# PRECISION TIMING AND VERY LONG BASELINE INTERFEROMETRY (VLBI)

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## INTRODUCTION

Very long baseline interferometry (VLBI) is a technique which was developed by radio astronomers for investigating small angular features in galactic and extragalactic radio sources. If an interferometer is formed from two separate elements along a baseline vector $\overline{B}$ and operated at wavelength $\lambda$, interference fringes will result with an angular separation

$$\theta = \lambda/|\overline{B}| \text{ radians}$$
$$= 206265\ \lambda/|\overline{B}| \text{ seconds of arc}$$

For the Goldstone–Haystack ("Goldstack") baseline which will be discussed later, $B \cong 4000$ km and $\lambda \cong 4$ cm, so $\theta \simeq 10^{-8}$ radians $\simeq 2$ milliseconds of arc. The resultant fringes may be thought of as Doppler "beats" resulting from the differential velocities of the stations when viewed from the source. The resultant fringe frequency varies as a diurnal sinusoid which has a maximum frequency (when the baseline is "broadside" to the source) of

$$f \cong \frac{B' \cos\delta}{13713\ \lambda} \text{ Hz}$$

where $B'$ is the equatorial component of the baseline and $\delta$ is the declination of the source. For sources at low declinations, the Goldstack interferometer has fringe rates of $\cong 7$ kHz.

An interferometer will respond only to signals which arise from sources smaller than a fringe. The various sources which have apparent angular sizes smaller than ~ 1 millisecond of arc include

- Nucleii of quasars and certain peculiar galaxies
- Maser-like galactic sources emitting in the OH ($\lambda \cong 18$ cm) and $H_2O$ ($\lambda \cong 1.35$ cm) spectral lines
- Pulsars
- Man-made sources such as satellites and lunar beacons.

Table 1
Current VLBI Experimental Programs.

| Program | Frequency | Stations | Collaborating Institutions |
|---|---|---|---|
| "Quasar Patrol" (to investigate the structure and variability of extragalactic radio sources) | 7.8 GHz<br>14.5 GHz | Haystack-Goldstone<br>Plus Onsala and Greenbank | GSFC-Univ. of Md.<br>MIT Haystack Obs.<br>JPL |
| Astrometric and Geodetic observations with VLBI | 7.8 GHz | Haystack-Goldstone plus Fairbanks, Onsala, and Greenbank | GSFC-Univ. of Md.<br>MIT Haystack Obs.<br>NOAA<br>Chalmers |
| Differential Astrometry<br>• Quasar proper motions<br>• general relativity tests | <br>7.8 GHz<br>8.1 GHz | Haystack-Goldstone<br><br>Haystack-Westford-Greenbank | GSFC-Univ. of Md.<br>MIT Haystack Obs. |
| • pulsar proper motions | 2.3 GHz | Greenbank-Goldstone | GSFC-Univ. of Md.<br>JPL |
| Meter wavelength VLBI<br>• studies of the Crab Nebula and associated pulsar<br>• studies of extragalactic radio source structure and spectra<br>• studies of the interstellar medium<br>• supernova remnant mapping<br>• interplanetary scintillations | 196.5 MHz<br>111.5 MHz<br>73.8 MHz | Greenbank<br>Sugar Grove<br>Arecibo | GSFC-Univ. of Md.<br>NRL<br>Arecibo Obs. |
| Decameter wavelength VLBI<br>• (same as meter wavelength program)<br>• studies of sporadic radio emission from Jupiter and Saturn | 26.3 MHz | Boulder-Haswell and Boulder-Ames | GSFC-Univ. of Md.<br>NOAA<br>Univ. of Iowa<br>Iowa State Univ. |

Table 2
Telescope Employed In VLBI Program.

| Telescope Location | Sponsoring Organization | Observing Frequency | Size | System Temperature | Site Time/ Freq. Standard |
|---|---|---|---|---|---|
| Haystack, Mass. | MIT-NEROC | 7.8 GHz | 120 ft | 50-80K | Maser |
| Westford, Mass. | | | 60 ft | 200K | Maser |
| Goldstone, Calif. | JPL | 14.5 GHz<br>7.8 GHz<br>2.3 GHz<br>2.3 GHz | 210 ft<br>210 ft<br>210 ft<br>85 ft | 40K<br>30K<br>20K<br>20K | Maser<br>Maser<br>Maser<br>Maser or Rubidium |
| Fairbanks, Alaska | NOAA | 7.8 GHz | 85 ft | 150K | Maser or Rubidium |
| Onsala, Sweden | Chalmers Inst. of Technology | 7.8 GHz | 84 ft | 50K | Maser or Rubidium |
| Greenbank, W. Va. | NRAO | 14.5 GHz<br>8.1 GHz<br>2.3 GHz<br>73-196 MHz | 140 ft<br>3 @ 85 ft<br>140 ft<br>300 ft | 100K<br>100K<br>100K<br>1000-2000K | Maser<br>Maser<br>Maser<br>Rubidium |
| Sugar Grove, W. Va. | NRL | 73-196 MHz | 150 ft | 1000-2000K | Rubidium |
| Arecibo, Puerto Rico | NAIC Cornell | 73-196 MHz | 1000 ft | 1000-2000K | Rubidium |
| Boulder, Colo. Haswell, Colo. | NOAA | 26.3 MHz | Dipole Arrays $10^4 m^2$ area | 20000K | Rubidium |
| Ames, Iowa | Univ. of Iowa and Iowa State | | | | |

The experimental programs currently being pursued by the GSFC*/University of Maryland VLBI team are shown in Table 1. Our emphasis is on astronomical observations utilizing the VLBI technique. It should be noted that these programs fall into two distinct categories. At frequencies ⩾ 2 GHz, the program emphasis is on high-sensitivity receivers, large precision telescopes, and high-stability frequency standards (typically hydrogen masers). The meter and decameter wavelength programs also require large telescopes; but due to the bright sky, receiver performance is less critical. The lower observing frequency permits less precise frequency standards (rubidium). The long-wavelength programs are summarized in more detail by Clark and Erickson (1973). The properties of the telescopes we are using are given in Table 2 and the baselines we have formed over the past four years are shown in Figure 1.

