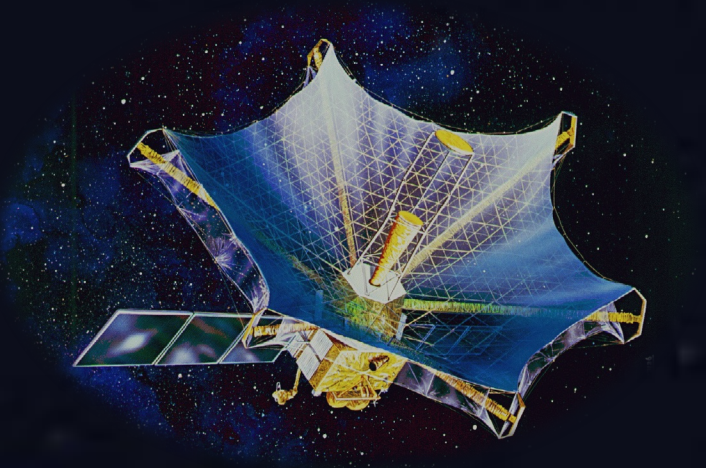
A brief history of Space VLBI



Leonid Gurvits

JIVE

TU Delft

HISTELCON
Florence, Italy
7–9 September 2023

2023: Radio Astronomy turns 90

Karl Jansky
1905–1950

2023: Radio Astronomy turns 90


"All the News That's Fit to Print."

The New York Times.

LATE CITY EDITION

VOL. LXXXII....No. 27,495. NEW YORK, FRIDAY, MAY 5, 1933. TWO CENTS

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

ROOSEVELT ASKS PAY RISE FOR WORKERS; PROMISES TO HELP BUSINESS END CHAOS; HE SENDS RAILROAD BILL TO CONGRESS

BIG NEW INVASION PLANNED BY JAPAN ON ROAD TO PEIPING

KIDNAPPERS URGED TO ANSWER PLEAS

FARM BILL CLAUSE BLOCKS AGREEMENT

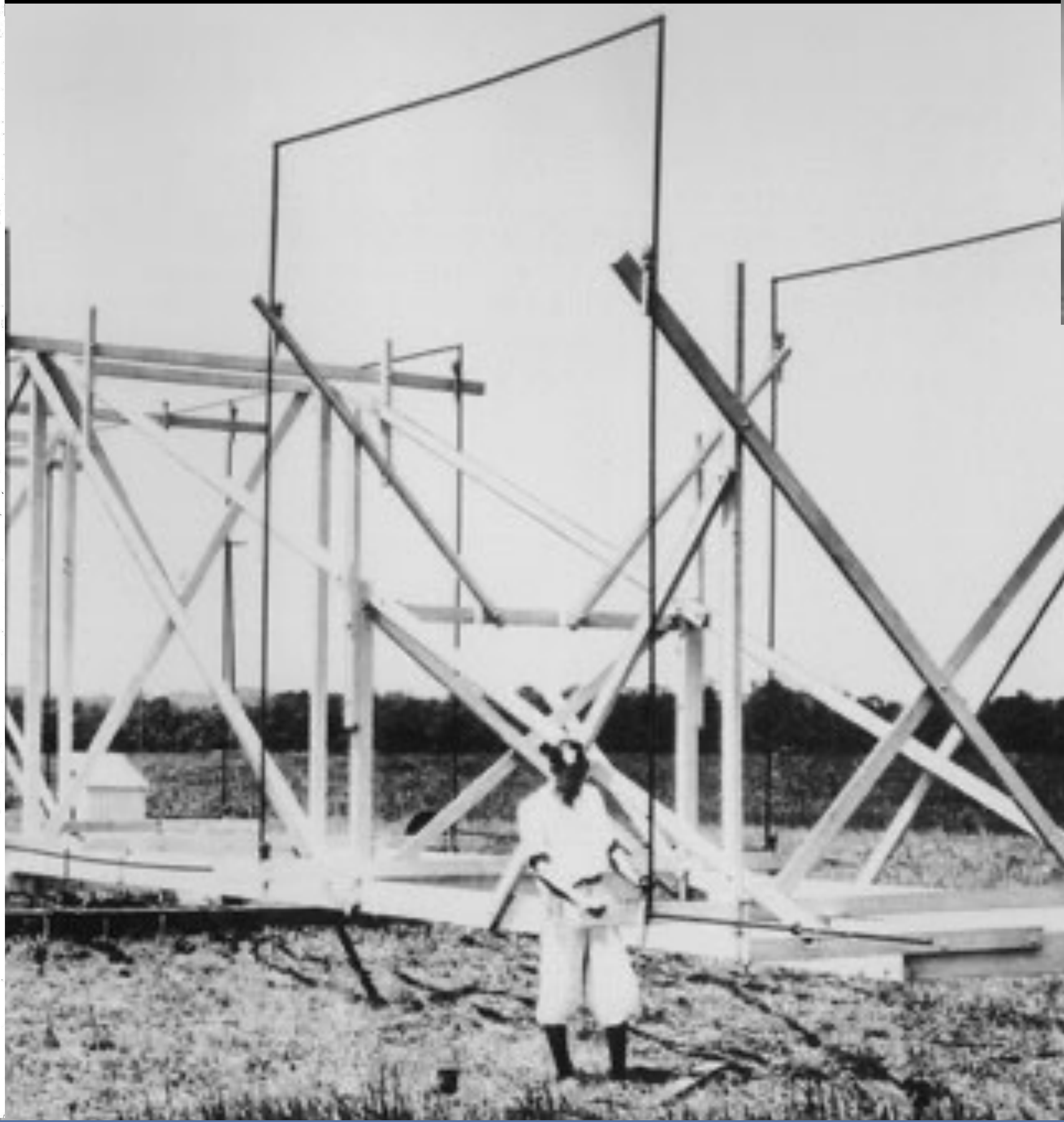
Features of Railroad Bill

PRESIDENT TELLS OF GAINS

BRITISH DEMANDING TARIFF 'SAFEGUARDS'

ITALIANS NOW BACK BRITISH ARMS PLAN

Nazis Plan Demonstration on the Rhine; Border Incidents Already Alarm French



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DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

INTENSITY IS LOW

Flier Asks Blame in Crash, But Inquest Absolves Him

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Larger-Scale Offensive Than Last Is Announced to Open Soon in North China.

CHIANG RUSHES AID NORTH

League Reserve Cut Million By Drop in Dollar Value

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RAIL PROGRAM WIDENED

Recapture Repeal Made Retroactive Under a Far-Reaching Plan.

