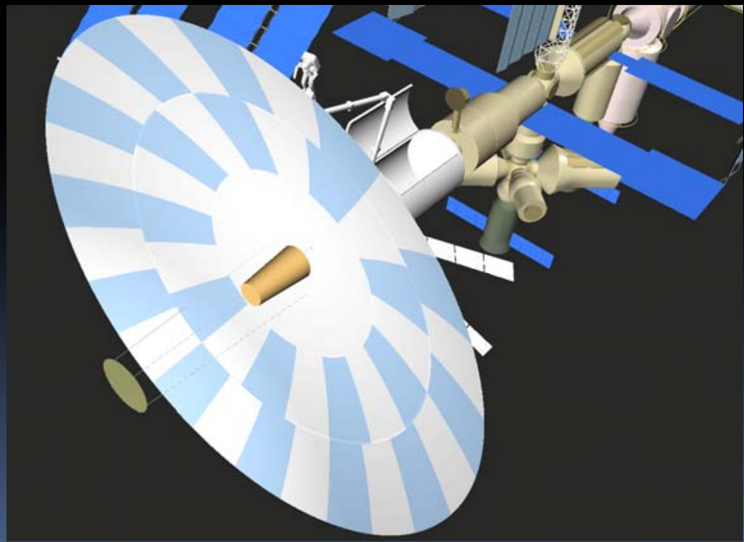
SVLBI beyond RadioAstron



Shanghai, 2011.09.13

- New Space VLBI initiatives
  - *Chinese SVLBI project under consideration*
  - *New "old" ideas in Europe (wrt the ISS beyond 2020)*





Second generation SVLBI: ideas

- Smaller high-frequency antenna
- On-board recording (buffering) of data
- Data to Earth through the same antenna (a-la Cassini)

  or

- Large lower frequency antenna assembled in low orbit
- Low-thrust placement onto the operational orbit

  or/and

- Ultra-long-wavelength astronomy (ULWA) facility
  - *Free-flyers (OLFAR)*
  - *Moon-based*

- **Ad-hoc brain-storming meeting during IAU GA 2012**

Spacecraft as a VLBI target

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

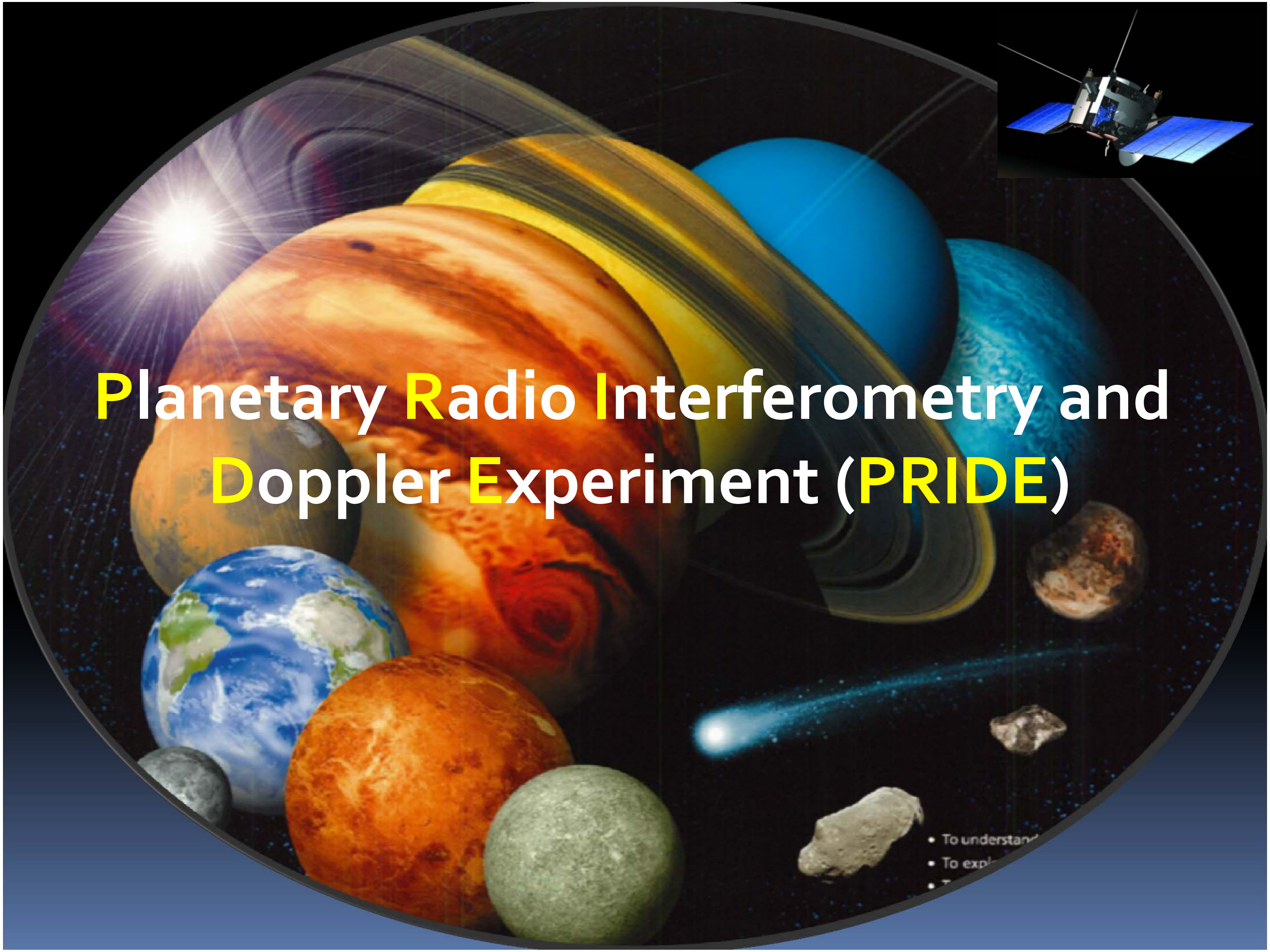
Flux density ≈ 0.5 mJy=$0.5 \cdot 10^{-29}$ $Wm^{-2}Hz^{-1}$

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

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

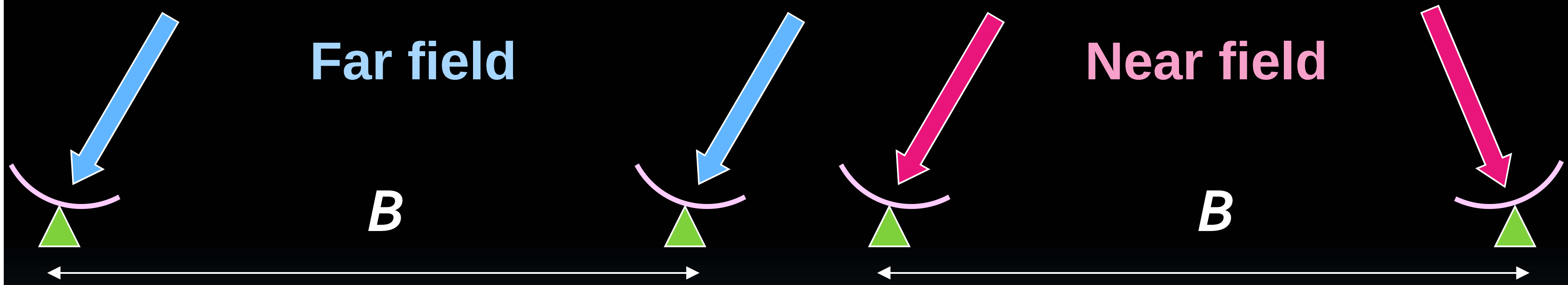
- Estimates of state-vectors of spacecraft:
  - Need for "higher-than-standard" accuracy in special cases
    - *Geodynamics and planetology*
    - *Trajectory measurements in close vicinity of Solar System bodies (e.g. landings)*
    - *Fundamental physics*
    - *Space-borne astrometry missions (e.g.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

