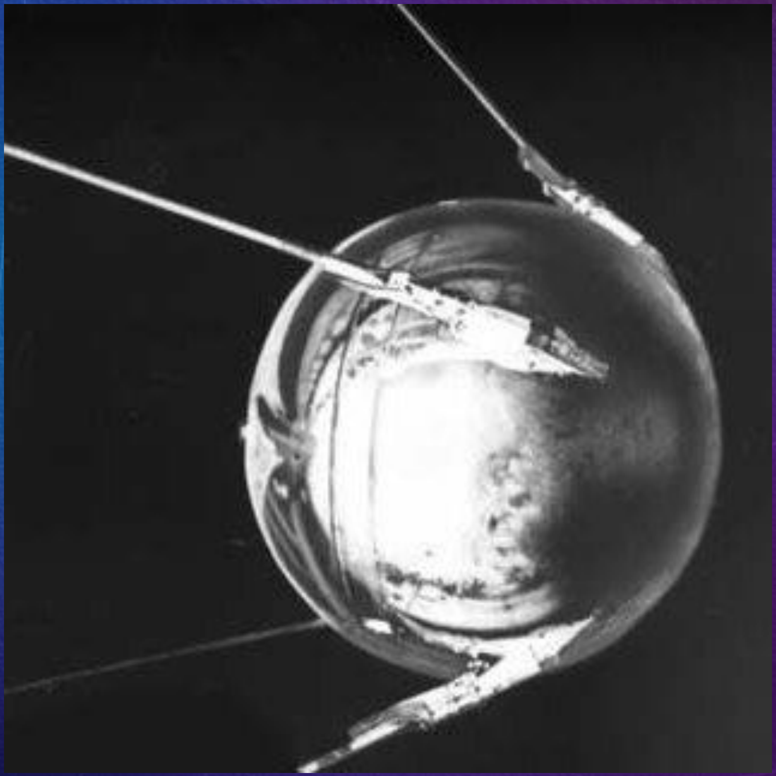
Space science frontier of VLBI: the case for the Zolochiv 32-m radio telescope

Leonid Gurvits
JIVE and TU Delft

Zolochiv, Ukraine
4-5 October 2021

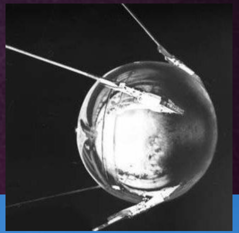
4 October 2021

1,000,000 (binary) years of the Space Era



Space exploration & radio astronomy: 64 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

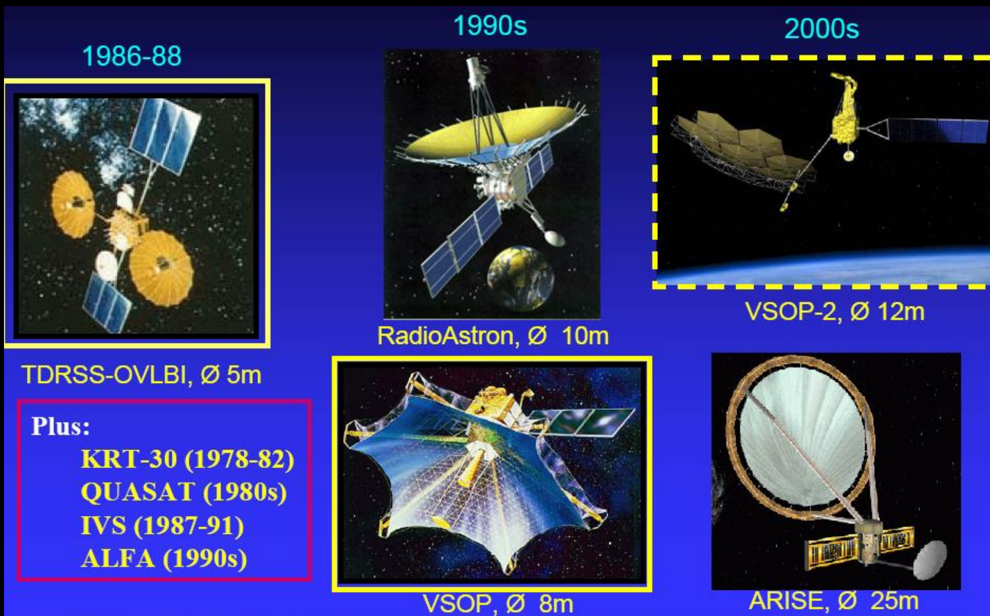
Parkes 70 m, NSW, Australia

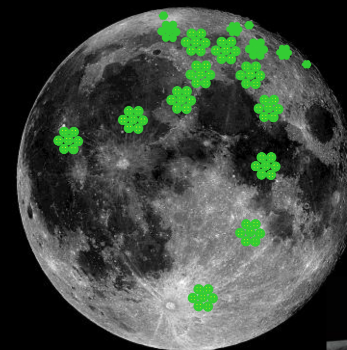
ADU-1000, Evpatoria, Ukraine

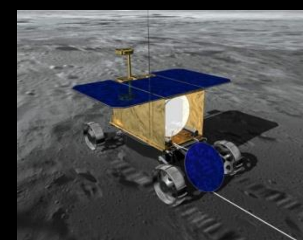
- Discovery of variability of extragalactic radio sources using deeps space communication antenna by G.B.Sholomitsky, 1965

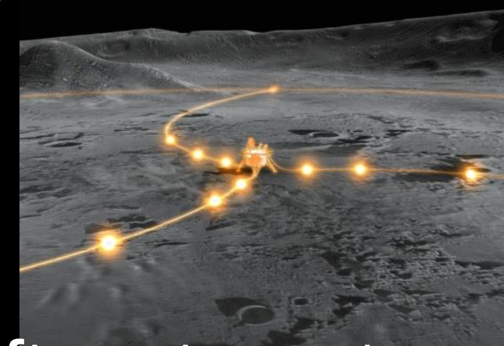
Radio interferometry and space science

- Radio interferometry in Space: Space VLBI









- VLBI tracking of (science) spacecraft as targets

VLBI in Space

**Baikonur,
18 July 2011
02:31 UTC**

RadioAstron – Spektr-R

- 10-m antenna
- 0.327, 1.6, 5 and 22 GHz
- Dual-polarisation
- 128 Mbps
- 2 on-board H-masers
- Apogee (initial) – 343,000 km
- Data reception – Pushchino and Green Bank

In preparation since 1978

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. Ропа[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]

Nikolai Kardashev, 1932–2019

How high can be T_B in AGN?

Theory:

Inverse Compton Cooling: $T_B \leq 10^{11.5}$ K

Kellermann & Pauliny-Toth 1969

Equilibrium ($E_p = E_m$): $T_B \leq 10^{10.5}$ K

Readhead 1994

Observations:

TDRSS OVLBI: $T_B \geq 10^{12}$ K

Linfield et al. 1989

VSOP, AO0235+164: $T_B \geq 6\mathrm{x}10^{13}$ K

Frey et al.. 2000

VLBA, 2 cm survey: $T_B \geq 3\mathrm{x}10^{12}$ K

Kovalev et al.. 2006

RadioAstron measurements of 3C273

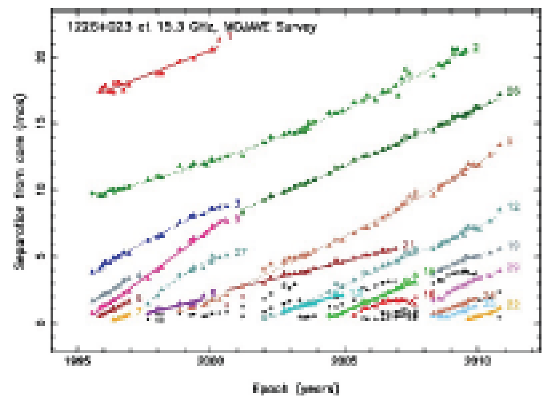
λ [cm]	GRT	B	S_B [mJy]	θ μasec	T_B [K]
18	GBT Arecibo	165,000 km 0.9 Giga λ	65±10	270±10	10^{14}
6	Arecibo	84,500 km 1.6 Giga λ	130±20	150±10	$3x10^{13}$
1.3	GBT/VLA	99,300 km 7.6 Giga λ	250±40	22±2	$2x10^{13}$

Observed T_B is 10^2 to 10^3 times higher than the theory predictions

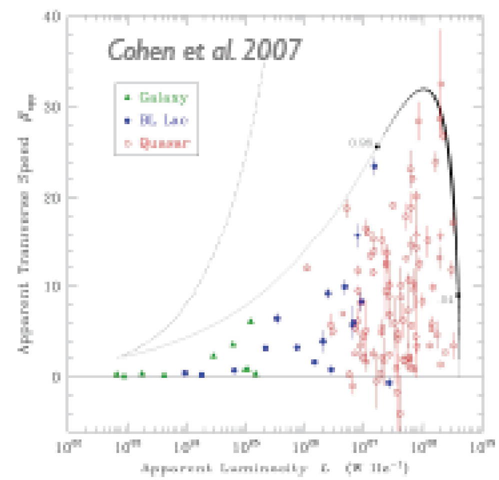
Kovalev et al. 2016, ApJ 820 L9
Johnson et al. 2016, ApJ 820 L10

How can this be?!

- Relativistic Doppler boosting
  - $T_{obs} \equiv \delta T_{int} \sim \gamma T_{int}$
  - $\gamma \sim 15$
  - $v_p \neq v_b$? NO!



- Complex geometry
- Non Stationary Processes (acceleration/injection)
- Proton synchrotron radiation
  - $T_b(p)/T_b(e) = (m_p/m_e)^{9/7} \sim 10^4$
- Coherent emission
- Stimulated (maser) emission



Further RadioAstron story – in the talk by Petr Voytsik at this conference, 23 August

THEZA: TeraHertz Exploration and Zooming-in for Astrophysics

Zsolt Paragi
Ricardo Amils
Ilse van Bemmel
Paul Boven
Viviana Casasola
John Conway
Jordy Davelaar
Carmen Diez
Heino Falcke
Rob Fender
Sándor Frey
Christian M. Fromm
Juan Gallego
Cristina García Miró
Michael Garrett
Marcello Giroletti
Ciriaco Goddi
José-Luis Gómez
Jeffrey van der Gucht
Jose Carlos Guirado
Zoltán Haiman
Frank Helmich
Ben Hudson
Elizabeth Humphreys
Violette Impellizzeri
Michael Janssen
Yuri Y. Kovalev
Michael Kramer
Michael Lindqvist
Hendrik Linz
Elisabetta Liuzzo
Andrei P. Lobanov
Isaac Lopez
Inmaculada Malo
Kunal Masania
Yosuke Mizuno
Alexander V. Plavin
Raj T. Rajan
Luciano Rezzolla
Freek Roelofs
Eduardo Ros
Kazi L.J. Rygl
Tuomas Savolainen
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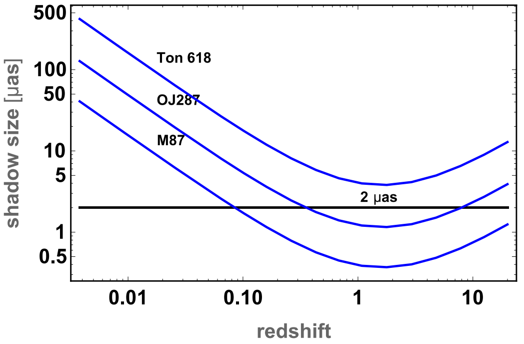
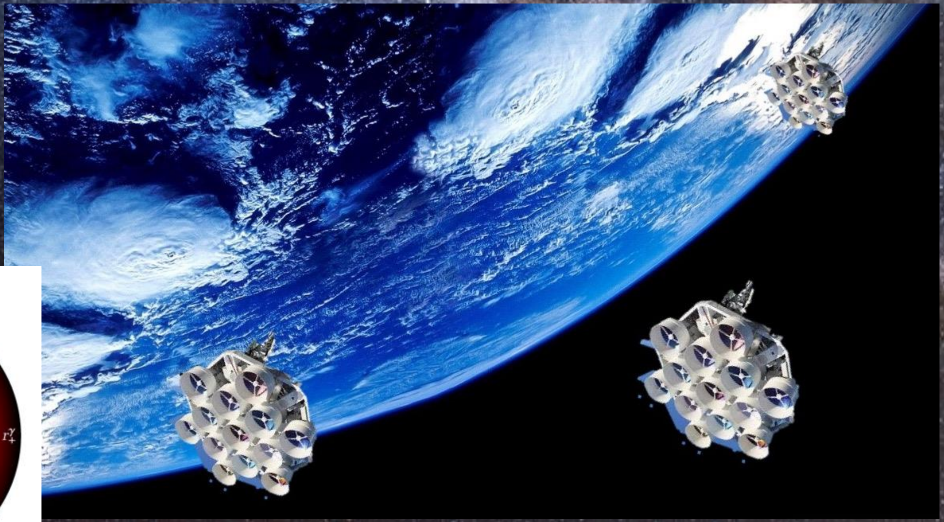
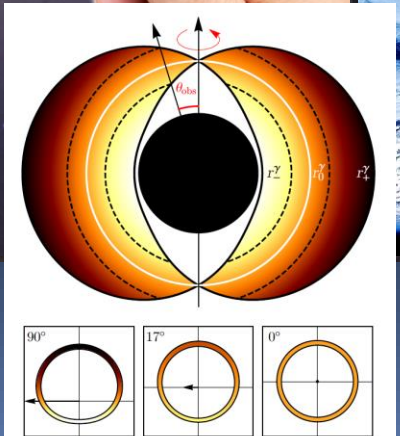
Harro Verkouter
Pablo de Vicente
Pieter N.A.M. Visser
Martina Wiedner
Kaj Wiik
J. Anton Zensus