RATE-MAKING RULE EASED

And I. C. C. Jurisdiction Would Be Extended to Embrace Holding Companies.

HEARINGS TO OPEN SOON

President Asks Swift Action, but Amendments in Senate Are Indicated by Dill.

Features of Railroad Bill

PRESIDENT TELLS OF GAINS

Chamber of Commerce Is Asked to Cooperate on Three Points.

NATIONAL UNITY URGED

Prosperity Held Possible Only If All the Branches of Industry Recover.

GOVERNMENT AID PLEDGED

Unfair Competition and Cut-throat Prices Must Be Fought, He Says.

Famous Units That Fought at Shanghai Are Dispatched to Help 50,000 at Front.

BRITISH QUIT MANCHURIA

KIDNAPPERS URGED TO ANSWER PLEAS

New Yorker Named to Act as Secret Agent for Return of McMath Child.

FARM BILL CLAUSE BLOCKS AGREEMENT

Conferees Reach Accord on All Except the Cost-of-Production Section.

PEEK SLATED FOR TASK

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1905–1950

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By The Canadian Press.

LONDON, May 4.—A chivalrous attempt to assume responsibility for the fatal crash of a Royal Air Force plane on May 1, in which Viscount Knebworth, pilot, and Aircraftman Harrison lost their lives, was made by Flight Lieutenant Eric Hobson at the inquest today. Despite Lieutenant Hobson's action, a verdict of "death due to misadventure" was returned.

Lieutenant Hobson, the leader of the section of which Lord Knebworth was a member, described how he unaccountably lost his height and at the end of a

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League Reserve Cut Million By Drop in Dollar Value

Special Cable to The New York Times.

GENEVA, May 4.—The League of Nations supervisory committee dispersed today after finding its already difficult task of balancing the League's $6,000,000 budget made much harder by the dollar leaving gold.

Practically all of the League's reserves, totaling $5,000,000, are kept in dollars. When the bank moratorium was proclaimed, League officials, after consulting bankers, decided to trust in the dollar. They have now sustained a paper loss of nearly $1,000,000 and have had to exchange part of the reserve at a loss of be-

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RAIL PROGRAM WIDENED

Recapture Repeal Made

Features of Railroad Bill

Special to The New York Times.

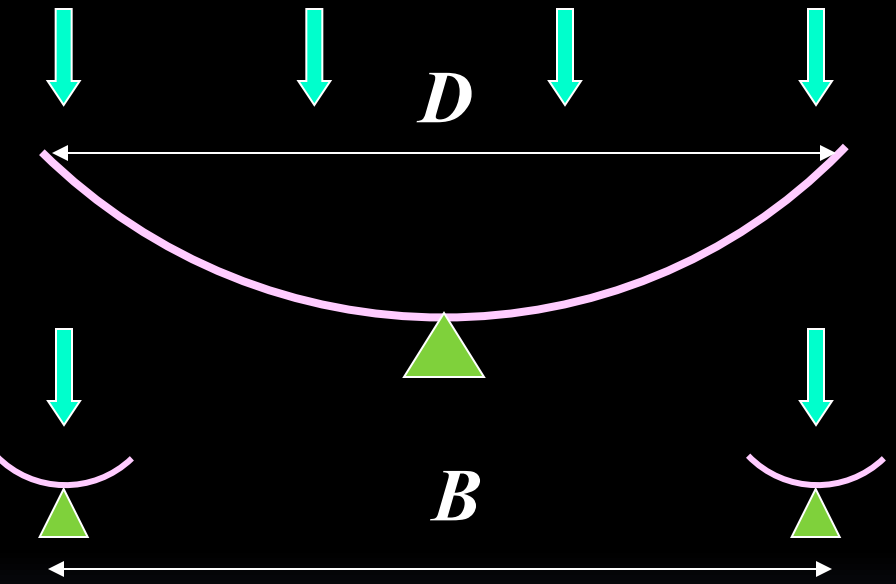
WASHINGTON, May 4.—High lights of the administration's emergency railroad bill, transmitted to Congress today, are as

PRESIDENT TELLS OF GAINS

Chamber of Commerce Is

Interferometry: one-slide tutorial

- Michelson & Young, 1890s: measurements of stars' diameters
- Synthesis of large apertures *(by poor and curious people)*



$$\vartheta = \frac{\lambda}{D}$$

Large aperture – high sensitivity

$$\vartheta = \frac{\lambda}{B}$$

Large size – high angular resolution

At present, interferometry in astrophysics covers wavelengths from 10^{3} cm (~30 MHz) to 10^{-4} cm (~300 THz), except sub-mm & far IR

Very Long Baseline Interferometry (VLBI)
– the ultimate angular resolution in astrophysics

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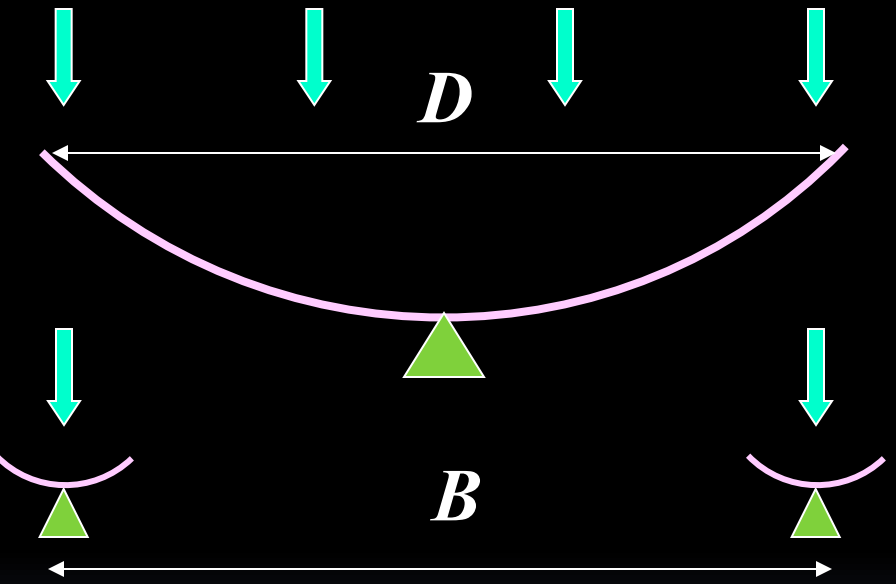