Planetary Radio Interferometry and Doppler Experiment (PRIDE)



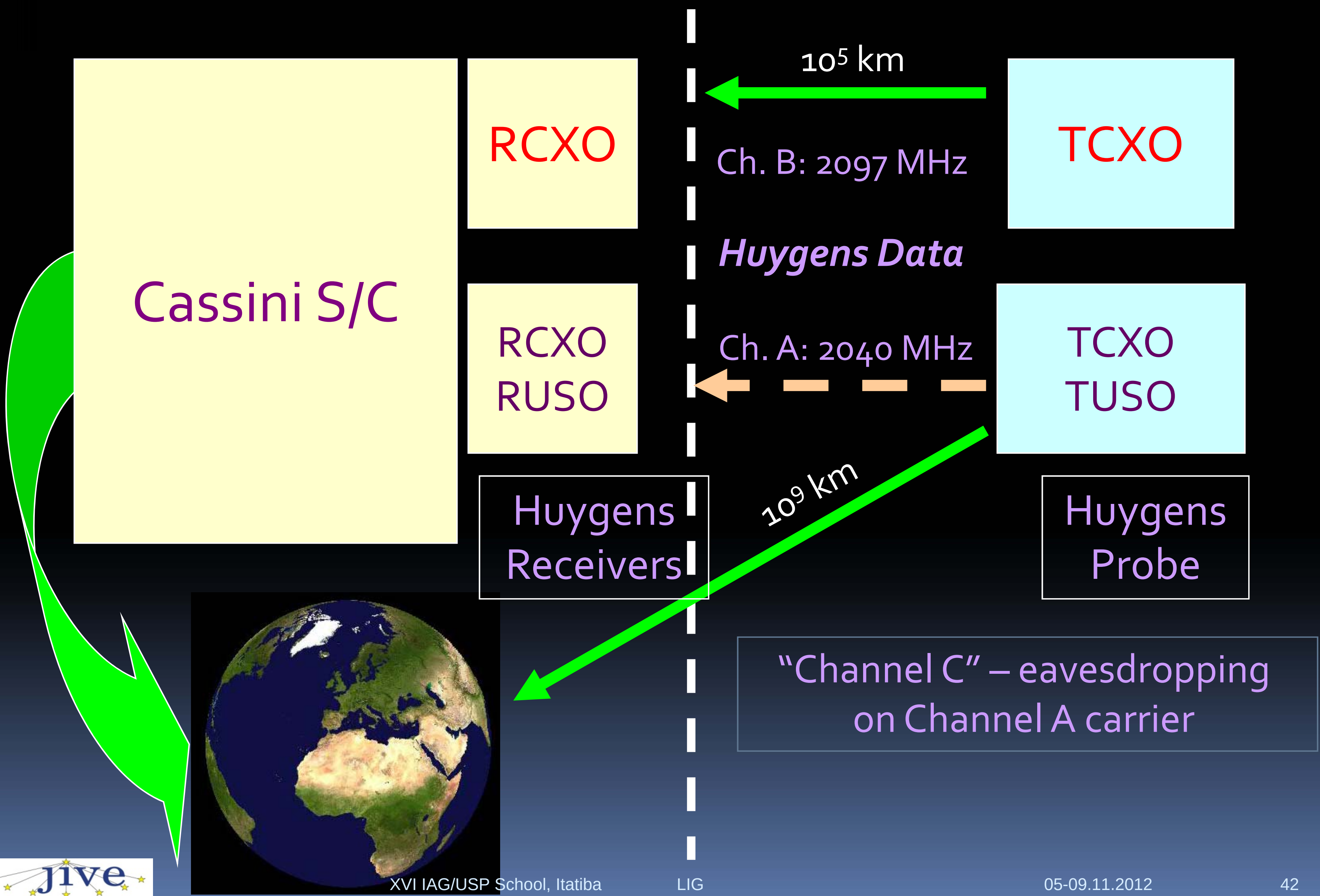
Working in the near field with PRIDE

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



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

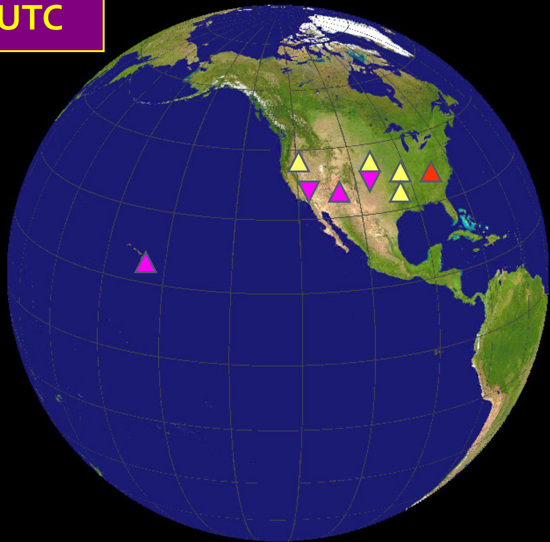
Huygens VLBI tracking: eavesdropping…

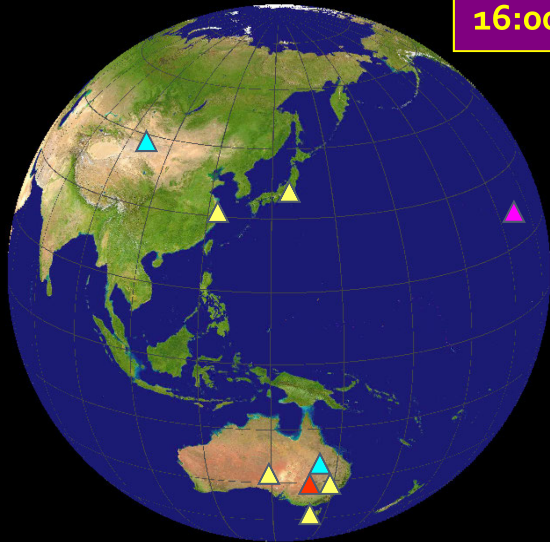


VLBI tracking of Huygens, 14 January 2005

09:30 UTC

16:00 UTC

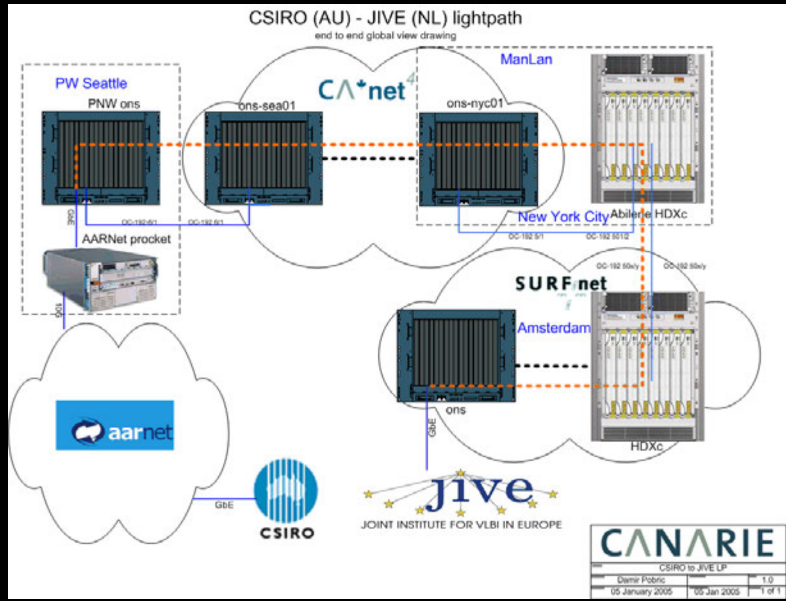


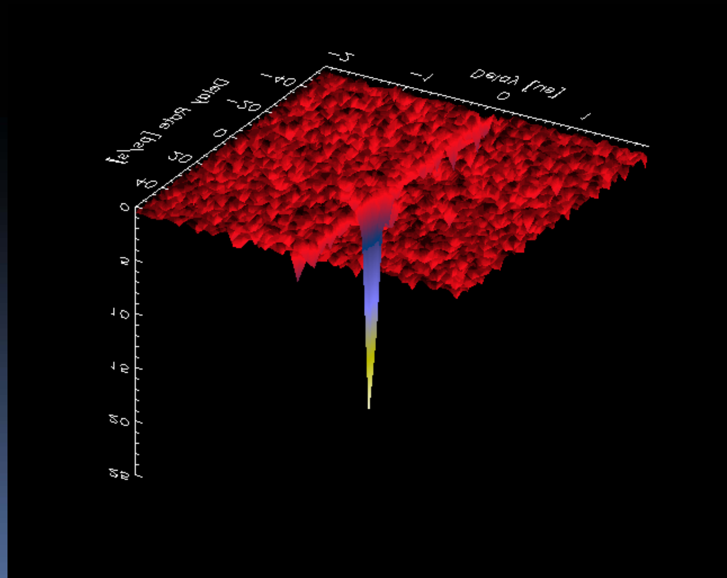


~20 radio photons per 25-m telescope per second…