## TECHNIQUES

In order to form an interferometer such as the one shown in Figure 2, let us consider that the baseline is a vector $\overline{B}$ and that a unit vector $\hat{S}$ describes the location of a point source. Since we can egocentrically think of the sky as moving over the earth, $\hat{S}$ is a time variable, $\hat{S}(t)$.

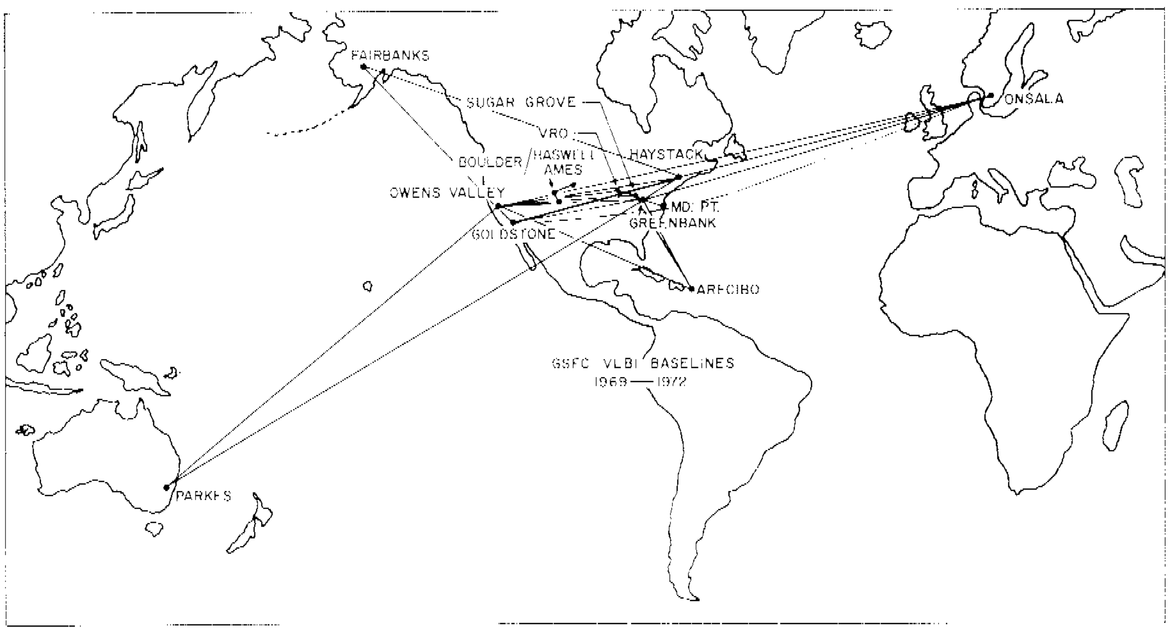


Figure 1. GSFC VLBI baselines, 1969-1972.

*There are two groups conducting VLBI investigations at GSFC. Dr. J. Ramasastry's group (Code 592) is involved in Earth Physics and Tracking Applications of VLBI. Dr. Clark's group (Code 693) is primarily involved in the Radio Astronomy aspects of VLBI. In this paper, GSFC refers to Dr. Clark's group.