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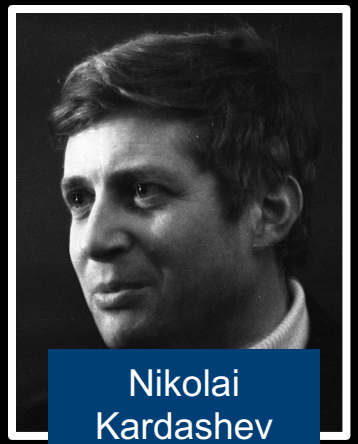
1963–1965: Space VLBI “conspiracy”

Matveenko, Kardashev, Sholomitsky 1965 (manuscript of 1963)

Gennady Sholomitsky

Leonid Matveenko



Nikolai Kardashev

Физический институт им. П. Н. Лебедева
АН СССР

ИЗВЕСТИЯ ВЫСШИХ УЧЕБНЫХ ЗАВЕДЕНИЙ

Том VIII, № 4 *РАДИОФИЗИКА* *1965*

Поступила в редакцию
27 января 1964 г.,
после доработки
14 января 1965 г.

ON RADIOINTERFEROMETER WITH A LARGE BASE

L. I. Matveenko, N. S. Kardashev, G. B. Sholomitsky

The radiointerferometer system without retranslation has been considered. The signal registration at the intermediate frequency is carried out independently by each antenna (by recording on a magnetic tape) with subsequent common processing of these results. The usage of two independent heterodynes imposes the following condition for their frequency stability $\sqrt{\overline{\Delta f_h^2}}/f_h \leqslant 1.6 \cdot 10^{-11} D$ (D is the base length in km). The merits of such interferometer have been discussed.

- The [interferometric] system proposed here can be used conveniently for radio astronomy observations from artificial Earth satellites. A system consisting of two antennas, placed on satellites, would allow getting not only amplitudes but also spatial phase parameters of interference on long baselines, thus enabling investigation of detailed brightness distribution in discrete radio sources of very small angular sizes. In this case, ionosphere and troposphere fluctuations that make phase measurements very difficult are eliminated.

- Предлагаемую систему удобно также использовать для радиоастрономических наблюдении с ИСЗ. Система из двух антенн, установленных на ИСЗ, работающая по описанному выше принципу, позволит получать при больших базах не только амплитудные, но и пространственно-фазовые характеристики интерференции, а, следовательно, детально исследовать распределение яркости дискретных источников очень малых угловых размеров. В этом случае устраняются ионосферные и тропосферные флуктуации, являющиеся основным препятствием при измерении фазы.

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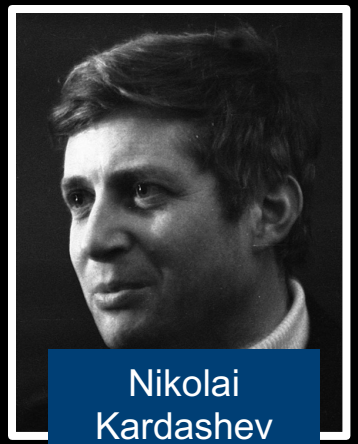

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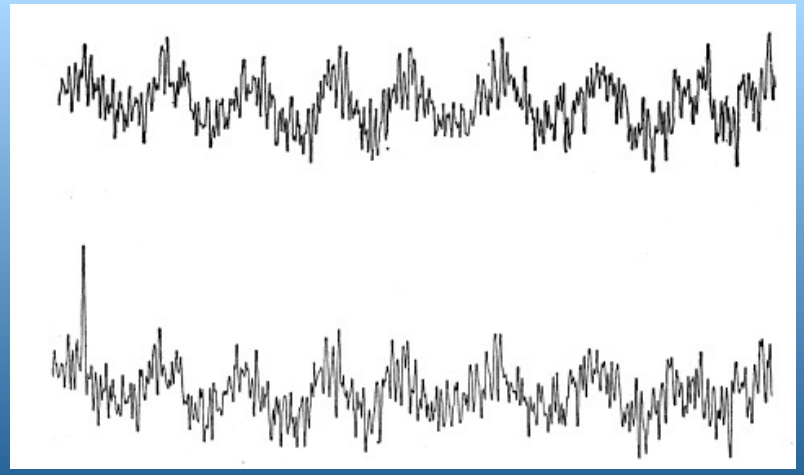
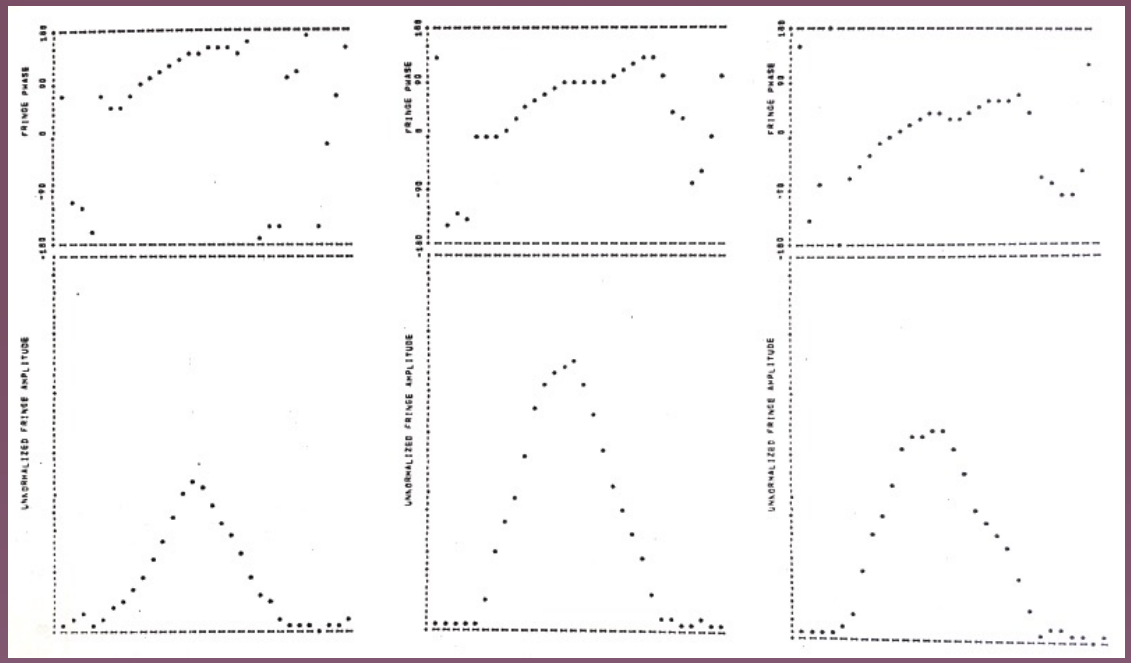
1967: the first VLBI fringes



VLBI fringes on 3C 294 (short baselines), VLBI technology demo
Broten et al. 1967, Science 156, 1592-93



VLBI detections (OH) Haystack–NRAO, observed 1967.06.08
Moran 1968, PhD thesis, MIT

Table 1. Interferometer fringe visibility. S_0, 21.5×10^{-21} watt/m² per hertz assumed flux for 3C 286 at 610 Mhz; S/S_0, assumed ratio of flux to that of 3C 286; F/F_0, ratio of fringe amplitude to that of 3C 286; γ, fringe visibility.