e-VLBI & “Night Flight”: 14 – 15 January

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

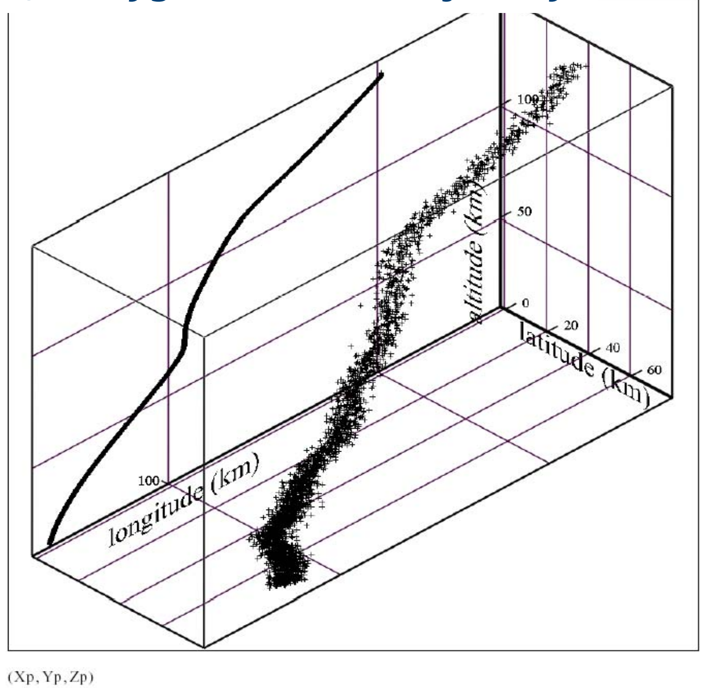


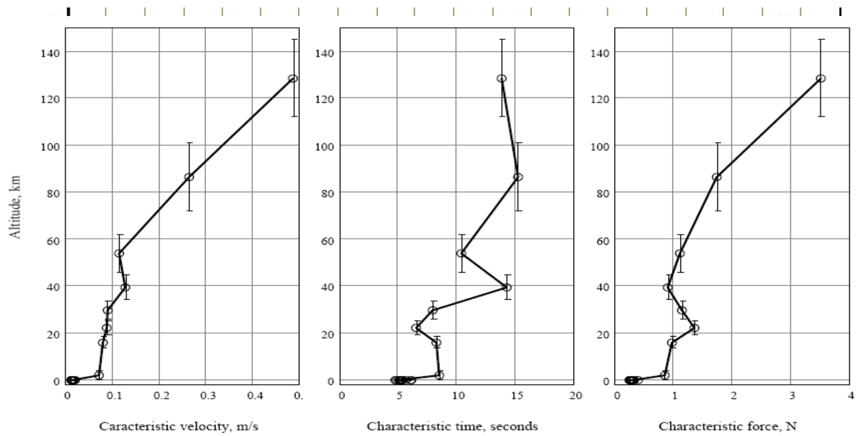


Huygens VLBI heritage: 20 photons/dish/s

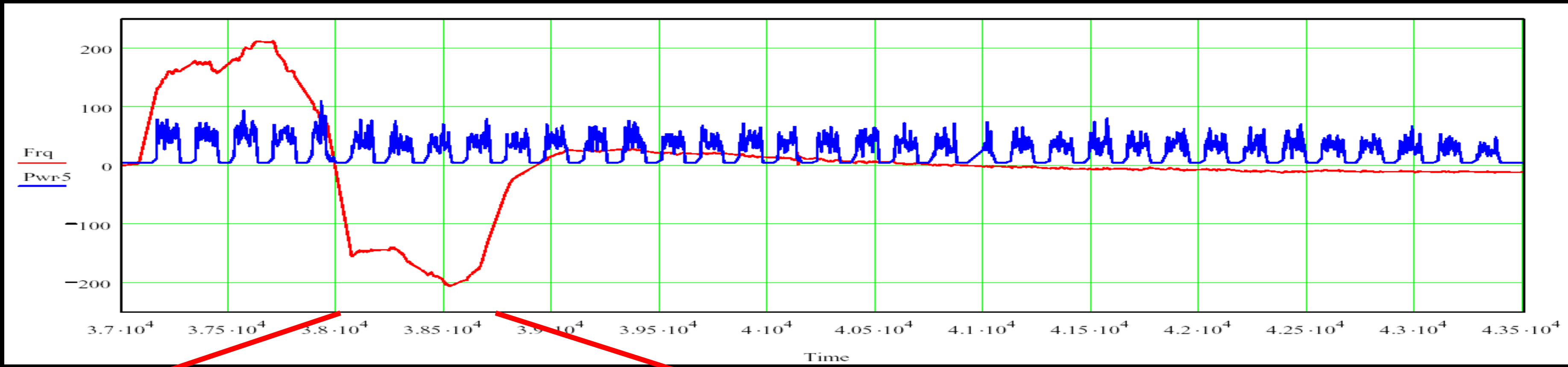
- Ad hoc use of the Huygens "uplink" carrier signal at 2040 MHz
- Utilised 17 Earth-based radio telescopes
- Non-optimal parameters of the experiment (not planned originally)
- Achieved 1 km accuracy of Probe's descent trajectory determination
- Assisted in achieving one of main science goals of the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