Angular resolution for Earth-based VLBI is limited:

Increase baseline beyond 10^4 km ⇒ go in space
Shorten wavelength below ~1 mm ⇒ go in space





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):

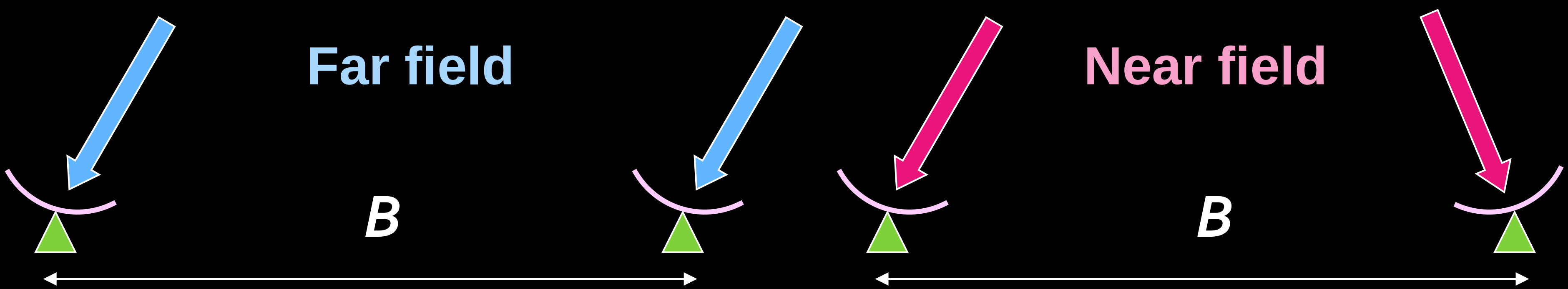
  UHF (400 and 800 MHz), S (2.3 GHz), X (8.4 GHz), Ka (32 GHz)

- 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…)

Working in the near field with PRIDE

While thinking of 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}	EVN
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

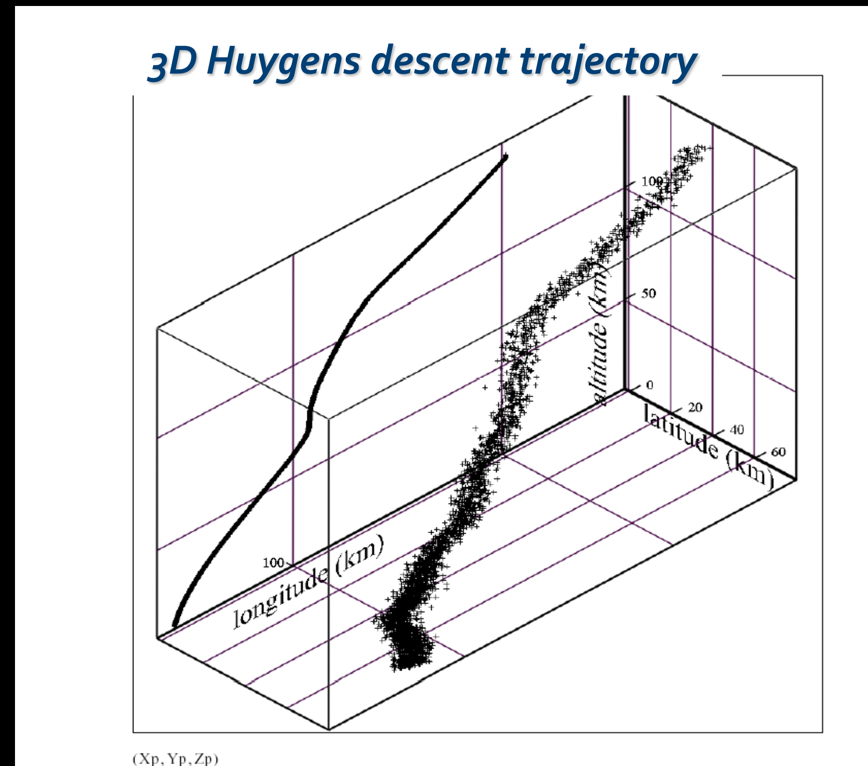
f = 1.6 GHz, Δ*f* = 2 MHz, 20 radio telescopes

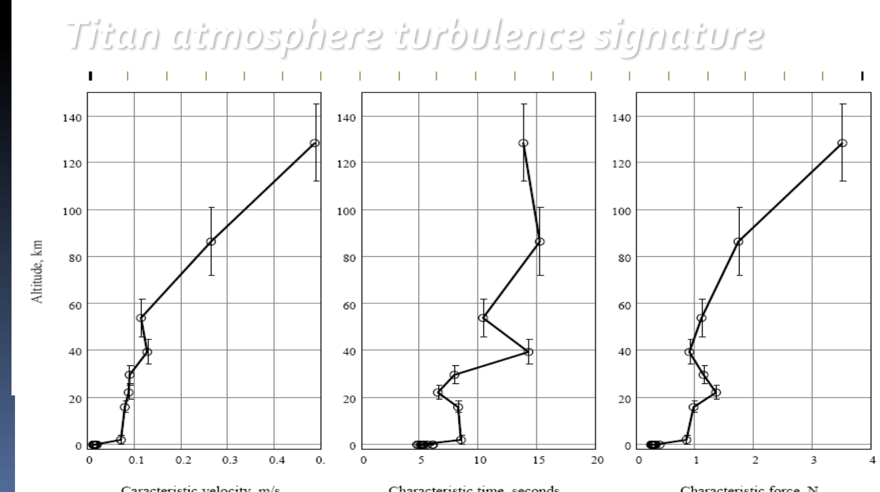
σ_x = 10 km
σ_v = 1 m/s

Preston et al. 1986, Science, 231, 1414

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





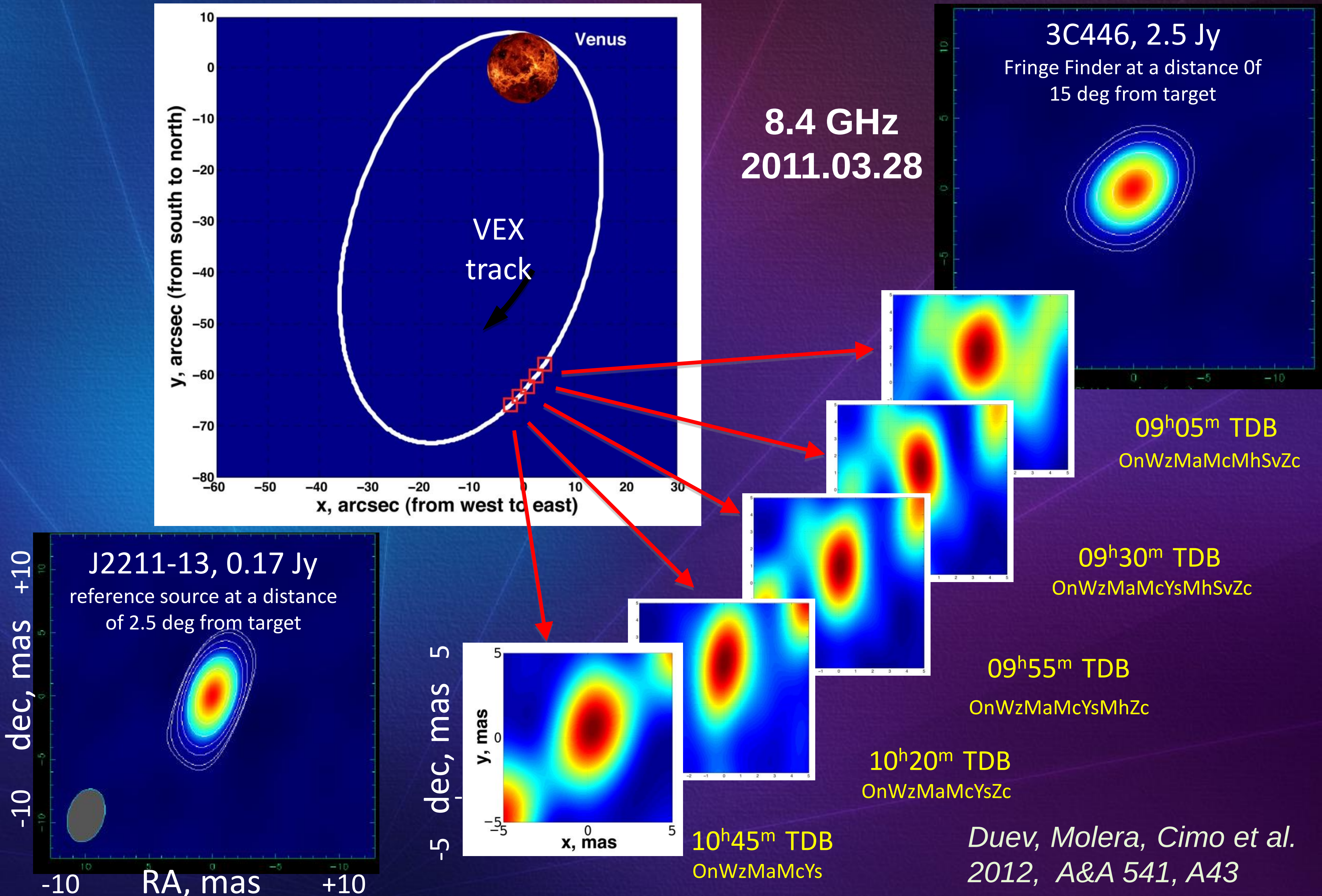
PRIDE 2021 vs Huygens VLBI tracking 2005

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

Garmin accuracy anywhere in Solar System

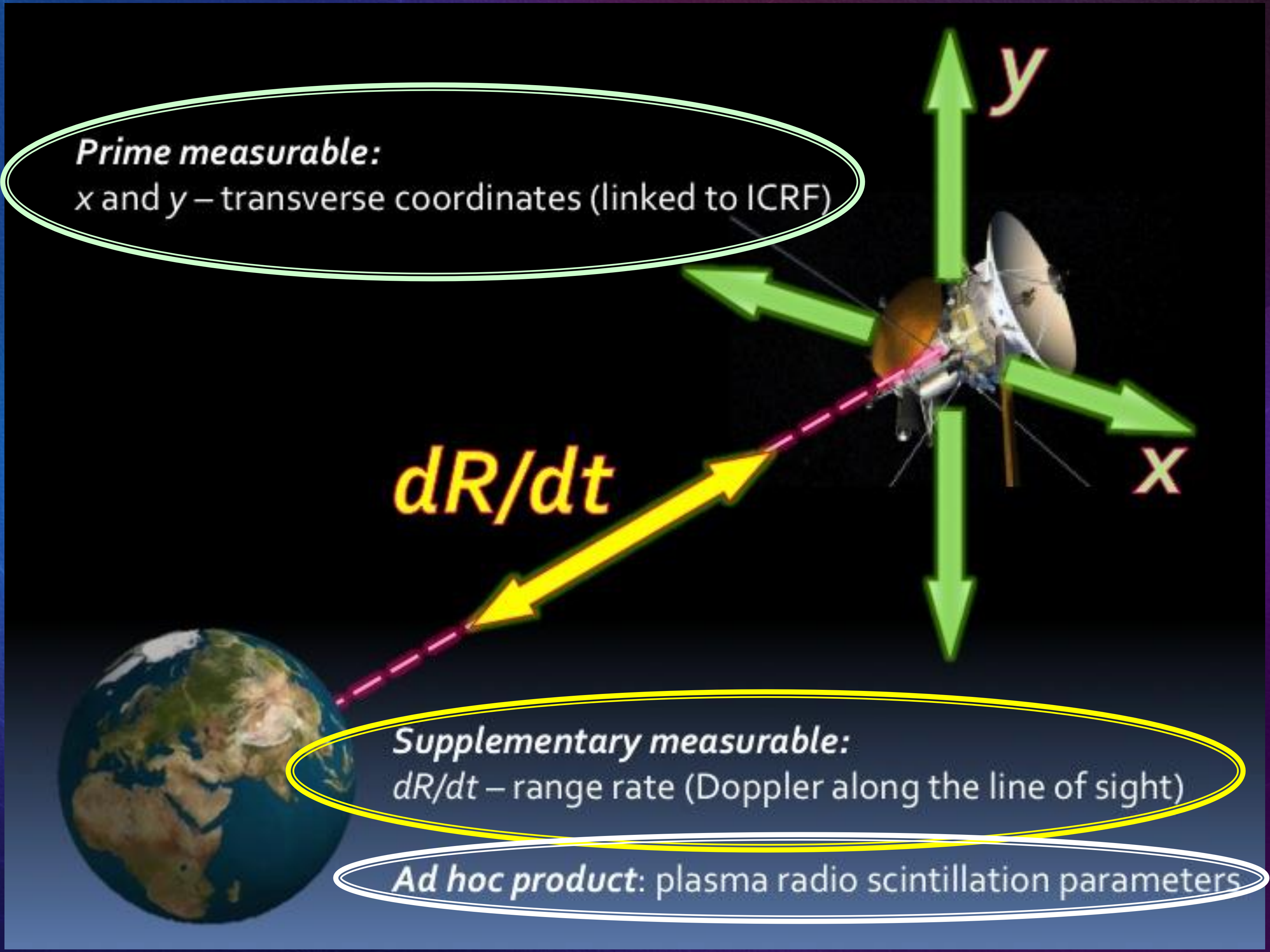
- **Conservative estimate, today's technology**
- **Minimal special requirements for the on-board instrumentation**
- **Helps to address the key science of EJSM-Laplace – search for undersurface liquid water by means of Europa tidal deformation monitoring**

