The Origins of VLBI
or 1967 – The Summer of Love

James Moran
Harvard-Smithsonian Center for Astrophysics

Black Hole Astrophysics with VLBI: Past, Present, and Future
Workshop in Honor of Professor Makoto Inoue's Retirement
March 27–29, 2017
Tokyo, Japan

Collaborations with Inoue-san
17 Papers (1991–2016)

- Early millimeter-wavelength VLBI
- NGC4258 megamaser
- Event Horizon Telescope (EHT)

Vera Rubin Presenting Makoto Inoue and Jim Moran (on Behalf of the NGC4258 Group*) the Rubin Prize, March 1995

*Miyoshi, Moran, Herrnstein, Greenhill, Nakai, Diamond, Inoue

Scientific Motivation for VLBI in the Mid-1960s

Quasars

- Unresolved on Jodrell Bank to Malvern baseline of 127 km at 5-cm wavelength
- Smaller than 0.025″
- Interplanetary Scintillation, less than 0.01″

OH Masers

- Unresolved on Haystack to Harvard baseline
- Baseline of 13 km at 18-cm wavelength and Jodrell Bank to Malvern
- Smaller than 0.1″

VLBI Technology Precursors

- One-bit sampling theory (Van Vleck, 1943)
- One-bit digital correlator (Weinreb, 1961)
- Rubidium clock (Varian/Hewlett-Packard, 1964)
- Hydrogen maser (Ramsey, Vessot, 1964)
- Video tape recorder (Ampex, 1963)
- IBM 6250 digital recorder (1964)
- Loran C and traveling clocks for time sync (1946)

Some Intellectual Roots of VLBI

1963 Lovell travels to USSR to discuss VLBI

1965 Kellermann and Cohen noted that newly released Varian R-20 Rb frequency standard would make VLBI easy. “VLB” after “VLA”
(term “VLBI” ~1970+)

1966 University of Florida group plans VLBI at 18 MHz using audio tape recorders

1965 Matveenko, Kardashev, Sholomitskii paper

First Published Paper Describing Radio Interferometry with Independent Local Oscillators and Tape Recorders

LARGE BASE-LINE RADIO INTERFEROMETERS

L. I. Matveenko, N. S. Kardashev, and G. B. Sholomitskii

Izvestiya VUZ. Radiofizika, Vol. 8, No. 4, pp. 651-654, 1965

A radio interferometer system is considered in which the intermediate frequency signals are recorded independently on magnetic tape at each antenna and then combined. The frequency stability of the two independent local oscillators must be such that $\sqrt{\overline{\Delta f_h^2}}/f_h \leqslant 1.6 \cdot 10^{-11} D$ (D is the baseline in km). The advantages of the system are discussed.

"The further apart the antennas, the smaller the required stability. In particular, for baselines of about 1000 km, crystal oscillators are sufficient."

Early VLBI Experiments

- **Canadian VLBI Group**

  April 1967 published: Broten et al., *Nature*, July 1, 1967

  Algonquin–Penticton; 448 MHz, 3074 km, res = 0.04″

  Analog system; bw = 1 MHz

- **Cornell-NRAO Group**

  May 1967 published: Bare et al., *Science*, July 14, 1967

  Green Bank–Maryland Point; 610 MHz, 220 km, res = 0.5″

  Mk1 digital system (1 bit/sample); bw = 360 KHz

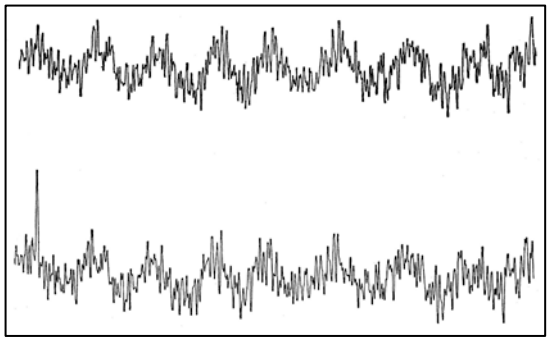
- **MIT Group**

  June 1967 published: Moran et al., *Science*, August 11, 1967

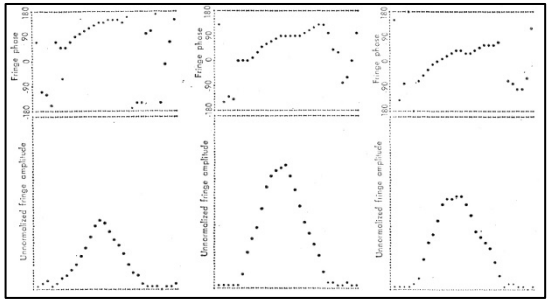
  Green Bank–Haystack; 1665 MHz, 845 km, res = 0.045″

  Modified MkI (5 and 120 KHz bw)

