RADIO INTERFEROMETRIC GEODESY USING A RUBIDIUM FREQUENCY SYSTEM

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ABSTRACT

In order to be useful for geophysical applications, geodetic baseline measurement accuracy must be at the few centimeter level. For independent station radio interferometric geodetic systems the accuracy requirement of a few centimeters is most often translated into frequency system performance of $\Delta f/f = 10^{-14}$ or better. However, for specific applications such as determining three baseline vector components and two or three instrumental parameters the frequency system requirements can be made a factor of approximately 30 less stringent so that the Rubidium frequency system comes close to meeting the required performance at S-band. A simplified analysis is developed which illustrates the performance needed to achieve 3 cm baseline precision in terms of short, medium and long term fractional frequency deviation. These analytic approaches have been tested in actual independent station radio interferometry. From December 1973 to June 1974, a series of four independent station interferometry experiments were conducted on a 307 meter baseline using the 9 meter transportable ARIES (Astronomical Radio Interferometric Earth Surveying) station, and the 64-meter MARS station of the Goldstone Deep Space Communications Complex. The ARIES station was equipped with an HP 5065A Rubidium frequency system while the 64-m station used a JPL Hydrogen maser. The three-dimensional baseline precisions obtained were 10 cm or better from individual six-hour experiments, 3-cm precision for a weighted average of 23 hours of data and accuracies of 0.1 cm to 4.9 cm when compared with a geodetic survey between the stations. The Rubidium frequency system performance achieved in these experiments was $\Delta f/f = 2 \times 10^{-13}$, about a factor of two better than the Hewlett Packard specification.

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INTRODUCTION

A cursory look at the requirements on a frequency and time system to be considered for use in an independent station radio interferometric geodetic measurement would likely conclude only a Hydrogen maser or similar device was adequate to the task.

For example, in the fringe frequency domain the partial derivative sensitivity to baseline is 0.5×10^{-3} Hz per meter. Thus, to achieve a 3 cm sensitivity at S-band (2.3 GHz) would require $\Delta f/f = 7 \times 10^{-15}$. In the time domain, the sensitivity is that imposed by the speed of light or about 3 nanoseconds per meter, so that over the duration of a six-hour experiment the 3 cm performance requirement appears to be $\Delta T/T = 5 \times 10^{-15}$.

Although Project ARIES (Astronomical Radio Interferometric Earth Surveying) has currently progressed to operating on baselines of about 200 km, the frequency system factors are best illustrated with data from earlier 307 m system verification experiments (Ref. 6). The reasoning is that the frequency system contributions to the overall behavior of the system are better understood when factors such as transmission media, source positions and Earth orientation parameters are minimized. Also, the 307 m baseline could be conveniently surveyed in three dimensions so that system accuracy can be assessed.

When the initial planning implementation of the ARIES station began in late 1972 and early 1973, it was clear that the resources available could not include a Hydrogen maser frequency system. Thus, alternative strategies were sought to make some other less expensive frequency system useable. The commercially available rubidium and cesium devices were, of course, the prime candidates. In late 1972, an interferometry experiment was conducted on the 16 km Goldstone baseline using a JPL H-maser at the 64-m MARS station and the operational ECHO (26m) tracking station standard, HP 5065A rubidium. The result was encouraging since the Rb/H-maser combination had baseline noise of 7 to 10 cm and agreed well with the 4 cm precision (signal to noise limited) results of that baseline when run with H-masers at each station. By this time the radio source observing strategy had evolved to the point of obtaining a set of sources to accomplish a baseline solution as quickly as possible which is further discussed in the requirements section of this paper.

The rubidium performance discussed here is pessimistic since a great many elements are involved in actually obtaining delay residuals from which fractional frequency deviations are deduced. Also, the Hydrogen maser used at the 64-m station is assumed to have contributed no significant noise in these measurements.

For those interested in the specifics of the geodetic surveying by radio interferometry, the reader will find the References useful.

FREQUENCY SYSTEM REQUIREMENTS

Short Term (1 to 10^2 Sec)

First there is the requirement that fringes be obtained and this forms short term requirements. The detailed mechanization of this processing is discussed elsewhere (Ref. 9 to 12) and we will merely state that the stability needed at each station is that neither local oscillator shall gain or lose a tenth of an RF cycle of the received frequency over whatever averaging time is required in the cross-correlation signal processing. For strong quasar sources, the coherent averaging time may be as small as 1 second while weak sources may require coherent averaging times of 100 seconds or more. At S-band the performance requirements then become $\Delta f/f = 5 \times 10^{-11}$ for strong sources and $\Delta f/f = 5 \times 10^{-13}$ or better for weak sources. At X-band (8.4 GHz) the requirements range from 1.4×10^{-11} to 1.4×10^{-13}. There is little that can be done here to relax these requirements except to redesign the telecommunications parameters to achieve larger signal to noise ratios to stay away from the weak signal case. Basically, a Rubidium system can be relied upon at S-band but would become marginal at X-band for satisfying these short term interferometry needs, see Figure 1 and 2.

