

The Origins of Very Long Baseline Interferometry

Jim Moran

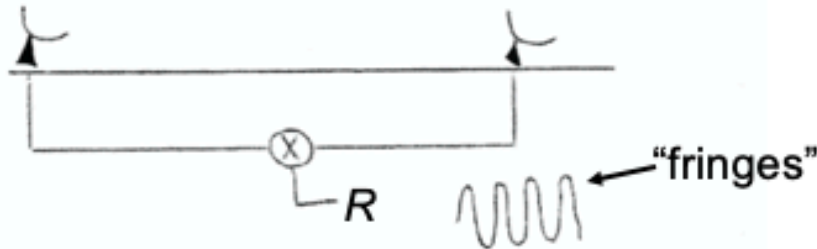
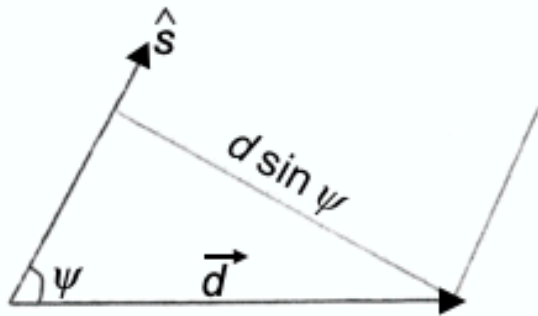
Harvard-Smithsonian Center for Astrophysics

**Receiver Lab Lunch Talk
Feb 27, 2025**



Student Ham Radio Station, BY1QH,
Tsinghua University, Beijing, April 2008

Simple Radio Interferometer



One Fourier Component
of Intensity Distribution

$$R = I \cos \phi$$

$$\phi = \frac{2\pi}{\lambda} \vec{d} \cdot \hat{s} = \frac{2\pi d}{\lambda} \cos \psi$$

$$\frac{d\phi}{dt} = \frac{2\pi d}{\lambda} \omega_e \sin \psi$$

$$\frac{d\phi}{d\psi} = \frac{2\pi d}{\lambda} \sin \psi$$

$$\Delta\phi = 2\pi = \frac{2\pi d \sin \psi}{\lambda} \Delta\psi$$

$$\Delta\psi = \frac{\lambda}{d \sin \psi} \leftarrow \text{projected baseline}$$

Albert Michelson Started It All

First Demonstration of an Astronomical Visibility Measurement

Measurement of Jupiter Satellites by Interference
Nature, 45, 160 (1891)

The general theory of these fringes may be found in the *Philosophical Magazine* for March 1891. The general equation showing the relation between the *visibility* of the fringes and the distance between the slits is

$$V^2 = \frac{\left[\int \phi(x) \cos kx dx \right]^2 + \left[\int \phi(x) \sin kx dx \right]^2}{\left[\int \phi(x) dx \right]^2} \quad (1)$$

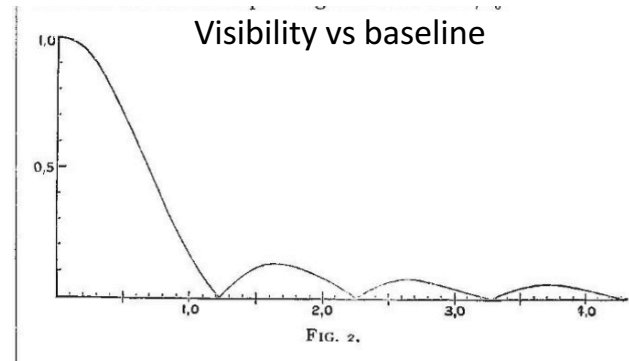
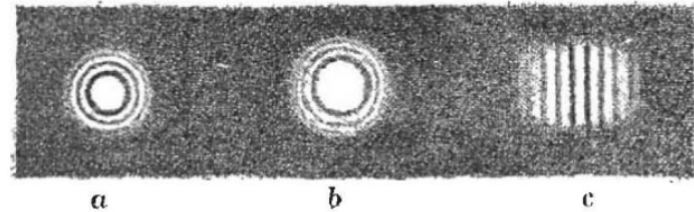
which reduces to the simpler form

$$V = \frac{\int \phi(x) \cos kx dx}{\int \phi(x) dx} \quad (2)$$

when the object viewed is symmetrical.

Note: ϕ = 1D strip integral of intensity

12 inch masked telescope on Mt. Hamilton



Michelson's idea was that the size of a source could be more easily determined by isolating a single Fourier component of the image. He *never* used the words "Fourier Transform" in linking image and visibility. However he used the word "Fourier" in his papers on spectroscopy, and he even wrote a mathematical paper on the problem of representing discontinuous functions with Fourier Series (*Nature*, 58,544, 1898)

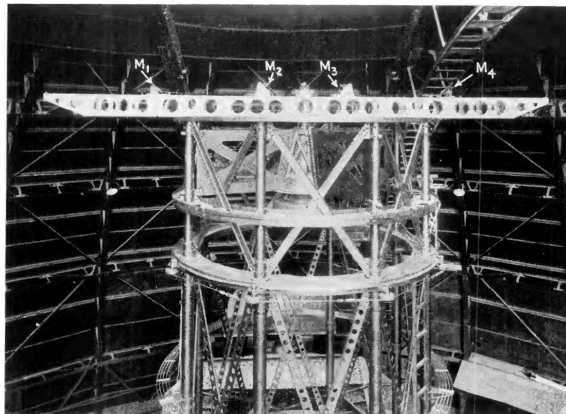
Measurement of the Diameter (**) of Alpha Orionis (*) with the Interferometer

A.A. Michelson and F.G Pease
Ap.J. 53, 249-259, 1921

- * aka Betelguse (a red super giant)
- ** 0.047 " or 550 x diameter of the sun

$$V = \frac{\int_0^R (R^2 - x^2)^{\frac{2n+1}{2}} \cos kx \, dx}{\int_0^R (R^2 - x^2)^{\frac{2n+1}{2}} \, dx}$$

This integral has been computed under the direction of Professor Moulton, the results being summarized in the accompanying



Interferometer on Hooker
100 inch telescope.

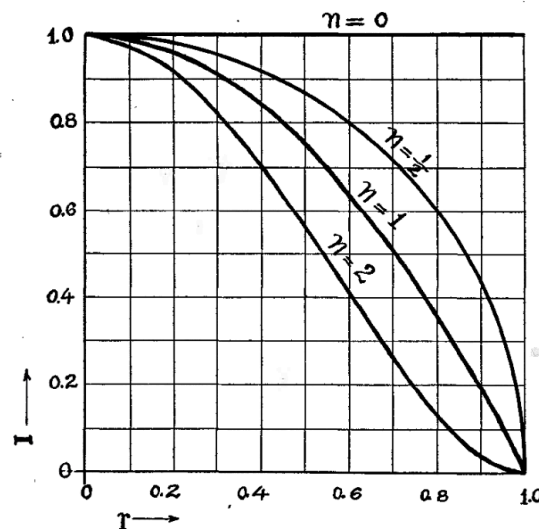
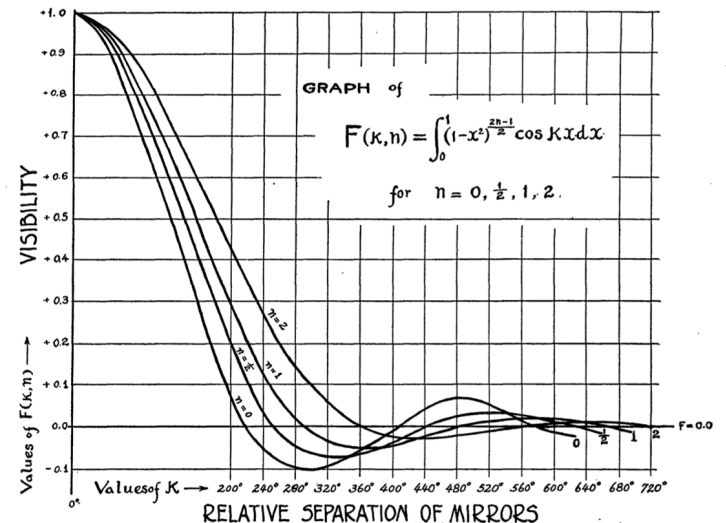