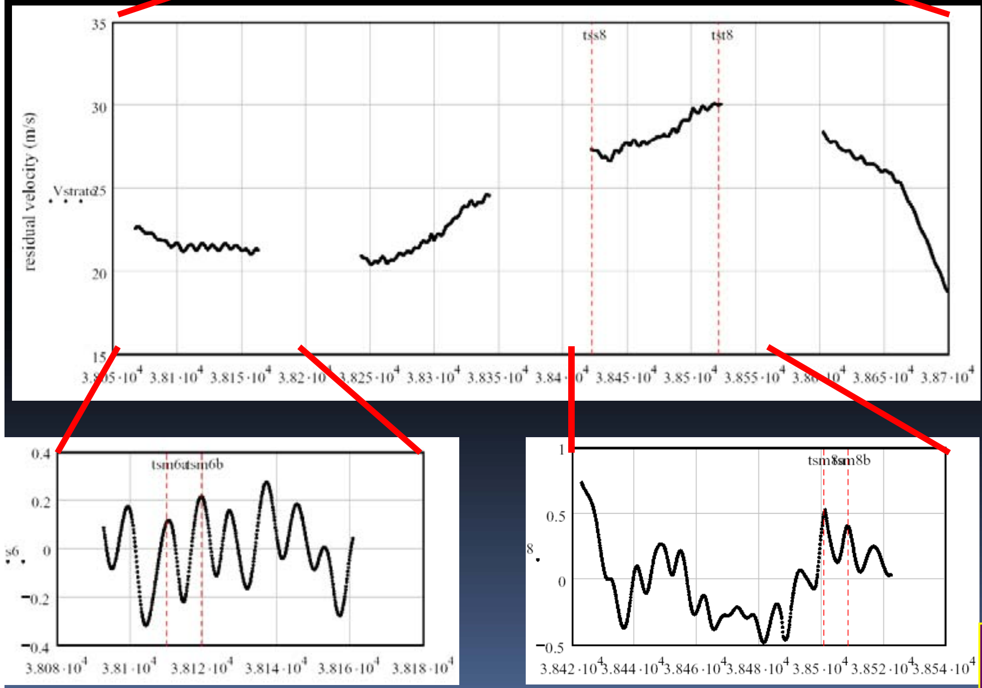
3D Huygens descent trajectory



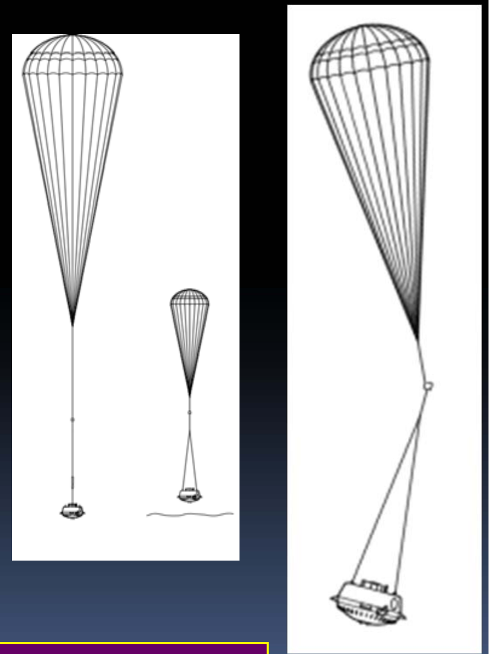


VLBI processing by-product: Doppler data (probe's motion)



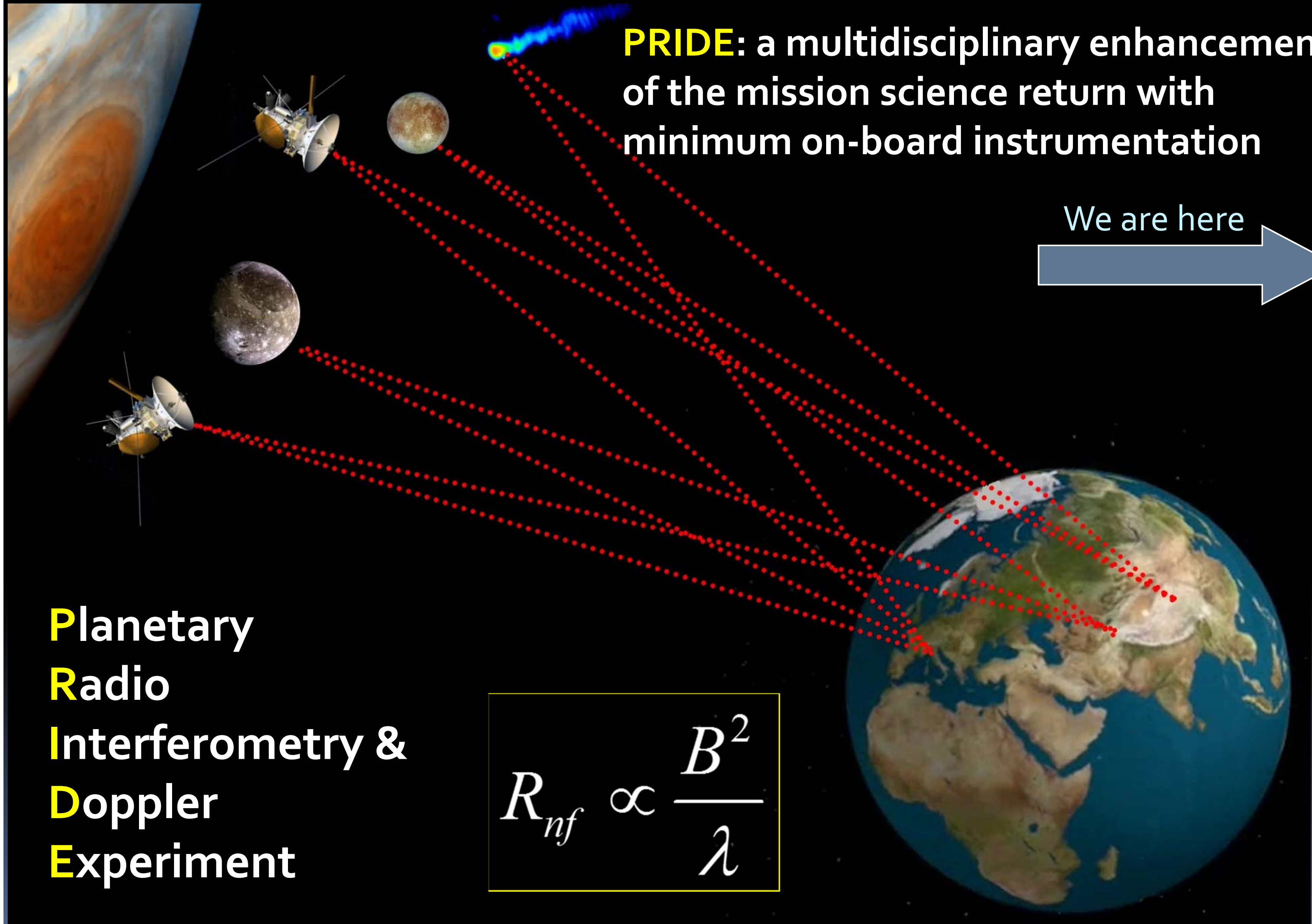


T = 8÷10 s
ΔV = 0.22 m/s
A ≈ 0.6 m



Data available for analysis!