Medium Term (10^3 Sec)

Over a period of several hours the two interferometry stations observe the extragalactic radio sources on a cycle of about six minutes on the source and ten minutes to move the antennas to the next source governed entirely by the slewing rate of the large antenna. Typically the sources are about 90 degrees apart on the sky. So that about 10^3 second elapses between individual source observations. Within a given six hour experiment, 24 observations are made of six or more sources. Assuming that we are solving for six parameters (three baseline and three instrumental) the solution set is a factor of 4 over-determined. If the desired baseline precision is 3 cm then the individual source observations need a precision of 6 cm since the over-determined nature of the solution will help by a factor of two assuming geometrically well distributed sources. The 6 cm implies 0.2 nsec over periods of 10^3 seconds or a $\Delta f/f = 2 \times 10^{-13}$. These performance levels have been seen with the HP 5065A in the actual experiments. Such performance is a factor of two better than the Hewlett Packard specified performance, see Figures 1 and 3.

Long Term (10^4 to 10^5 Sec)

Initially, there is the assumption that the phase noise introduced into the system be uncorrelated with the delay observable partial derivative sensitivity to the individual baseline components. This assumption is not always satisfied causing baseline solution degradations of a factor of 2 to 4, see Table 1 and Figures 4 and 5.

Using the 24 observations accumulated over six hours, a simultaneous solution must be accomplished for the three baseline vector components and either two or three instrumental parameters (clock and frequency synchronization plus a possible time dependent frequency term). It is possible to accomplish this simultaneous six parameter estimation because the instrumental parameters do not depend upon the directions in which the two antennas are pointed. Meanwhile, the delay of the incoming quasar wavefront, of course, depends upon the DOT product of the baseline vector and the vector direction to the radio source (i.e. the directions in which the antennas are pointed). One must be careful to examine the instrumentation to assure that such an assumption of electrical phase stability is in fact correct within required limits. For example, if differential phase shifts were occurring in cables as the antenna moved to different positions then the clock offset term would take on the appearance of being related to one or more baseline components. Actual measurements of such differential phase shifts have been performed for both the ARIES and MARS stations and have been found to be at about the 1 cm baseline vector equivalent level and are not thought to be of sufficient magnitude to warrant direct calibration at this time.

The ability to estimate clock and frequency offset terms affecting the entire data set is a strong self-calibration feature. It is only those frequency system instabilities that remain after the offset removals which forms the concern as to what will actually disturb the baseline vector estimation. In effect what is done is to find time spans during the experiment when the frequency system behavior is easily parameterized. Specifically that the delay be describable by a constant delay offset, a constant time rate of change of delay and possibly a quadratic delay term to account for frequency drift. Figure 3 is an example of an experiment with a six parameter estimation (three baseline, constant offset, constant rate and frequency drift). If situations are encountered where the system does not exhibit such easily parameterized behavior, then the solution set is segmented into regions where it does apply. The limit to such segmenting obviously occurs when an insufficient number of sources have been observed with a wide geometric sky spread. Figure 5 illustrates the breaking of a solution set to analytically describe long term performance. Thus, over periods of hours the frequency system needs to behave in a smooth continuous manner so that the medium term performance of $\Delta f/f = 2 \times 10^{-13}$ can be exploited to yield 3 cm baseline results. Abrupt changes in offset and slope, as seen in Figure 6, can be tolerated provided that there are stable intervals in which to obtain five or six parameter solutions. While the change in slope may appear large in Figure 6, it actually amounts to 5×10^{-13}, exactly the specified performance for the HP 5065A for averaging times of hours.

COMBINED FREQUENCY SYSTEM APPROACH

There exists the possibility of further system stabilization of the long term by using a cesium beam resonator in combination with the rubidium. In this way the rubidium would govern the short and medium term performance and the cesium the long term. Thus, the overall baseline solution would be stronger since fewer instrumental terms would have to be estimated.

There is the desire to make observations at X-band to minimize charged particle delay effects of the transmission medium but the rubidium is marginal for that short term application. Again, a combined frequency system of crystal and rubidium is useful as already shown in Reference 1.