FIG. 4.—Distribution of light in various sources
Circularly symmetric limb
darkened models



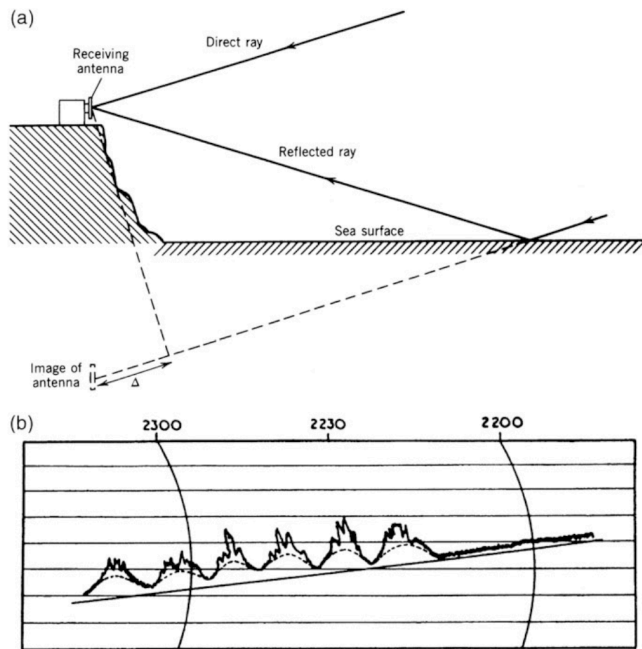
Visibility models

Solar Radiation at Radio Frequencies and Its Relation to Sun Spots

McCready, Pawsey, and Payne-Scott, Proc Roy Soc London A, 190,357 1947
 ***** submitted July 22, 1946

1.3 Development of Radio Interferometry

21



$$P = 2 \int f(\Delta - \alpha_1) (1 - \cos \Delta) d\Delta$$

$$= 2 \int f(\Delta - \alpha_1) d\Delta - 2 \int f(\Delta - \alpha_1) \cos \Delta d\Delta,$$

Since an indefinite number of distributions have identical Fourier components at one frequency, measurement of the phase and amplitude of the variation of intensity at one place at dawn cannot in general be used to determine the distribution over the sun without further information. It is possible in principle to determine the actual form of the distribution in a complex case by Fourier **synthesis** using information derived from a large number of components. In the interference method suggested here Δ is a function of h and λ , and different Fourier components may be obtained by varying h or λ . Variation of λ is inadvisable, as over the necessary wide range the distribution of radiation may be a function of wave-length. Variation of h would be feasible but clumsy. A different interference method may be more practicable.

Solar Radiation at 175 Mc/s

Ryle and Vonberg, Nature, 158, 339, 1946

****submitted August 22, 1946

Two element antenna pattern

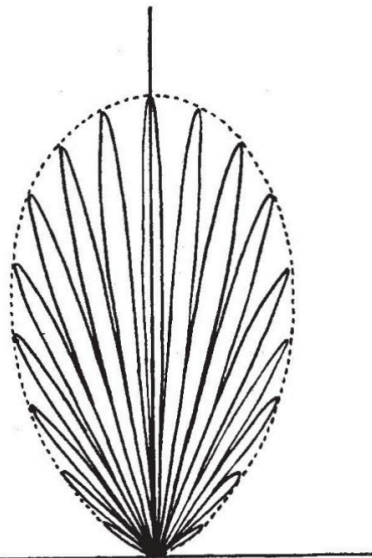
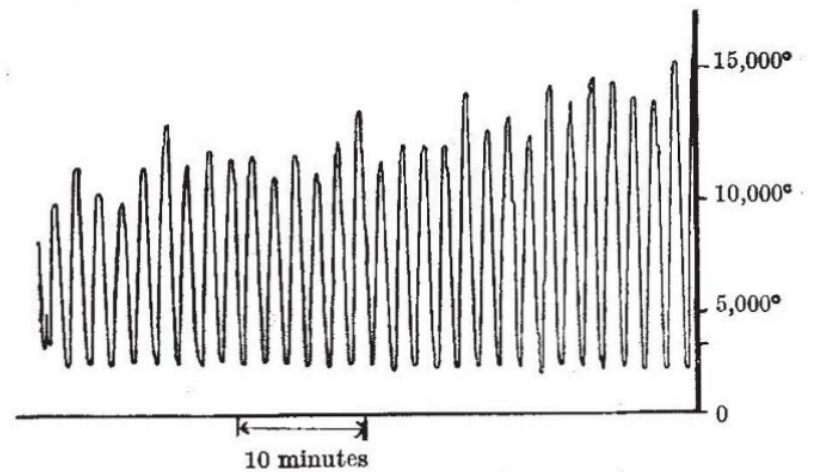


Fig. 1 POLAR DIAGRAM OF TWO 8-ELEMENT AERIAL SYSTEMS WITH SEPARATION OF 10λ

Fringes on a prominent sunspot



“An alternative method was therefore used, analogous to Michelson’s method of determining stellar diameters.”

THE DISTRIBUTION OF RADIO BRIGHTNESS OVER THE SOLAR DISK AT A WAVELENGTH OF 21 CENTIMETRES

III. THE QUIET SUN—TWO-DIMENSIONAL OBSERVATIONS

By W. N. CHRISTIANSEN* and J. A. WARBURTON*

Received for publication, 11 July 1955

Australian Journal of Physics, 8, 474, 1955

THE DERIVATION OF THE BRIGHTNESS DISTRIBUTION FROM THE OBSERVATIONS BY A METHOD OF FOURIER ANALYSIS

First pretty picture!