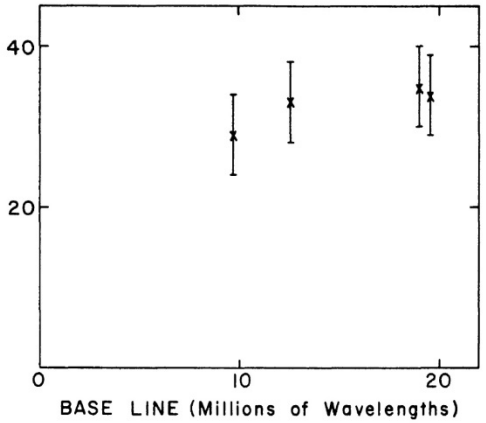
First VLBI Fringes



Broten et al., *Nature*, 1967
3C294
448 MHz



Moran et al., *Science*, 1967
W3(OH)
1665 MHz
Haystack–Green Bank

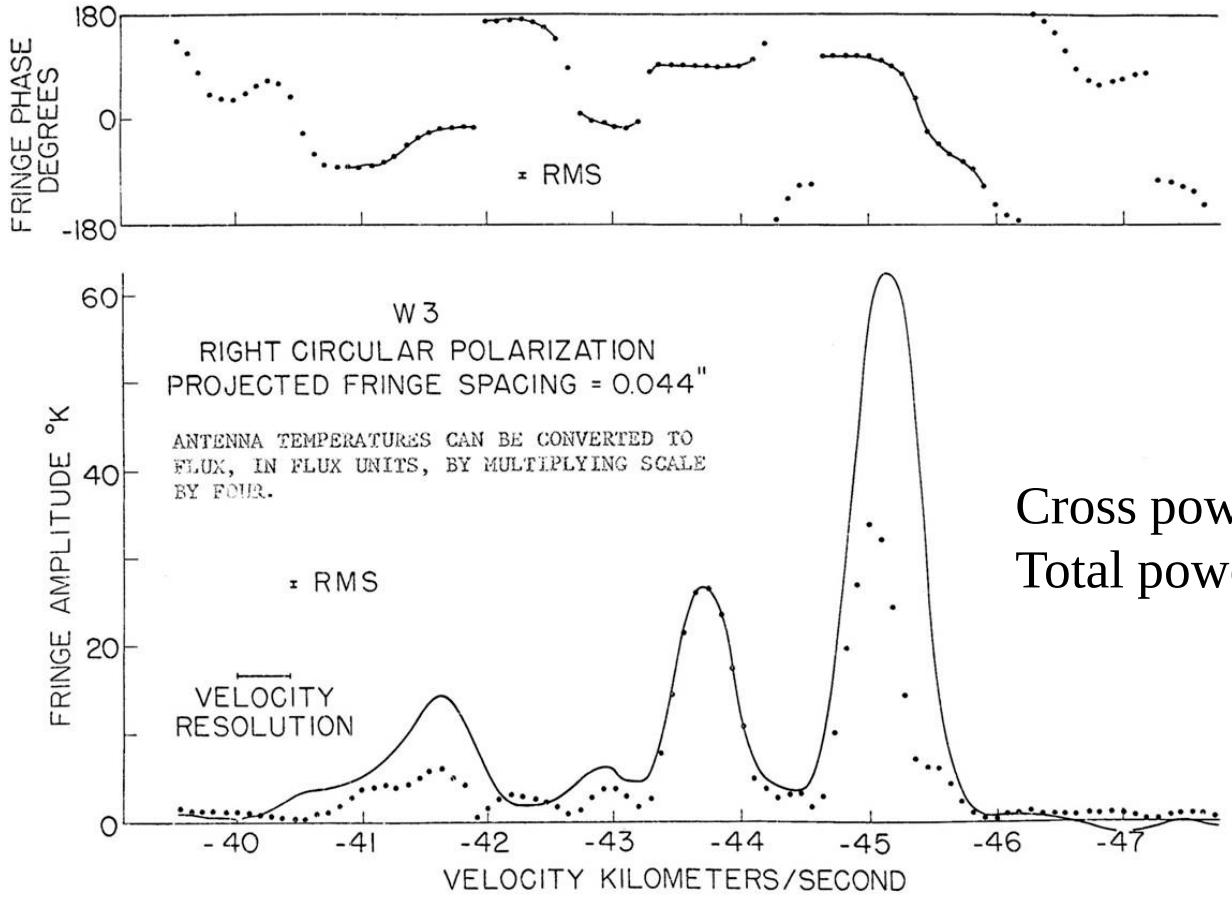


Clark et al., *ApJ*, 1967
3C273
1665 MHz
Haystack–Green Bank

Early Results

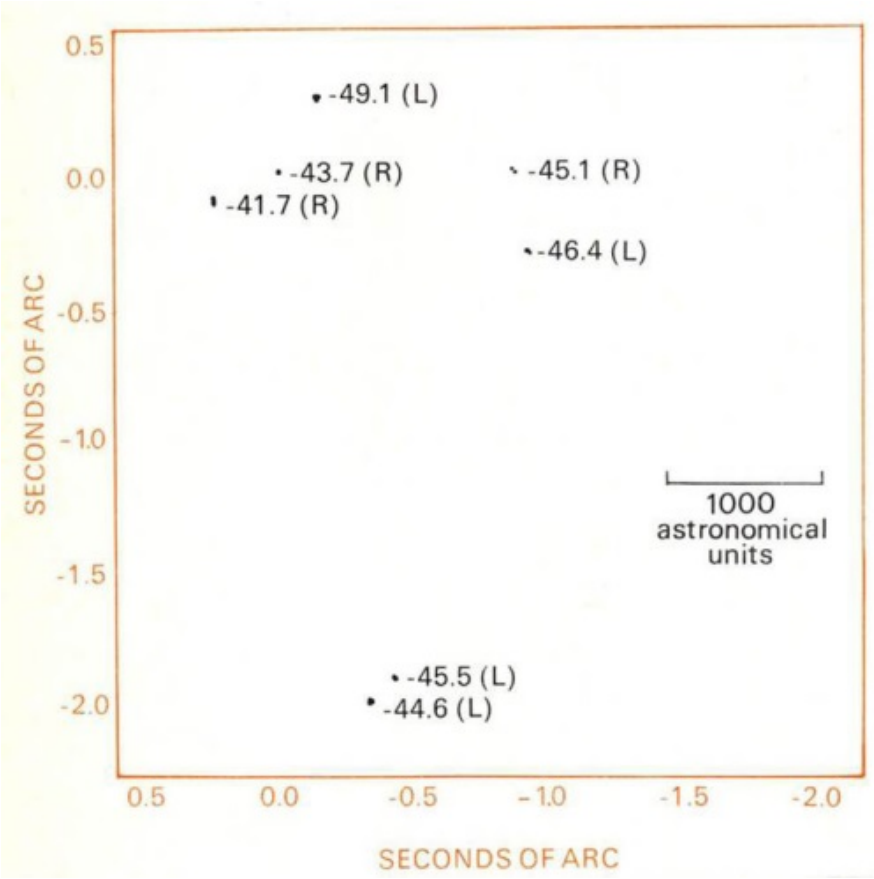
- Quasar brightness approaching Compton limit ~10^{13}K
- Superluminal expansion in quasars
- OH Masers resolved into compact “spots”
- Contemporary plate motions

Interferometer Spectrum of W3 in 120 KHz Band (June 1967)

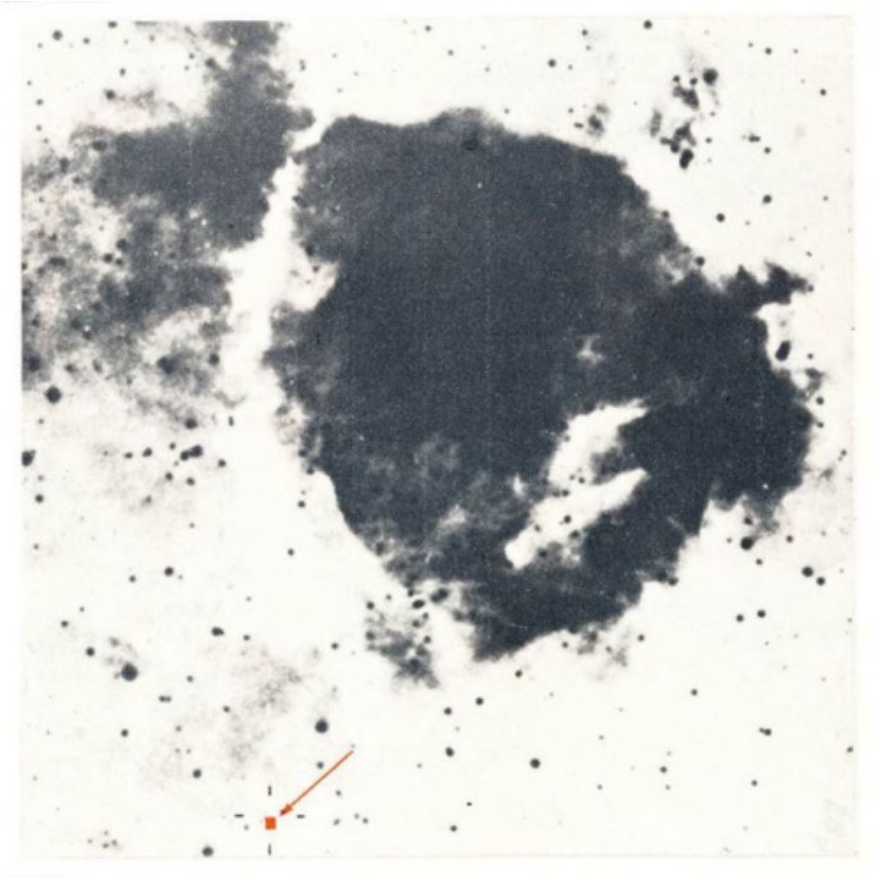


Cross power (solid)
Total power (dotted)

VLBI Image of W3 Maser

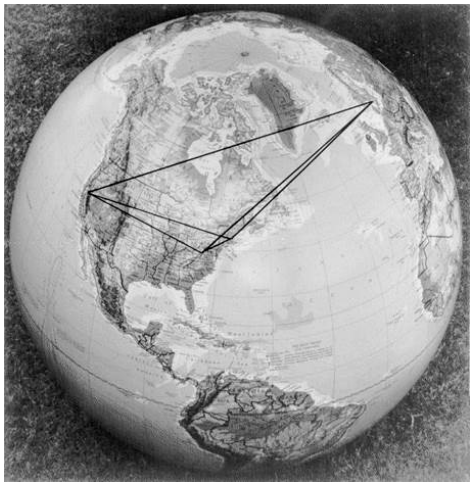


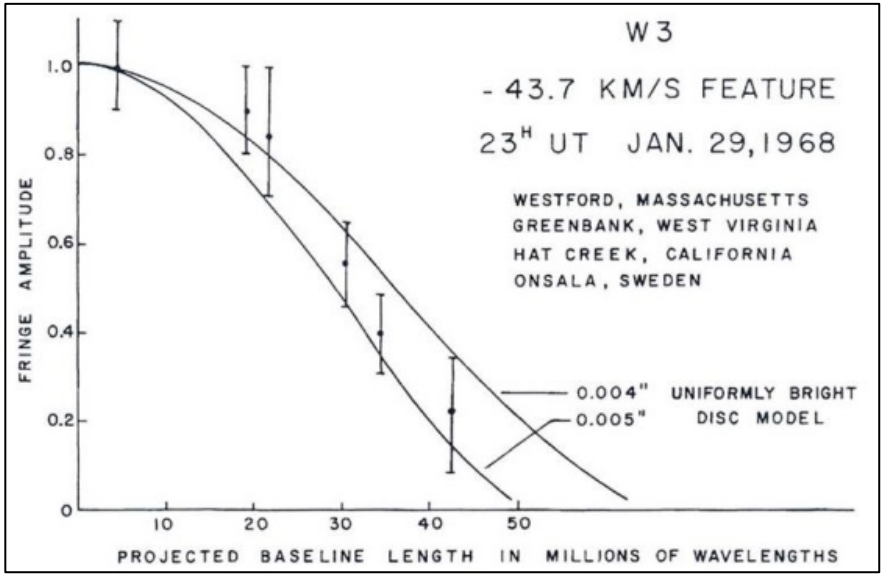
Palomar Sky Survey Image of W3 HII Region



