TIME, GEODESY, AND ASTROMETRY: RESULTS FROM RADIO INTERFEROMETRY

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ABSTRACT

The results from a total of a dozen transcontinental and intercontinental VLBI experiments will be discussed. Particular emphasis will be placed on: (1) the inferred behavior of the frequency standards, usually hydrogen masers, on time scales from 10 to 10^5 seconds; (2) the estimated celestial positions of the observed radio sources; (3) the determinations of the vector baselines; and (4) the inferred values of polar motion and UT.1.

INTRODUCTION

By now VLBI is all but a household word. Although lofty promises held out of centimeter accuracy geodesy and millisecond-of-arc accuracy astrometry have not yet been fulfilled, we have made much progress in the last two years. We present here the most recent results obtained by our group. To be precise, our group is a shifting amalgam of people and organizations who join together to do a particular experiment; to list all the individuals and their affiliations would nearly take up all the allotted space. Suffice it to say that, together with our colleagues at MIT and at the Haystack Observatory,* we have played the major role in organization, equipment development, and data processing with invaluable contributions by representatives from the University of Maryland, the National Oceanic and Atmospheric Administration (NOAA), the Jet Propulsion Laboratory (JPL), and the Onsala Space Observatory in Sweden.

EXPERIMENTS

Our results come from a number of experiments, all conducted at a radio frequency of about 8 GHz:

1. Goldstone (210') - Haystack (120')
   - April 1972-March 1973; nine separate ($\lesssim$1 day) experiments

*C. C. Counselman, H. F. Hinteregger, S. M. Kent, C. A. Knight, D. S. Robertson, A. E. E. Rogers, and A. R. Whitney.

2. Goldstone - Haystack - NOAA (85', Alaska)
   - May-June 1972; two separate (0.5-1 day) experiments

3. Haystack - Onsala (84', Sweden)
   - April-May 1973; two separate ($\lesssim$2 day) experiments

4. Haystack - Westford (60') - NRAO (two 85', West Virginia)
   - January-October 1972; two ($\lesssim$2 week) experiments.

The types of results include vector baselines, clock epoch and rate synchronizations, polar motion, UT.1 variations, and astrometric positions of radio sources. We omit for brevity the results we have obtained—using exactly the same body of data—on the structure and variability of extragalactic radio sources. We also omit the results from Goddard's extensive VLBI program at meter wavelengths, and mention only briefly our tests of the theory of general relativity.

The capability for the determination of all three components of each baseline vector, as well as for the accurate determination of the declination of sources near the equator, is dependent on our group's development and use of a wide-band synthesis technique that allows us to measure unambiguously the actual difference in arrival times at the sites of the signal from the extraterrestrial source being observed. As we shall see, our uncertainty in these measurements is at the sub-nanosecond level on each individual determination.

BASELINE RESULTS

In Table 1, we show the baseline results from all nine of the separate Goldstone-Haystack experiments. Note that the baseline-length determinations are consistent to within about 25 cm. The two baseline-orientation parameters show consistency only to within one to two meters.

In Figure 1, we show a "sample" of the post-fit residuals for observation of two sources from the August 1972 experiment. For reasons that we do not yet fully understand, this experiment yielded post-fit residuals with the smallest systematic trends.

In these baseline determinations—each was carried out separately and involved only the delay and delay-rate data taken during the course of that individual experiment—we solved for the following parameters: the zenith electrical path length of the atmosphere at each site; the clock epoch and rate offsets; the three components of the baseline; and all of the coordinates for the 7 to 11 sources

Table 1

Preliminary Coordinates from Nine Experiments to Determine the Goldstone-Haystack Baseline*

Date	Length (m)	Hour Angle† (hr x 10^6)	Declination† (deg x 10^5)
April 14-15, 1972	3,899,998.51 ±0.22	7,051,413.6 ±0.3	-914,473.4 ±1.8
May 9-10, 1972**	7.61 ±0.76	4.6 ±2.8	87.1 ±5.2
May 29-30, 1972	8.64 ±0.33	5.4 ±0.8	83.0 ±1.4
June 3-6, 1972	8.60 ±0.45	3.7 ±1.1	82.8 ±2.2
June 27-28, 1972	8.56 ±0.28	2.1 ±0.7	77.8 ±1.4
August 29-30, 1972	8.77 ±0.09	5.9 ±0.3	81.6 ±0.6
November 7, 1972	8.99 ±0.15	5.5 ±0.4	82.1 ±1.1
February 4-5, 1973	8.83 ±0.10	3.7 ±0.4	81.6 ±0.4
March 30-31, 1973	8.99 ±0.11	6.1 ±0.3	84.7 ±0.5
Weighted Average ± weighted rms spread of solutions about the weighted mean	3,899,998.75 ±0.23	7,051,414.8 ±1.3	-914,481.8 ±2.8

*The reference point at both Haystack and Goldstone is the intersection of the azimuth and elevation axes of the antenna. The baseline vector points from Haystack to Goldstone. The hour angle is measured from the Haystack meridian, defined by the International Latitude Service mean pole of 1900-05; the declination is measured from the plane that passes through Haystack and is parallel to the equator defined by this mean pole. The uncertainties shown are the formal standard errors, based on a value of unity for the weighted rms of the post-fit residuals. The coordinates describing the baseline direction are clearly being affected by systematic errors (see text).