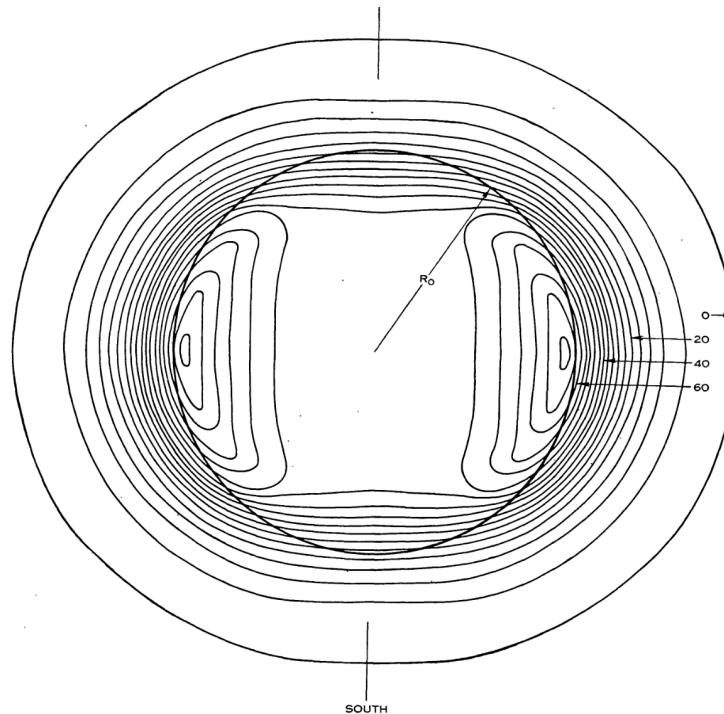


Fig. 10.—Derived two-dimensional radio brightness distribution. The contours are at equal intervals of 4×10^4 °K. The central brightness temperature is 4.7×10^4 °K, and the maximum peak brightness is 6.8×10^4 °K.

Scientific Motivation for VLBI in Mid 1960s

- **Quasars**

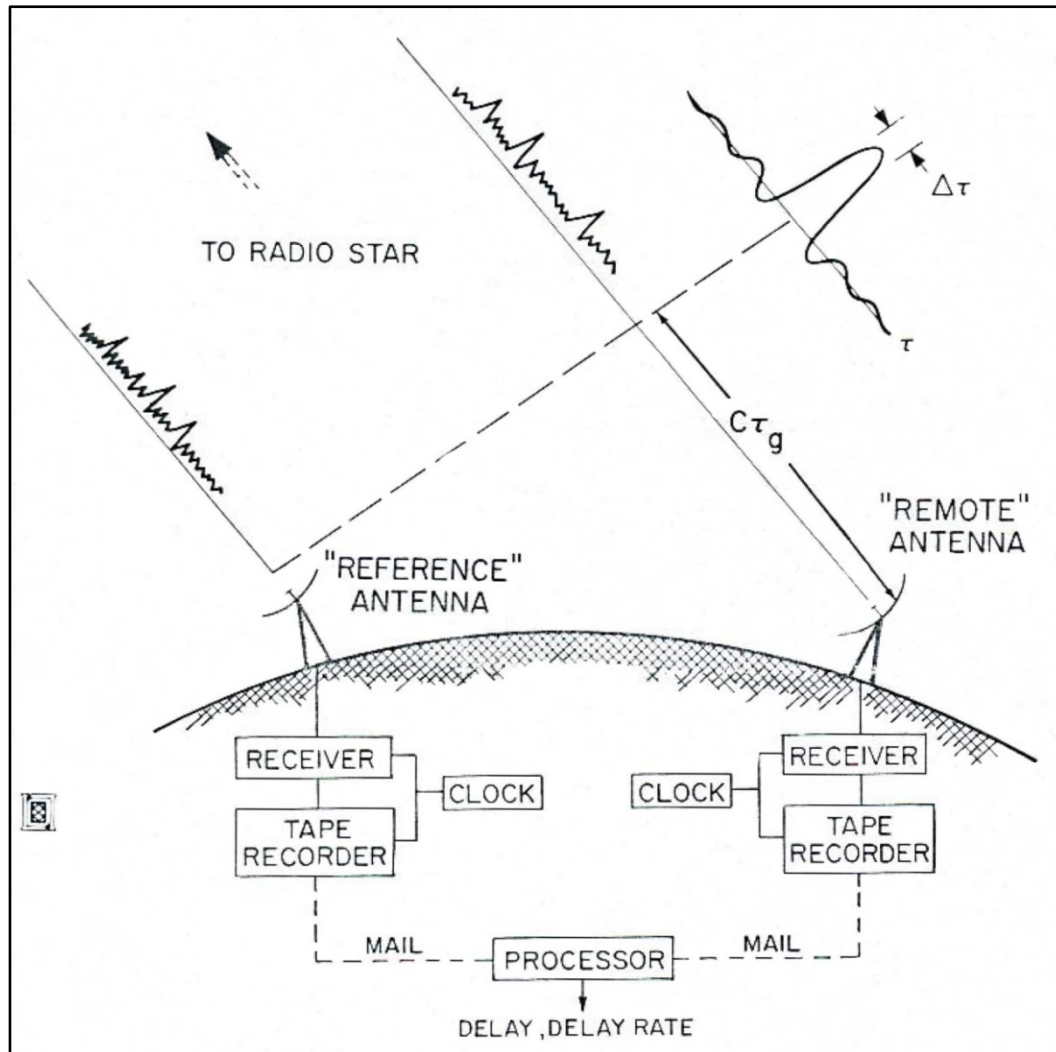
Unresolved on Jodrell-Bank to Malvern
Baseline of 127 km at 5 cm wavelength
Smaller than 0.025''

Interplanetary Scintillation, less than 0.01''

- **OH Masers**

Unresolved on Haystack-Harvard Baseline
(13 km) at 18 cm wavelength
and Jodrell Bank-Malvern (127 km).
Smaller than 0.1''

Components of a VLBI System



Roger, 1967

VLBI Technology Precursors

- One-bit signal representation (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 note 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 to observe Jupiter radio bursts
- * 1965 Matveenko, Kardashev, Sholomitskii write technical feasibility paper

1967 – A Highly Selective History

- Hippie Summer of Love in San Francisco
- Six Day War between Egypt and Israel
- NASA Launched Lunar Orbiter 3/Surveyor 3
- Expo 67 in Montreal (100th ann British NA Act)
- Elvis Presley Marries Priscilla
- Pulsars Discovered
- Texas Instruments Develops Pocket Calc (note: HP35, 1972)
- SST Concorde unveiled to public
- UK Applied for EEC Membership
- First Heart Transplant (South Africa)
- Sgt Pepper's Lonely Heart Club Band
- Charles DeGaulle, President of France
- 25th Amend to US Constitution (Presidential Succession)
- Vietnam War ("Much remains to be Done" Lyndon Johnson)

Early VLBI Experiments (aka: The Frantic Spring of 1967)

- **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

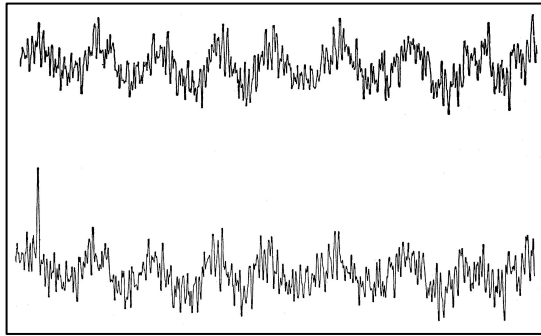
- **Cornell-NRAO Group**

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**

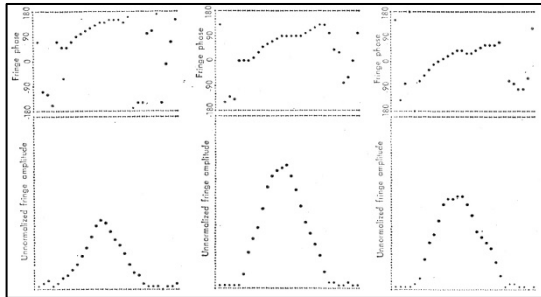
June 1967. Published: Moran et al., Science, August 11, 1967
Green Bank – Haystack; 1665 MHz, 845 km, res = 0.045"
Modified Mk1 (5 and 120 KHz bw)