Moran et al., ApJ, 1967

First Resolution of a Maser “Spot”





First VLBI Fringes

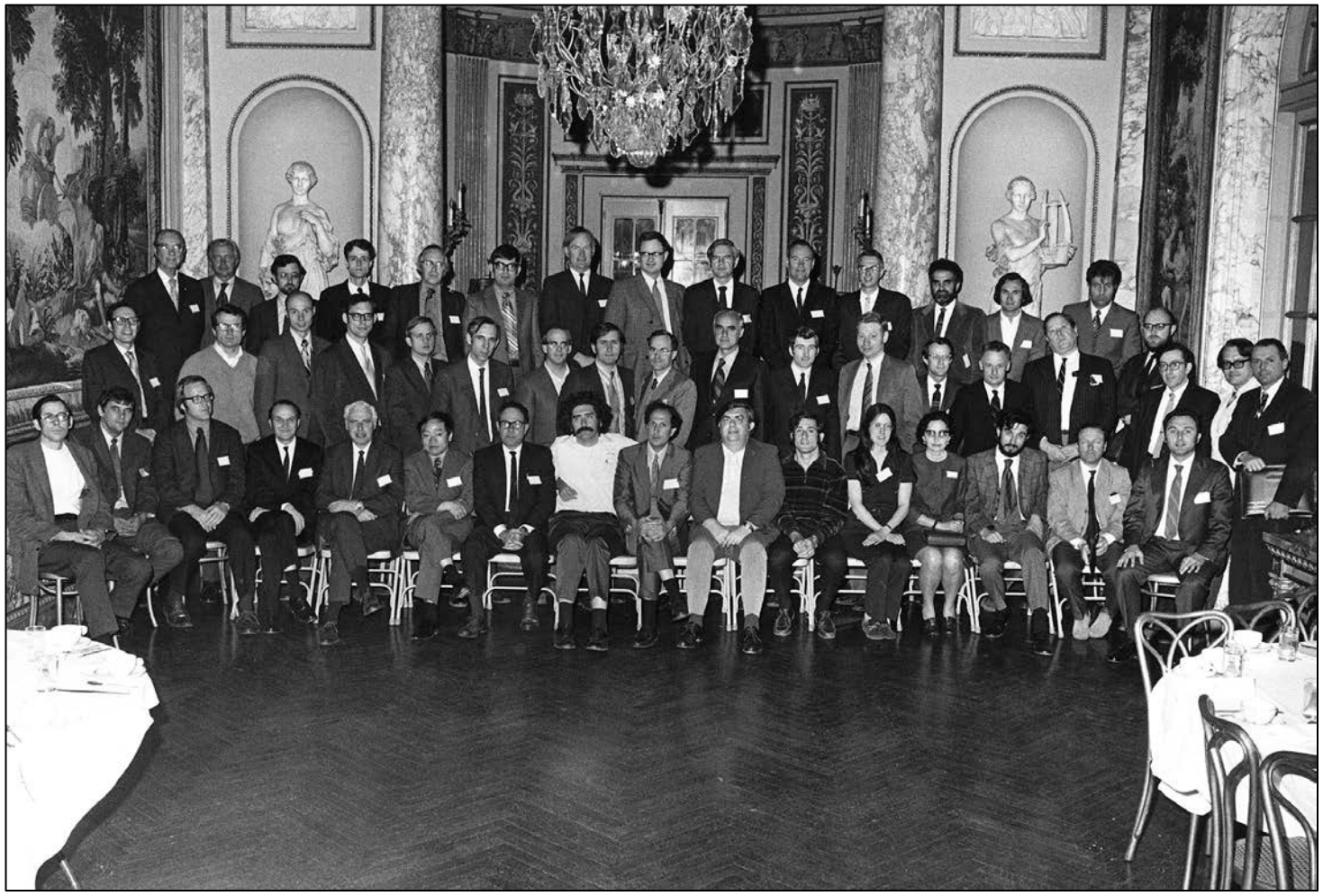
Canadian Group–(DRAO–Algonquin)	17 April 1967
NRAO/Cornell–(NRL–Green Bank)	8 May 1967
MIT–(Haystack–Green Bank)	5 June 1967

Canadian	**NRAO**	**MIT**
Norm Broten (D)	Claude Bare (D)	Jim Moran (A)
Tom Legg (D)	Barry Clark (R)	Al Barrett (D)
Jack Locke (D)	Ken Kellermann (A)	Bernie Burke (A)
Charles McLeish (D)	Marshall Cohen (R)	Alan Rogers (A)
Roger Richards (D)	Dave Jauncey (A)	Joe Carter (R)
Richard Chisholm (D)		Patty Crowther (R)*
Herb Gush (R)		John Ball (R)
Alan Yen (D)		
John Galt (D)		

American Academy of Arts and Sciences Rumford Award, 1971

*sole woman
A = active, R = retired, D = deceased

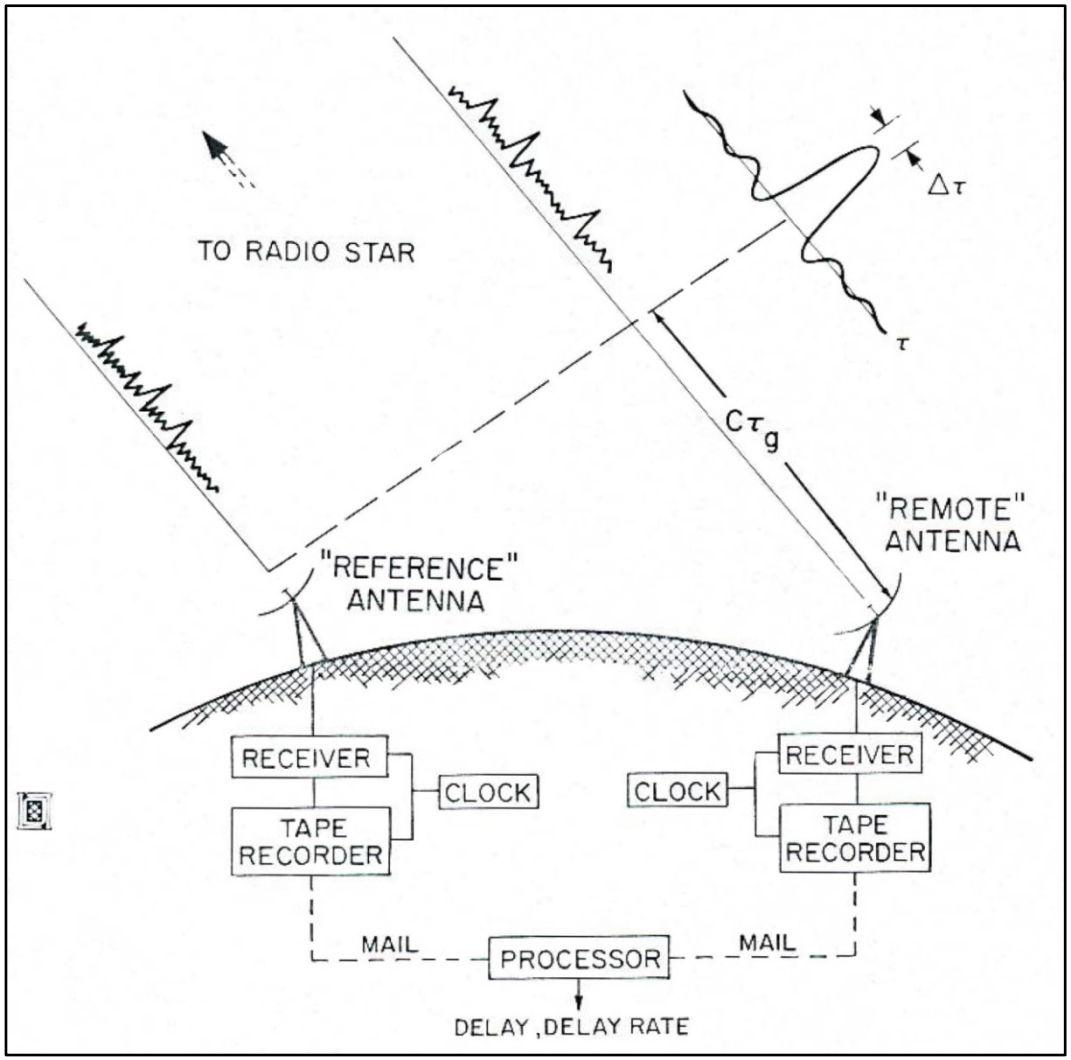
Rumford Prize Symposium, Boston, April 1971