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

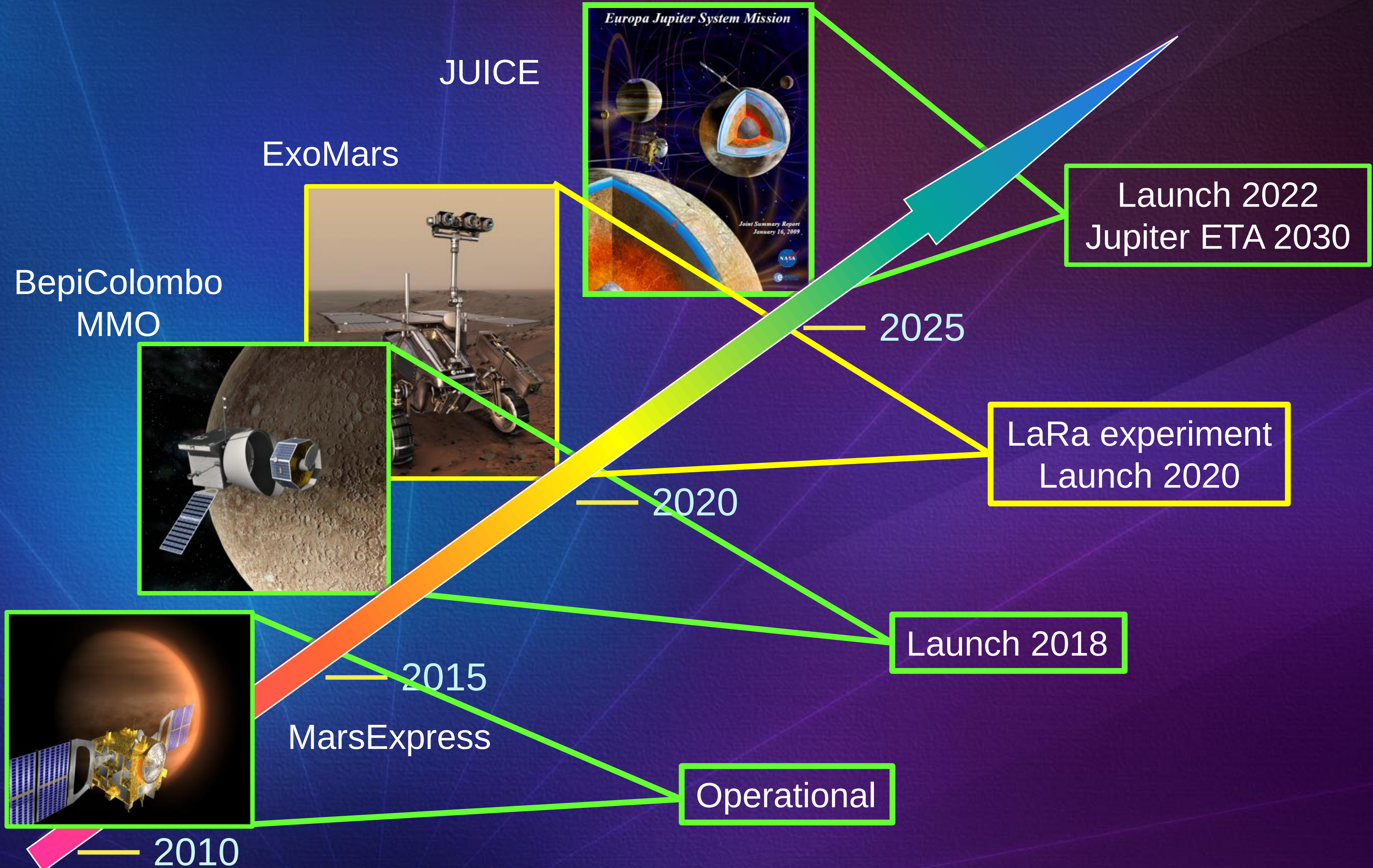


Duev, Molera, Cimo et al. 2012, A&A 541, A43

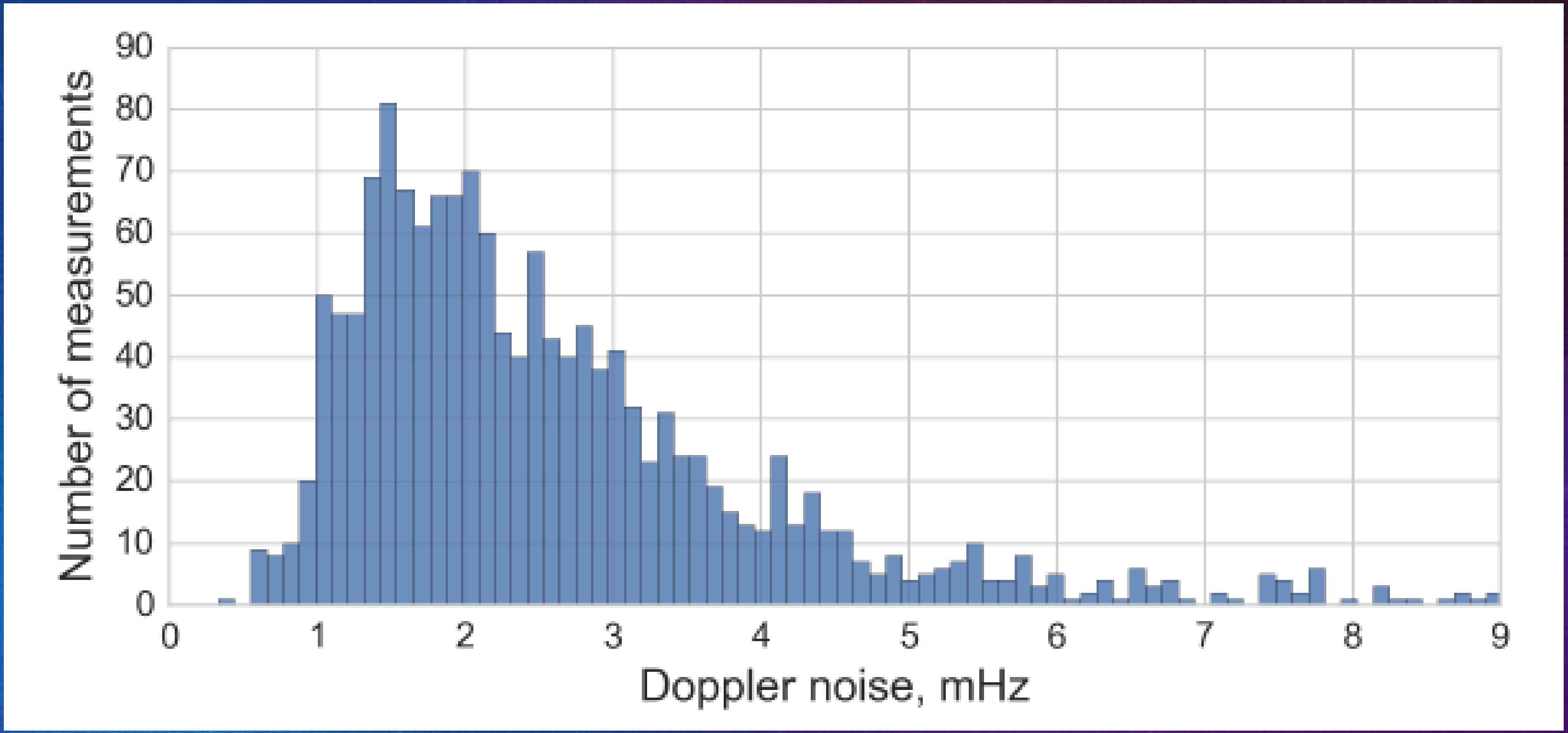
PRIDE measurables



ESA planetary science missions – VLBI "customers"



GR035, Doppler detections - I



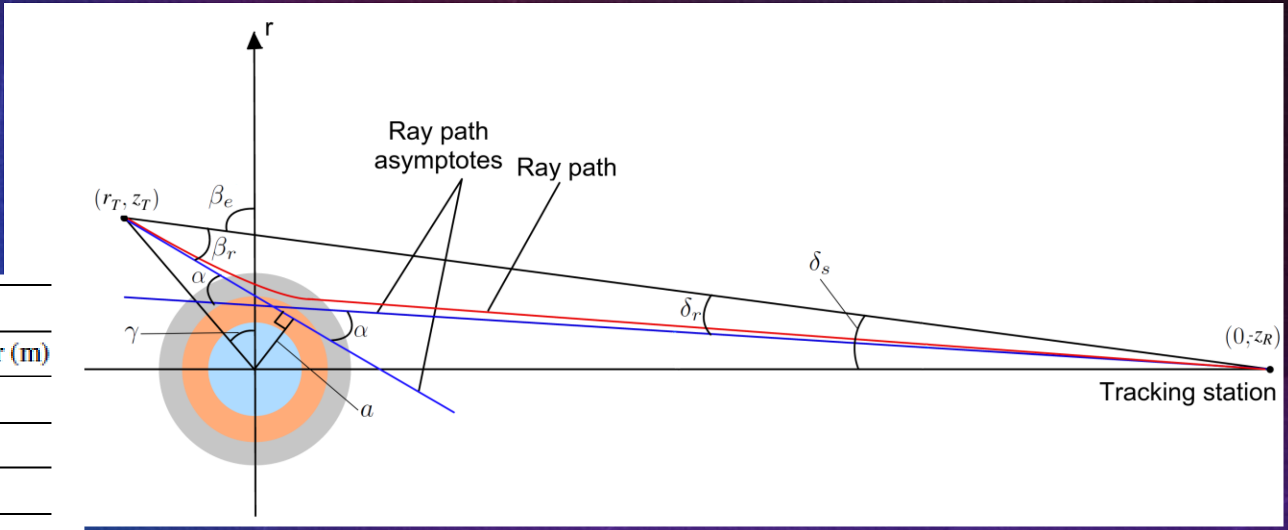
Doppler detection noise, 10 s integration:

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

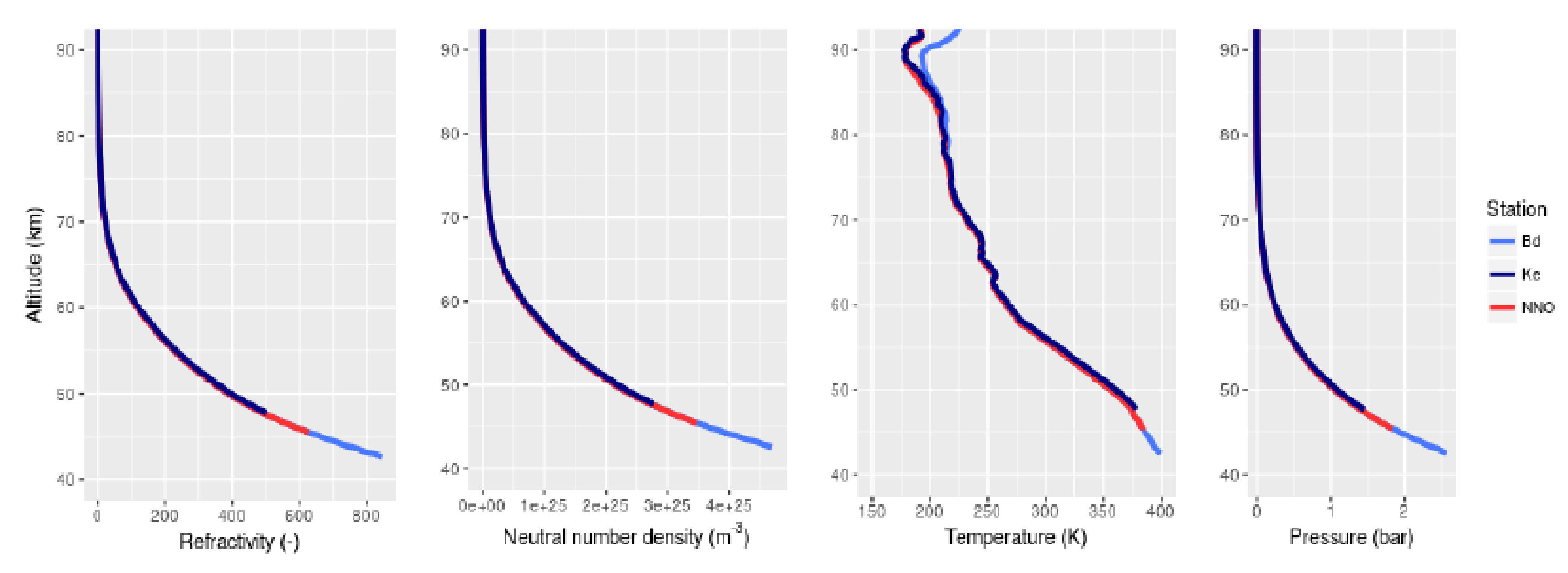
Full description of the algorithm: Bocanegra et al. 2018, A&A 609, A59