Earliest VLBI Detections



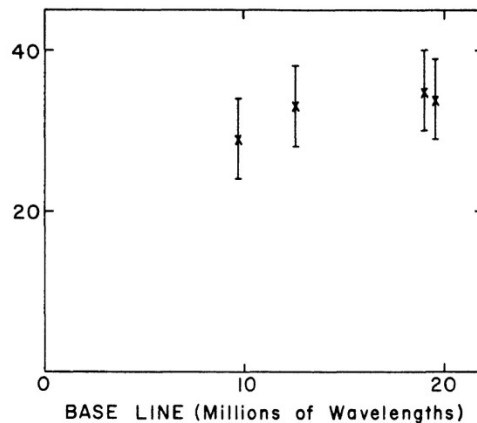
time

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



frequency

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



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

Rumford Prize for the 21 Participants in the Development of VLBI American Academy of Arts and Sciences (1971)

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

Canadian

Norm Broten (D)
Tom Legg (D)
Jack Locke (D)
Charles McLeish (D)
Roger Richards (D)
Richard Chisholm (D)
Herb Gush
Alan Yen (D)
John Galt (D)

NRAO

Claude Bare (D)
Barry Clark
Ken Kellermann
Marshall Cohen**
Dave Jauncey

MIT

Jim Moran
Alan Barrett (D)
Bernie Burke (D)
Alan Rogers
Joe Carter
Patty Crowther *
John Ball (D)

*sole woman

** 98 years old in 2025

D = deceased

Rumford Prize Symposium, Boston, April 1971

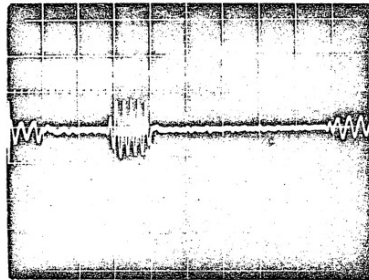


Station Timing via WWV (5 MHz) and Loran C (100 kHz)

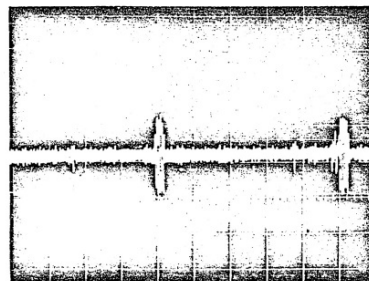
TIME SYNCHRONIZATION

WWV FORT COLLINS, COLORADO

1. SECOND TICK 5 ms/cm

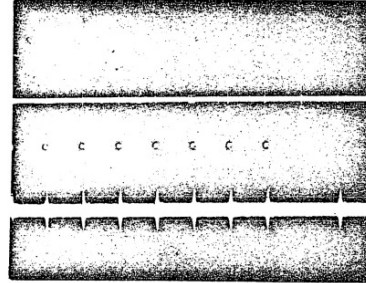


2. DOUBLE TICK 20 ms/cm

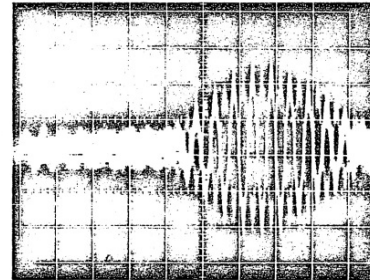


LORAN C CAPE FEAR, N.C.

3. TOP: SYNC PULSE 1 ms/cm



4. LORAN PULSE 20 μs/cm



5. 5 μs/cm

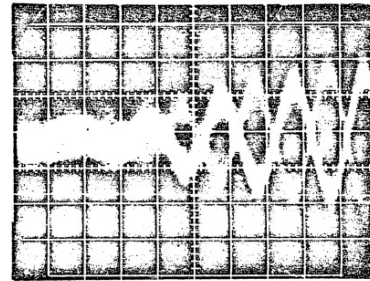


FIGURE 4-6.

Station Time Synchronization (carrying a Rubidium Clock to the USSR 1971)



Paris Observatory, 1971
Emile Blum, Steve Knowles

Semeiz,
Crimea,
USSR,
(later Ukraine)

VLBI Equipment Used at Haystack for First Fringes 8 June 1967



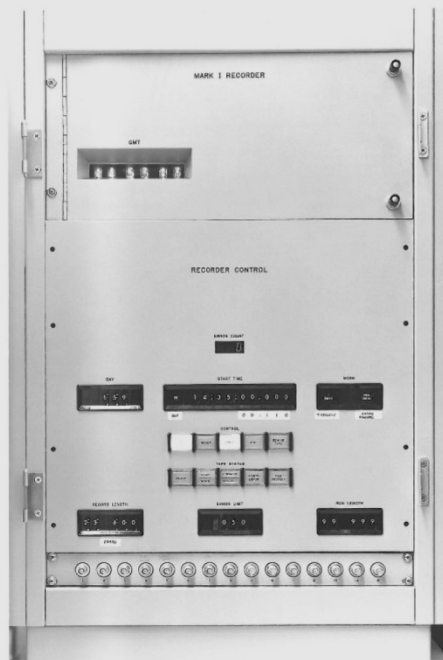
Video converter



Hewlett-Packard 5065A
Rubidium clock



Varian H-10 hydrogen maser



Digitizer and recorder
controller



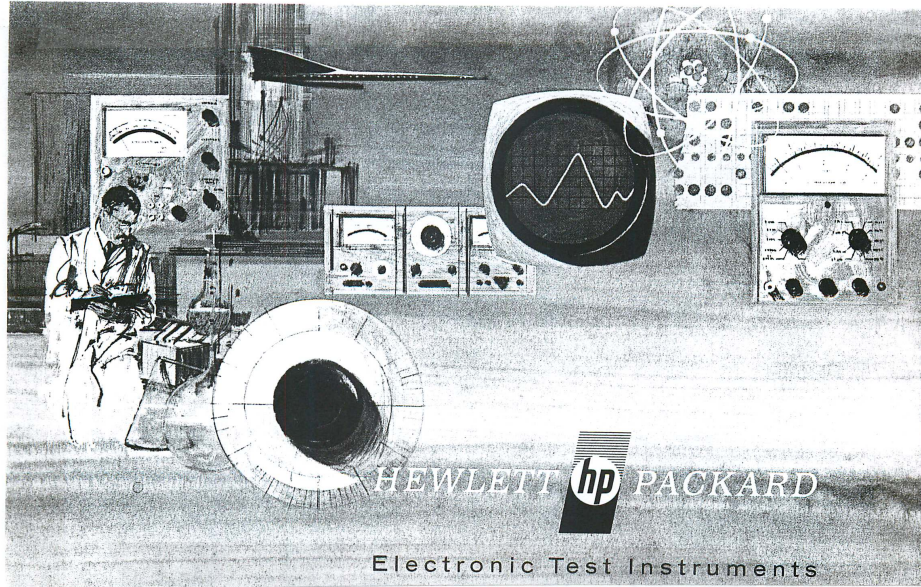
Recorder

Canadian Analog and NRAO Digital Mk II Systems Ampex VR660 Television Recorder (3 x 10¹⁰ bits)



1965 cost: \$25K (see Broten, JRASC , 1988) **\$195K (2017 dollars)**

Hewlett-Packard Catalog 1967



Since its founding in Palo Alto, California, in 1939, Hewlett-Packard has grown from a two-man operation into a world-wide organization of more than 7000 people, with an annual sales volume exceeding \$125 million.