Important Early Innovations in VLBI

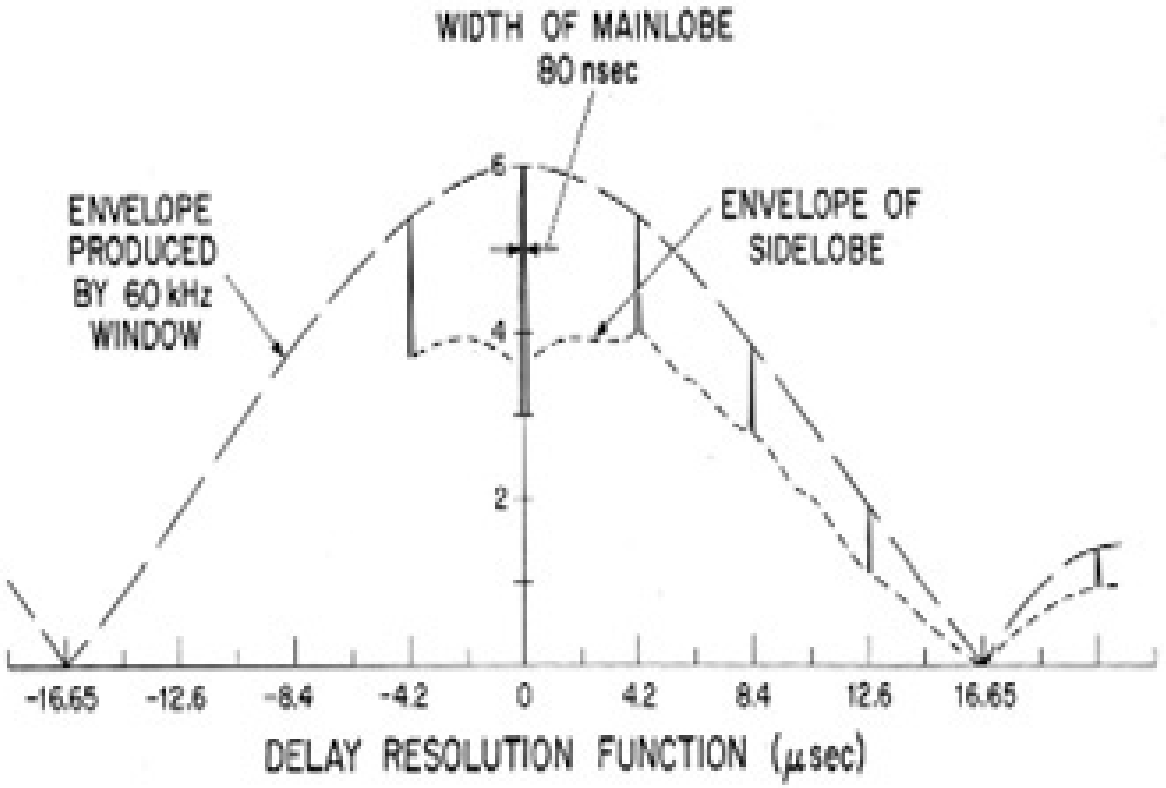
- Digital fringe rotation (Clark, 1968)
- Bandwidth synthesis (Rogers, 1968)
- Partially coherent interferometers (Clark, 1968)
- Spectral line phase referencing (Moran, 1968)
- Phase closure (Jennison, 1958; rediscovered by Rogers, 1974)
- Hybrid mapping (Readhead and Wilkinson, 1978)