Source	S/S_0	F/F_0	γ
3C 237	0.51	0.37	0.71
3C 273B	.82	.86	1.02
3C 286	1.00	1.00	0.97
3C 287	0.49	0.54	1.07

VLBI detections NRAO-USNO
Bare, Clark, Kellermann, Cohen, and Jauncey 1967, Science 157, 189-191

Plus: “unrecorded MkIII-style VLBI developments @ Jodrell Bank, 1967 (*P.Diamond, 19***)

For first-hand history details – see
Moran J.M. 1998, ASP Conf. Ser. v. 144

SVLBI science drives: λ/B at work

- The quest of high brightness in extragalactic sources
  - related physics of the innermost regions in AGN
    - *pro memoria: tackling high T_B needs physically long baselines!*
    - *Earth (~10^4 km) matches perfectly T_B ~10^{12} K in ~ 1 Jy source*
- Enigmatic (stellar) maser sources known to be compact
- Above all: pushing the parameter space envelope

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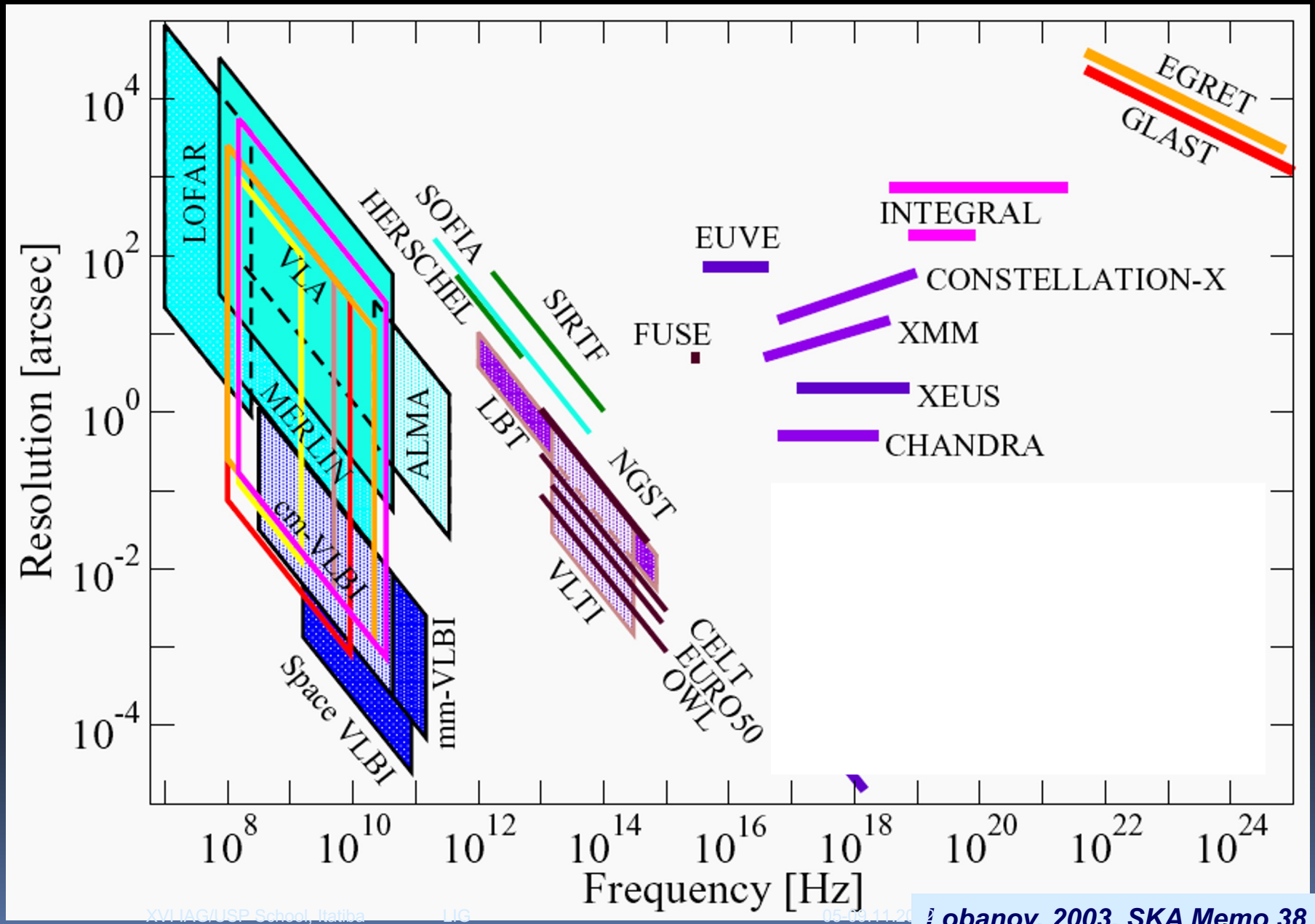
- Above all: pushing the parameter space envelope

"We do it not because it's simple but because it's hard"

– John F. Kennedy, May 1961

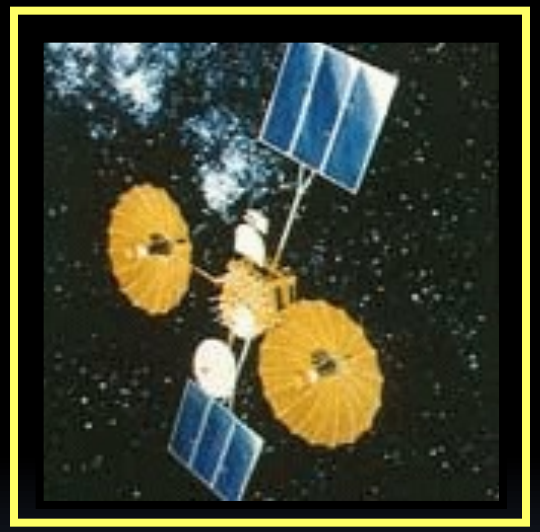
Best (imaging) angular resolution across EM spectrum