Generic PRIDE configuration



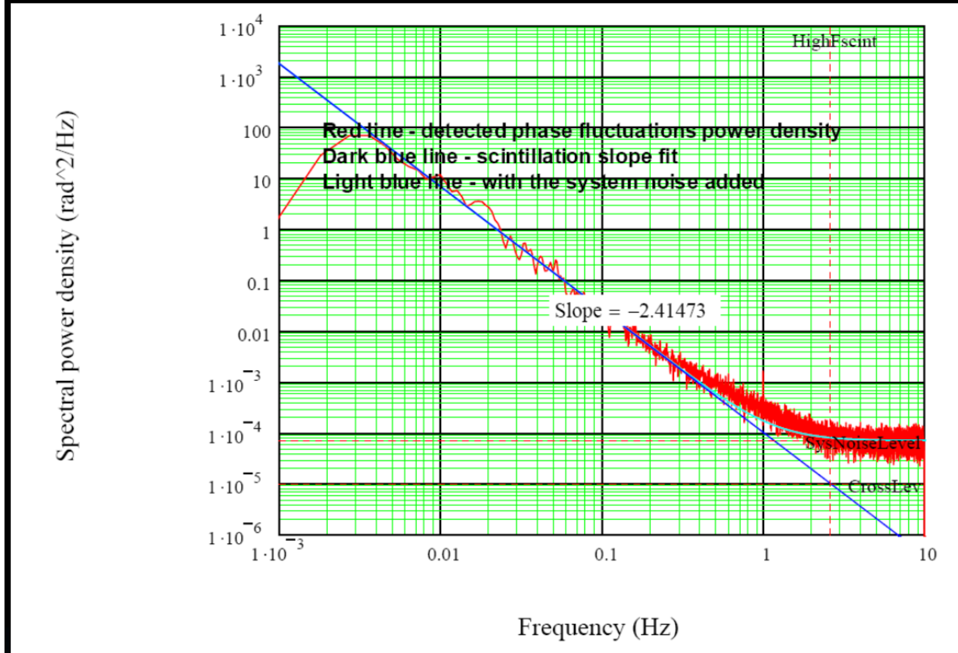
PRIDE: a multidisciplinary enhancement of the mission science return with minimum on-board instrumentation

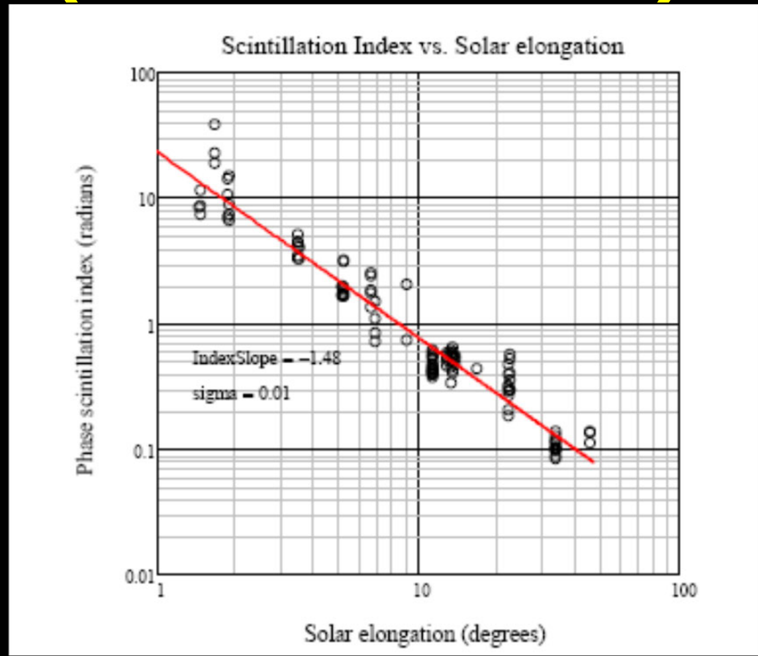
Planetary
Radio
Interferometry &
Doppler
Experiment

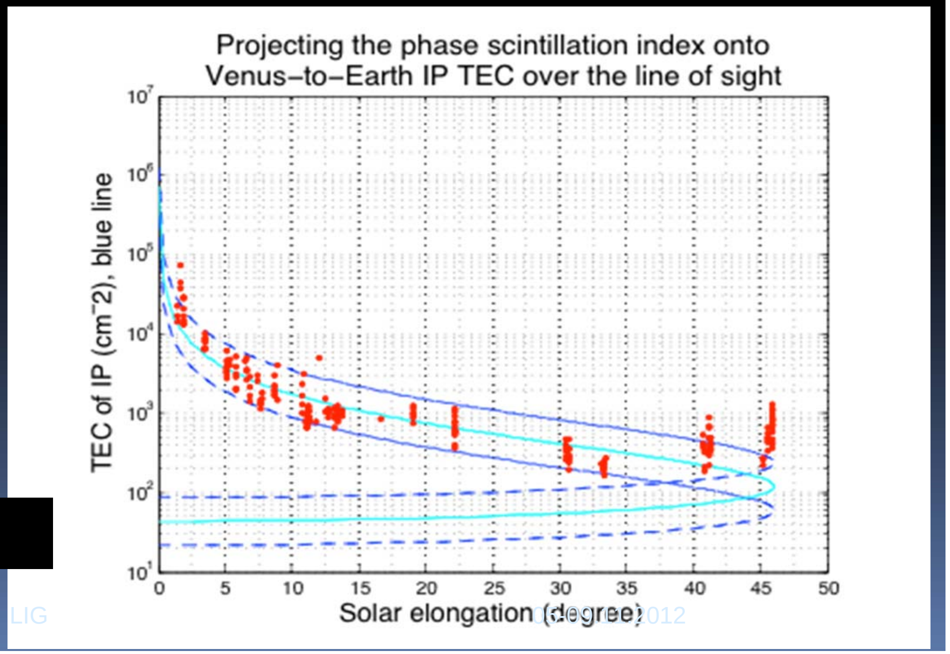
$$R_{nf} \propto \frac{B^2}{\lambda}$$

PRIDE 2010: Venus Express (results so far…)

Spectral power density of slow fluctuation phase turbulence below 10 Hz.