THE INTERPLAY OF FREQUENCY STABILITY AND CHOICE OF ANTENNAS

As seen in the actual rubidium data, (Figures 5 and 6) the system tends to behave well over time intervals of 30-90 minutes and even out to 10 hours (see Figure 3) but occasionally makes an abrupt change in phase offset and rate which forces the interferometer baseline solution to be restarted to estimate new instrumental parameters. If an insufficient set of sources have been observed during the well-behaved interval, the baseline vector solution will tend to absorb the frequency system excursion as being similar in character to the baseline components.

The use of the 64-m MARS station brings with it a factor of 2.8 better signal-to-noise ratio than a 26-m station but also requires longer move times between sources. The 64-m station needs between 6 and 30 minutes to go between sources depending upon the cable wraps. A 26-m station can move at a faster slewing rate so that only 2 to 3 minutes are needed to cover a 90 degree move. Thus, one can choose an option to observe sets of five or six sources in one-half hour and obtain stand-alone data sets (possessing sufficient data to solve for baseline and instrumental parameters) during probable periods of well-behaved Rubidium performance. These half-hour data sets would then be combined together over the 8 to 24 hour data acquisition interval to yield an overall baseline precision of 4 to 6 cm.

Thus, the apparent paradox that using a smaller diameter antenna can improve the baseline measurement accuracy.

CONCLUSION

A cursory estimation of frequency system requirements to accomplish independent station radio interferometry baseline measurements might conclude that only a Hydrogen maser could perform the job.

However, such an estimation needs to take into account the ability of the radio interferometer to be somewhat self-calibrating. It has been shown, analytically and experimentally with 307 m baseline data, that the frequency system requirements are actually $\Delta f/f = 2 \times 10^{-13}$ to achieve 3 cm baseline accuracy at S-band. This amounts to being a factor of 30 to 40 less severe than the cursory estimate and makes the Rubidium (HP 5065A) system a very useful device for geodesy by radio interferometry.