Lobanov. 2003, SKA Memo 38

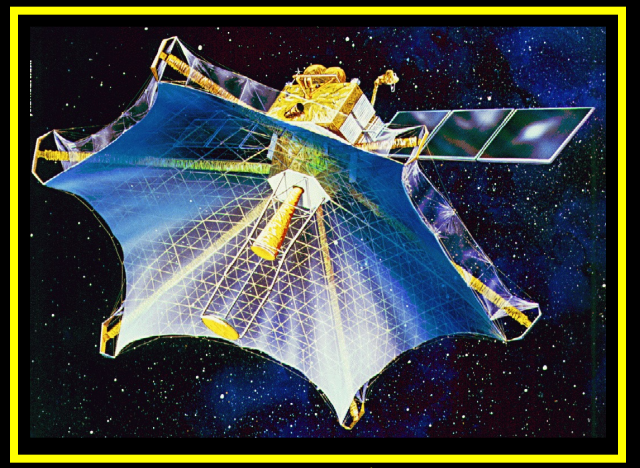
Three generations of Space VLBI

1986–88



TDRSS-OVLBI, Ø 5m

1997–2019



VSOP, Ø 8m

RadioAstron, Ø 10m

>2030

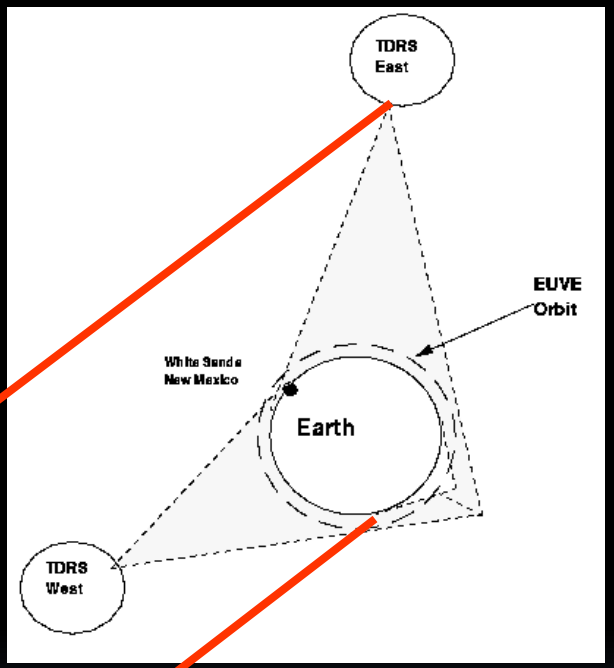
?

Must be more sensitive!
Must be versatile
Must be more efficient
Must be user friendly

Design studies:

- **KRT-30 (1978-82)**
- **QUASAT (1980s)**
- **IVS (1987-91)**
- **ALFA (1990s)**
- **(i)ARISE (2000s)**
- **VSOP-2/Astro-G**
- **Chinese SVLBI**
- **THEZA, EHE**