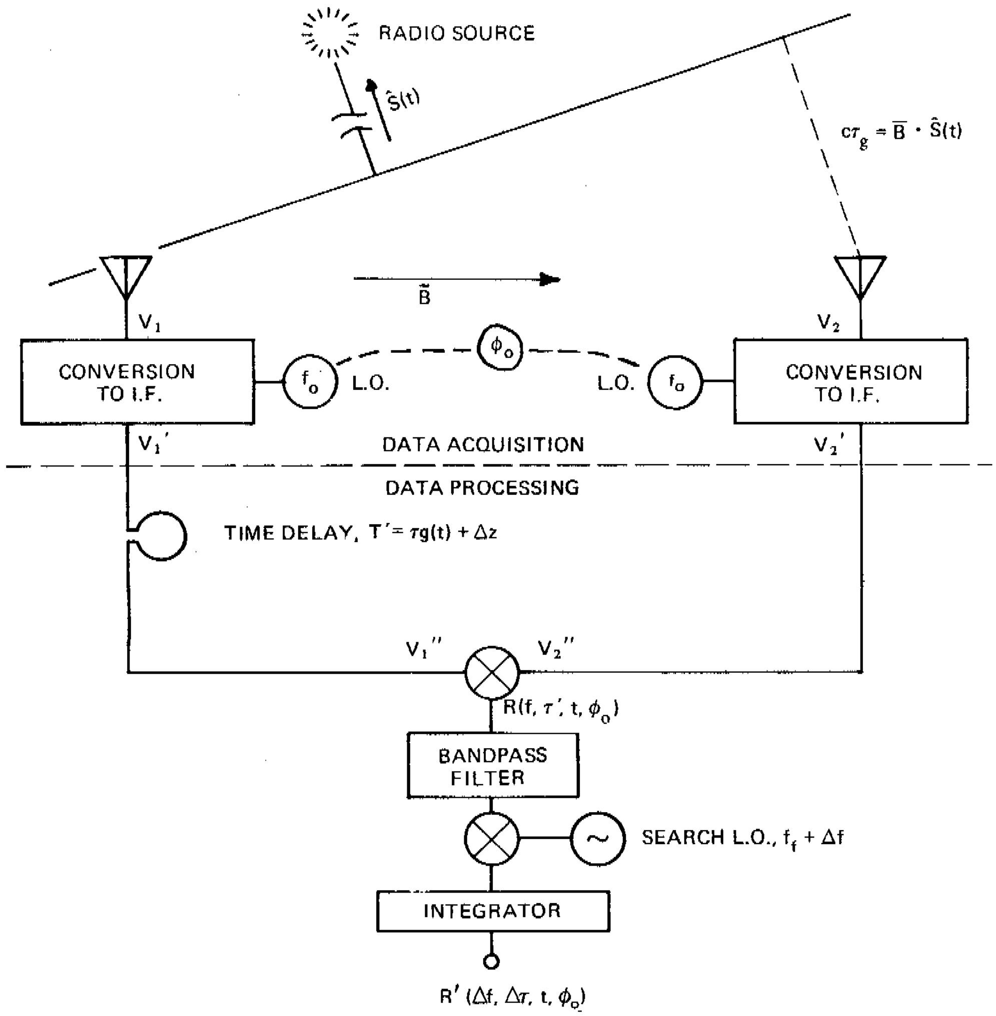


Figure 2. Simplified block diagram of an interferometer.

A wavefront from the source arrives at the left-hand station $\tau_g$ earlier than at the right-hand station, where

$$c\,\tau_g(t) = \bar{B} \cdot \hat{S}(t)$$

Our antennas have effective collecting areas $A_1$ and $A_2$, so the voltage induced by the source will be proportional to the incoming wave's electric field by

$$V_1 \propto \sqrt{A_1}\, E_o\, e^{2\pi i f t}$$

$$V_2 \propto \sqrt{A_2}\, E_o\, e^{2\pi i f (t-\tau_g)}$$

where f is the frequency of observation. To facilitate processing, the signal is amplified and converted to a convenient intermediate frequency (IF). This is done by heterodyning with a local oscillator at a frequency $\nu_o$, where we permit a phase shift $\phi_o$ (which may be time variable) to exist between the local oscillator sources. Therefore, the outputs from the IF converters will be

$$V_1' \propto \sqrt{A_1}\, E_o\, e^{2\pi i(f-f_o)t}$$

$$V_2' \propto \sqrt{A_2}\, E_o\, e^{2\pi i[(f-f_o)t - f\tau_g]}\, e^{i\phi_o}$$

If the signal in the left-hand channel is now delayed by $\tau'$ (which is nominally $= \tau_g$), then

$$V_1'' \propto V_1'\, e^{-2\pi i(f-f_o)\tau'} \propto \sqrt{A_1}\, e^{2\pi i(f-f_o)(t-\tau')}$$

$$V_2'' = V_2'$$

Note that the phase shift of the delay line $\tau'$ enters at the intermediate frequency $(f-f_o)$.

The cross correlator multiplies the two signals $V_1''$ and $V_2''$. If we assume that only the difference terms are passed by the bandpass filter, i.e., frequencies of $\sim 2f_{if} = 2(f-f_o)$ are attenuated, then

$$R(f,\tau,t,\phi_o) = V_1'' \cdot V_2''^{*}$$

$$\propto \sqrt{A_1 A_2}\, E_o^2\, \underbrace{e^{2\pi i f_o \tau_g}}_{A}\, \underbrace{e^{2\pi i(f-f_o)(\tau_g - \tau')}}_{B}\, \underbrace{e^{-i\phi_o}}_{C}$$

The "A" term represents the fringes, since it is the variation of $\tau_g$ with time that results in a periodic sinusoidal interference pattern. Note that when the delay line $\tau'$ is "tracked" with $\tau_g$, it is the local oscillator frequency $f_o$, and not the signal frequency f which describes the fringes.

In order to conveniently process these fringes, we next slow them down further by removing the nominal fringe frequency $f_f$, where

$$f_f = \frac{d}{dt}(f_o \tau_g) = f_o \cdot \dot{\tau}_g$$

By suitably "searching" about $f_f$ we can define the true fringe frequency $f_f + \Delta f$. Since the output from this last heterodyning operation is at dc, we can now integrate for long periods of time. We are limited by the time interval $t_c$ of the "C" term over which the local oscillators maintain coherence, i.e., when $< \phi_o(t + t_c) - \phi_o(t) > \sim 1$ radian. The uncertainty principle dictates that the fringe frequency can be measured with a accuracy of $\sim(2\pi \times \text{integration time})^{-1}$, or about 1 mHz for our normal three-minute recording time. The "B" term describes the phenomenon of the "white-light" fringe, which we more properly call the delay resolution function (DRF). In general, we observe a band of noise frequencies, and not a discrete, unique frequency. For the extragalactic radio sources, the intrinsic radiation is so broadband that it may be considered as uniform over any realizable passband. (The OH and $H_2O$ sources in our galaxy and manmade sources in general do not meet this criterion.)