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FREQUENCY SYSTEM REQUIREMENTS TO ACHIEVE 3 cm BASELINE PRECISION

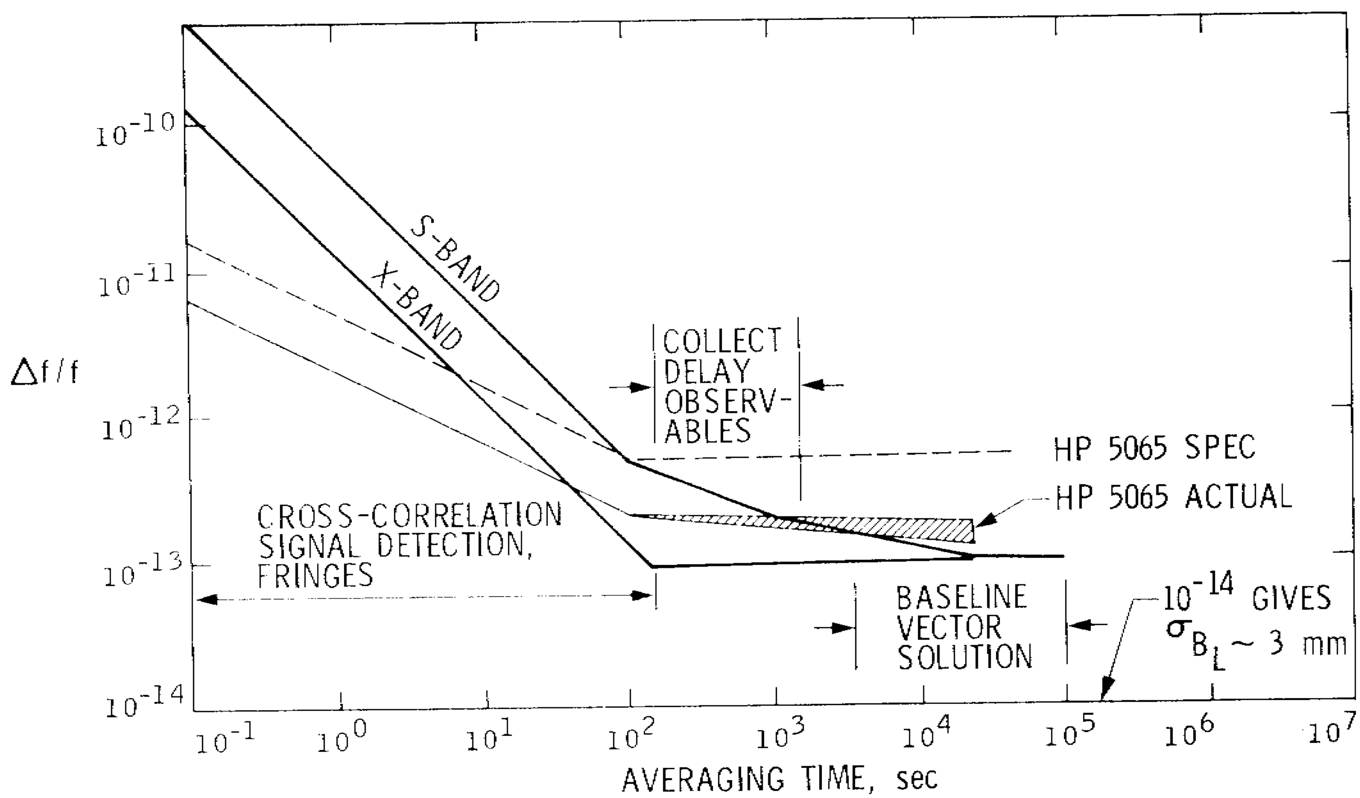


Figure 1