Sounding planetary atmosphere with PRIDE (Venus)

Observatory	Country	Telescope	
		Code	Diameter (m)
Sheshan (Shanghai)	China	Sh	25
Nanshan (Urumqi)	China	Ur	25
Tianma	China	T6	65
Badary	Russia	Bd	32
Katherine	Australia	Ke	12
Kashima	Japan	Ks	34



Bocanegra et al. 2019, AA 624, A59

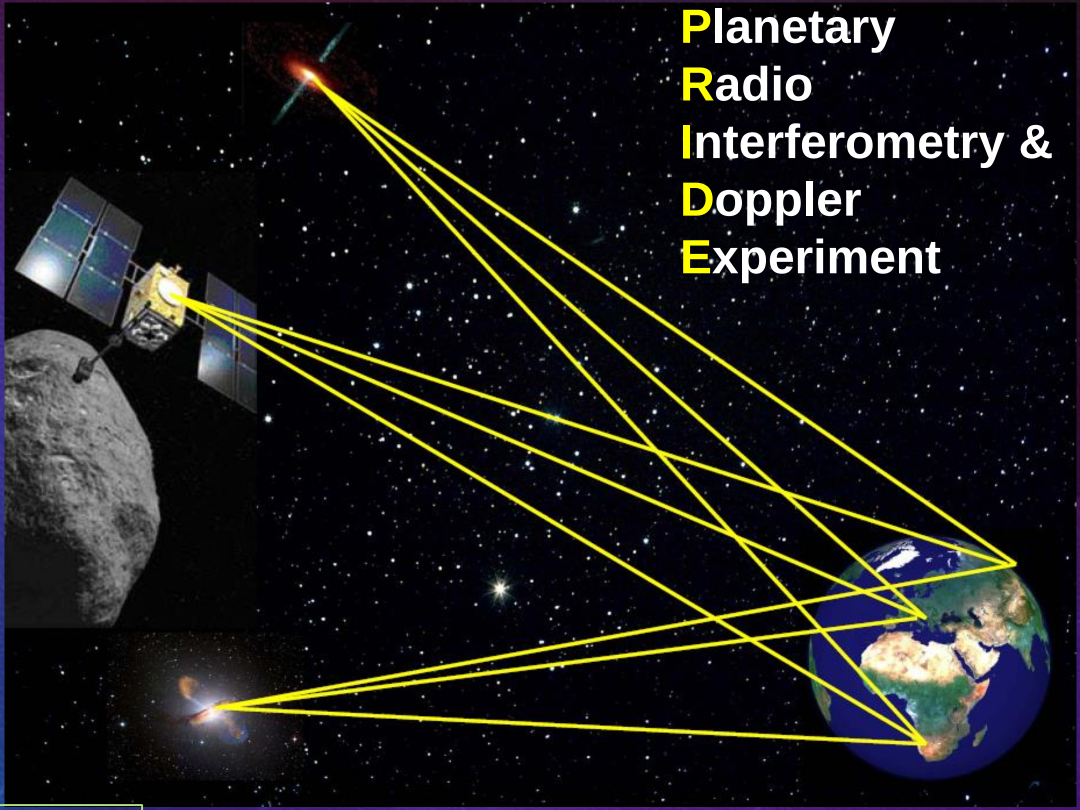


Near field VLBI

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

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	3×10^7km	20 AU	2×10^3AU	1 pc	100 pc	10 kpc	1 Mpc

Astrometry of extragalactic pulsars?

Дякую!
Thank you!

Additional slides

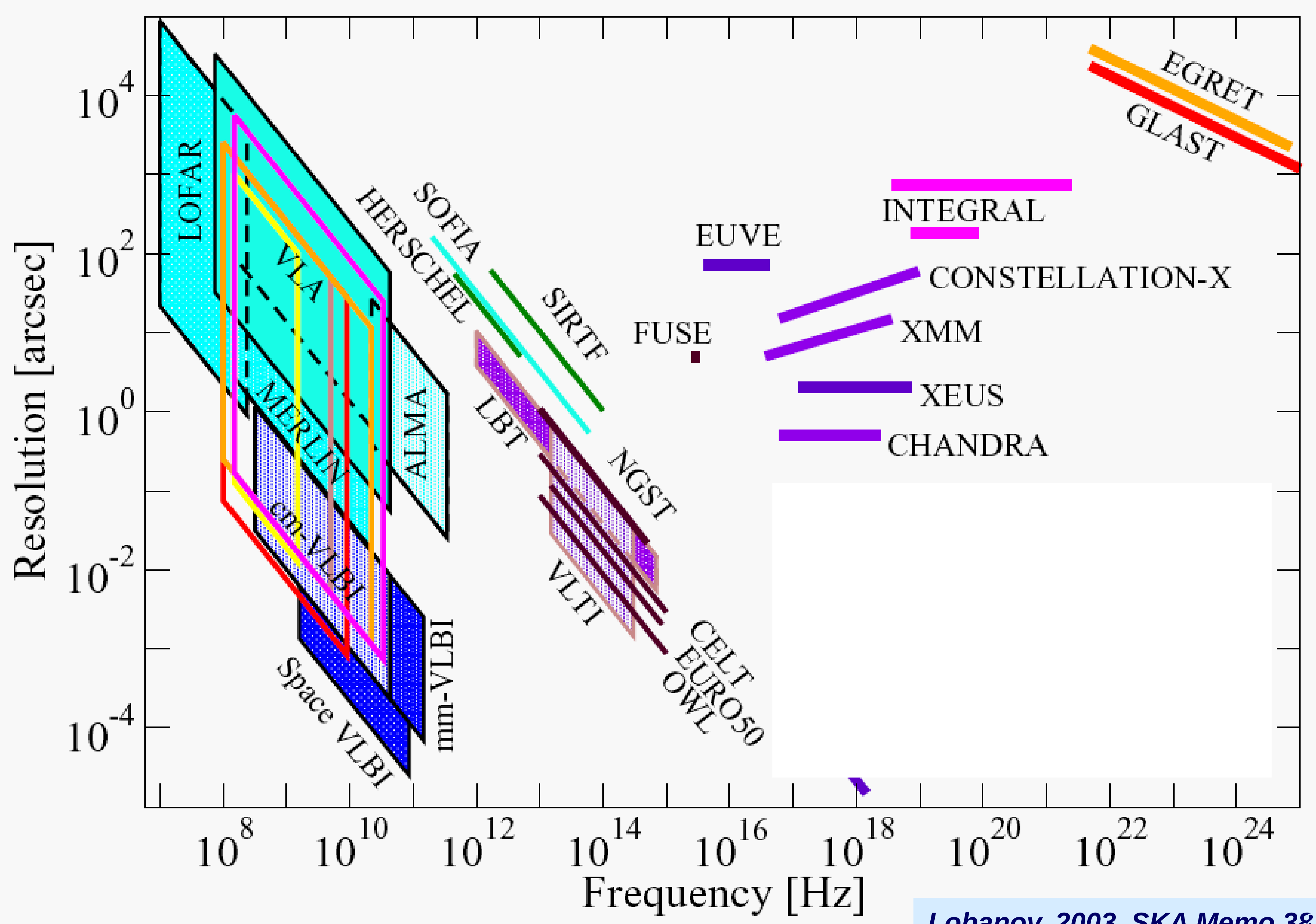
VLBI in Latvia

Irbene RT-32

Irbene RT-16

A perfect match to many space science applications of VLBI !

Best (imaging) angular resolution across EM spectrum



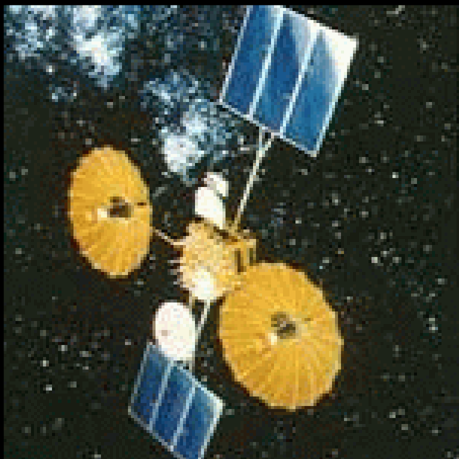
Lobanov. 2003, SKA Memo 38

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*)

Three generations of VLBI in Space

1986-88



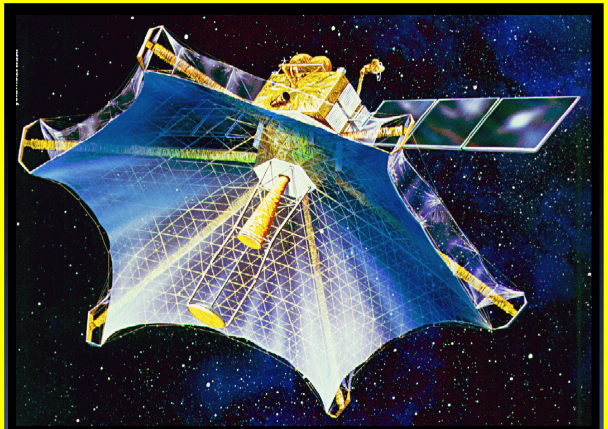
TDRSS-OVLBI, Ø 5m

Plus:

- KRT-30 (1978-82)
- QUASAT (1980s)
- IVS (1987-91)
- ALFA (1990s)
- ARISE (2000s)
- VSOP-2 (2000s)
- CSVLBI (2010s)