If each of the IF converters had a filter with a power response $G(f_{if})$, where $f_{if} = f - f_o$, then the response of the correlator to broadband signals would be

$$R'(\Delta f, \Delta\tau, t, \phi_o) = \frac{\int G(f_{if}) R(f_{if}, \Delta f, t, \phi_o)\, df_{if}}{\int G(f_{if})\, df_{if}}$$

$$\propto \int G(f_{if})\, e^{-2\pi i f_{if} \Delta\tau}\, df_{if}$$

where $\Delta\tau = \tau' - \tau_g$. The latter relation should be recognized as the Fourier transform of the response function G, measured in residual delay ($\Delta\tau$) units. We call the envelope of $R'(\Delta\tau)$ the DRF. It has a characteristic width $\sim (2\pi \times \text{bandwidth})^{-1}$. For a rectangular passband of width $\Delta F_R$, the DRF will have the form

$$R(\Delta\tau)\ \alpha\ \frac{\sin(\pi \Delta F_R\, \Delta\tau)}{\pi\, \Delta F_R\, \Delta\tau}$$

which is ~ 3 $\mu$sec wide for our normal 360-kHz recording bandwidth. In order to narrow the DRF, we have developed a technique of synthesizing a wide bandwidth (Rogers, 1970; Hinteregger, 1972; Hinteregger et al., 1972) by sequentially sampling a number of discrete 360-kHz bands over a range of up to ~ 100 MHz. Figure 3 shows an observed DRF utilizing the Goldstack configuration with five switching steps over ~40 MHz. Note that the delay $\Delta\tau$ can easily be measured to a few nanoseconds (ns).

Let us briefly describe the actual VLBI recording system. We use adaptations of the "Mark-1" recording system developed at the National Radio Astronomy Observatory (Bare et al., 1967). This system records 360-kHz bandwidth noise at a 720 kbps rate on ordinary seven-track, 800 bites per inch computer tapes running at 150 inches per second. Data is blocked into 0.2-second records (~ 140 kb), and the time at which each bit was sampled (at a 1.4 $\mu$sec rate) is known to a few hundred ns with respect to a local UTC clock. Tapes are started at each station on a nominal (and prenegotiated) minute, and tape formatting (record counts + bit counts within a record) establishes synchronization. Tapes are then brought together at a later time and are played back on an ordinary digital computer. The computer calculates a priori values of $\tau_g$ and $\dot{\tau}_g$, changes the bit alighment by $\tau' \cong \tau_g \pm n$ bits (where n = 3,2,1,0) to allow for the finite width of the DRF and some clock errors, and cross-correlates the bits. Fringe rates ($f_o \dot{\tau}_g$) are then removed by phase rotations on the cross-correlation values. Small residual $\Delta f$'s are measured by additional offset "oscillators" (actually by performing fast Fourier transforms) and best-fit values of $\Delta\tau$, $\Delta f$, $|R|$ and $\phi_o$ (t) are derived. These computer programs have been implemented for IBM 360 computers here at GSFC, where the bit correlations are done in software, and for the CDC 3300 computer at Haystack, where the bit correlations are done in a hard-wired integrated-circuit correlator.

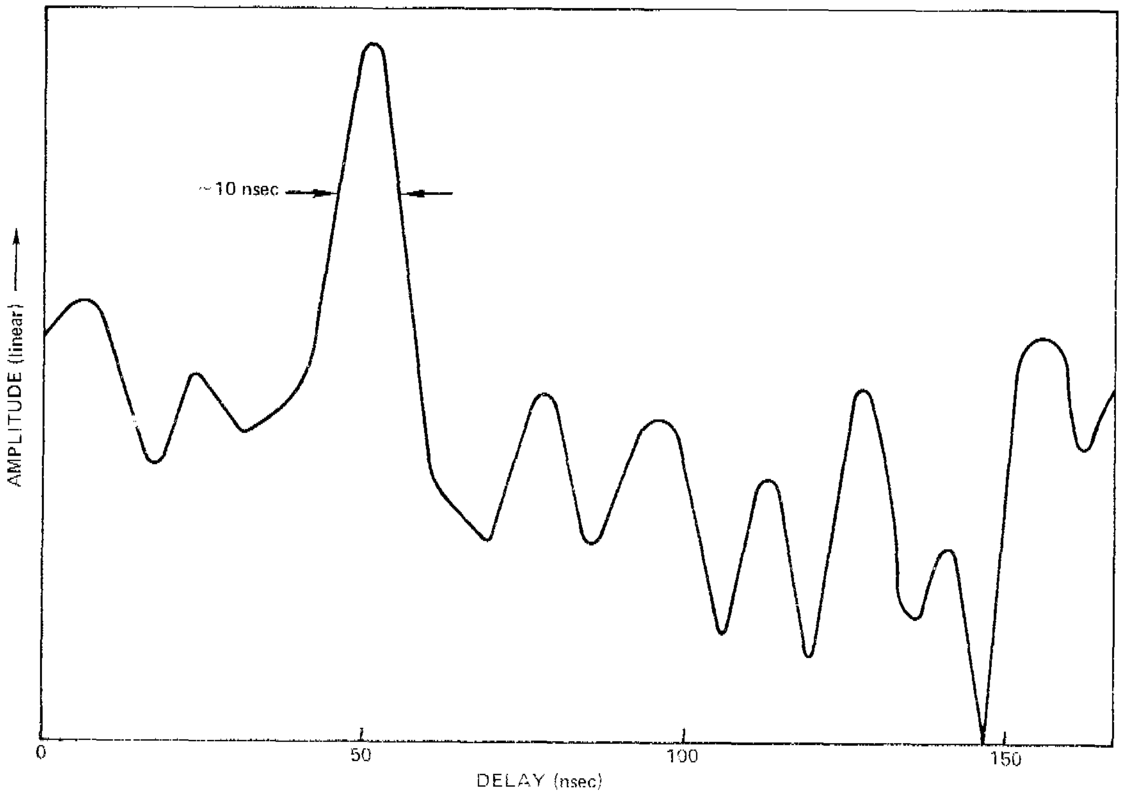


Figure 3. Delay resolution function, Goldstack, April 15, 1972. Source: VRO 42.22.01.