**In this experiment, for another purpose, half of the time was utilized for special observations of two source pairs, thus accounting for the relatively large errors.

†Note that 10^{-6} hr $\simeq 1.0$ m and 10^{-5} deg $\simeq 0.68$ m for this baseline.

observed in a given experiment, save the right ascension of 3C273 which was set in accord with the results of Hazard et al. (Nature Physical Science, 233, 89, 1971) from lunar occultation data and optical photographs. Since the VLBI observations of extragalactic radio sources are extremely insensitive to the earth's orbital motion, we must choose an arbitrary origin for right ascension. The choice of the value of Hazard et al. for 3C273 should provide us with a good "tie" to the FK4 system, to which conventional astrometric results are referenced.

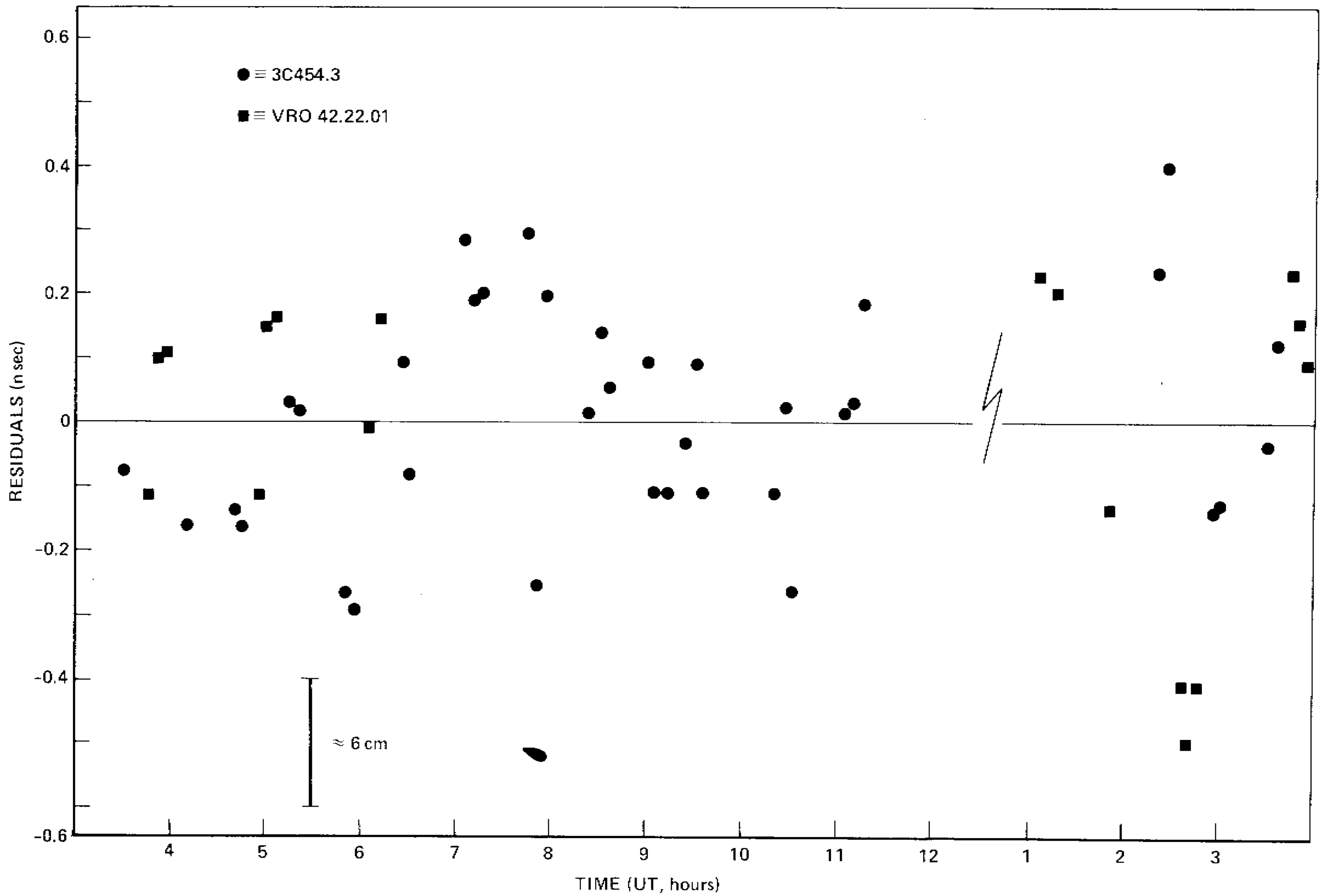

Figure 1. Postfit residuals from Observations of the Extragalactic Radio Sources VRO 42.22.01 and 3C454.3 during the Goldstone-Haystack VLBI Experiment of 29-30 August 1972

The results for the antennas in Alaska and Sweden are much poorer than the "Goldstack" results, primarily due to reduced sensitivity. Both of these sites use only ~85'-diameter telescopes which have surfaces designed for operation at frequencies much lower than 8 GHz and we have had to content ourselves with 10 to 20% antenna efficiencies. The receiver in Alaska was also poorer, with a system temperature of about 300°K instead of the 25-60°K we have on the other telescopes. Thus, we find that the baseline-length determinations here have uncertainties of about 2 m instead of the ~25 cm uncertainty for the Goldstack baseline.