♈ TIME DELAY MEASUREMENT PRECISION

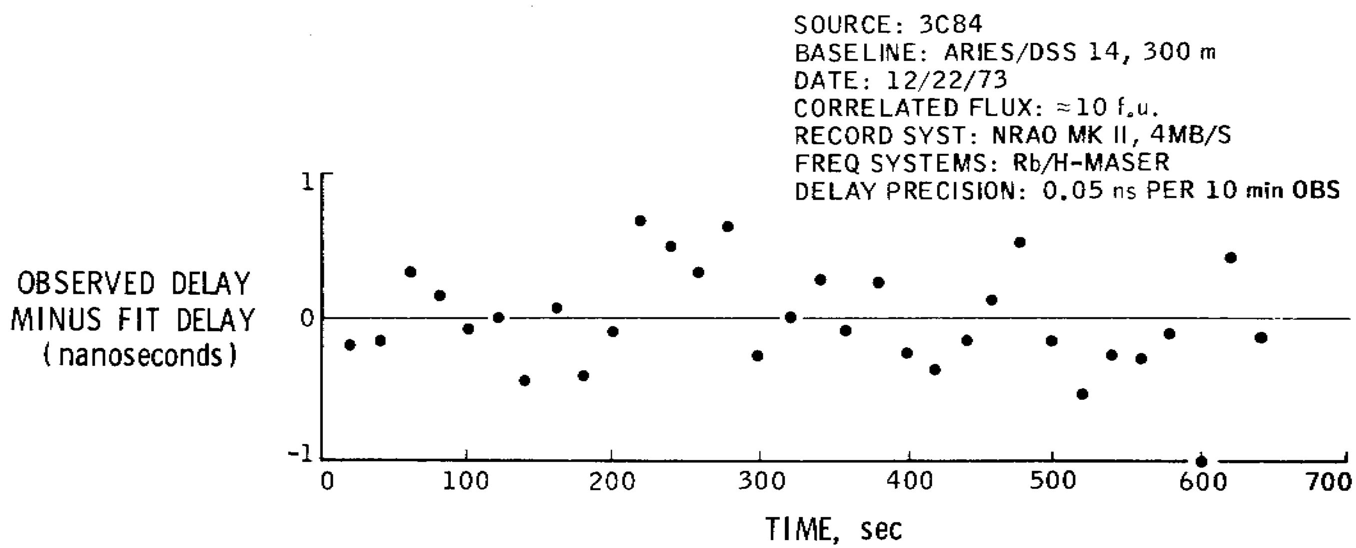


Figure 2

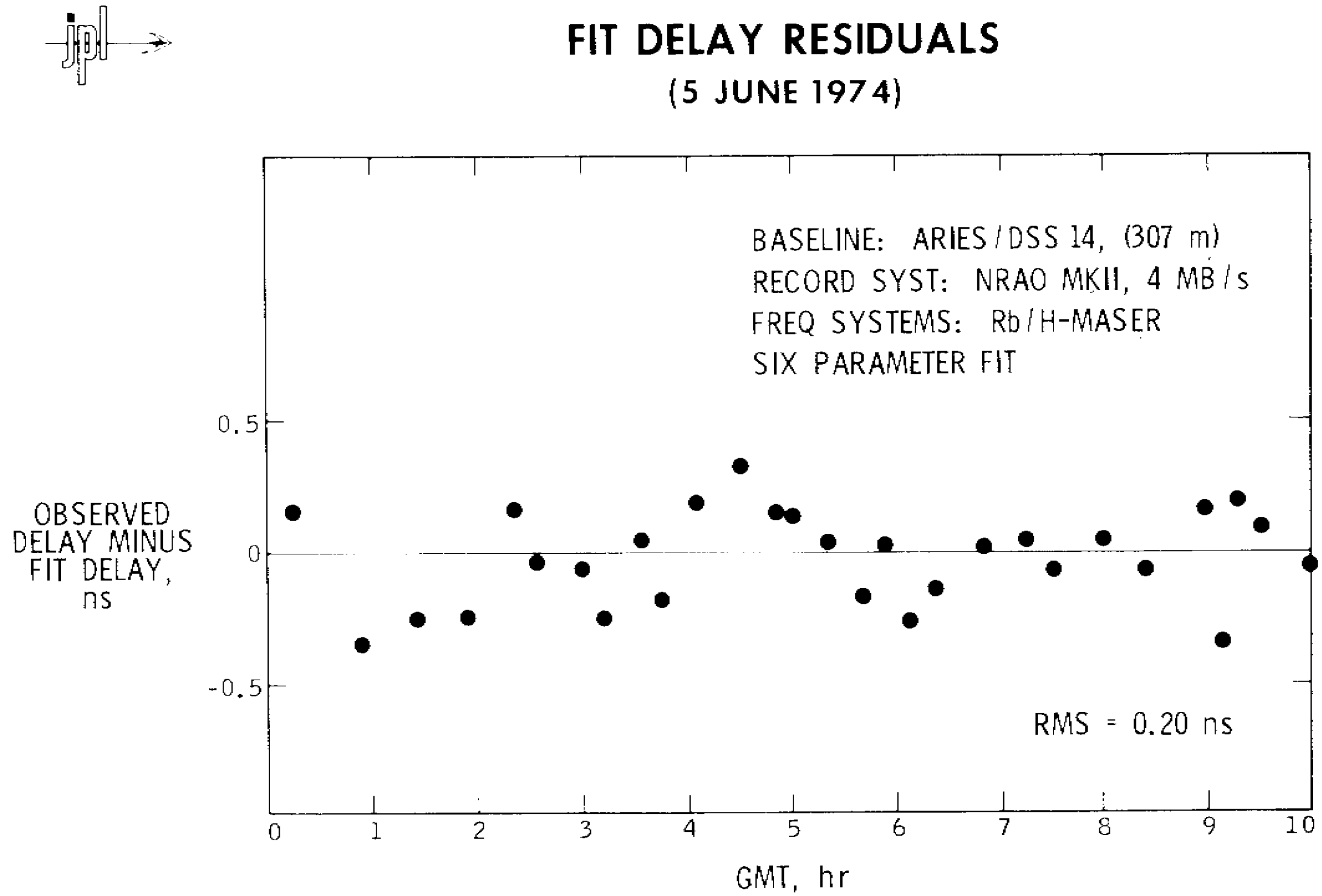
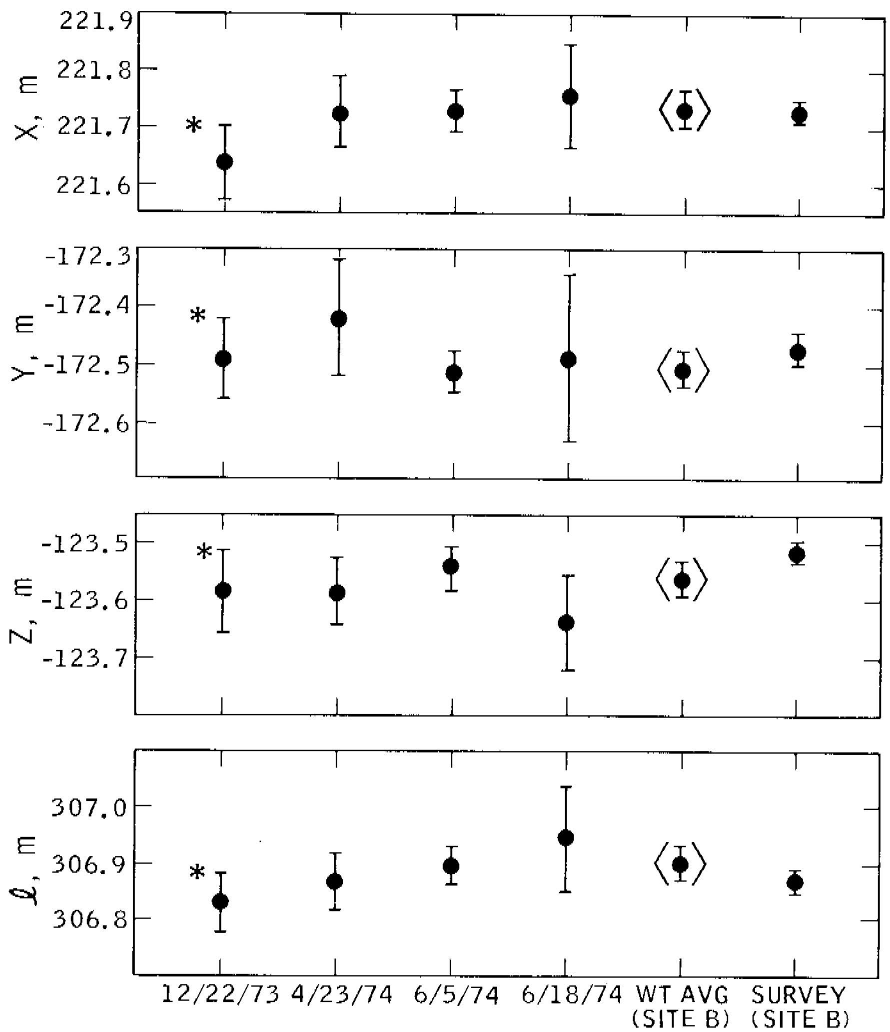