In order to minimize the number of trials necessary to process these data, we like to know that portion of $\Delta\tau$ which arises from the clocks which sample the bits and format the tapes to ~ 10 $\mu$sec or better. We further want the clocks to remain stable to ~ 1 $\mu$sec for the several days that an experiment may be in progress. Our long-term clock requirements therefore are at the $\Delta t/t \sim 10^{-11}$ to $10^{-12}$ level, well within the state-of-the-art even for rubidium clocks.

In the previous discussion, we assumed that the local oscillators were similar and that their differences were characterized by a phase offset $\phi_0(t)$. In order to "break the wires" of a conventional interferometer so that the stations can be separated by large distances, it is necessary that we have oscillators which are as nearly identical as possible. Since we can never hope to measure $\phi_0(t)$ explicitly, we must have frequency standards with good phase stability. A typical requirement is less than one radian rms phase perturbation accumulated in our integration period. We record data for three minutes on one tape, so at 8 GHz we need short term phase stability of

$$\frac{<\Delta\phi>}{\phi} = \frac{1}{2\pi \cdot 8 \cdot 10^9 \cdot 180} \cong 1 \times 10^{-13}$$

Many experiments we perform call for measuring times on several tapes, so 10-20 minute stability levels of ~ $10^{-14}$ are desirable.

In order to achieve these levels of stability, we began collaborating with Mr. H. Peters of GSFC more than four years ago on deploying hydrogen masers to radio astronomy observatories, and on making masers and the associated local oscillator multipliers more stable and reliable. Mr. Peters has made available two older Varian H-10 masers which now reside at Greenbank, West Virginia, and at Haystack, Massachusetts. His NP masers have been successfully used at Haystack; Owens Valley, California; Fairbanks, Alaska; Maryland Point, Maryland; Tidbinbilla, Australia; Johannesburg, South Africa; Madrid, Spain; and soon Onsala, Sweden, for astronomical VLBI experiments. Masers built by Dr. Vessot of the Smithsonian have been used at Agassiz Observatory, Massachusetts; Owens Valley, California; and Madrid, Spain; while masers built by Dr. Sydnor of JPL are regularly used at the Goldstone 210-foot telescope. Haystack owns another H-10, which has been used for radar and VLBI for a number of years. The Canadian VLBI team owns two H-10s, which they have used extensively. Apologies are offered to those who have been slighted by omission from this list. It should be clear that VLBI requires the best standards available, and is one of the major users of those that are available in the field.

In Figure 4 we show the phase stability which we achieve with hydrogen masers at X-band. To form this plot we have removed the a priori fringe phase due to the source-interferometer geometry ($2\pi f_0 \dot{\tau}_g$) and a $5 \times 10^{-13}$ linear offset. The dotted line shows the trend of the mean phase as determined from three-minute observations. The short solid lines show the phase trend during each three-minute run. The data span 42 minutes. No correction for phase noise due to the neutral atmosphere was possible for these data. The ionospheric contribution should be negligible. These data show three distinct regions. During the first half two slopes appear, zero and $-3 \times 10^{-13}$. The last half has a constant slope of $+4 \times 10^{-14}$. The phase during the three-minute runs fits the longer term curve well except for "glitches" at ~ 0720 UT and 0735 UT. These short transients could easily be due to clouds passing through the beam of one of the telescopes, since the phase seems to return to the mean line after a few minutes.

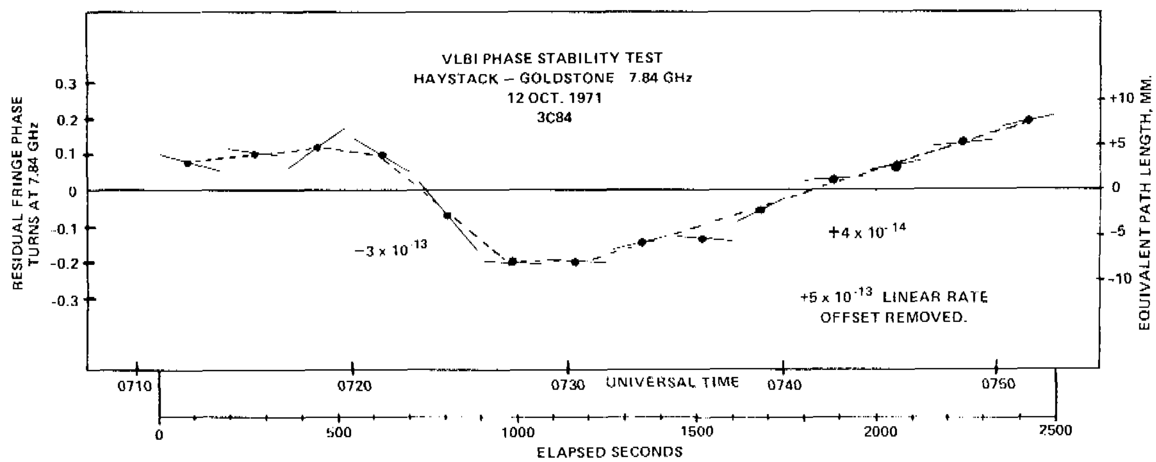


Figure 4. VLBI phase stability test, Haystack-Goldstone, 7.84 GHz, October 12, 1971, 3C84.

Some similar plots obtained with rubidium standards at meter wavelengths are shown in Figures 5 (from Erickson et al., 1972) and 6. Most of the phase noise at these low frequencies is due to the ionosphere since the stability required to give $<\Delta\phi> \lesssim 1$ radian is only $\sim 10^{-11}$.