Delay Measurements via VLBI

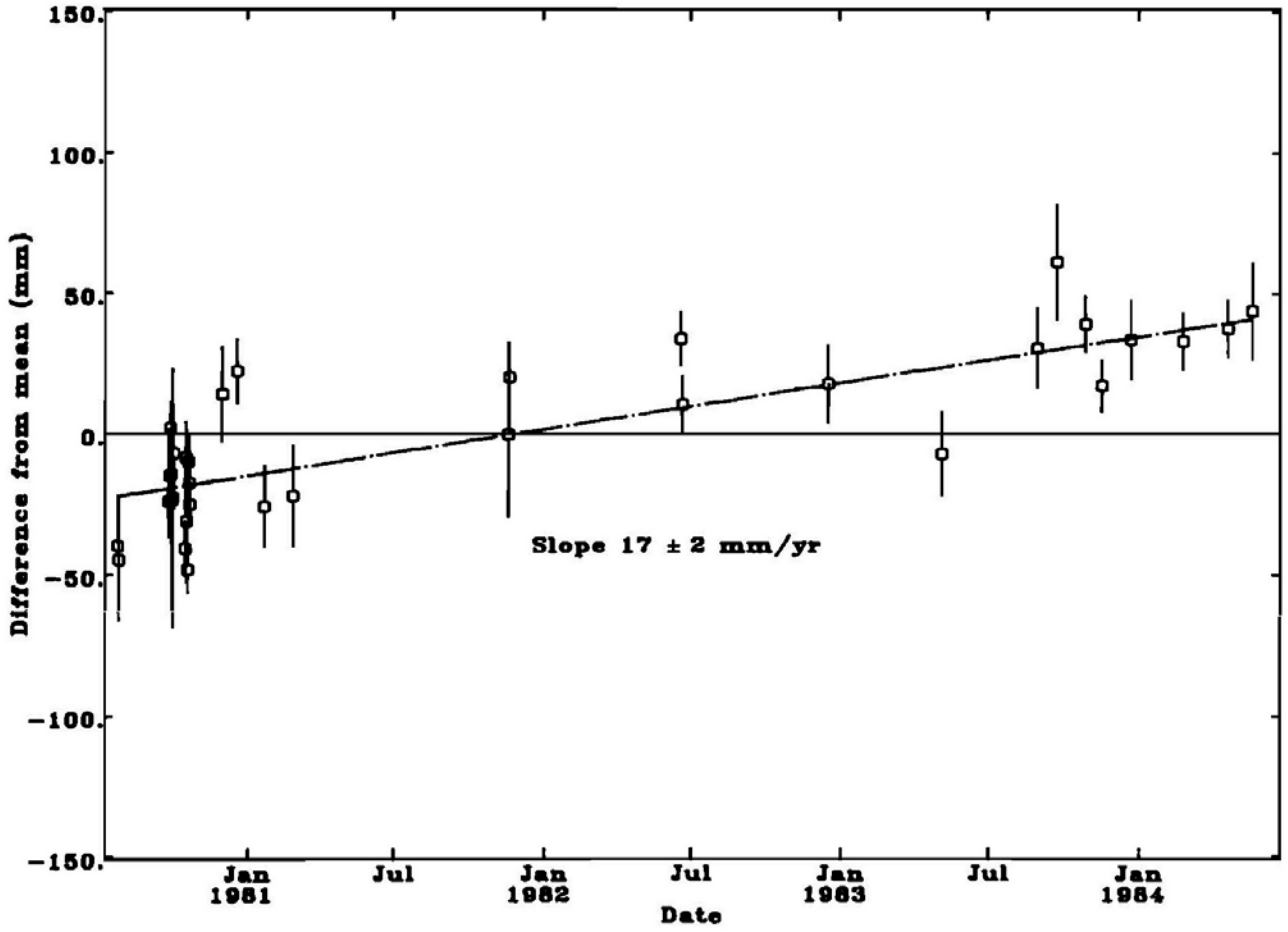


Rogers, 1967

Bandwidth Synthesis Using “Arsac” Array of Frequencies

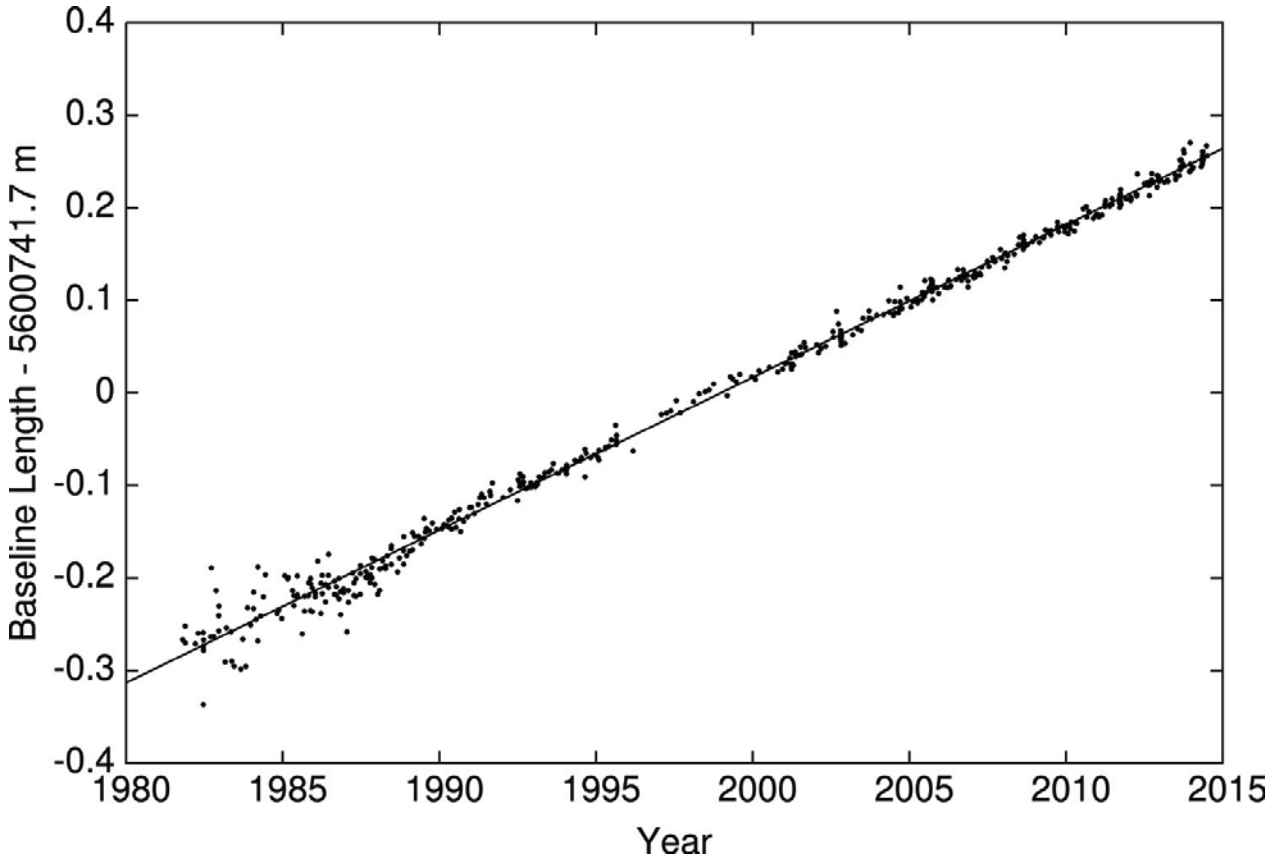


First Measurement of Contemporary Plate Tectonics
Westford-Onsala Baseline length