TDRSS-OVLBI: proof of SVLBI concept, 1986



Gerry Levy

$B=2.2D_{Earth}$

- 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

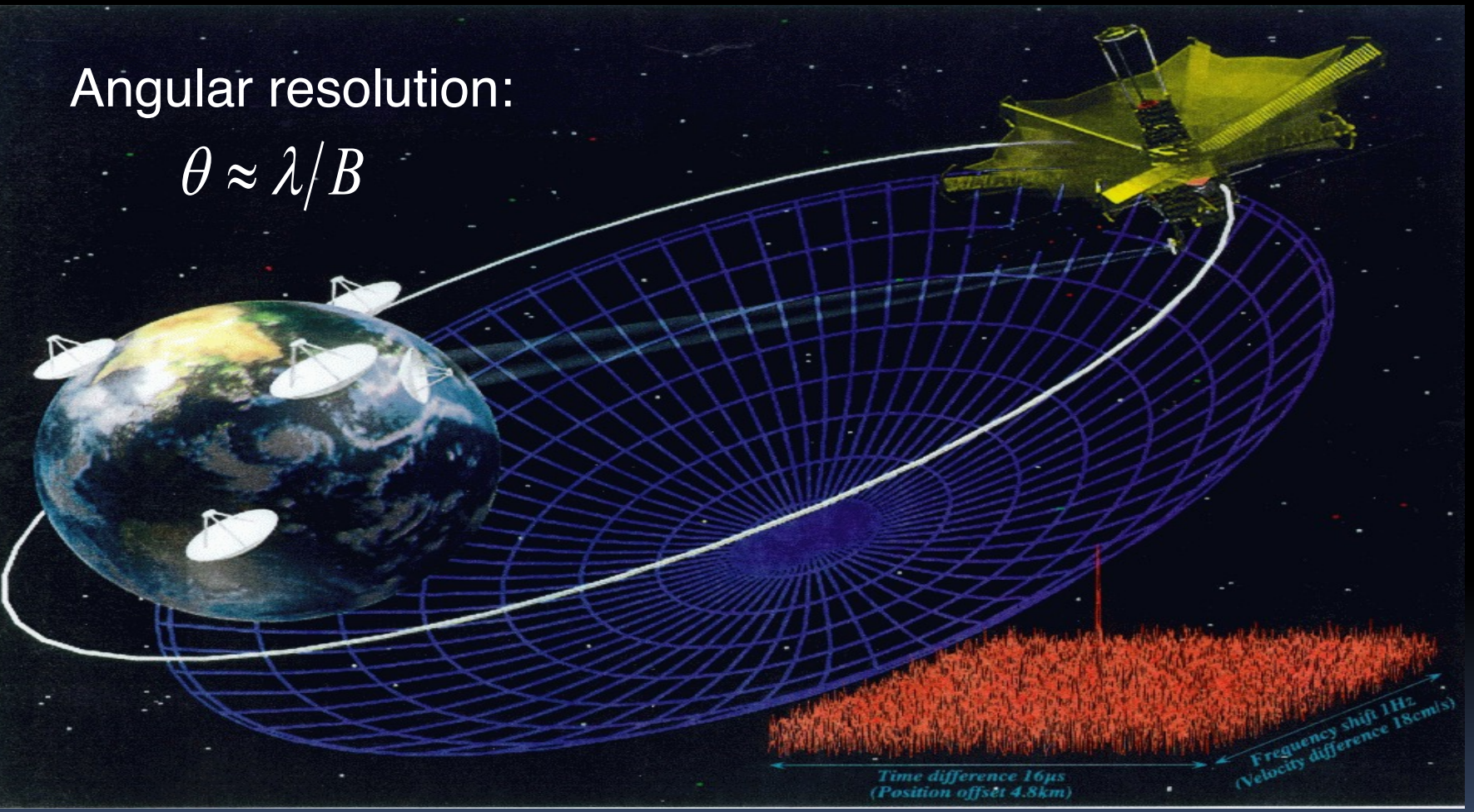
Levy et al. 1986, Science 234, 187

VLBI beyond the Earth diameter: VSOP mission

ISAS, Japan + world-wide collaboration (1988; 1997–2003)

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

Inter-Agency Consultative Group, Rome, 7 Nov 1986

Inter-Agency Consultative Group, Rome, 7 Nov 1986

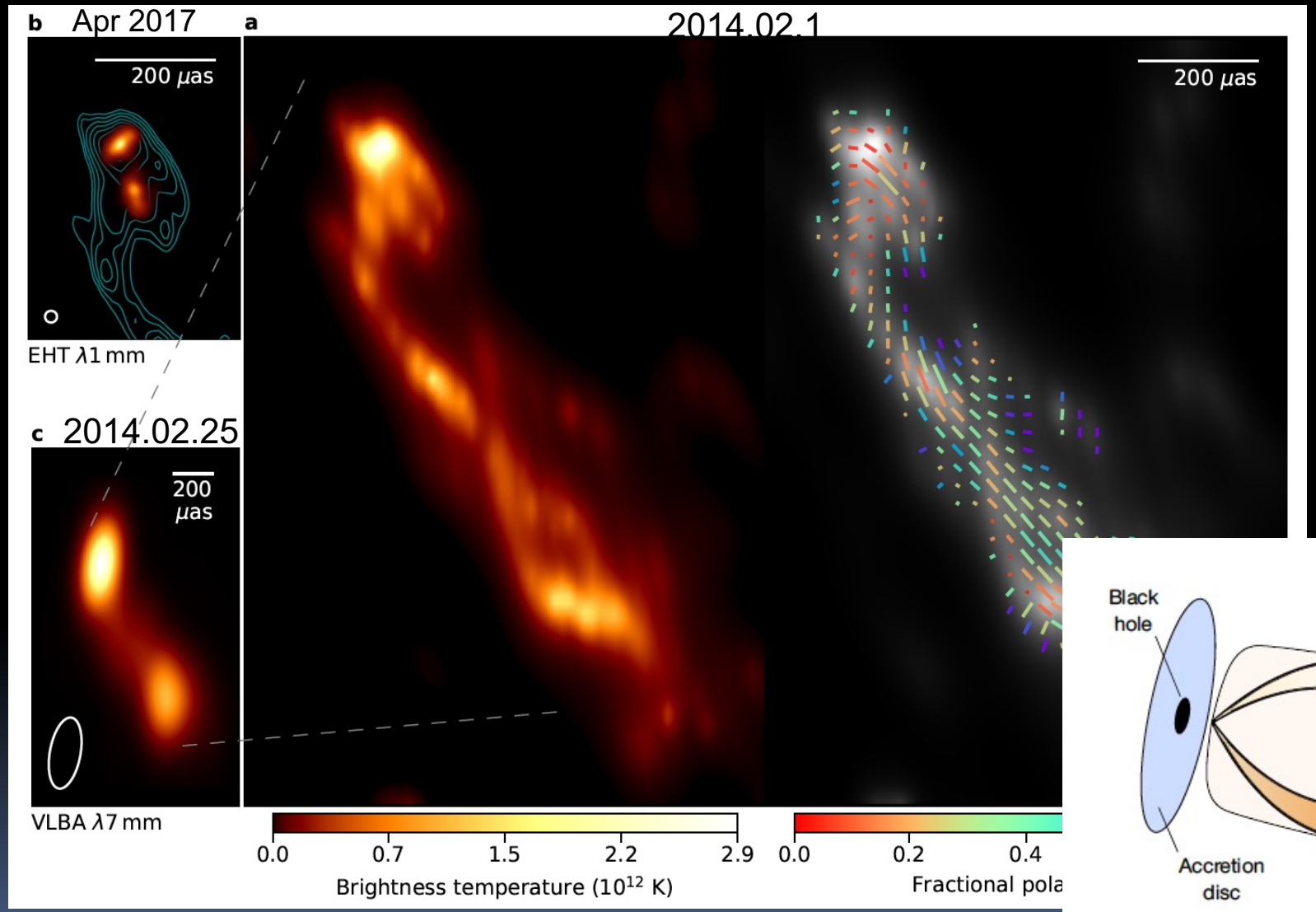
RadioAstron (development since 1978; 2011-2019)

- 10-m antenna
- 0.327, 1.6, 5 and 22 GHz
- Dual-polarization
- Data rate128 Mbps
- 2 on-board H-masers
- Apogee (initial) – 343,000 km
- Data reception – Pushchino (RU), Green Bank (USA)