1997-2019

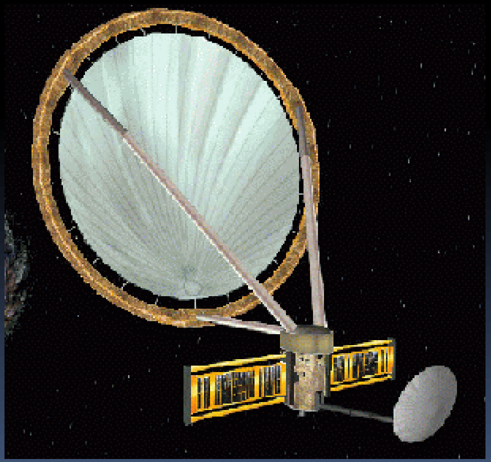
RadioAstron, Ø 10m



VSOP, Ø 8m

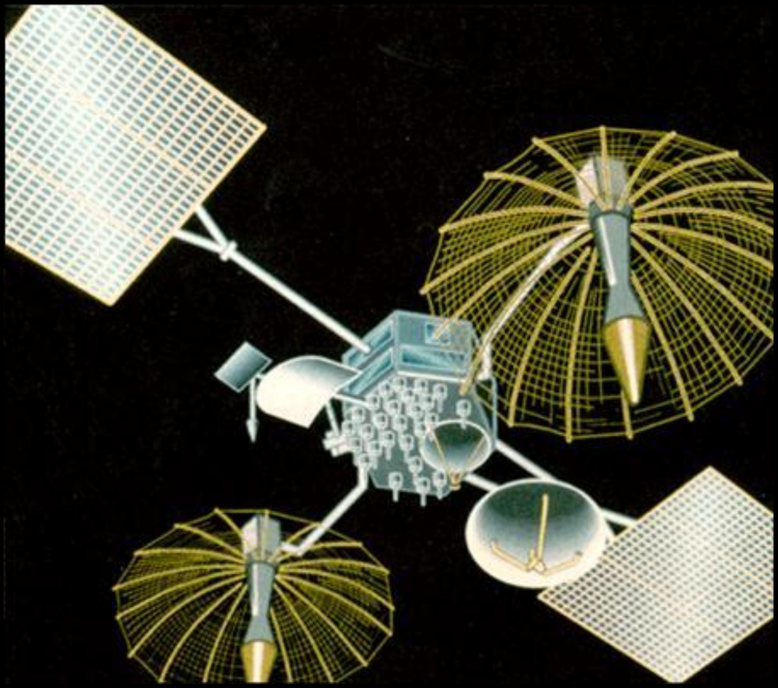
>2030

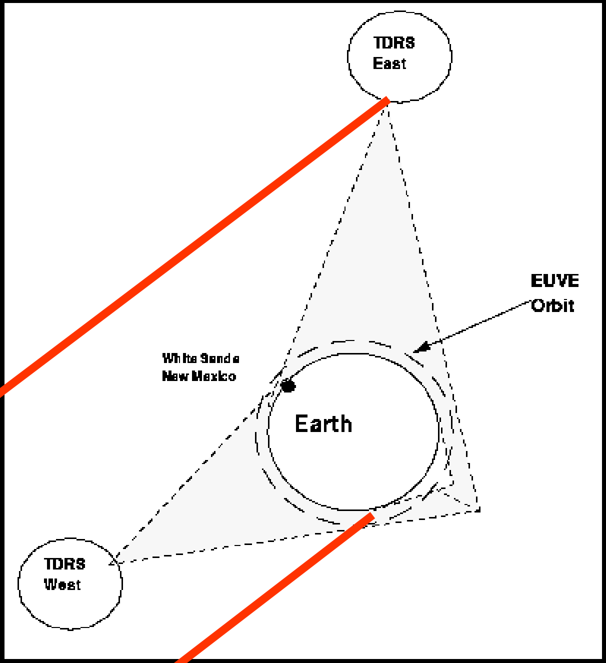
~~VSOP-2, Ø 12m~~



~~ARISE, Ø 25m~~

TDRSS-OVLBI: proof of SVLBI concept



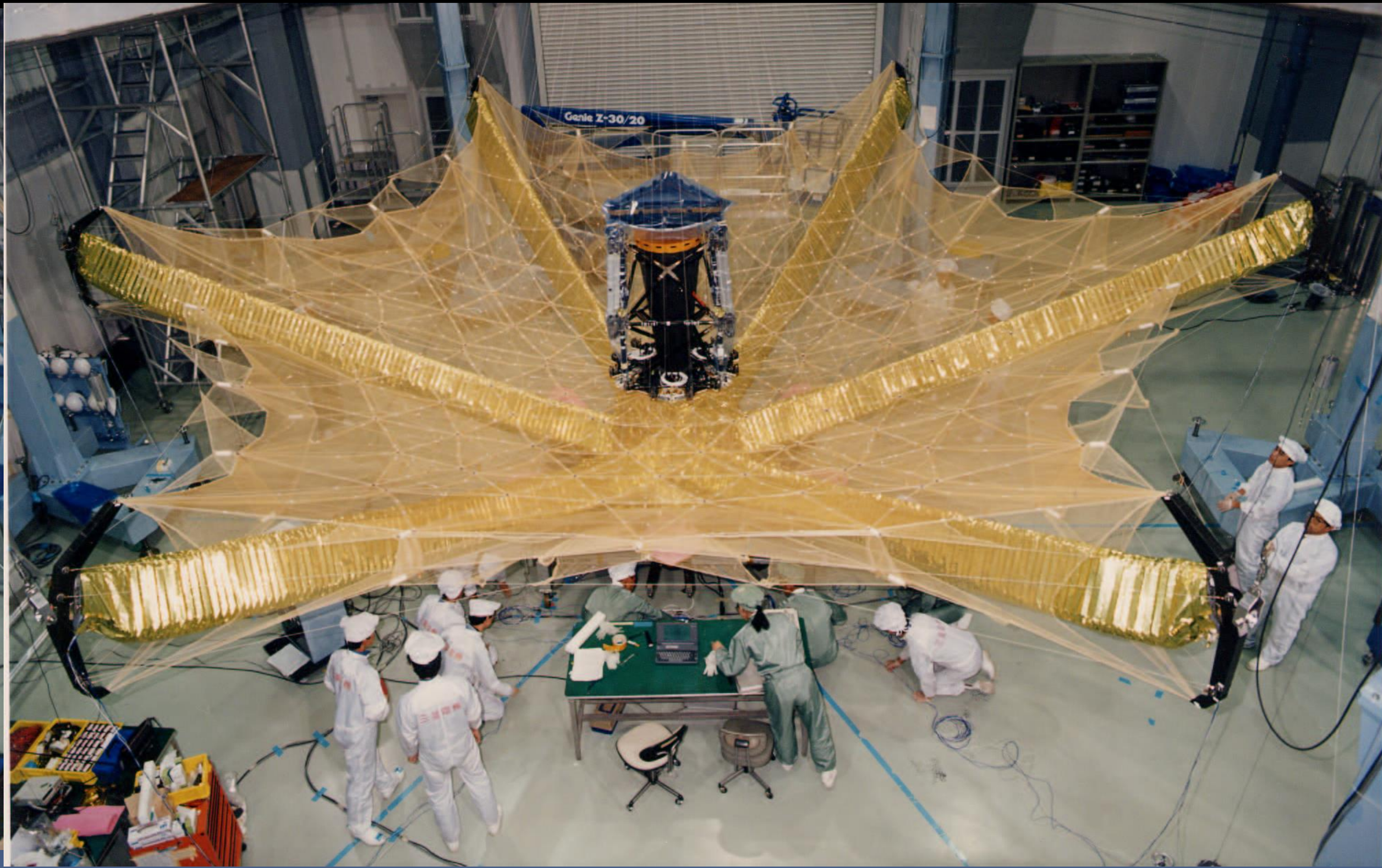


$B = 2.2 D_{Earth}$

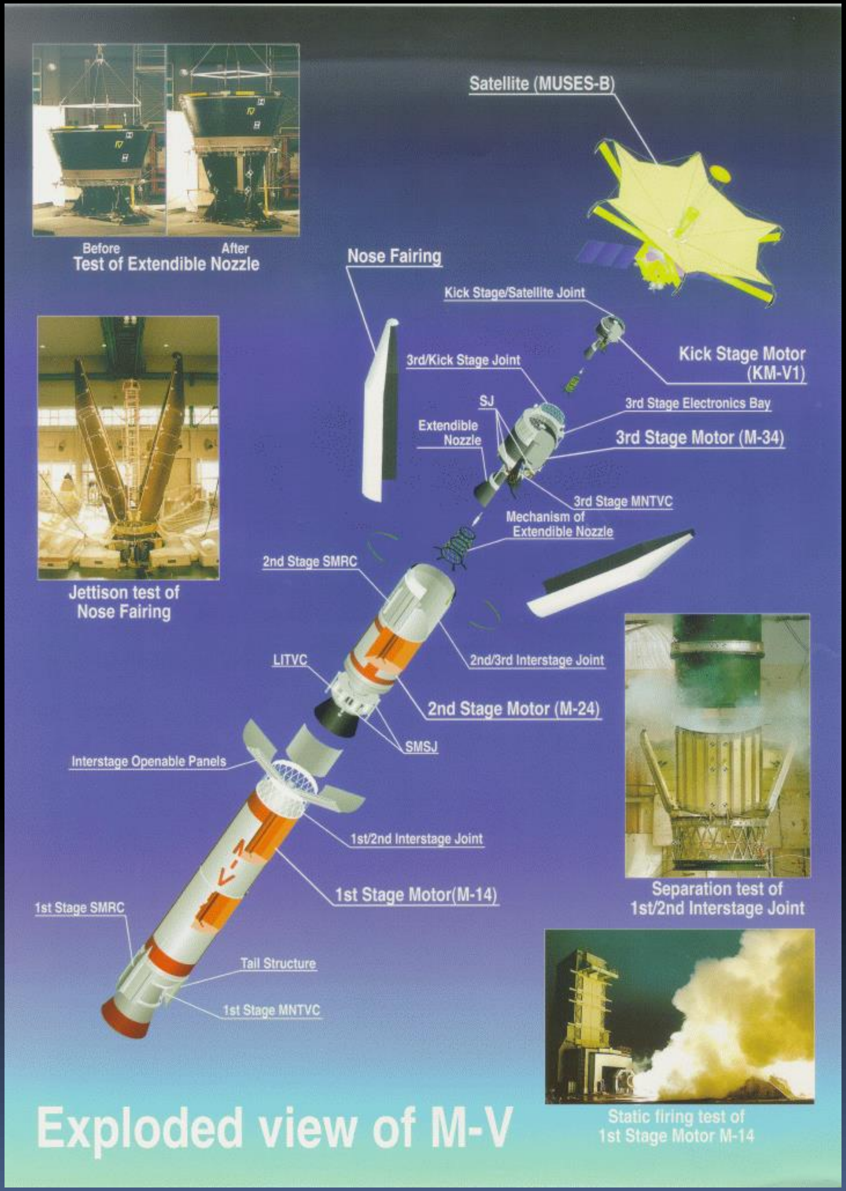
- First Space-Earth VLBI fringes in 1986
- 2.3 and 15 GHz, 3/4 ground-based telescopes, Mk3 (28 MHz /width)
- A dozen of strong quasars detected

Levy et al. 1986, Science 234, 187

VSOP/HALCA antenna deployment test



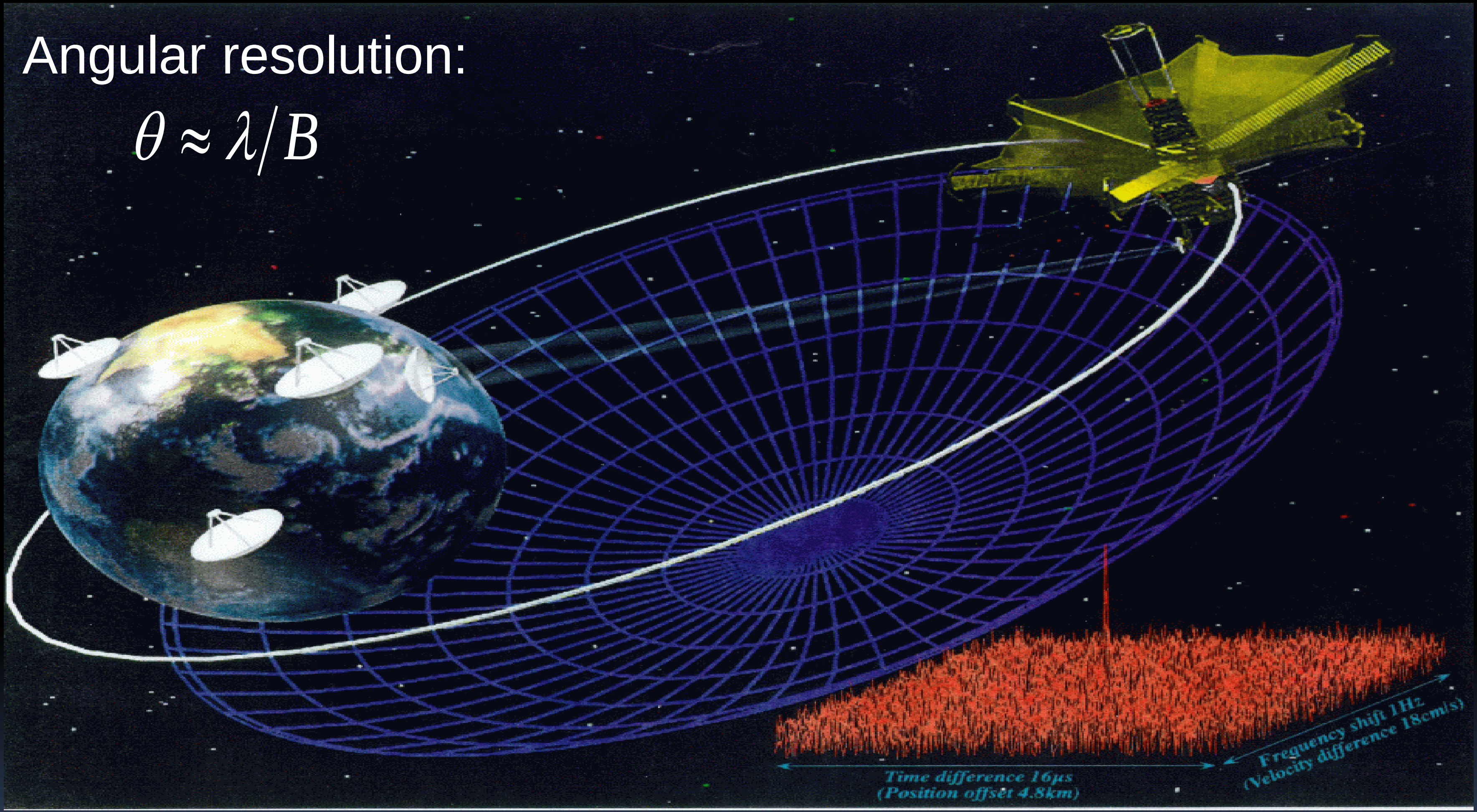
VSOP/HALCA launch 12 February 1997



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

Angular resolution:

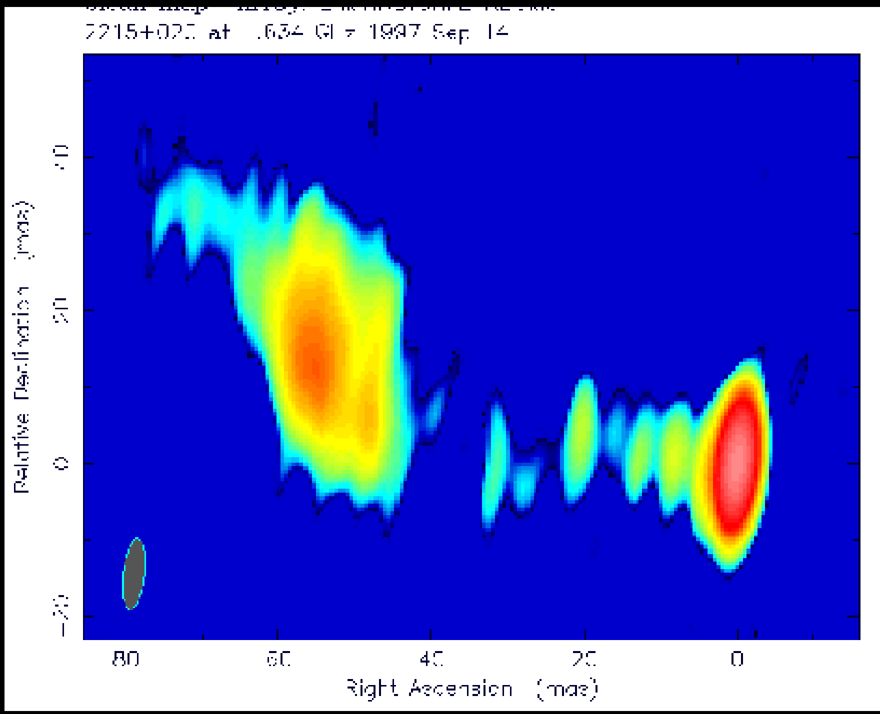
$$\theta \approx \lambda / B$$

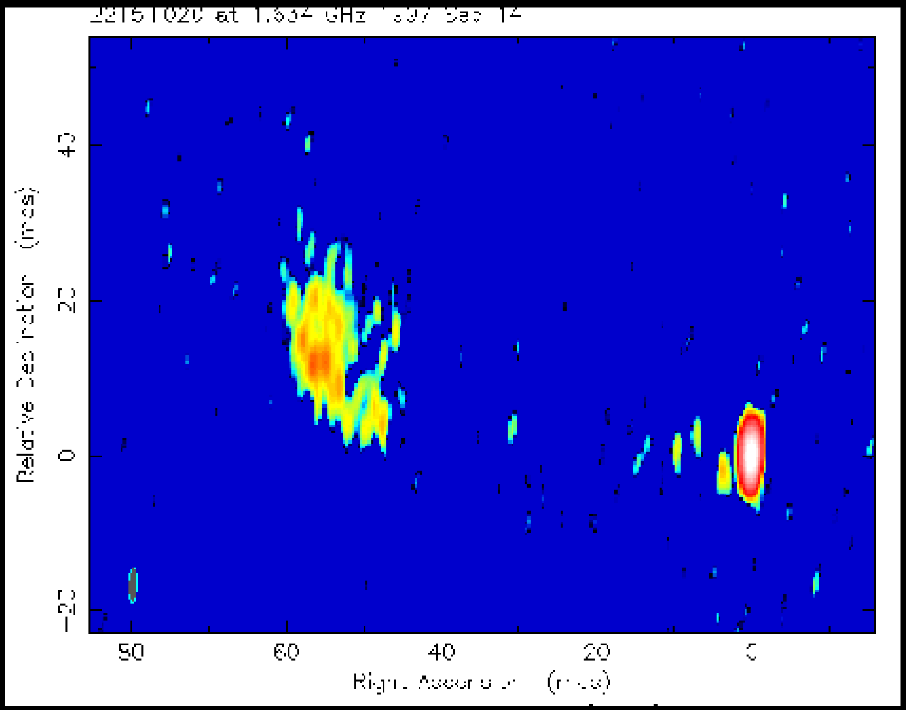


Ground-based VLBI: $\lambda = 6\ \mathrm{cm};\ \ B = 10000\ \mathrm{km}\ \Rightarrow \theta \approx 1.5\ \mathrm{mas}$

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

2215+020 (z=3.55): jet resolved by VSOP





- Cross-section of the jet appears resolved: $5 \le \theta_{jet} \le 9\ \mathrm{mas}$
- Theoretical prediction for jet cross-section (Beskin 1997):

$$r_{\mathrm{jet}} \approx 3\times10^{5}\,\frac{M_{\mathrm{BH}}}{M_{\mathrm{o}}}\left(\frac{B_{\mathrm{in}}}{B_{\mathrm{ext}}}\right)^{0.5}\,[\mathrm{cm}]$$

2215+020 (z=3.55): jet cross-section resolved

$$B_{\text{ext}} = 10^{-5}\,\text{G}\,(\text{Beck}\,2000)$$

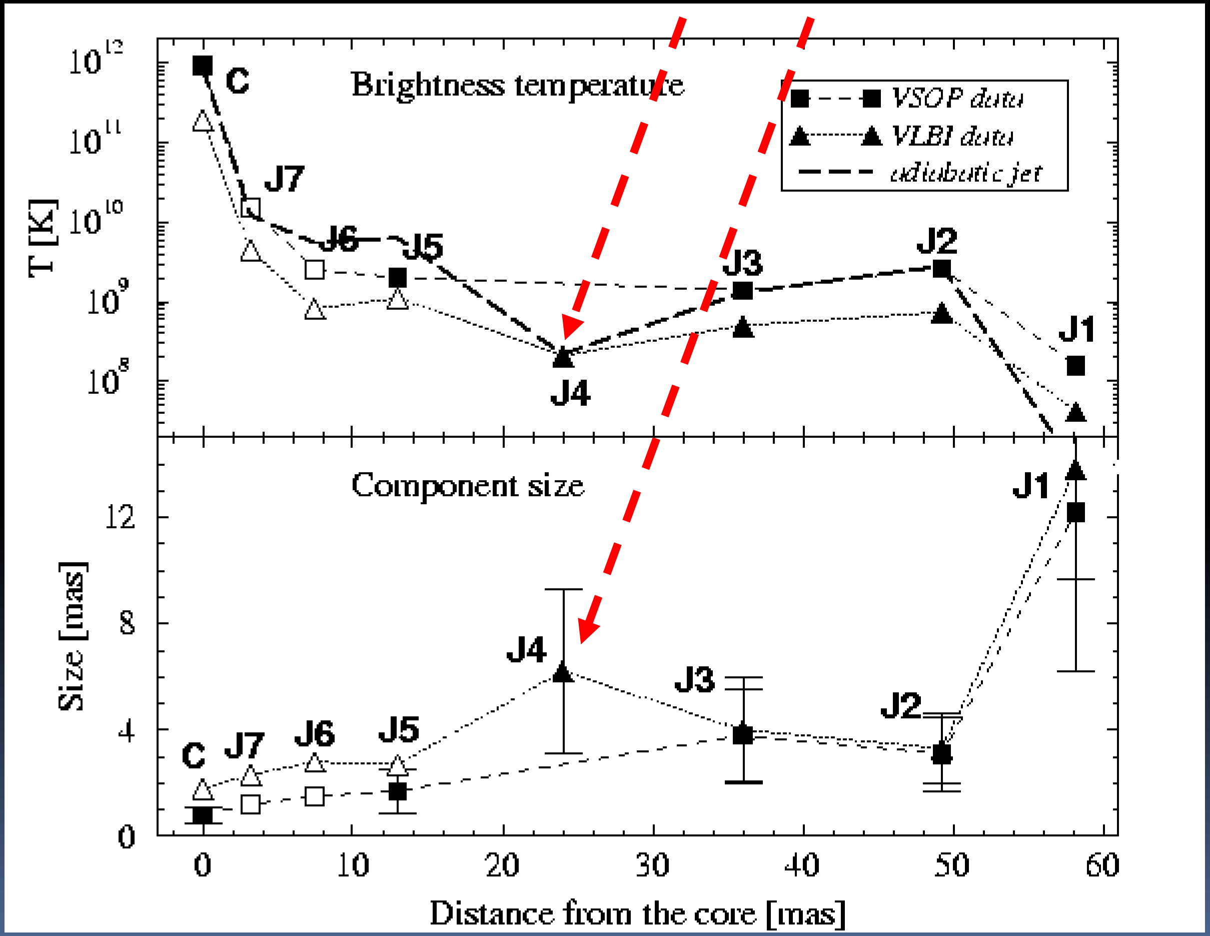
$$B_{\text{in}} = 10^{4}\,\text{G}\,(\text{Field}\,\&\,\text{Rogers})$$

$$r_{\text{jet}} \approx 20h^{-1}\,\text{pc}$$

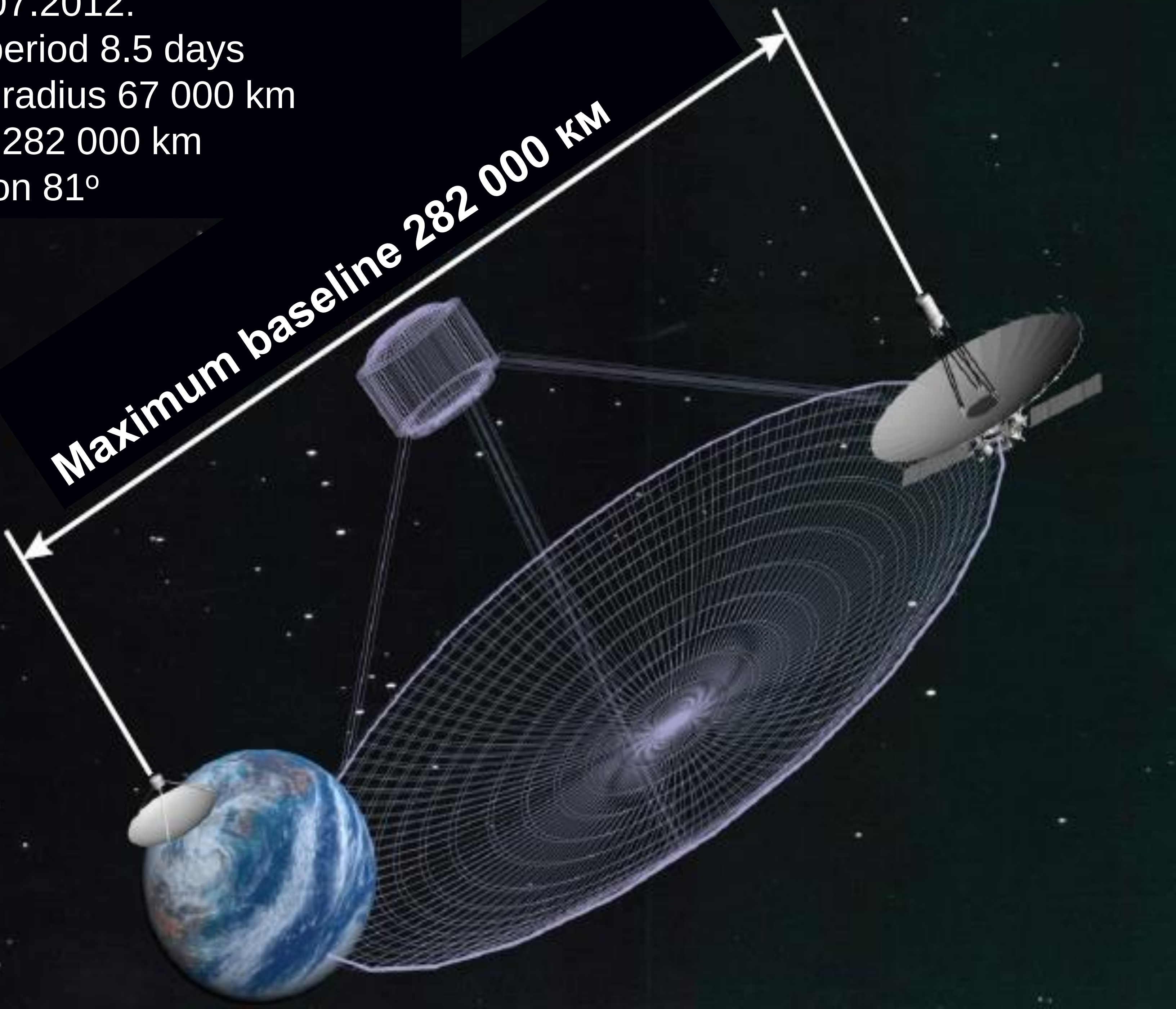
$$M_{\text{BH}} \cong 6\times10^{9}\,h^{-1}M_{\text{o}}$$

Potentially powerful method for estimating M_{BH} in AGN, especially in statistical studies

Lobanov et al. 2001



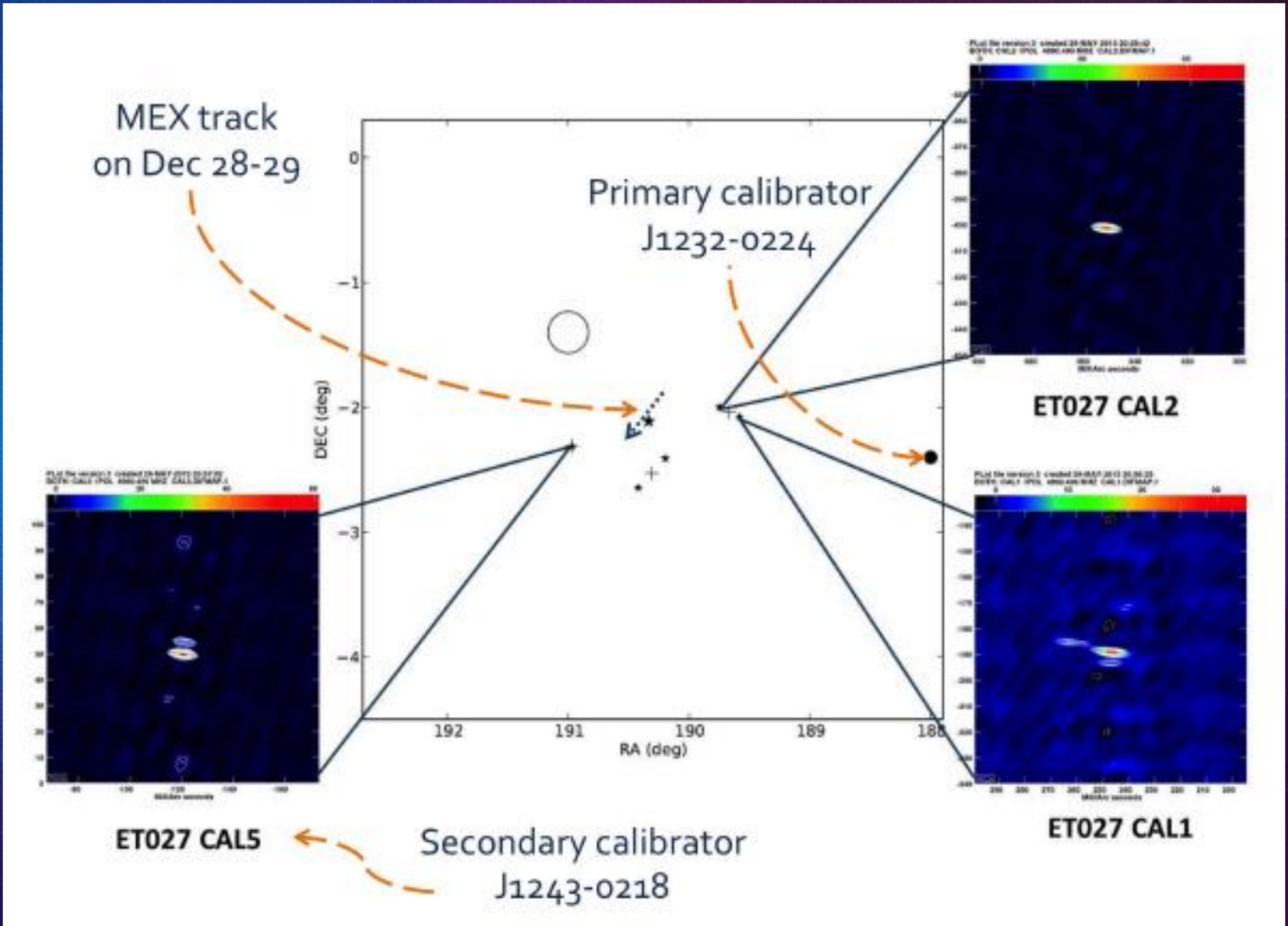
18.07.2012:
Orbital period 8.5 days
Perigee radius 67 000 km
Apogee 282 000 km
Inclination 81º