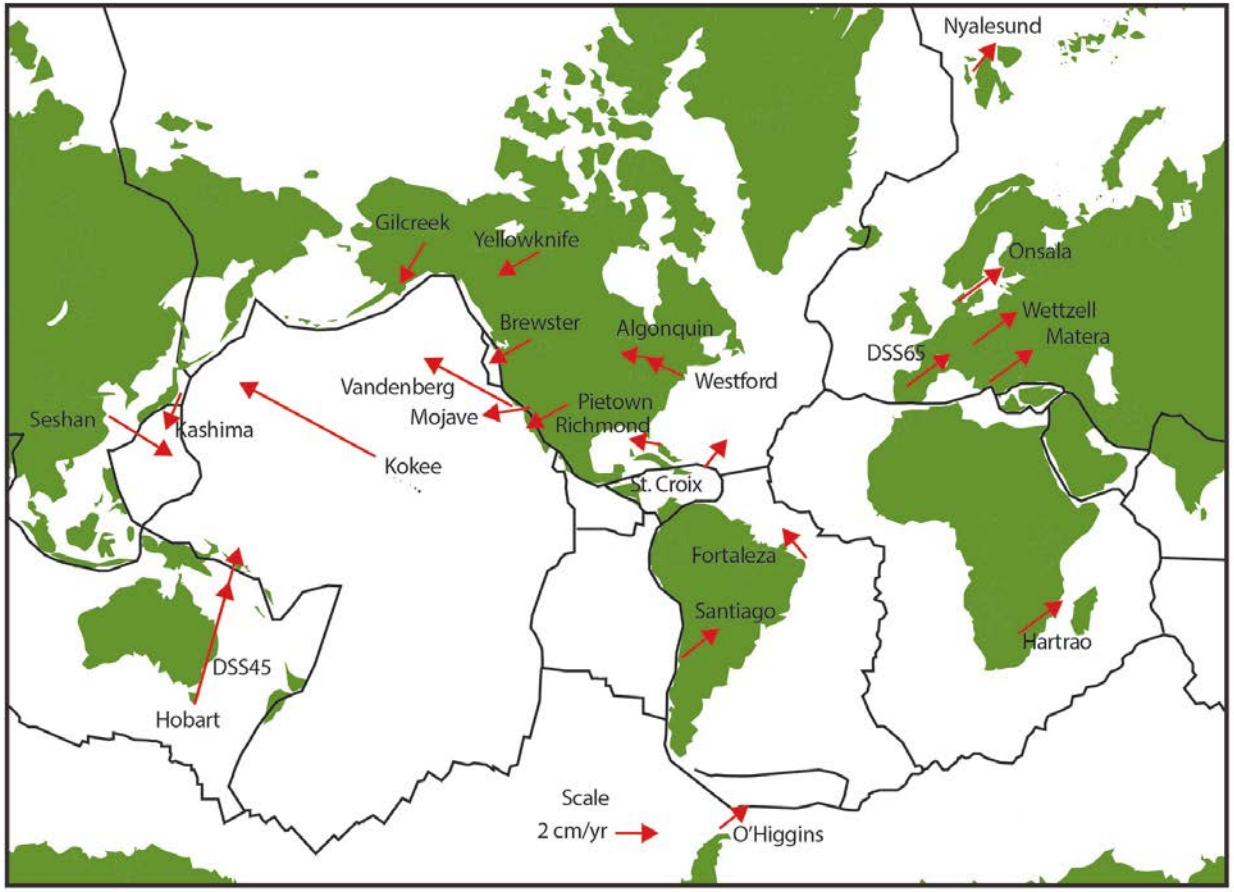
Herring et al., *JGR*, 1986

Westford–Onsala Baseline Length vs. Time Determined by VLBI

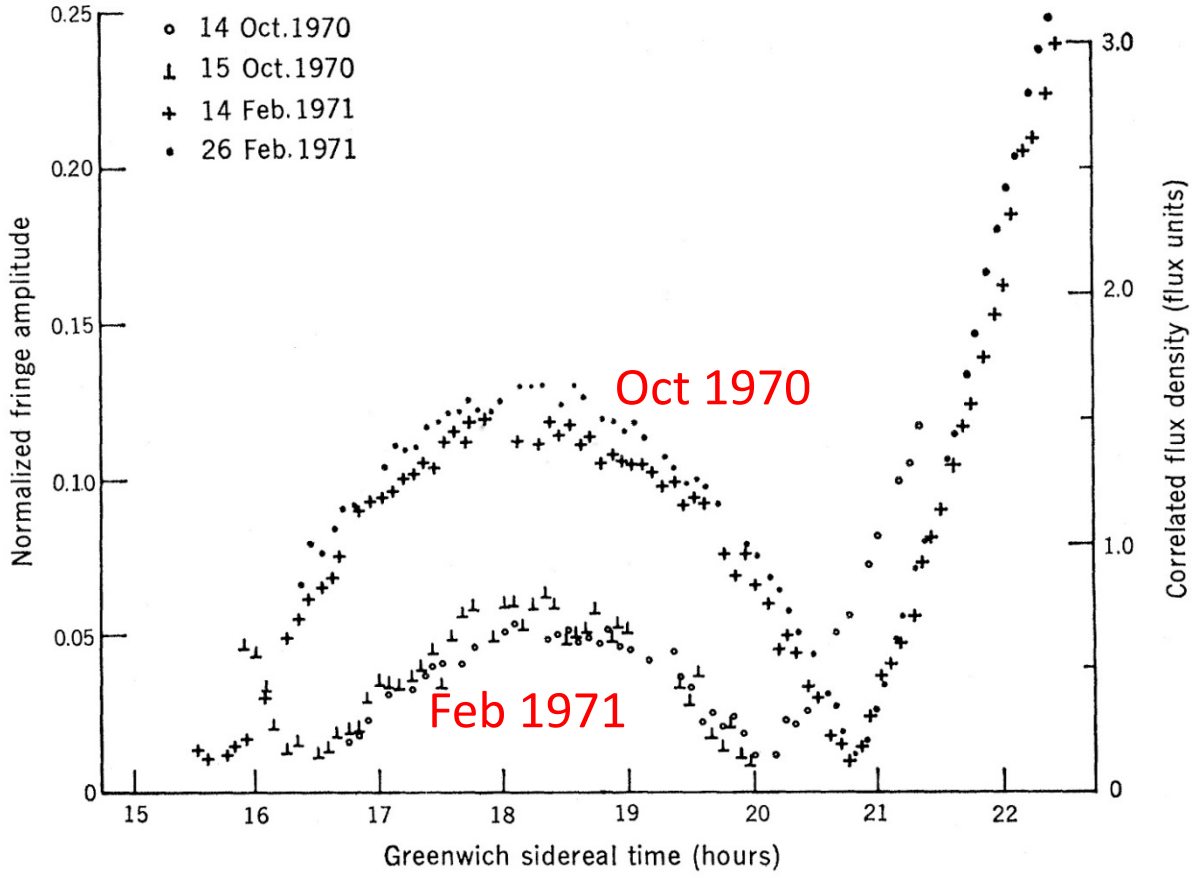


VLBI Service for Geodesy and Astrometry (see Thompson, Moran, and Swenson, 2017)

Tectonic Plate Motions Measured with VLBI

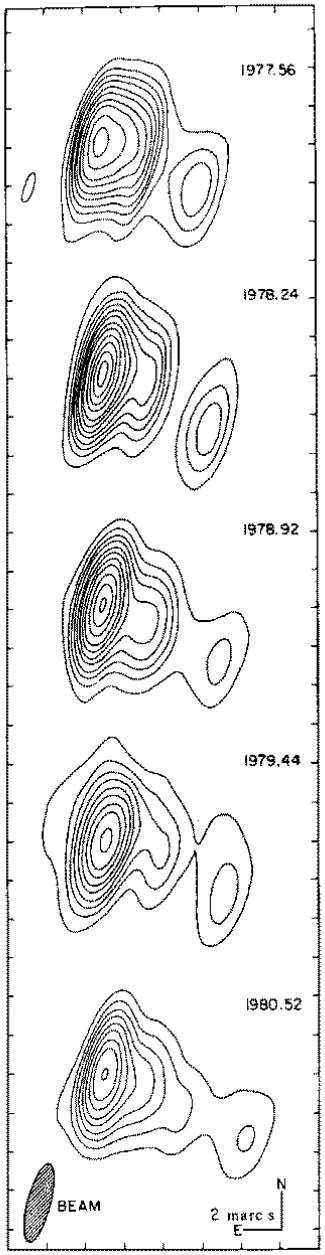


Discovery of Superluminal Motion: Fringe Visibility on 3C279 Haystack – Goldstone Baseline