FIT DELAY RESIDUALS
(5 JUNE 1974)
BASELINE: ARIES/DSS 14, (307 m)
RECORD SYST: NRAO MKII, 4 MB/s
FREQ SYSTEMS: Rb/H-MASER
SIX PARAMETER FIT
RMS = 0.20 ns
OBSERVED DELAY MINUS FIT DELAY, ns
0.5
0
-0.5
0
1
2
3
4
5
6
7
8
9
10
GMT, hr

Figure 3

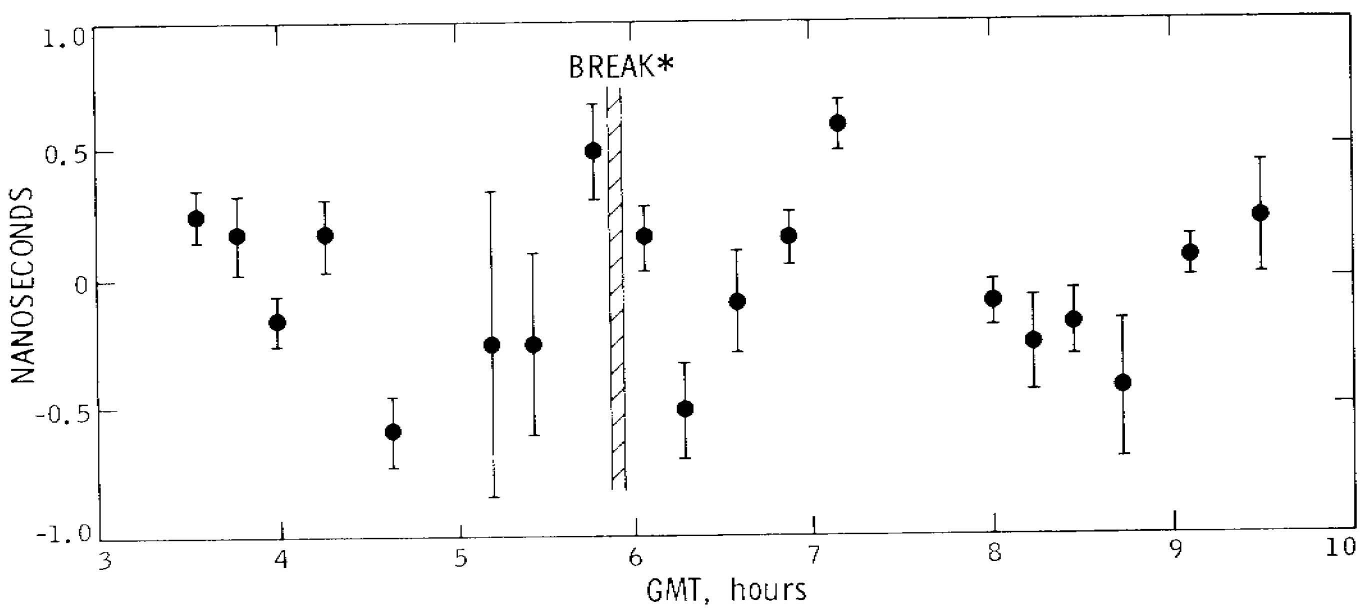
ARIES 307 m BASELINE VECTOR MEASUREMENTS COMPARISON OF INTERFEROMETER WITH SURVEY