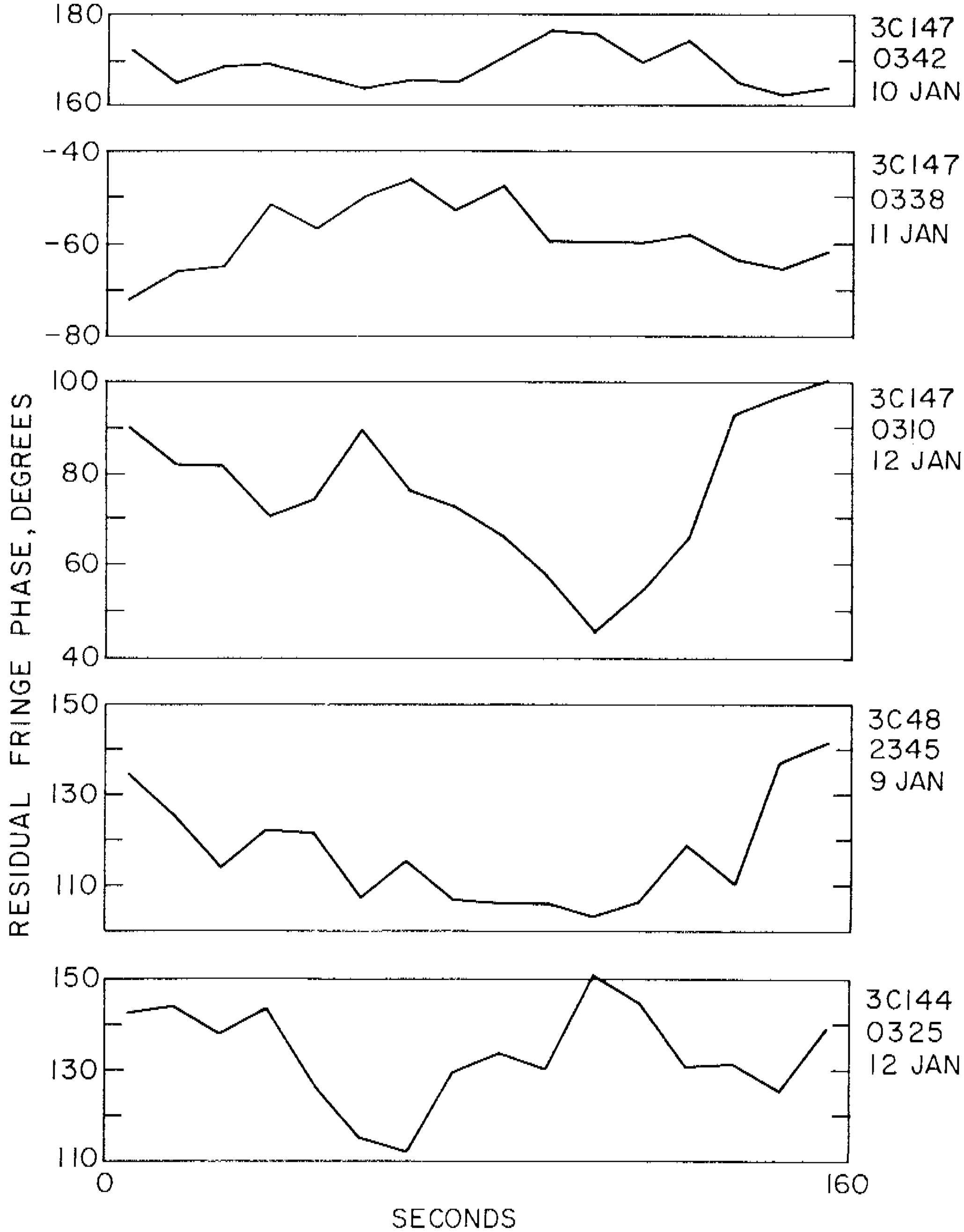


Figure 5. Phase stability plots with rubidium standards.