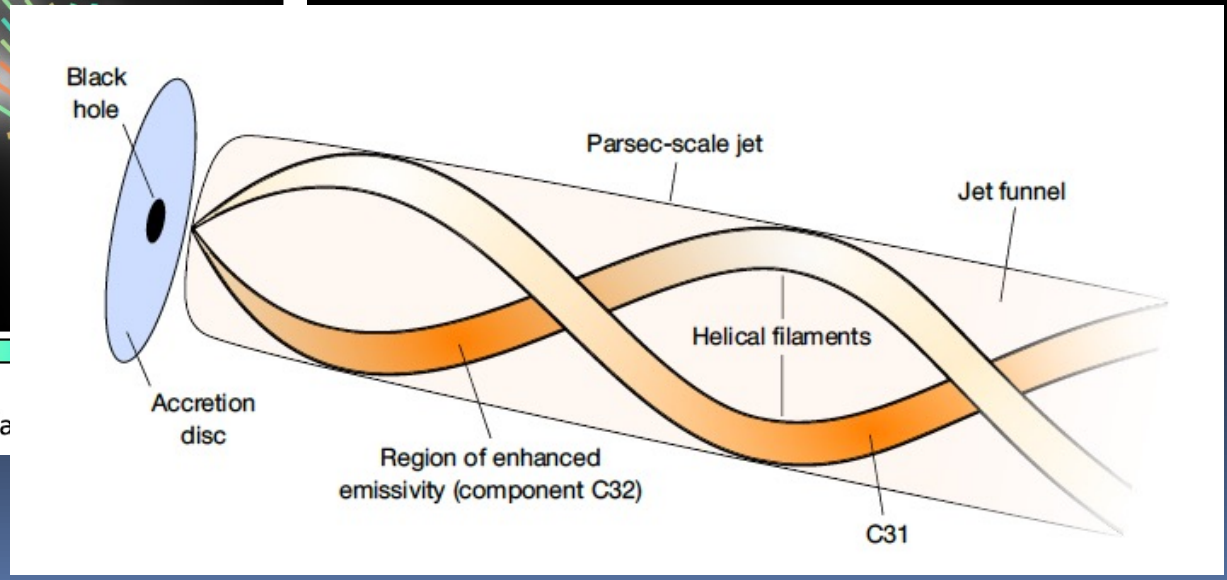
- Leading agencies:
  - *Roscosmos*
  - *Russian Academy of Sciences*
- In development since 1978
- Launch: Baikonur, 18 July 2011
- End of mission June 2019

3C 279 with RadioAstron: spiral filaments

Fuentes et al., 2023, in prep



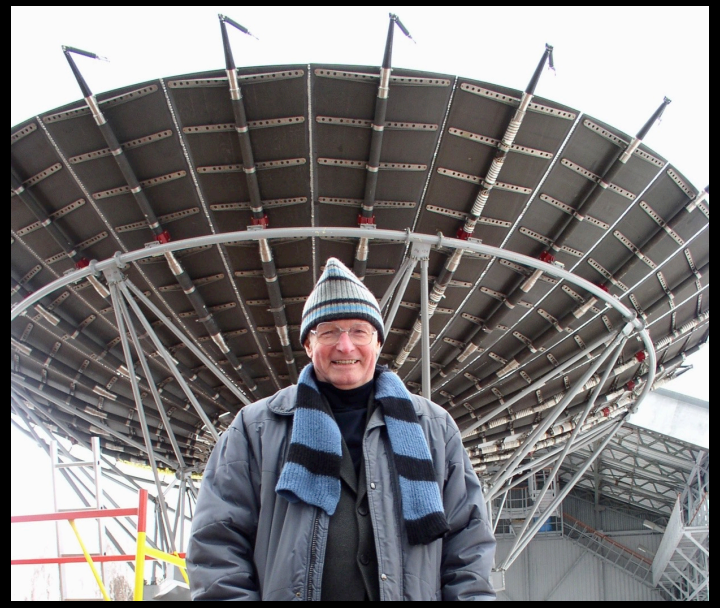
- 27 μas in EW dir.
- Alignment vs. core shift (~35 μas)
- $DR_{RA} \approx 100 \times DR_{EHT}$
- Messy inner morphology
- Spirales and knots



SVLBI space-borne hardware (TRL=?)

- Antennas ~10 m and larger: tests, tests, tests…

Lessons learned…



- "Analogue" instrumentation: problems with
  - *HALCA: 22 GHz*
  - *RadioAstron: 5 GHz*
- Digital instrumentation:
- well behaving, but
  - *Data rate lower than needed*

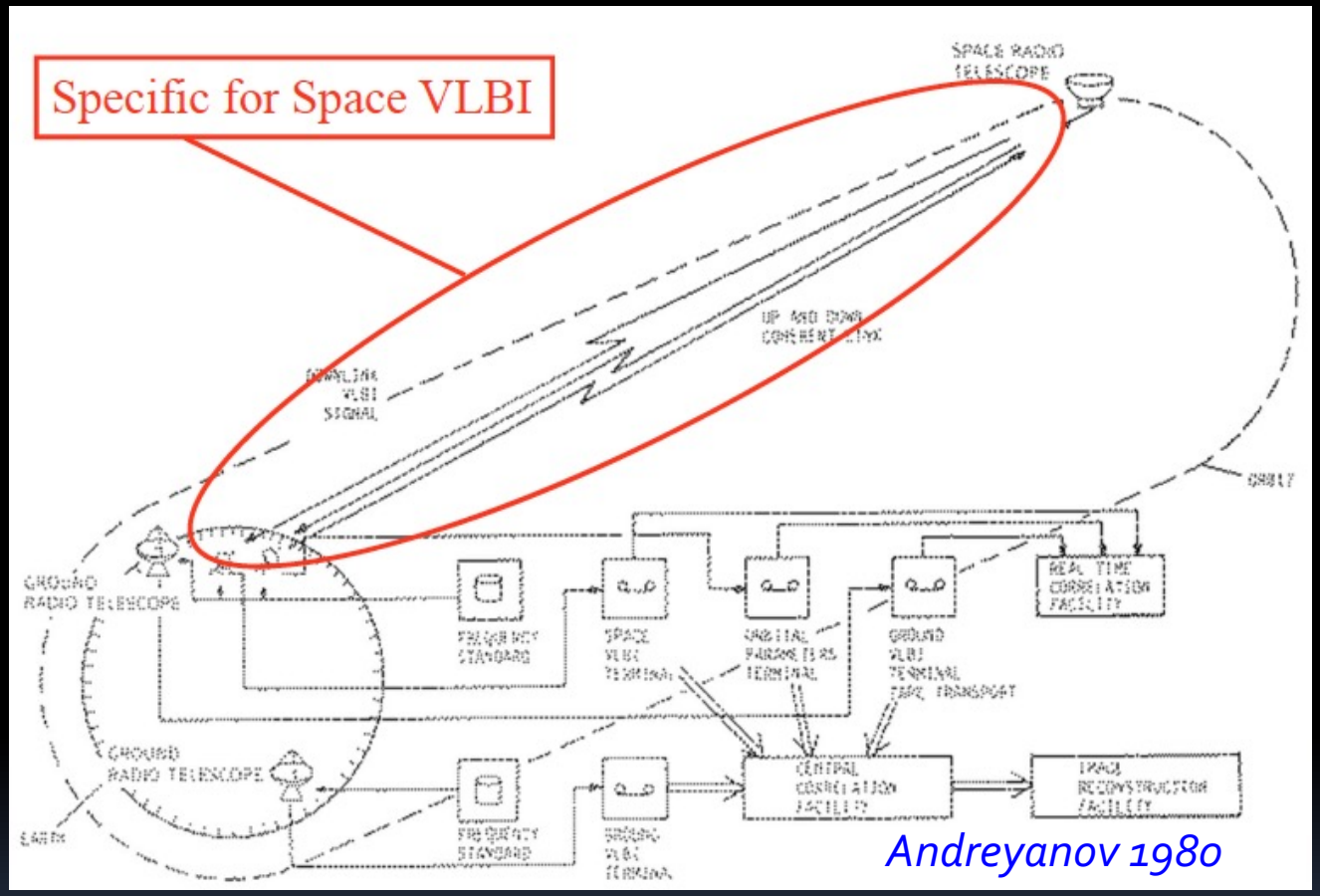
- *Above all:*
  both missions – great success!