*DEC '73 ARIES POSITION (SITE A) ADJUSTED TO POST FEB'74 POSITION (SITE B) BY ΔX = -16 cm, ΔY = -36 cm, ΔZ = -25 cm, $\Delta \ell$ = 19 cm

Figure 4

DELAY RESIDUALS FOR THE ARIES EXPERIMENT OF 18 JUNE 1974



*INSTRUMENTAL PARAMETERS SEPARATELY ESTIMATED

Figure 5

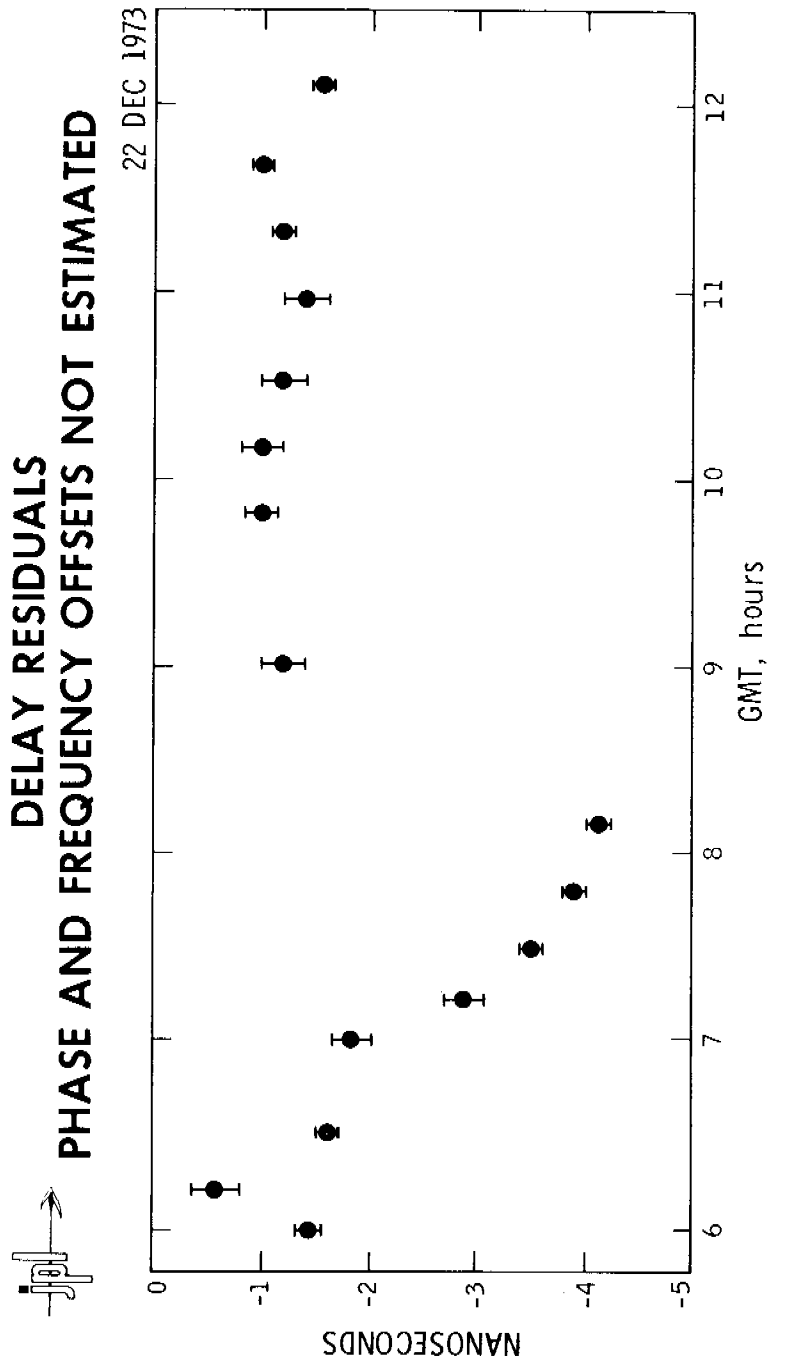

DELAY RESIDUALS
PHASE AND FREQUENCY OFFSETS NOT ESTIMATED
22 DEC 1973
NANOSECONDS
0
-1
-2
-3
-4
-5
6
7
8
9
10
11
12
GMT, hours