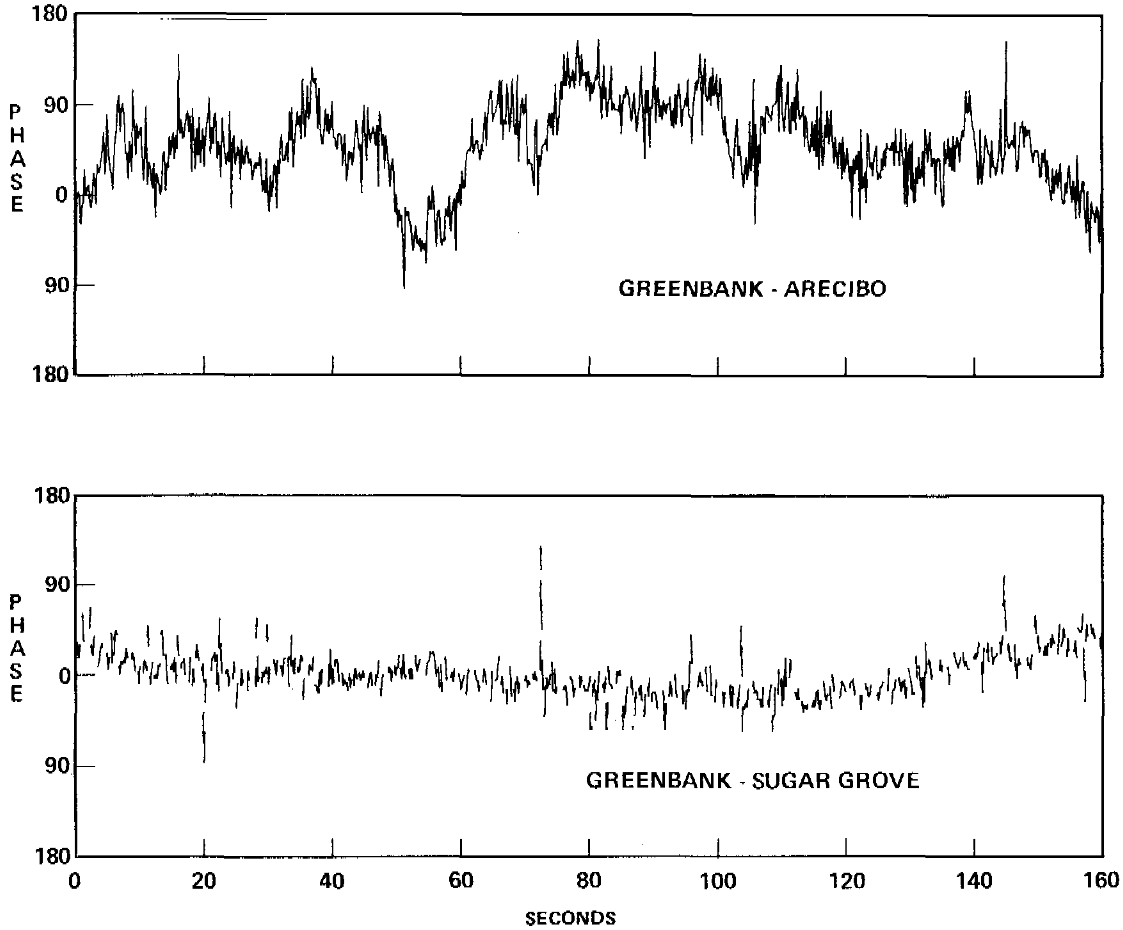


Figure 6. VLBI phase stability, 196.5 MHz, December 19, 1971, 3C287.

## RESULTS

Let us now discuss some of the more interesting results from our VLBI program.

(1) Structure of Quasars: We began using the Goldstack configuration in the fall of 1970. Our initial experiment was to be a test of general relativity by measuring the change in position of the Quasar 3C279 as it is occulted by the sun (this is an annual event and has become our "Oktoberfest"). As a surprise to us, we found that 3C279 showed significant fringe amplitude variations (see Figure 7) which could be interpreted in terms of 3C279 being an equal double source with a separation of 1.55 ± 0.03 milliseconds of arc (Knight el al., 1971). When we repeated the experiment four months later, the spacing between components had increased to 1.69 ± 0.02 milliseconds of arc. The resultant expansion rate of 1.2 microsecond of arc per day corresponds to ten times the velocity of light if 3C279 is at the distance (~ 6 X $10^9$ light years) indicated by its red shift (Whitney et al., 1971). Since this startling discovery, a number of other sources have also been observed

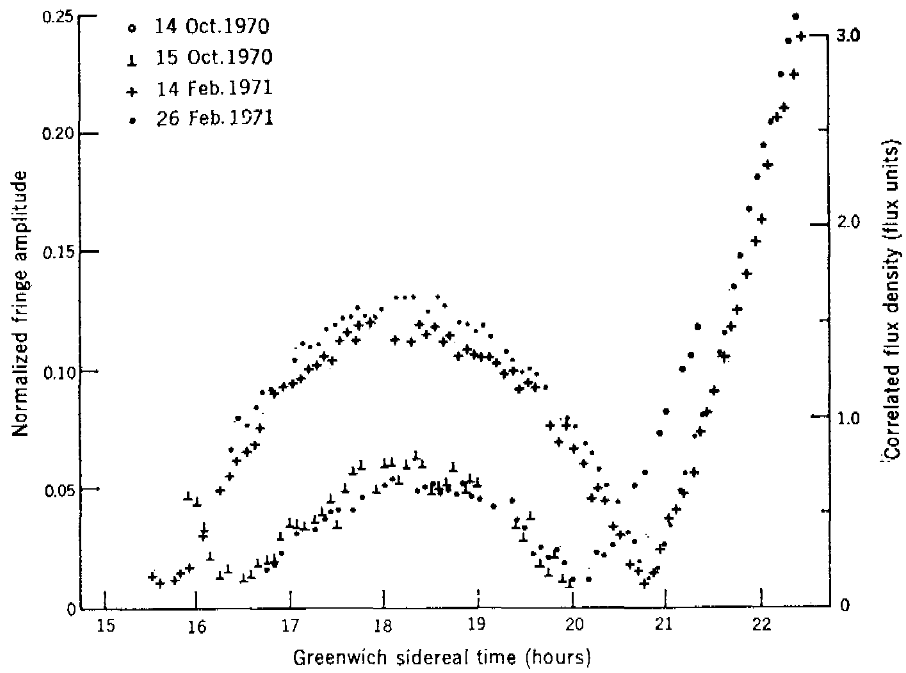


Figure 7. Significant quasar fringe amplitude variations.

to change their structure on short time scales and a synoptic observing program known as the "Quasar Patrol" has been set up to study these phenomena (Shapiro et al., 1973).

(2) Geodesy and Astrometry: VLBI shows great promise of being able to perform geodetic measurements over large distances to accuracies of better than one meter. Because of our inability to measure the phase offsets of the independent local oscillators [$\phi_o$ (t)], we will find it difficult to work to the levels of a fraction of a fringe in angle ($\lesssim$ 1 cm in length) directly. However, we can observe the fringe phase ($2\pi f_o \tau_g$) either as a function of time to define the fringe rate

$$f_f(t) = \frac{1}{2\pi}\frac{d}{dt}\phi$$

or as a function of frequency to define the group delay

$$\tau_g(t) = \frac{d}{df}\phi$$

independent of the value of $\phi_o$.