MAJOR SPECIFICATIONS OF THE IMPLEMENTED TO DATE SVLBI SYSTEMS

	TDRSS	*VSOP*	*RadioAstron*
In-orbit operations	1986–1988	1997–2003	2011–2019
Diameter of antenna [m]	5.8.	8.8	10
B_{max} [ED][a]	2.2	3	28
Wavelengths [cm]	13, 2	18, 6	92, 18, 6, 1.3
Data rate [Mbps]	28	128	128

[a]Maximal baseline projection on the image plane in units of Earth Diameters [ED].

It’s about coherency…

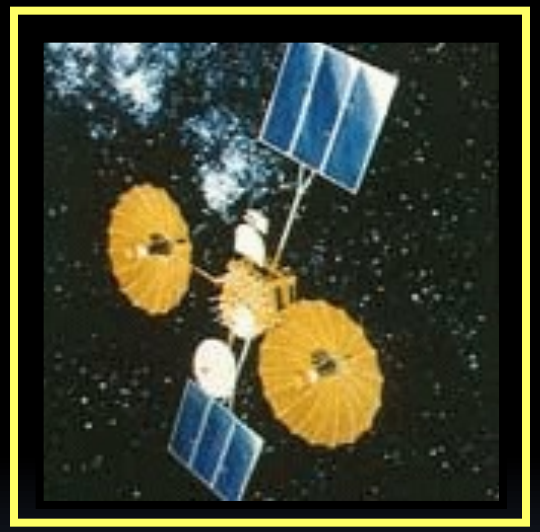


Active space-qualified H-maser
ASC, ~2008

- Both, PLL (HALCA and RadioAstron) and on-board H-maser (RadioAstron only) worked fine
- So, optimise the cost or operational parameters

Three generations of Space VLBI

1986–88



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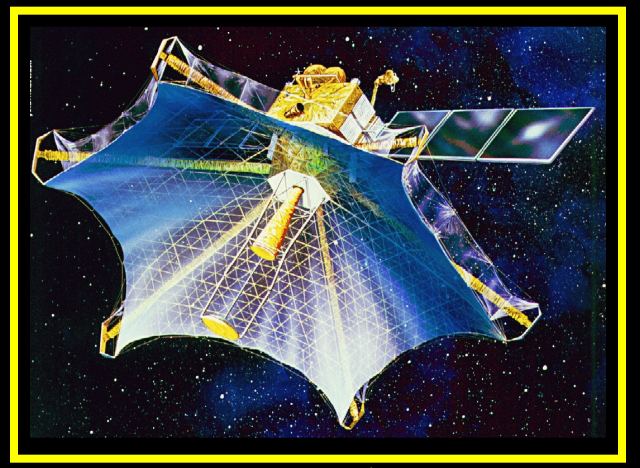

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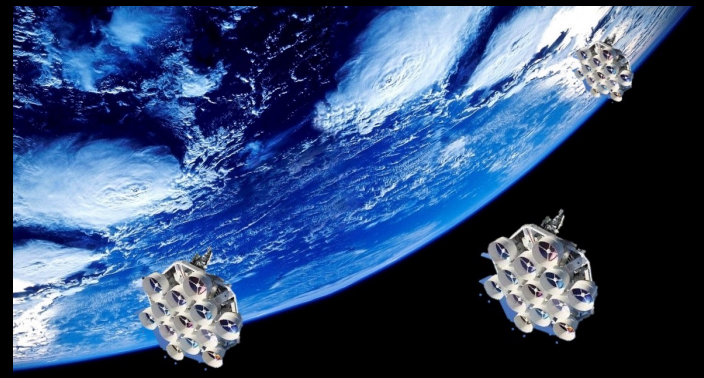
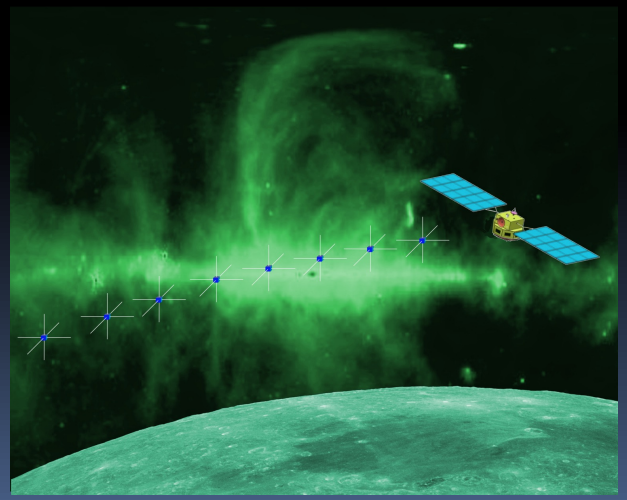


THEZA



ULWA DSL

VLBI and Space VLBI must be international!

RadioAstron–EVN MoA
1986, N. Kardashev & G.Setti

Summary

- Space VLBI: inevitable, difficult, but doable

- Science legacy:
  - Brightness in AGN is somewhat above theory limits
  - No “stunning” T_B values?
  - Stellar and mega-masers: brighter than expected?
  - Refractive scattering at work?

- The main technical bottle-neck – data downlink (data rate – likely to be driven by industry)

The pioneers of Space VLBI

Vladimir Andreyanov
1931–2016
RadioAstron

Haruto Hirosawa
b.1940
VSOP–HALCA

Nikolai Kardashev
1932–2019
RadioAstron

Hisashi Hirabayashi
b. 1943
VSOP–HALCA

Gerry Levy
1929–2017
TDRSS–OVLBI

Inter-Union IAU URSI WG on Historical Radio Astronomy

https://rahist.nrao.edu