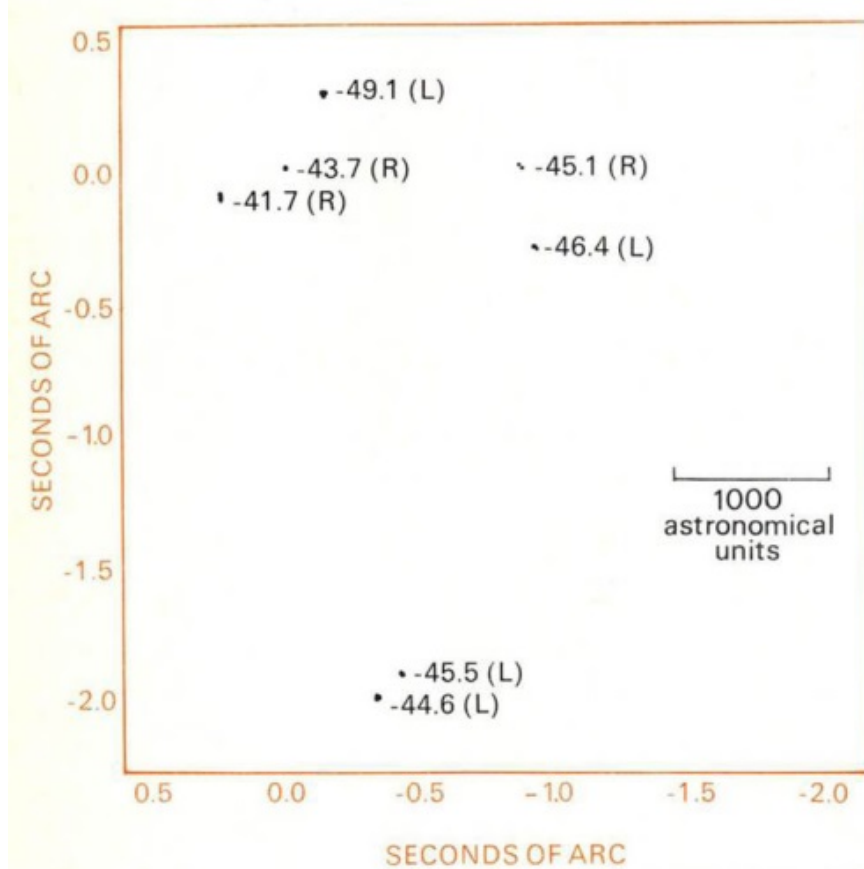
HP5100A Frequency Synthesizer

5100A-5110A

Early Results

- Quasar brightness approaching Compton limit $\sim 10^{13}\text{K}$
- OH Masers resolved into compact “spots”
- Superluminal expansion in quasars (1971)
- Contemporary plate motions (1986)

VLBI Image of W3 Maser

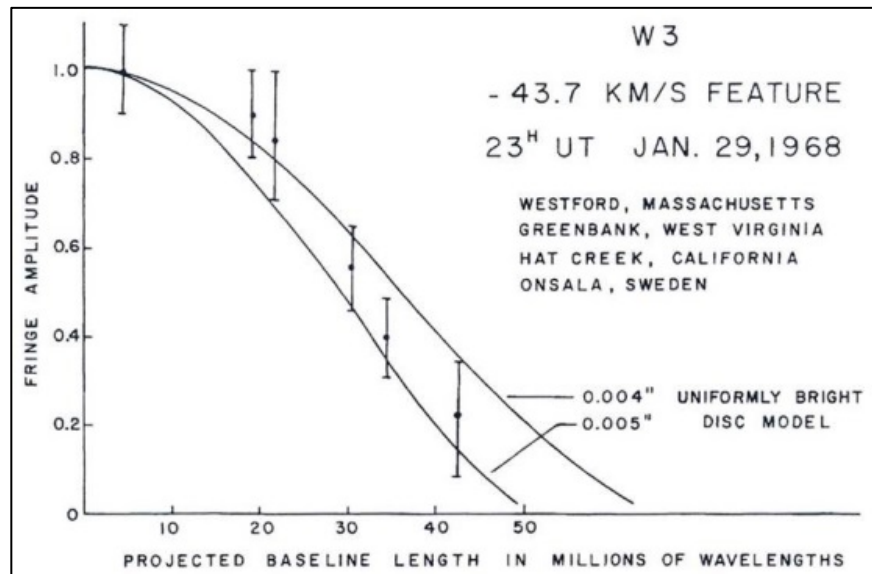
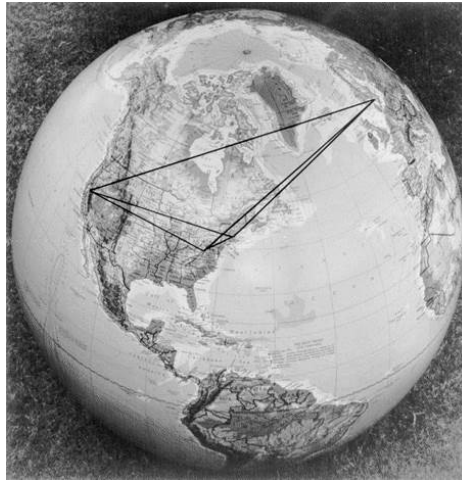