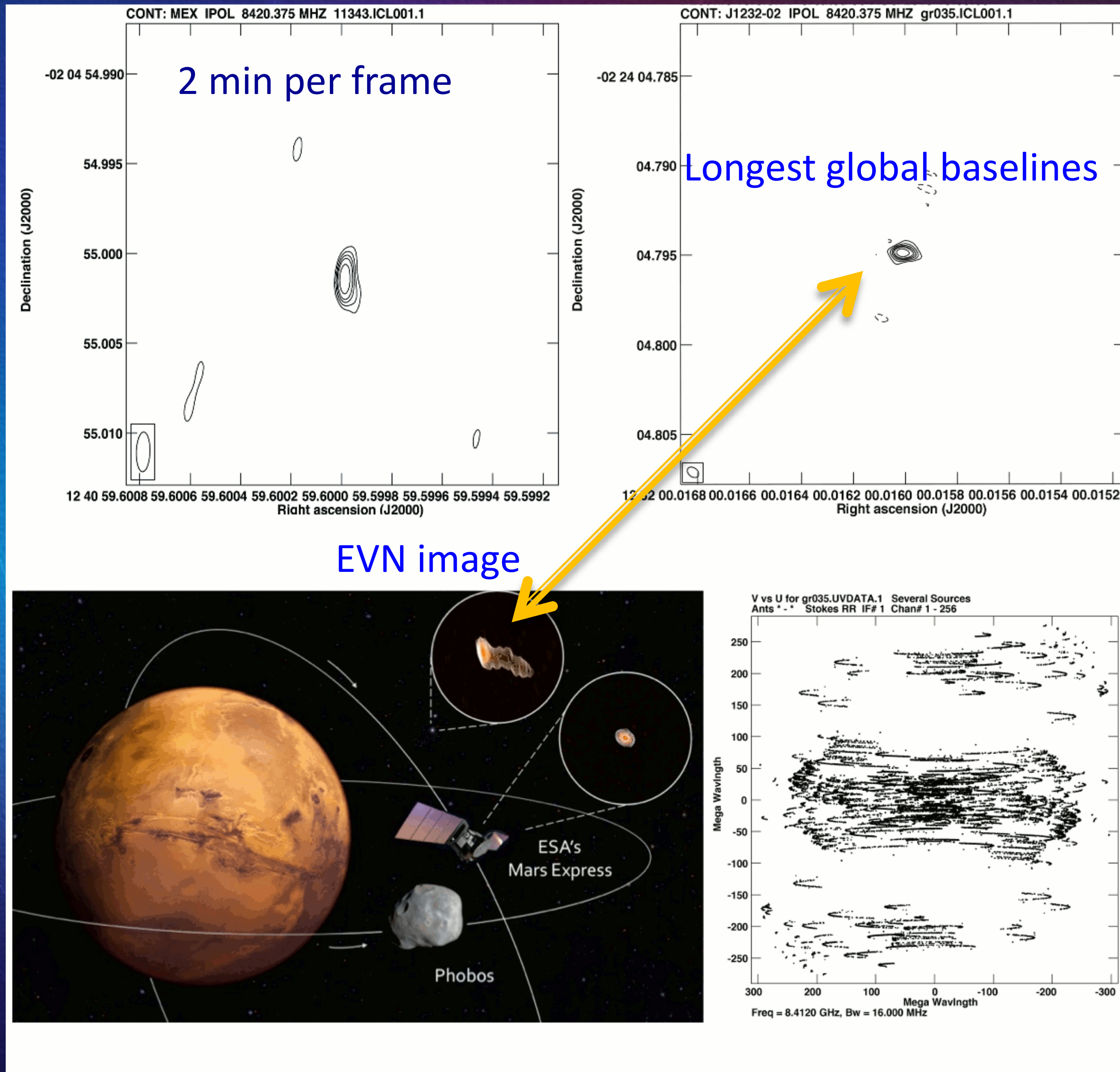
MEX/Phobos flyby as a test case

- 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

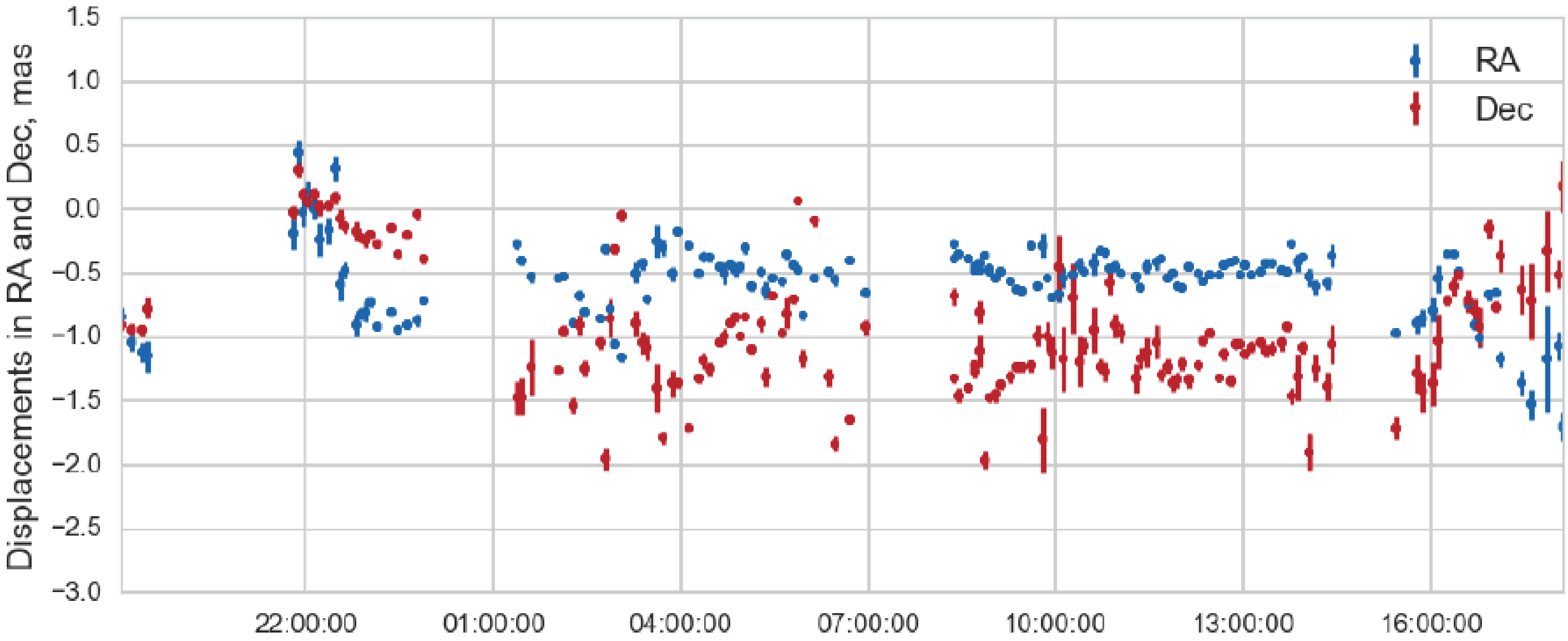
GR035 finding chart



GR035, VLBI astrometry



GR035, VLBI astrometry



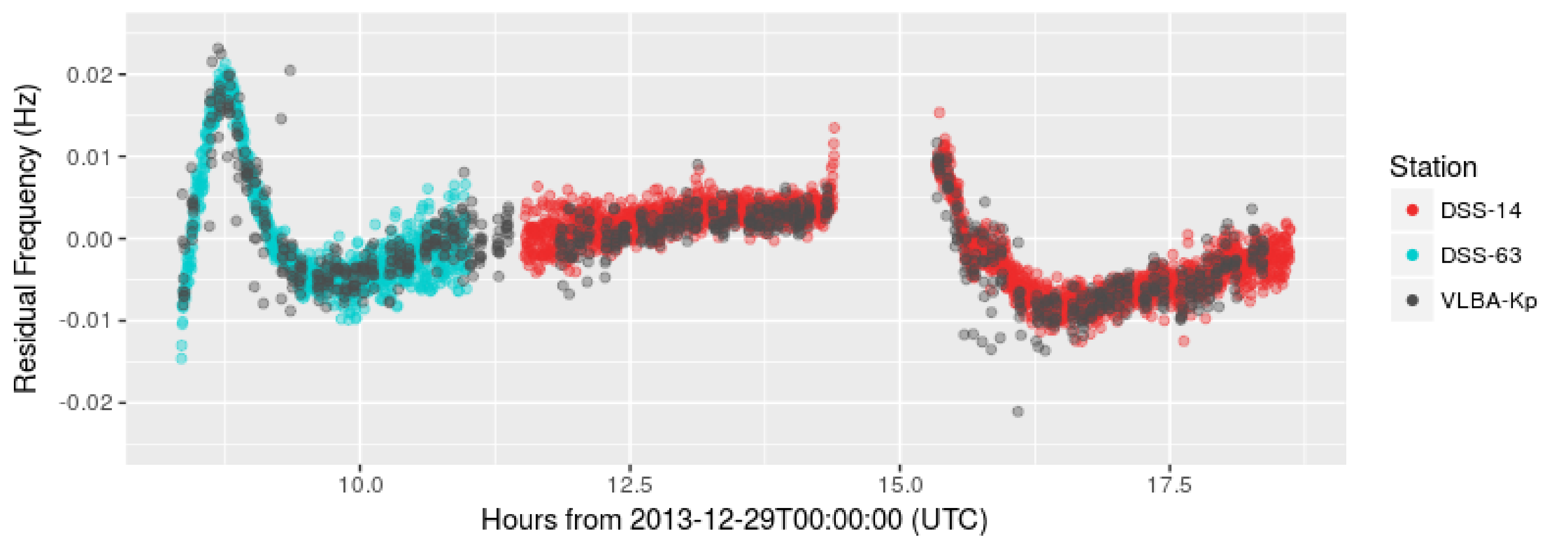
Displacement between measured and predicted MEX celestial position, 2 min per point (imaging approach). “Geodetic approach with ±10 µas.