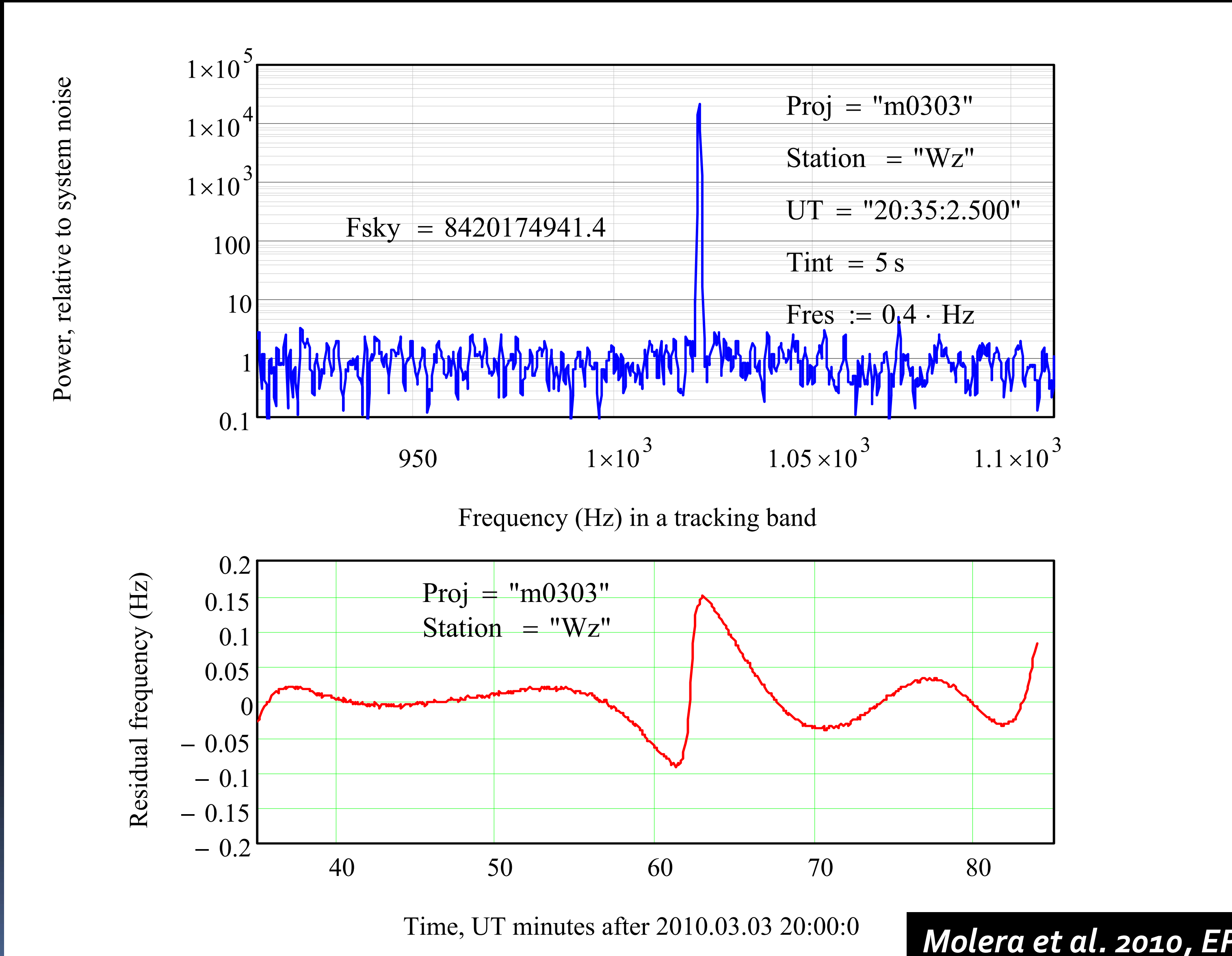




Participating VLBI stations:
Medicina, Metsahovi, Noto, Wettzell, Yebes, Pushchino

Molera et al. 2010, EPSC

MEX Phobos fly-by 2010.03.03 seen by PRIDE



Molera et al. 2010, EPSC

PRIDE-2012 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

GPS 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**

XVI IAG/USP School, Ita

ESA: Jupiter Icy Satellites Explorer (JUICE)

Progressing from exploration to characterisation of habitable worlds

JUICE Science Themes

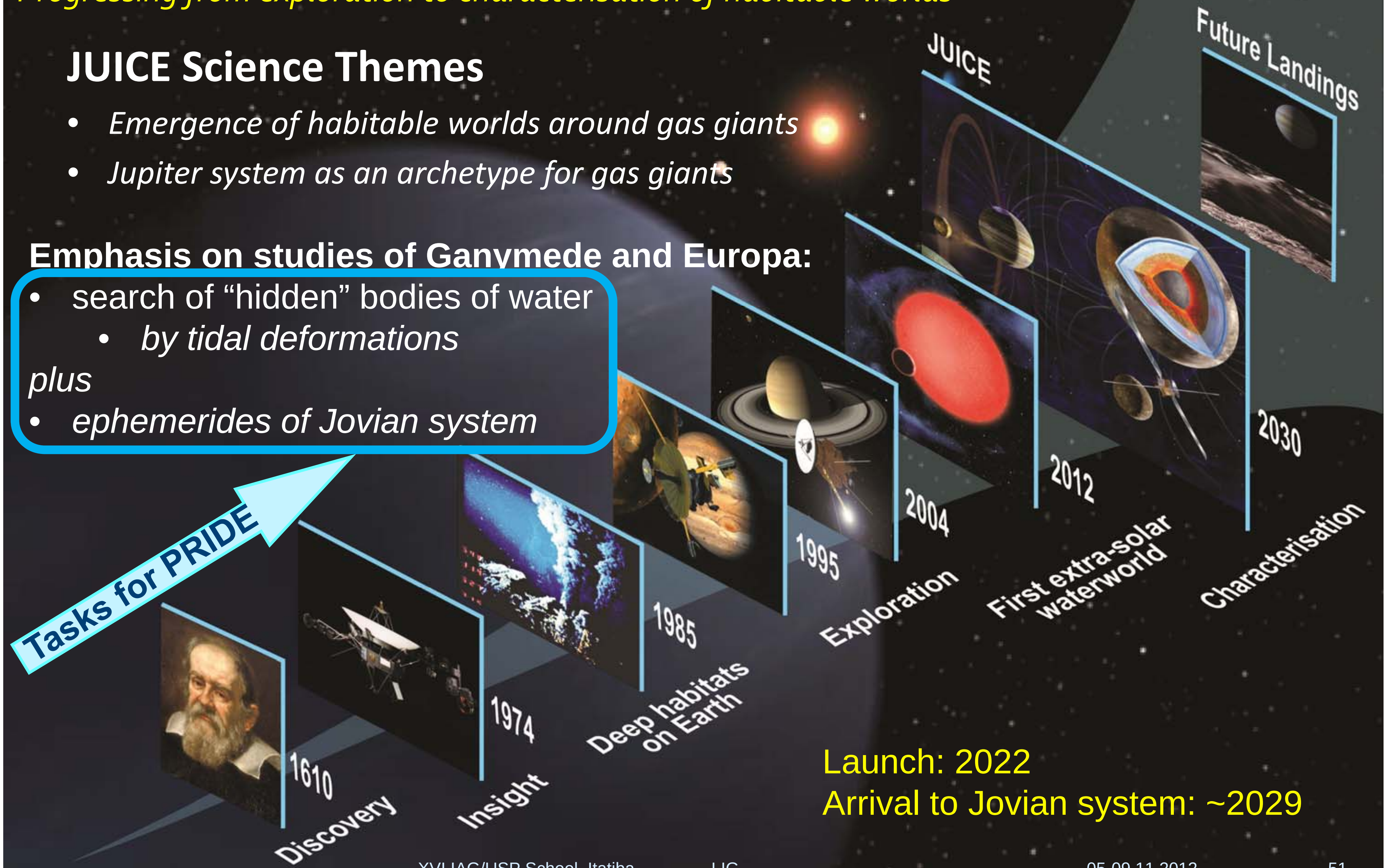
- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*