Palomar Sky Survey Image of W3 HII Region

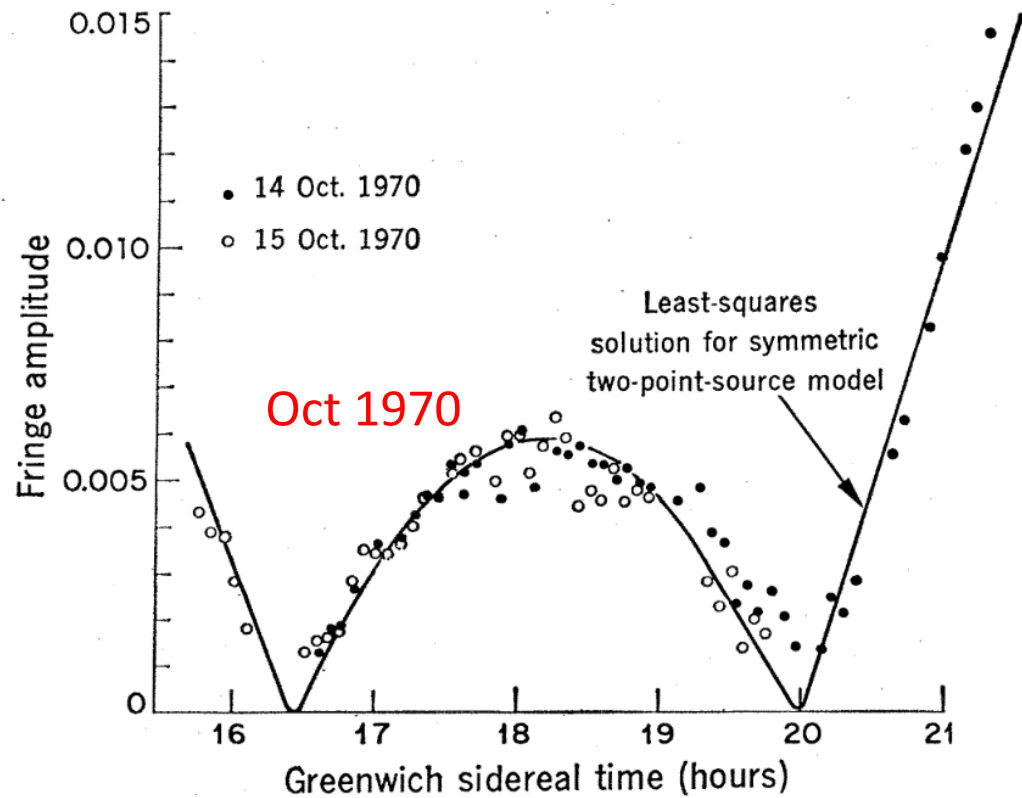


Moran et al., ApJ 1967

First Resolution of a Maser “Spot”

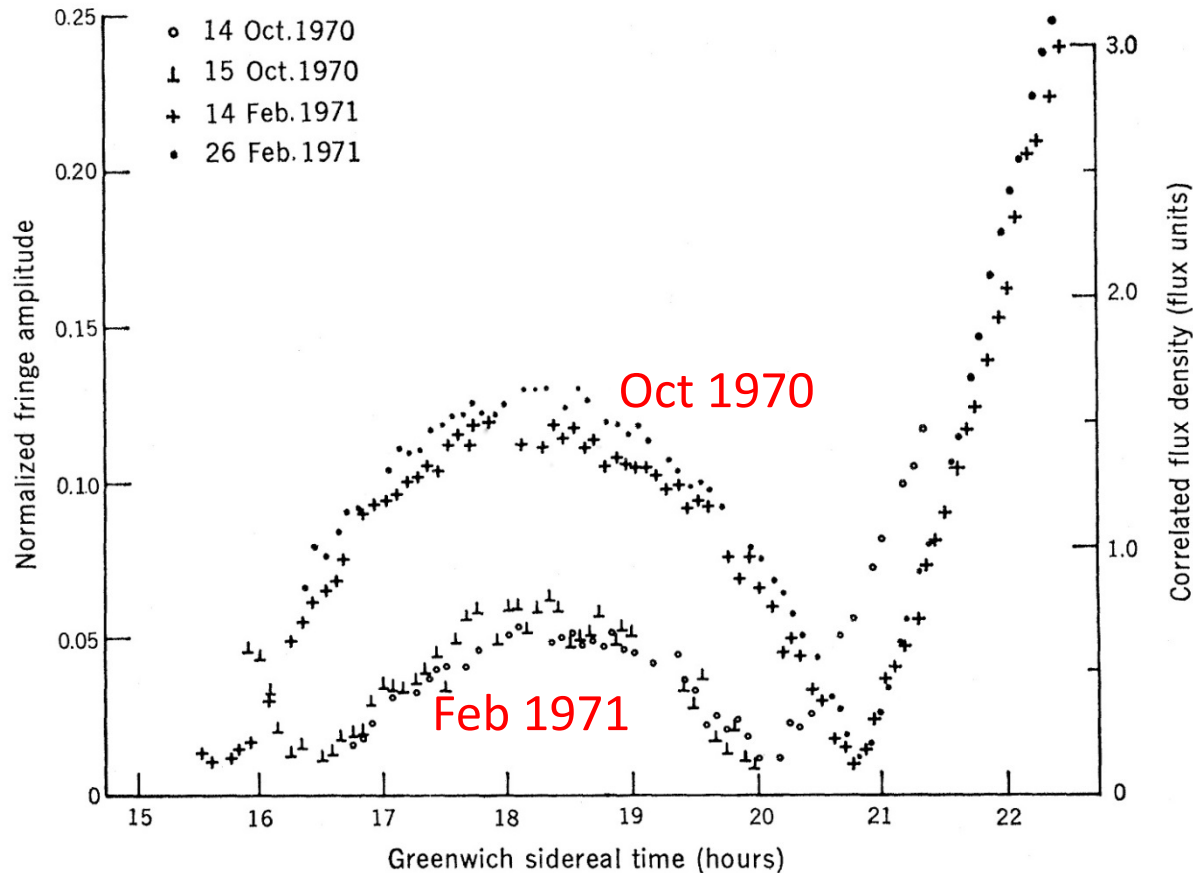


Discovery of Superluminal Motion: Fringe Visibility on 3C279 Haystack-Goldstone Baseline First Epoch



Knight, et al., *Science*, April 2, 1971

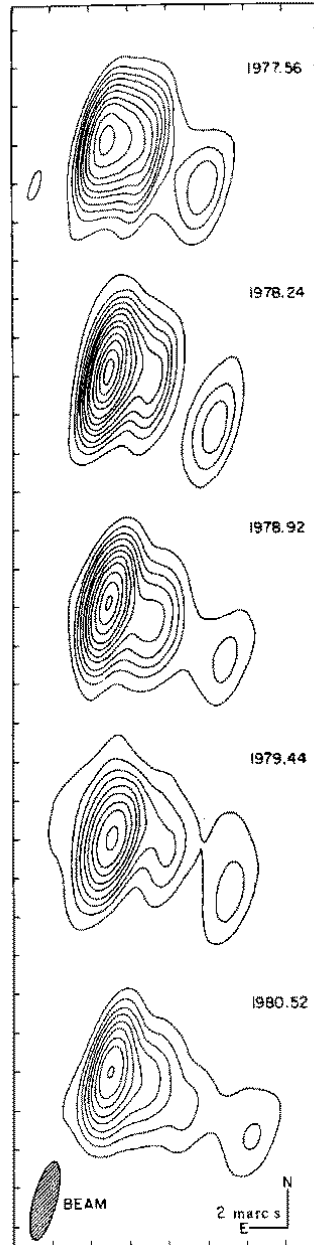
Discovery of Superluminal Motion: Fringe Visibility on 3C279 Haystack – Goldstone Baseline