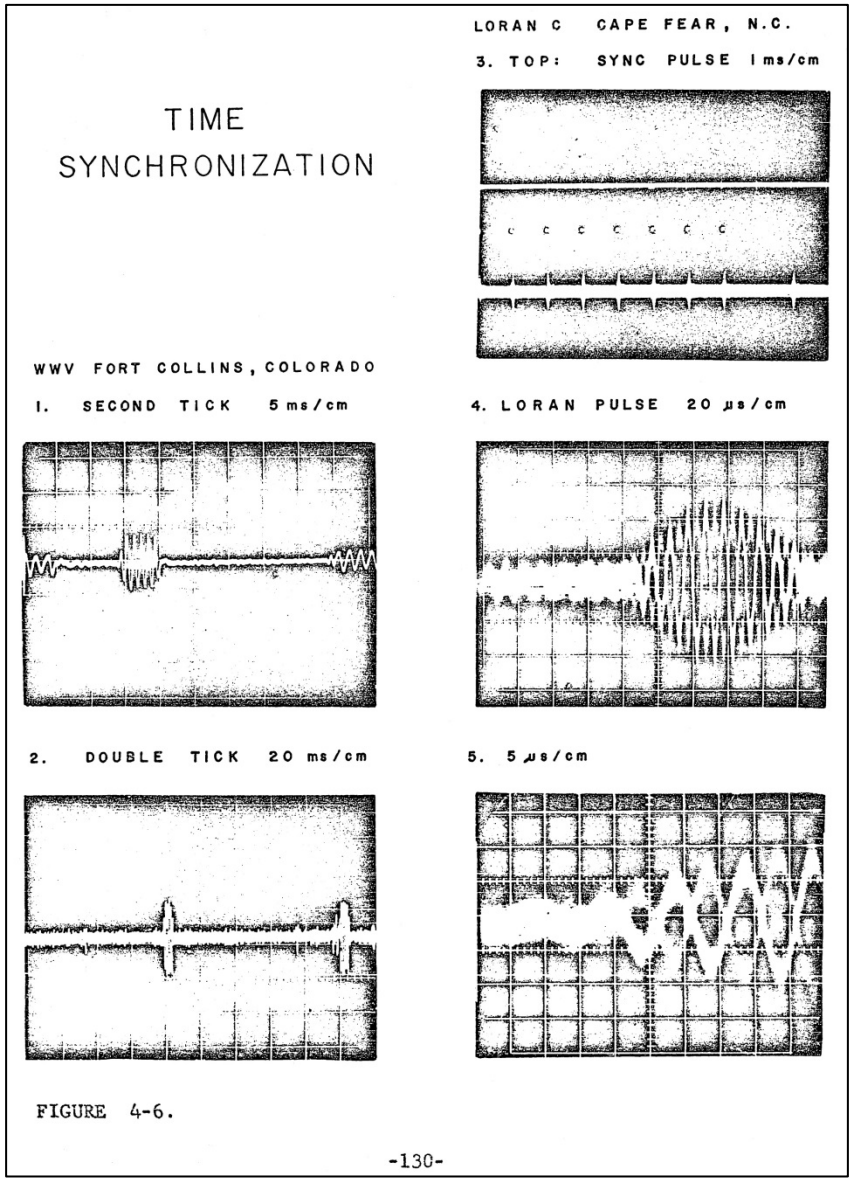
Whitney et al., *Science*, 1971

Hybrid Mapping of 3C273 for Five Epochs at 10GHz



Pearson et al., *ApJ*, 1981

Station Timing via WWV and Loran C



Moran, PhD thesis, 1968

Station Time Synchronization

Paris Observatory
Emile Blum, Steve Knowles

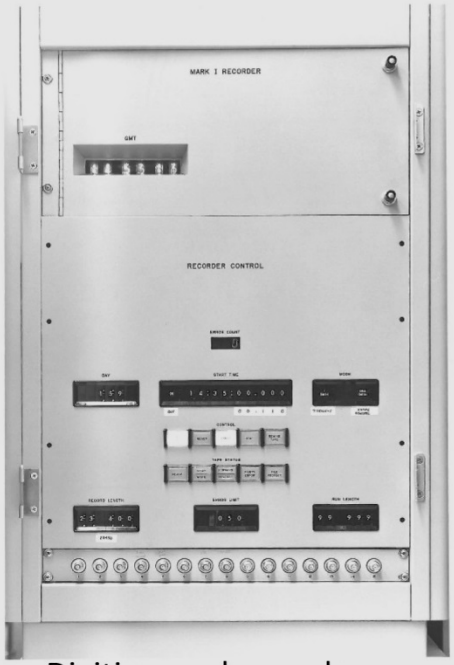
Simeiz,
Crimea,
USSR

VLBI Equipment Used at Haystack for First Fringes
8 June 1967

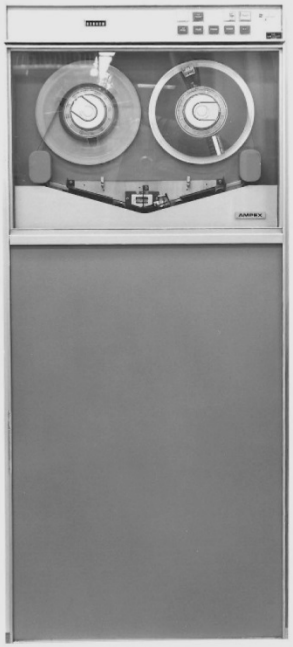
Video converter

Hewett-Packard 5065A
Rubidium clock

Varian H-10 hydrogen maser



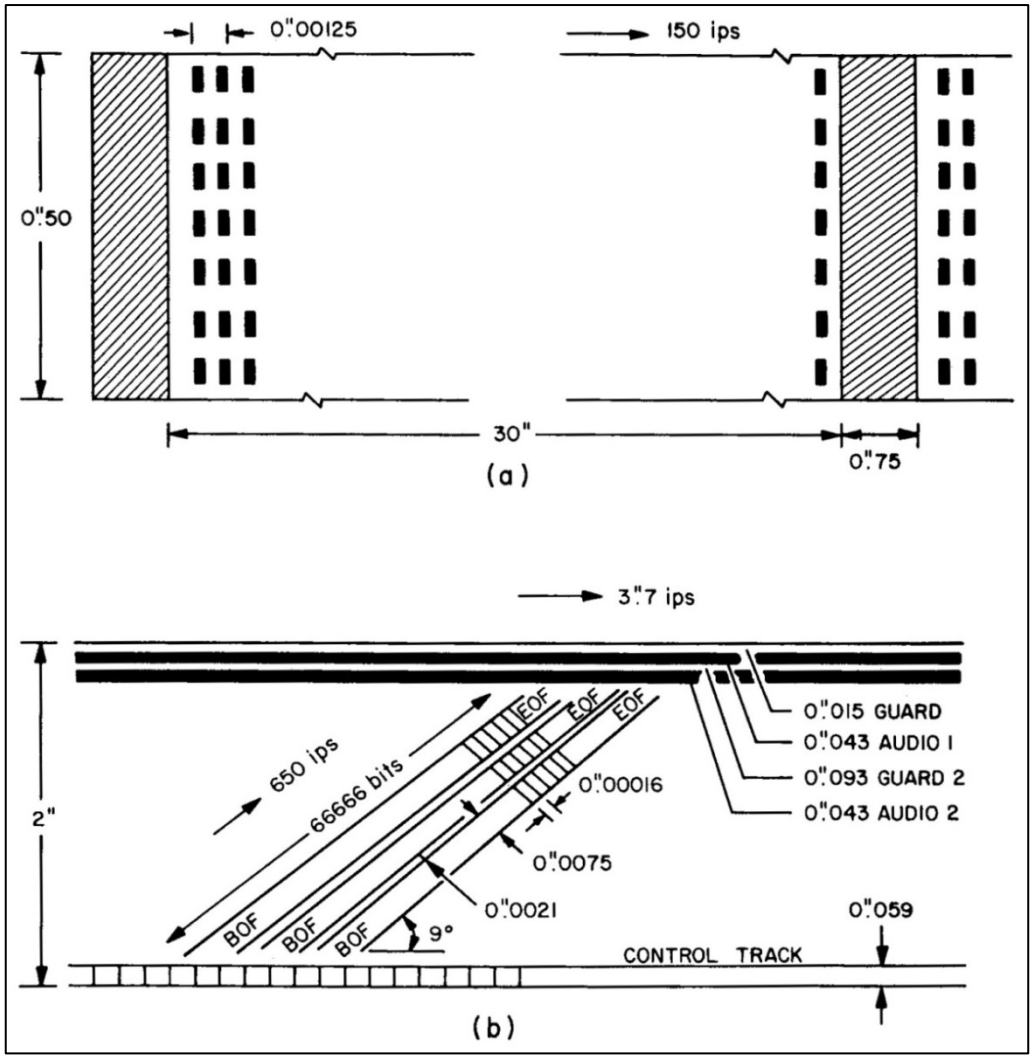
Digitizer and recorder
controller



Recorder

Canadian Analog and US Digital Mk II Systems
Ampex VR660 Television Recorder (10^11 bits)

Tape Formats

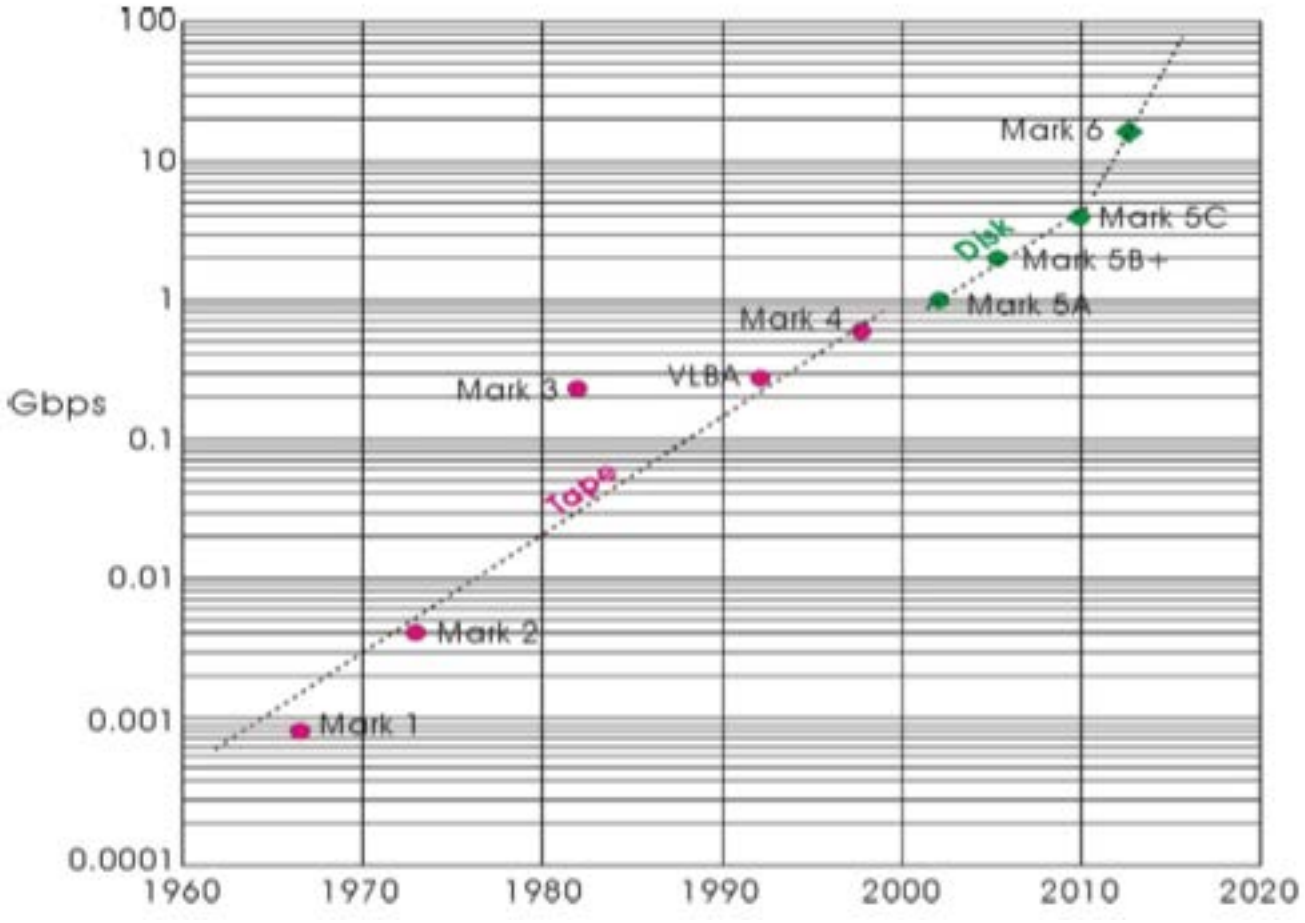


NRAO MK1

NRAO MK2

Mk 6 Module with 8 x 4 = 32 Terabytes of Disks (2 x 10^14 bits)