Emphasis on studies of Ganymede and Europa:

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

plus

- *ephemerides of Jovian system*



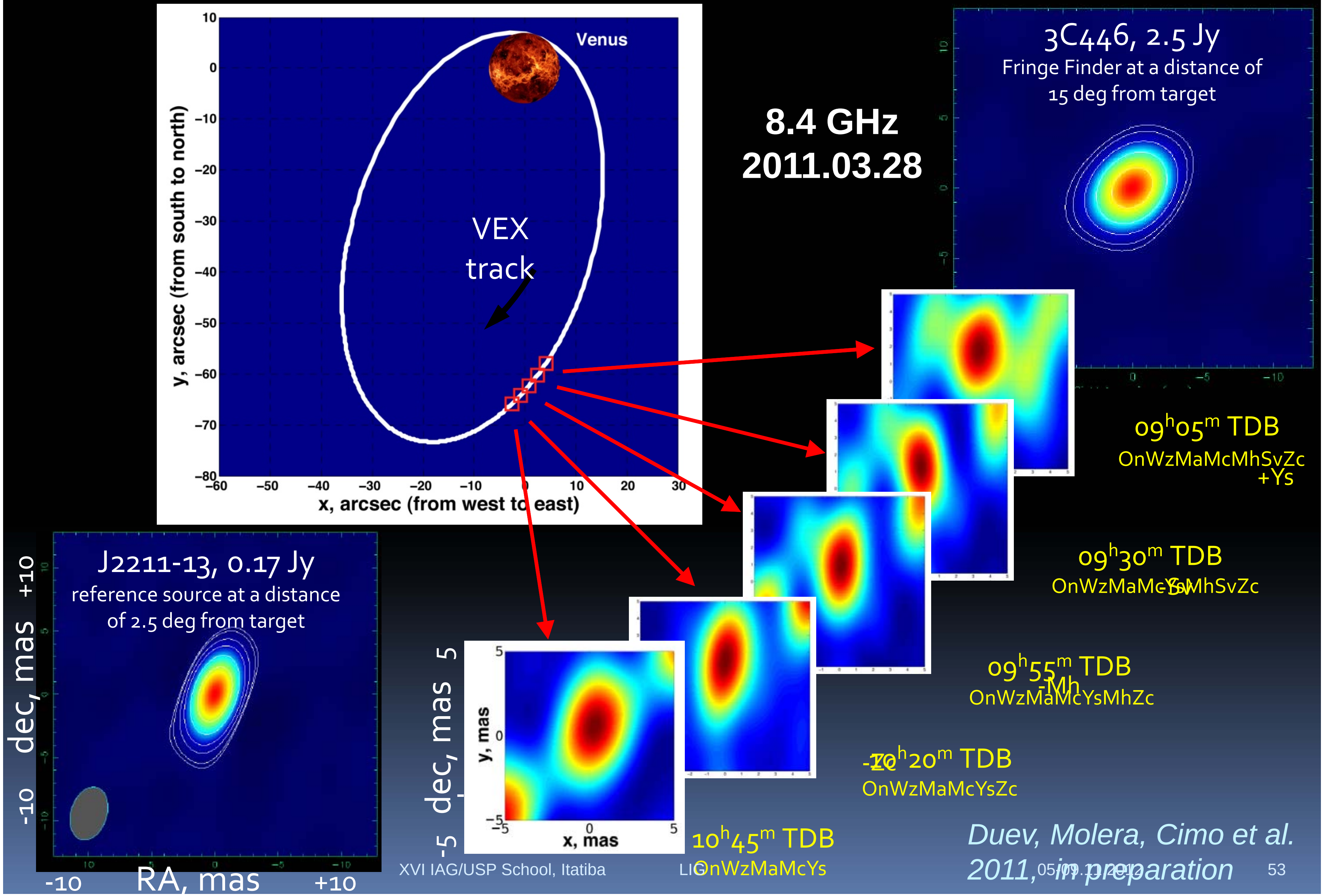
Launch: 2022
Arrival to Jovian system: ~2029

PRIDE "mission statement"

- Enhancement of science output of space missions by providing ultra-precise estimates of spacecraft state vectors in the interests of:
  - Celestial mechanics (incl. relativistic)
  - Garvimetry
  - Planetology (origins of planets)
  - Habitability and origins of life
  - Dynamics of planetary atmospheres
  - Fundamental (gravitational) physics