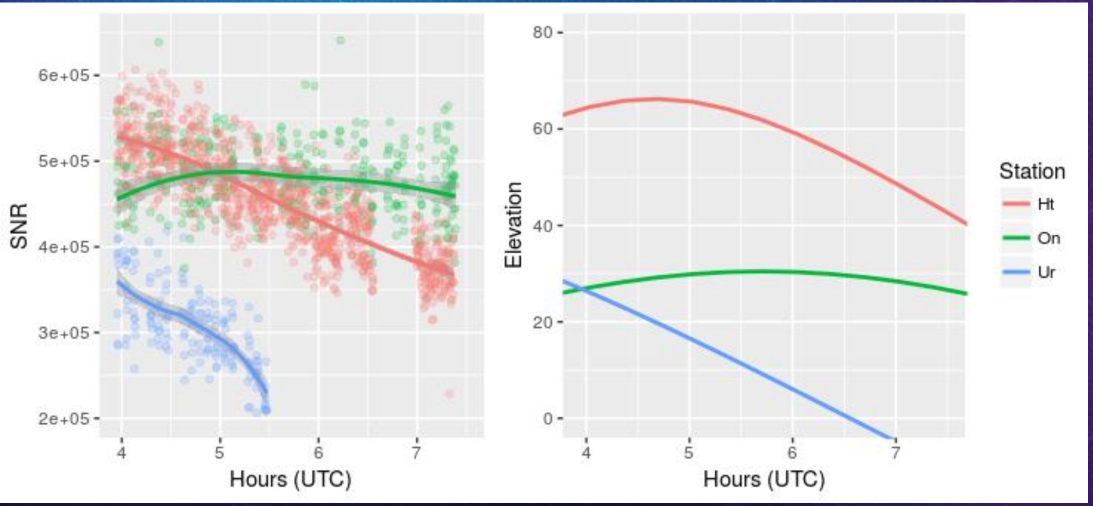
Formal precision (3σ):

RA	**34 µas**	**35 m**
Dec	**58 µas**	**60 m**

Duev et al. 2016, A&A 593, A34

GR035, Doppler detections - II



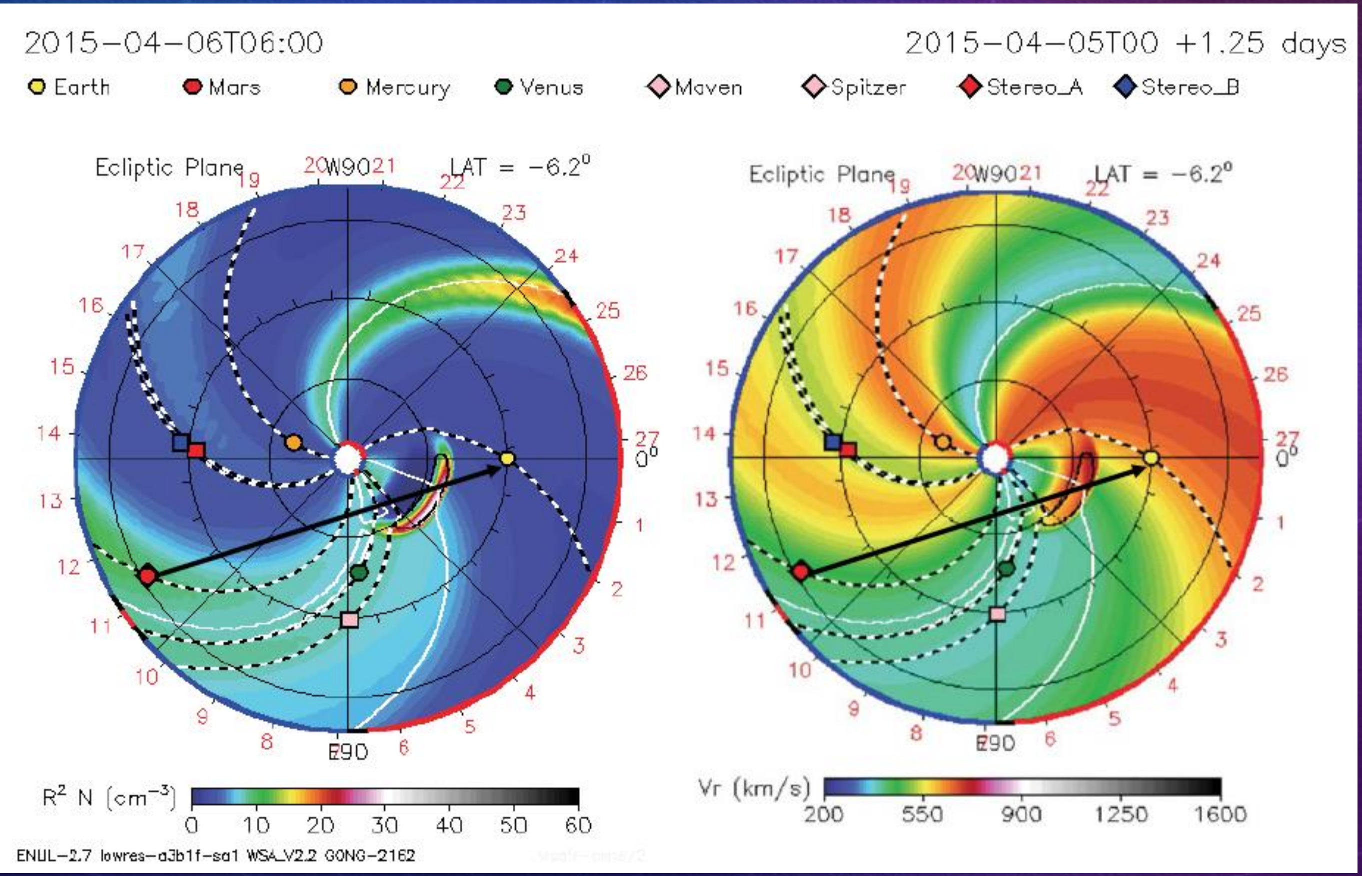


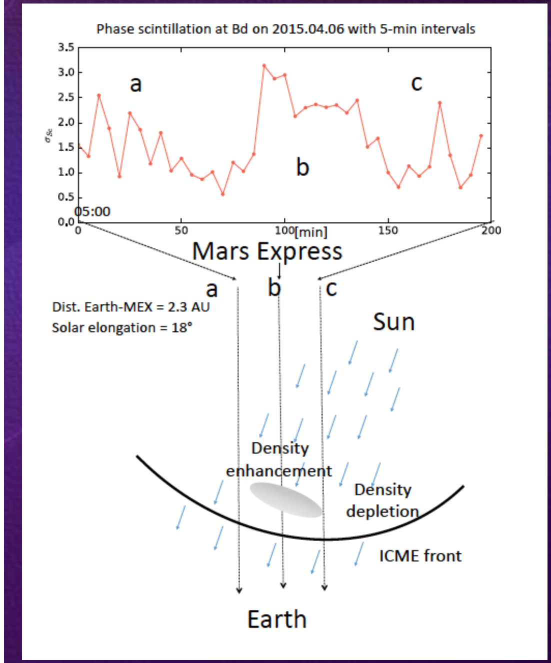
No miracles: more antennas – more choice to pick up the best

Bocanegra et al. 2018, A&A 609, A59

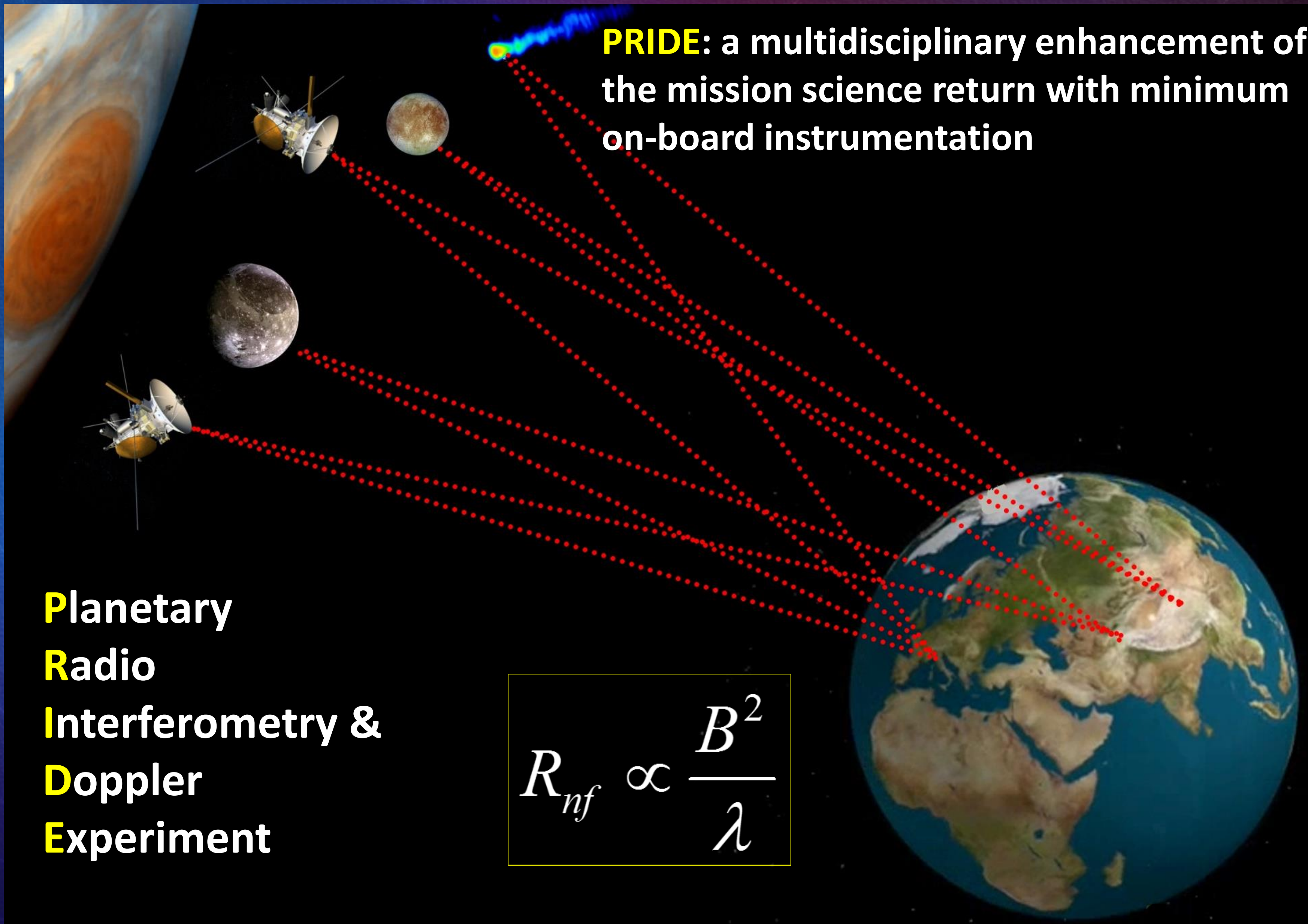
PRIDE by-product: CME detection

Analysis of an Interplanetary Coronal Mass Ejection 1 by a spacecraft radio signal
Molera Calves et al. 2018, Space Weather 15, 1523-1534

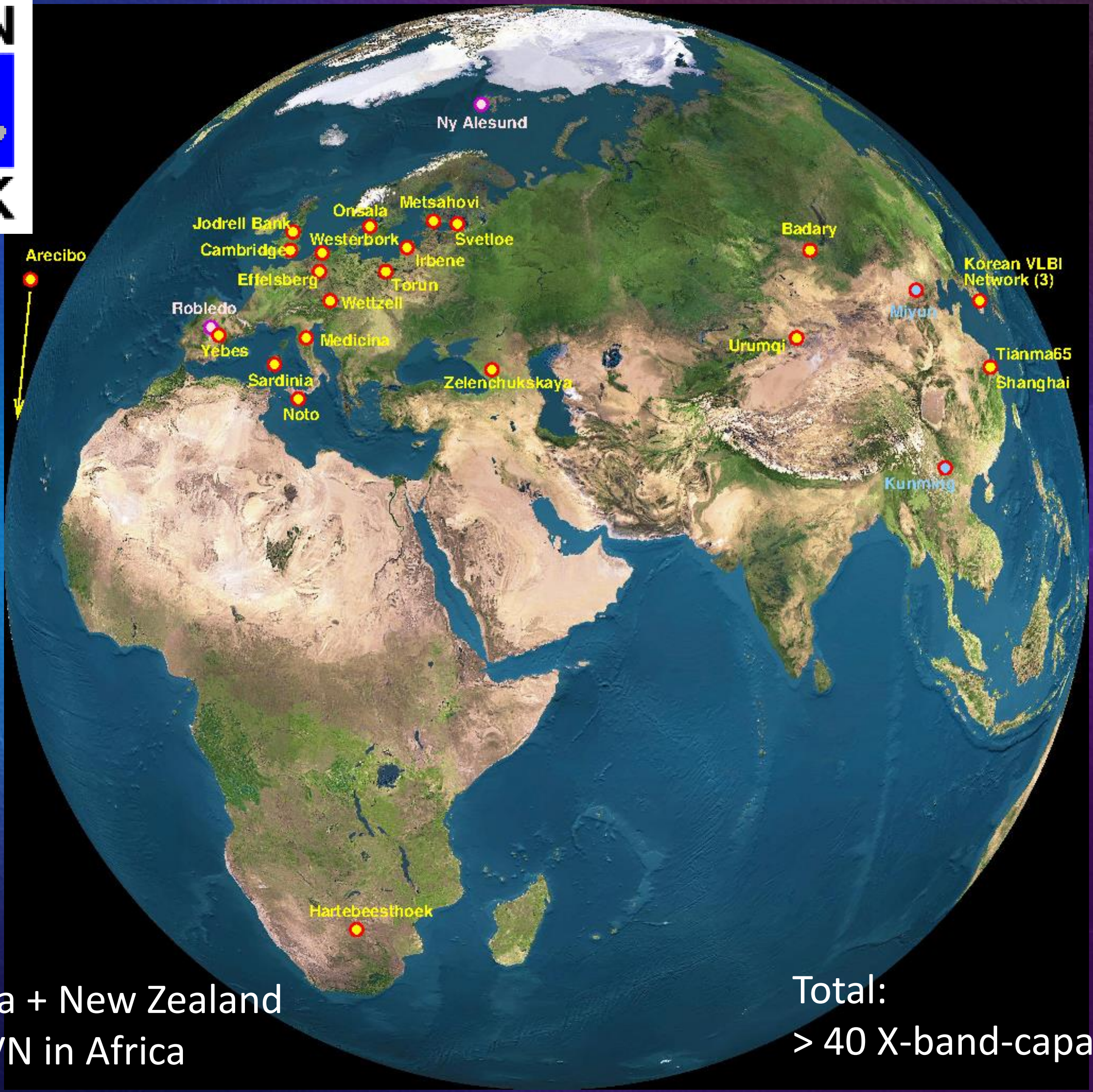




Generic PRIDE configuration



Earth-based segment of PRIDE



Plus:

- VLBA in USA
- LBA in Australia + New Zealand
- Prospective AVN in Africa

Total:
> 40 X-band-capable telescopes