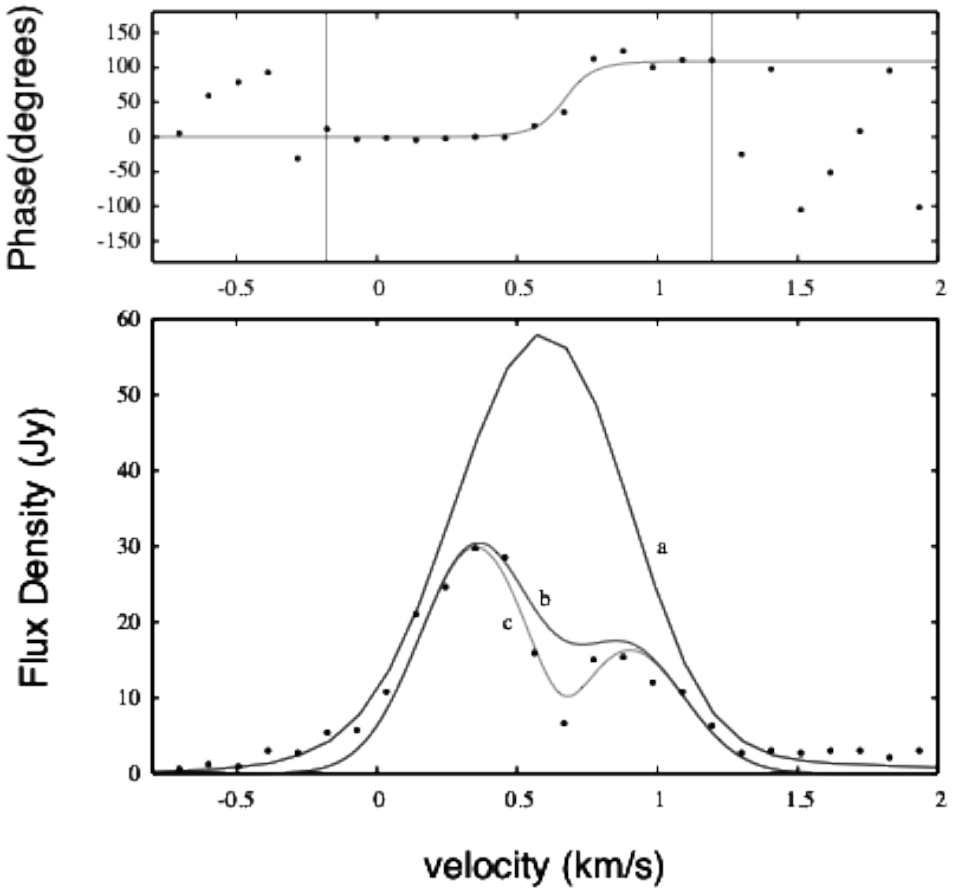
Data Rate vs. Time



Hewlett-Packard HP-5100 Frequency Synthesizer (0–50 MHz)

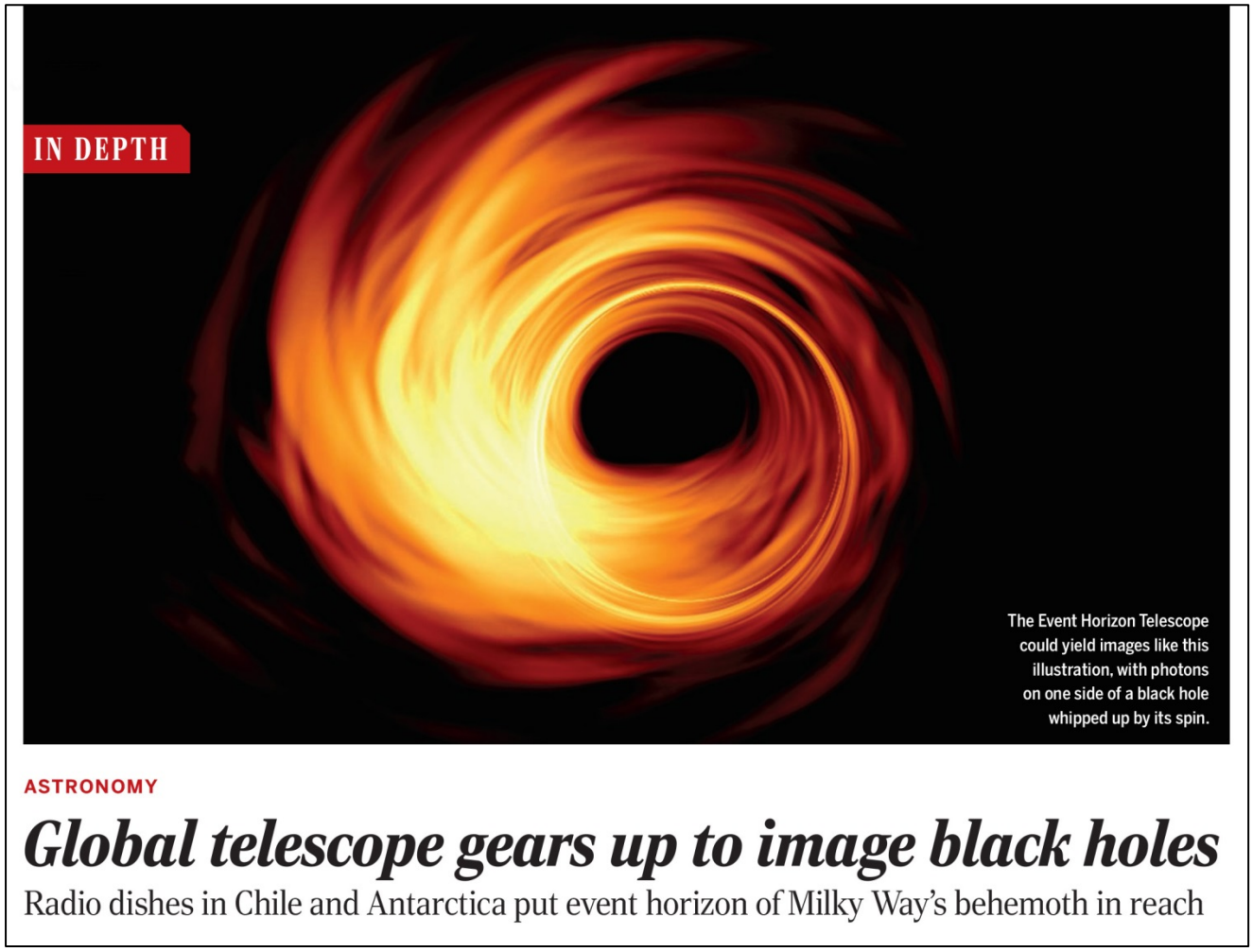
From 1967 HP catalogue

Visibility of Cepheus A Water Maser on 3.5 Earth-Diameter Baseline (RadioAstron–Yebes)



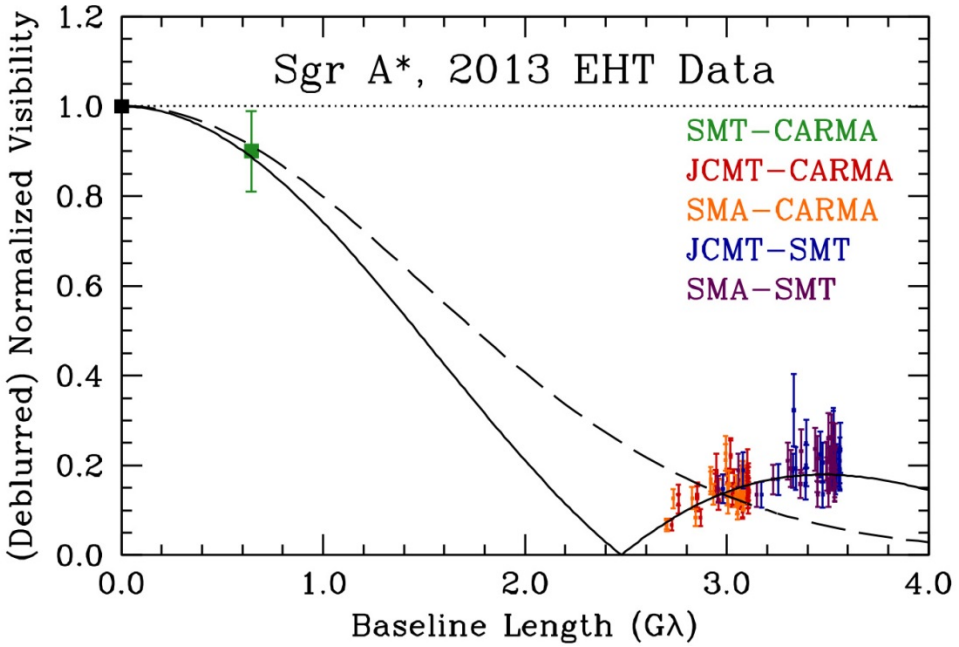
Visibility model (c): Double source, 24 μas separation, 15 μas diameter
Sobolev et al., 2017, in preparation

Hydrodynamic Simulation of Black Hole Accretion Disk



Science, **355**, 893, March 21, 2017

Pre-EHT (Maunakea–CARMA–SMT) Observations of SgrA* at 230 GHz



dashed line: circular Gaussian model (FWHM = 52 μas)
solid line: uniform annulus model
(inner diameter = 21 μas, outer diameter = 97 μas

Johnson … Inoue … et al., *Science*, 2015