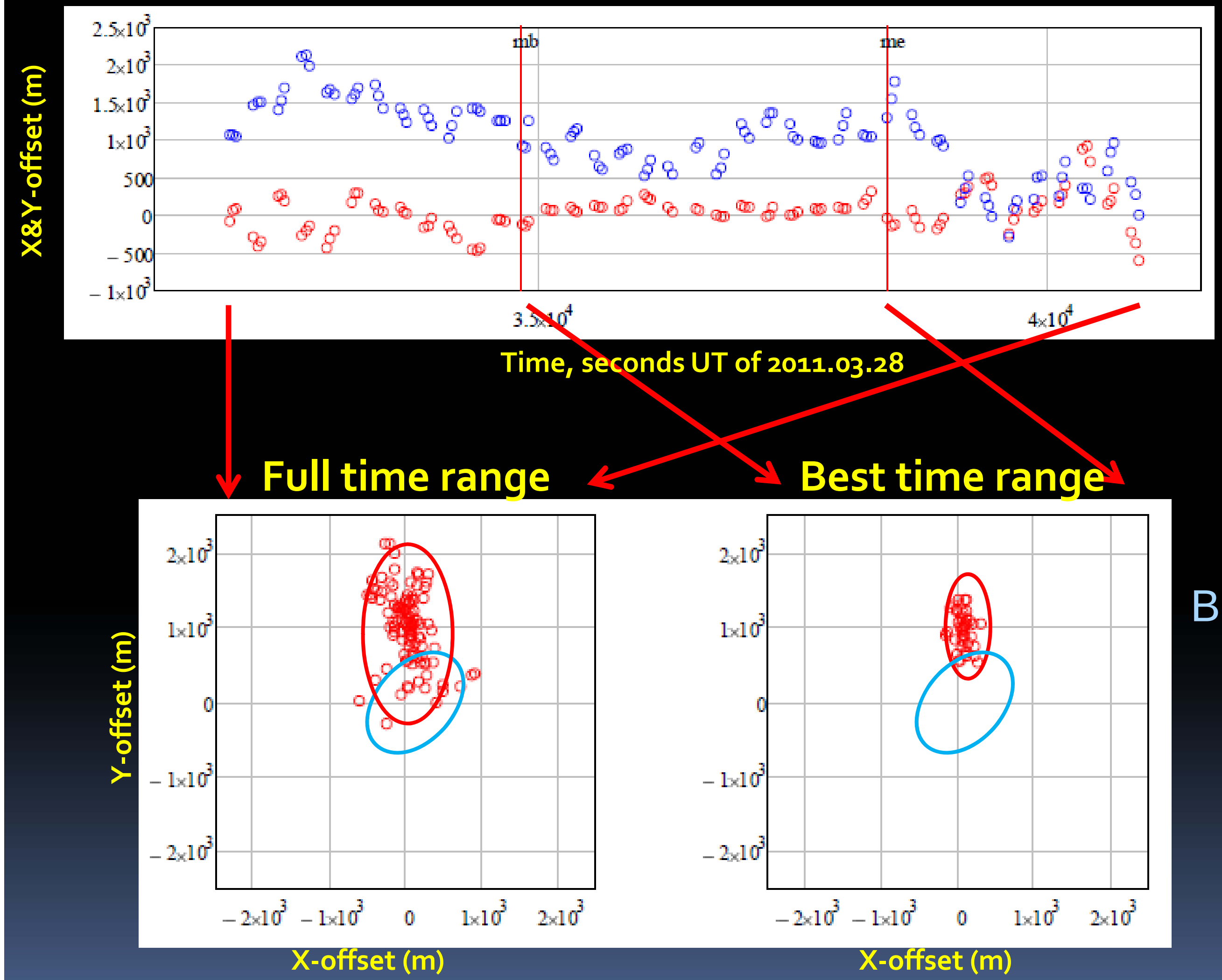
PRIDE is "cheap" – just eavesdropping on radio link…

EM081c: On, Wz, Mc, Ma, Ys, Mh, Sv, Zc



Duev, Molera, Cimo et al. 2011, in preparation

EM081c (2011.03.28): results so far

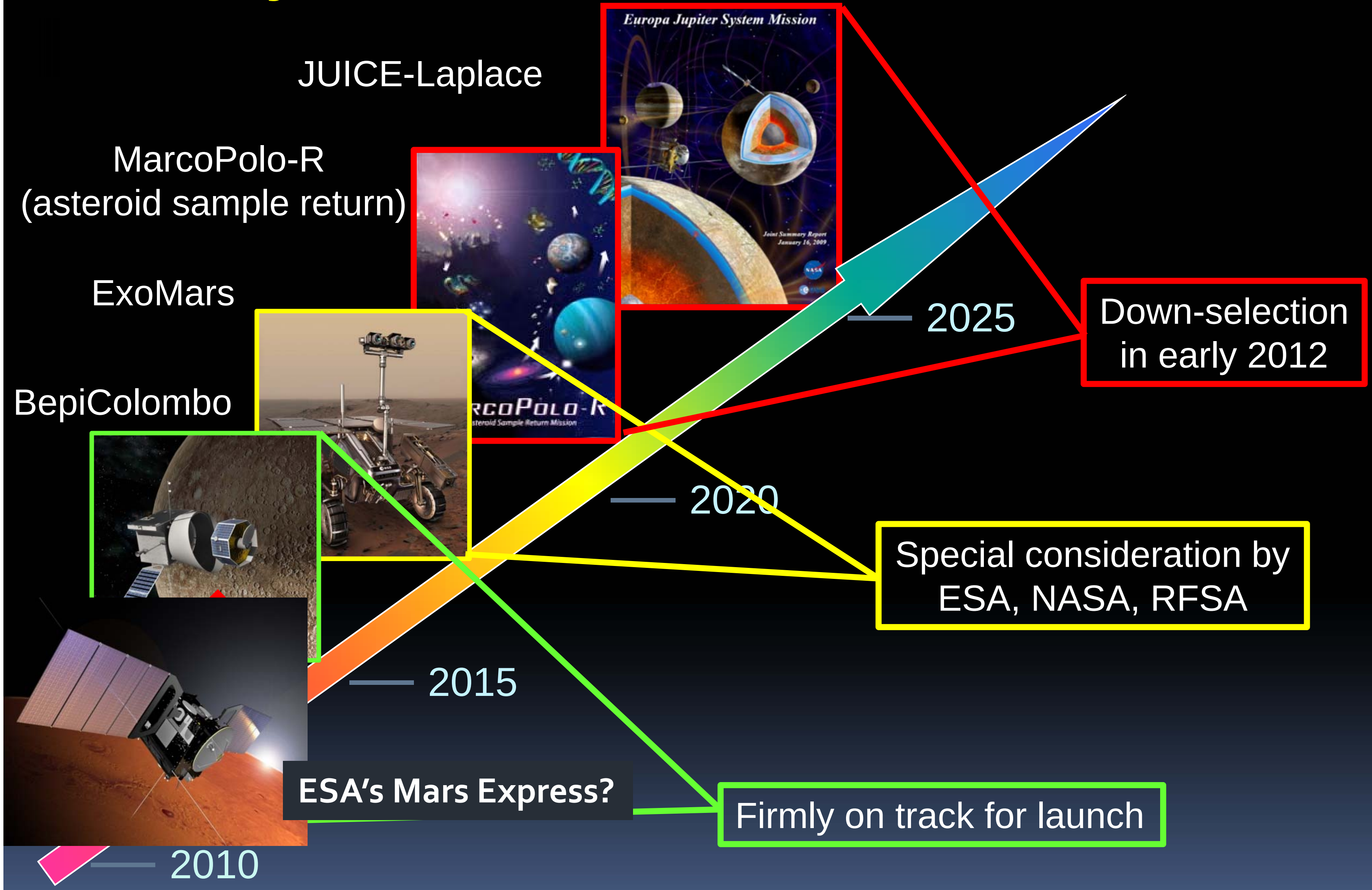


Measured offsets wrt
***a priori* trajectory (ESOC)**
X-- red, Y– blue.
(X @Y approx RA and Dec)
Time sampling – 30 s,
1 km = 1.1 mas at 1.24 AU distance

Blue ellipse: ESOC prediction
Red points: EM081 data

σ_{RA} = 90 m (100 μas)
σ_{Dec} = 250 m (300 μas)

Planetary science missions – VLBI “customers”



Useful reading on radio interferometry

- B. Burke, F. Graham-Smith, An introduction to Radio Astronomy
- A.R. Thompson, J.M. Moran, G.W. Swenson, Interferometry and Synthesis in Radio Astronomy
- Radio Astronomy from Karl Jansky to Microjansky, eds. L.I. Gurvits, S. Frey, S.Rawlings, EDP Sciences, 2005
- VLBI Technologies, eds. M. Felli, R.Spencer, 1989
- J.S. Shklovsky (+C. Sagan)

Questions? -> *lgurvits@jive.nl*