A least-squares fit on $f_f(t)$ and/or $\tau_g(t)$ for data spanning a number of hours of time on a number of sources permits the separation of the baseline and source geometry terms. We have demonstrated (Hinteregger et al., 1972) that we can perform geodetic measurements at the ~ 1 meter level in the length of $\overline{B}$ and a few meters in the orientation of $\overline{B}$ and our

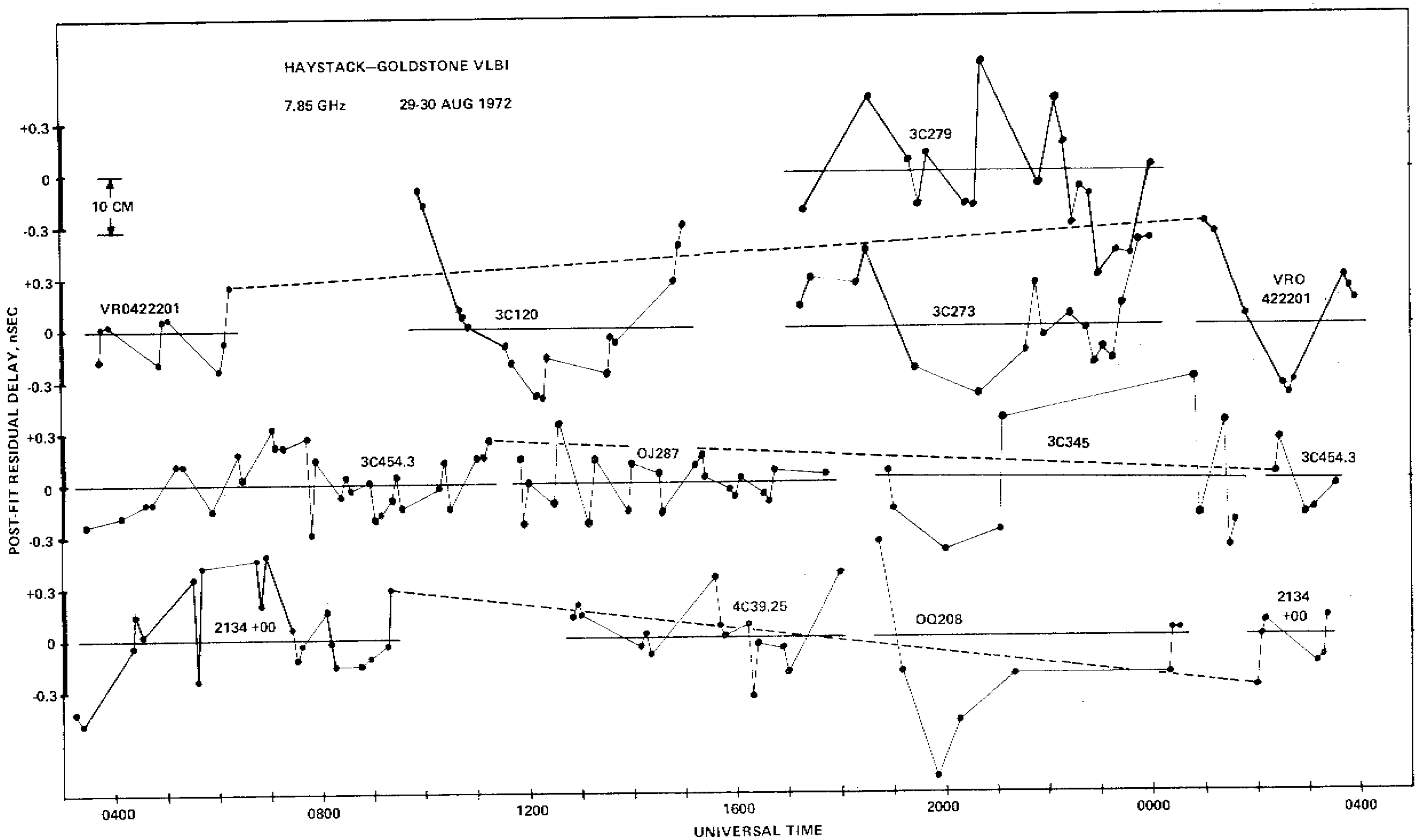


Figure 9. The ensemble of group delay residuals. Haystack-Goldstone VLBI, 7.85 GHz, August 29-30, 1972.

The lower frequency experiments are of purely astronomical interest and beyond the scope of this paper.

## SUMMARY

In summary, VLBI is finding applications in a number of distinct areas, including

- Astronomical studies of quasars, pulsars, and so on
- Precision geodesy
- Tests of fundamental physical laws
- Satellite tracking

In order to perform VLBI measurements we need precise time and frequency standards. VLBI has been one of the main driving forces in the development of field-operational hydrogen masers. VLBI in return shows promise at achieving operational time and frequency coordination on an intercontinental basis. The continued progress of the technique requires the close cooperation of radio astronomers and the engineers developing advanced standards.

The work described in this report reflects the combined efforts of a number of individuals at a number of institutions. It would be futile to try to list them all, but the MIT members of our team (consisting of I. Shapiro, A. Rogers, A. Whitney, H. Hinteregger, C. Knight, D. Robertson, and a number of others) have spearheaded the geodetic and astrometric work described here. They derive financial support from the NSF and ARPA.

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