Figure 6

INTERFEROMETRY BASELINE RESULTS FOR THE ARIES 307 m EXPERIMENTS

DATE	SITE	X, m	Y, m	Z, m	ℓ, m
12/22/73	A	221.795 ± 0.066	-172.126 ± 0.075	-123.332 ± 0.075	306.645 ± 0.050
4/23/74	B	221.728 ± 0.06	-172.423 ± 0.10	-123.584 ± 0.06	306.866 ± 0.05
6/05/74	B	221.732 ± 0.039	-172.516 ± 0.032	-123.538 ± 0.038	306.902 ± 0.034
6/18/74	B	221.763 ± 0.091	-172.488 ± 0.145	-123.639 ± 0.084	306.948 ± 0.086
WT AVG	B	221.734 ± 0.031	-172.507 ± 0.030	-123.562 ± 0.030	306.896 ± 0.027
SURVEY	B	221.733 ± 0.02	-172.471 ± 0.03	-123.513 ± 0.02	306.867 ± 0.02

Table 1

QUESTION AND ANSWER PERIOD

MR. WARD.

Sam Ward, Jet Propulsion Lab.

Have there been any observable results as to the basic purpose of the thing, the relative drift of the east and the west side of the San Andreas Fault?

DR. VESSOT:

That is not the real purpose for this, is it?

DR. MELBOURNE:

Yes, for those of us who live out there in Earthquakeville, that is a real concern. What we see could be explained by other factors. There is no clear signal. Let me give a little bit of insight into this.

One of the mechanisms that appears to be going on in the geophysics area is something called dilatantcy, which says something about the rock failure mechanism prior to the quake, and that says that the ground underneath of the rocks down 5 kilometers or so, begin opening up little cracks and the ground swells up.

Now, the Soviet version of the observed phenomena regarding seismic velocities from which dilatantcy was deduced, claim that the uplift is going to be at the several meter level and is going to happen over hundreds of kilometers. The seismological lab at Cal Tech says yes, it could be like 1 or 2 meters, but they don't believe that the 10 meter approximations the Soviets make are realistic, but we are talking about pretty big, definite signals as a possibility. It depends upon the porosity of rocks, where the dilatantcy is occurring, but possible uplifted geometric signals are maybe at the meter level, with lower limits down around 10 centimeters. Now, if something is going on there at the 10 centimeter level, we probably have difficulty seeing it right now.

If it is a signal, a geometric deformation that is occurring at the 1 meter level, I think that we would definitely see this.

DR. VESSOT:

I should think you would probably see it as plate motion in a matter of a few years.

DR. MELBOURNE:

That is right.

DR. VESSOT:

These are motions of tectonic plates that describe the geological surface of the earth, and they have been very well proven to be moving.

DR. MELBOURNE:

Yes, it seems an incontrovertible fact that there is some kind of a horizontal deformation going on. It is only a debate about the magnitude. One line of reasoning would hold that the rate could be as much as 6 centimeters per year. Well, you can see that even with the current accuracy that we have of 10 centimeters, within a period of a decade or less, we are going to be able to see those kinds of deformations.

Now, we see, by the way, many ways of improving the system. I have talked about just the time and frequency aspects, but certainly with regard to transmission media, calibrations, and the telecommunication parameters and so on, one can see ways of making this system accurate to about 1 centimeter, given about 30 hours of data at a given location, so once you get down to those kinds of levels, then you are going to be able to resolve differences; whether deformation rates in the horizontal are 2 or 3 or 6 centimeters.

DR. VESSOT:

I would like to ask a question of how many oil companies have been beating a path to your door for doing surveys, notably in regions of our world that are not accessible. I can think of no more miserable task than surveying my way up into Alaska or the Yukon Territory, a job that certainly would take a great many years, and the accuracy, I think, would depend an awful lot on just plain luck. Whereas here you are with a helicopter, presumably you could drop this gadget, and within several days or weeks, you may end up with numbers on the order of centimeters.

DR. MELBOURNE:

Well, there has been expressed some interest from the Trans-Alaska Pipeline people, as well as from local utilities wanting to build nuclear power plants; not so much that this is going to be an integral part, but this is new technology. We are up against a real bind in a lot of areas. Some of them are environmental -- well, particularly in environmental impact, and I think they are legitimately trying to wrestle with those problems and deal with them properly, and they are looking to these new kinds of technologies.

DR. VESSOT:

I just want to make one other comment. It is astonishing to me to look at the prospect of using random noise from these celestial objects as a means for time synchronization. It means that we are going back to astronomy or astrology to get our time. We mustn't forget that for, I think, probably thousands of years, that time has been an astronomical behavior. It has been inexorably linked in our heritage that time is the motion of heavenly bodies. We now have gone to atoms, and I am just wondering whether or not we are not going to go looking out to space again for time.

It might take awhile, so I think a few of us clock makers may be safe for a while.