Whitney et al., *Science*, July 16, 1971

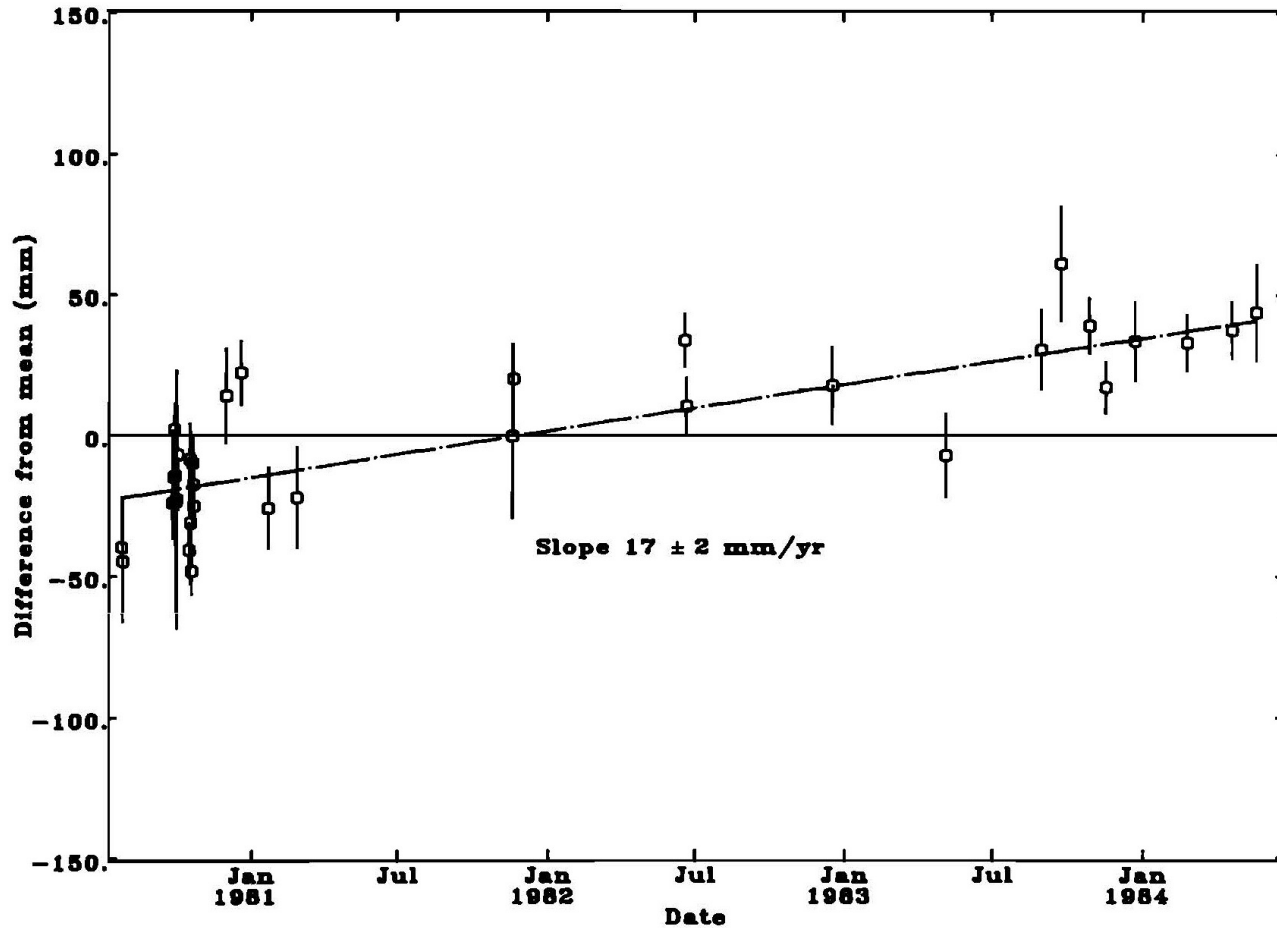
Cohen et al., *Astrophysical Journal*, December 1, 1971

Hybrid Mapping of 3C273 for Five Epochs at 10GHz



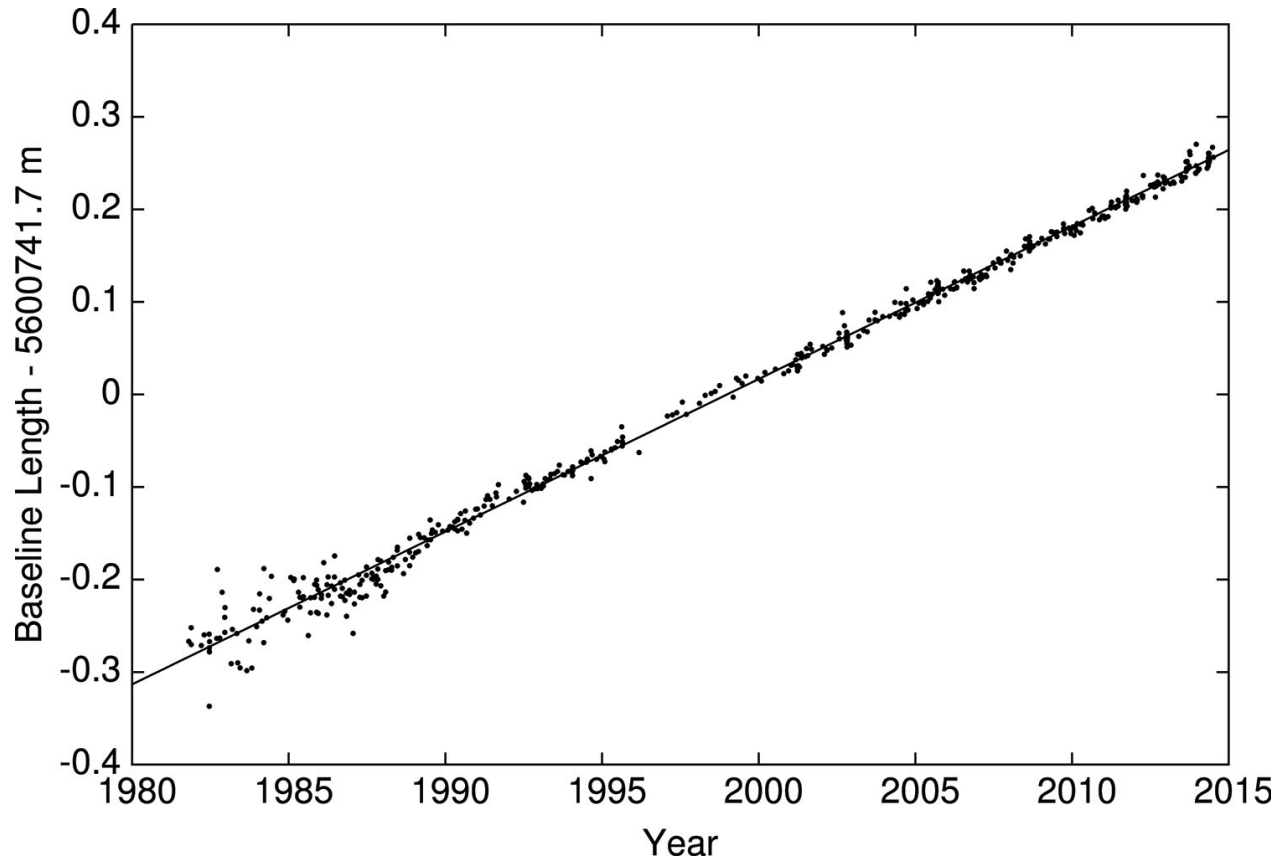
Pearson et al., *ApJ*, 1981

First Measurement of Contemporary Plate Tectonics Westford-Onsala Baseline length



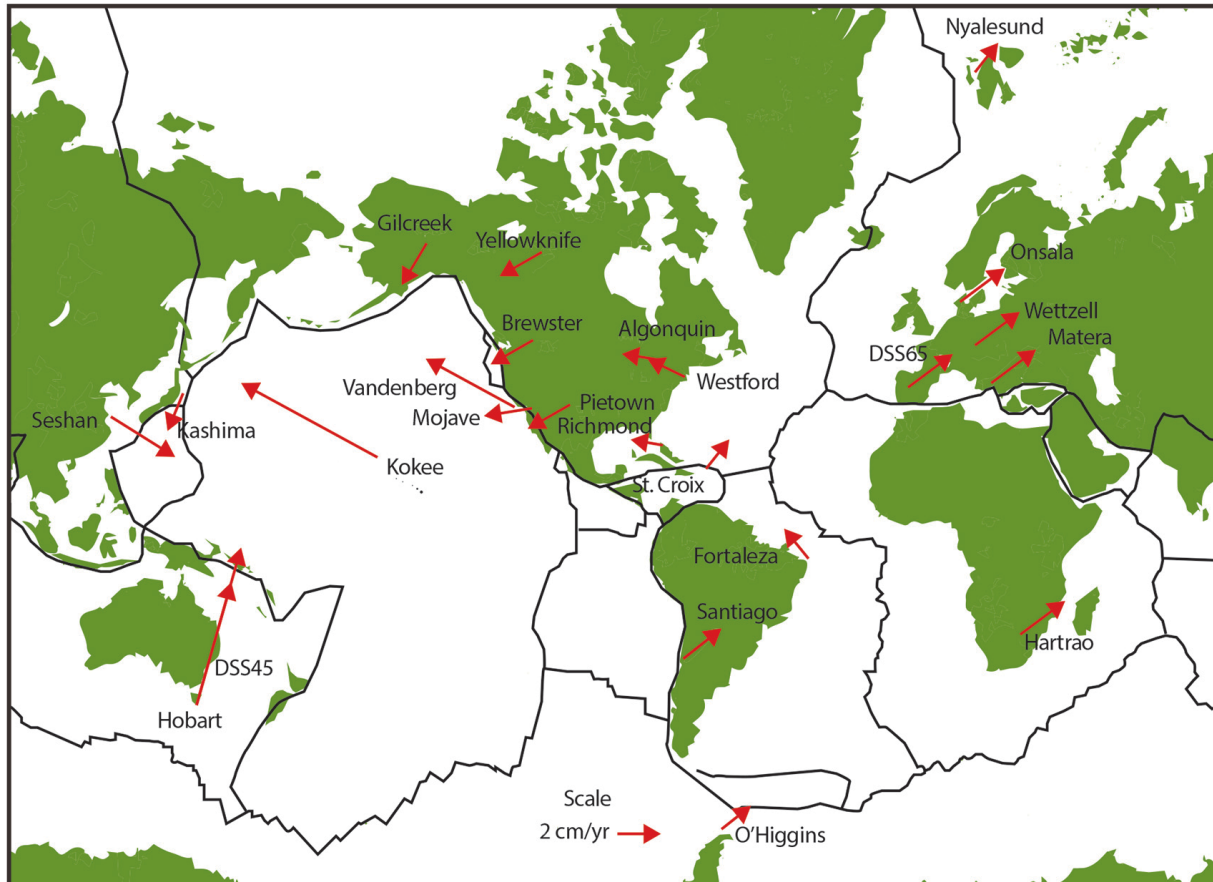
Herring et al., *JGR*, 1986

Westford–Onsala Baseline Length vs. Time Determined by VLBI



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

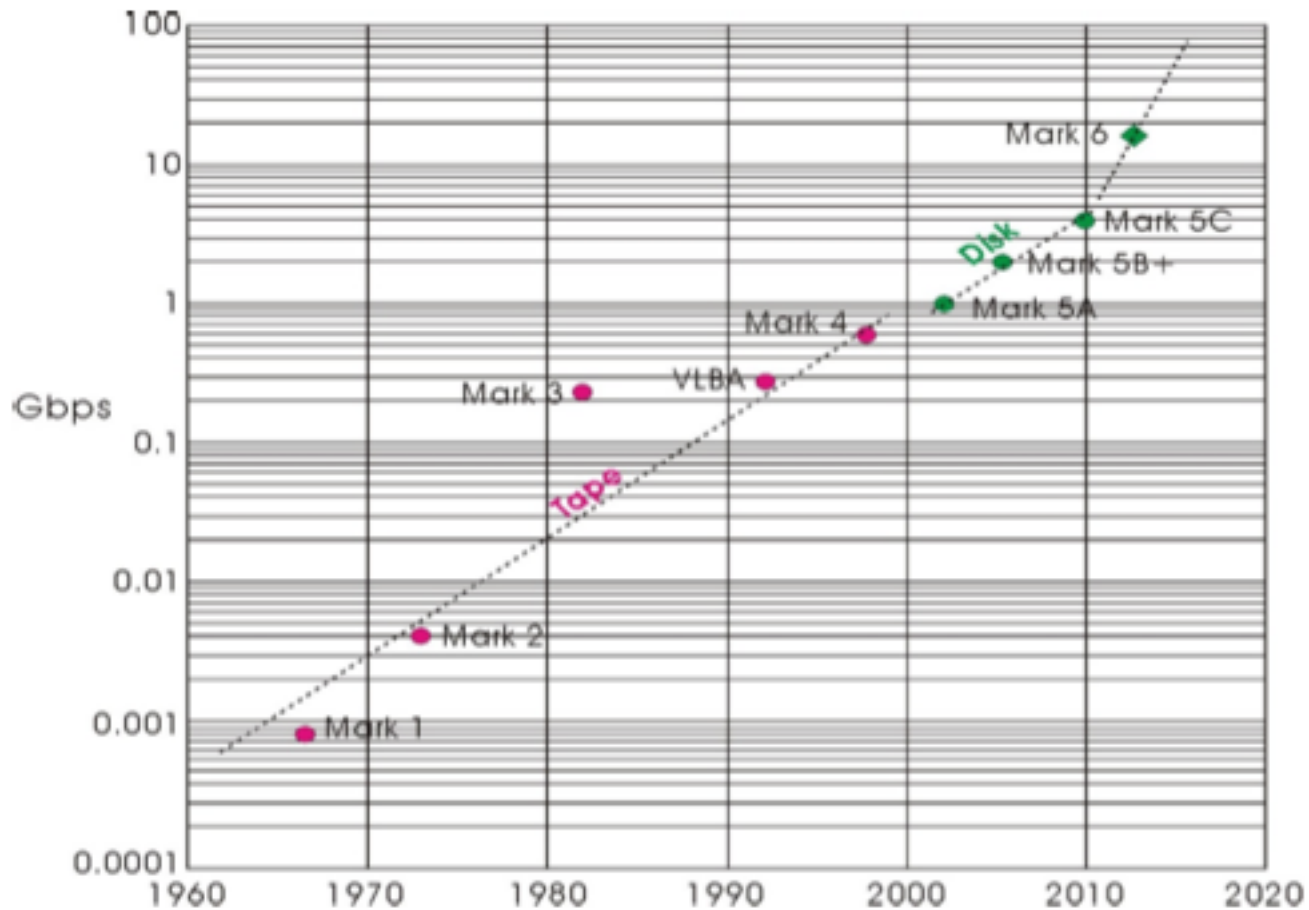
Tectonic Plate Motions Measured with VLBI



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)

Digital Data Rate vs Time



About 1 order of magnitude increase per decade

Future Instruments

- ngVLA
- SKA(mid)
- ngEHT
- BHEX (Black Hole Explorer)