One interesting fact is that the antenna in Alaska has an X-Y mount, with two horizontal non-intersecting axes. We modelled the offset between these axes and solved for it from the relevant VLBI data to provide a good independent check of our results. (This procedure is almost equivalent to moving the dish a known amount and seeing how well the offset can be determined.) Our result was 6.3 ±0.9 m for the distance between the axes, as compared with the true value—scaled from the original telescope plans—of 7.23 meters.

CLOCK SYNCHRONIZATION

In Table 2, we present the epoch and rate offsets determined for the Goldstack experiments. Here again, the errors are formal standard errors based on scaling the weighted rms of the post-fit residuals to unity. The rather large rate offsets are due to the fact that the hydrogen-maser standard at Goldstone was set "off-frequency" during most of 1972. The epoch errors reflect difficulties in a priori synchronization at Goldstone, where Loran-C is unavailable. Haystack and the other stations routinely synchronize clocks with Loran-C to within 1 to 3 μsec.

POLAR MOTION AND UT.1

The Goldstack data, being the most accurate, are best suited for estimates of polar motion and variations in UT.1. (Note, however, that a single baseline is sensitive to only one component of polar motion.) To estimate these quantities, we used the August 1972 experiment as a reference since it yielded data with the smallest systematic trends. We combined all the data—actually in two separate runs, each containing the August 1972 data and those from four other experiments—and estimated parameters corresponding to the polar motion and UT.1 differences between each of the experiments and the August 1972 experiment.

Table 2

Clock Synchronization for Goldstone-Haystack Experiments*

Date	Epoch Offset (μsec)	Rate Offset (psec/sec)
April 14-15, 1972	-5.009 ±0.002	10.88 ±0.03
May 9-10, 1972	-13.040 ±0.002	12.18 ±0.01
May 29-30, 1972	-3.008 ±0.002	13.20 ±0.01
June 6-7, 1972	-28.211 ±0.006	13.64 ±0.04
June 27, 1972	-7.717 ±0.003	13.04 ±0.03
August 29-30, 1972	-15.320 ±0.001	14.140 ±0.001
November 7, 1972	-2.088 ±0.001	-3.640 ±0.001
February 4-5, 1973	-6.813 ±0.003	-8.611 ±0.06
March 30-31, 1973	4.398 ±0.001	-1.070 ±0.001

*Results are given in sense of Goldstone value minus Haystack value and are referred to start time of first observation of experiment.

The results presented in Table 3 are still quite preliminary and undoubtedly are affected by systematic errors. From the comparison shown between the BIH and USNO values for these quantities and ours, we see that the polar-motion differences are nowhere worse than the equivalent of about 5 meters, and that the UT.1 estimates differ very systematically. But, at this point-in-time—to use an overused cliché—we would emphasize that our results may not be the most accurate, although we expect them to be in the not-too-distant future.

SOURCE POSITIONS AND ASTROMETRY

In each of these experiments we simultaneously estimated source coordinates. Our averaged results, with errors based on consistency between independent sets of data—and considered to be conservative—are shown in Table 4. We have compared our results with other determinations of high accuracy, including VLBI results obtained at JPL and short-baseline phase-stable interferometer results obtained in England and the U. S. We find quite reasonable agreement. The accuracy of radio techniques has now surpassed that available to our "optical" colleagues.

Table 3

Preliminary Polar Motion and UT.1 Variations from Goldstone-Haystack Experiments

Date	Universal Time (UT.1)*		X-Component of Polar Motion
	USNO-VLBI (msec)	BIH-VLBI (msec)	BIH-VLBI (m)
14-15 April 1972	10.7	1.1 ±0.8	2.2 ±0.3
9-10 May	7.7	-3.2 ±1.2	-1.6 ±0.6
29-30 May	3.6	4.9 ±0.8	-1.2 ±0.3
6-7 June	5.5	-1.6 ±1.3	-2.0 ±0.5
27 June	-4.9	-10.1 ±4.8	-4.4 ±1.5
29-30 August	—	—	—
7 November	2.2	-1.5 ±0.5	0.3 ±0.2
4-5 February 1973	6.3	0.4 ±0.8	0.6 ±0.2
30-31 March	3.2	-6.4 ±0.6	1.8 ±0.2

*Note that for 29 August 1972, BIH-USNO = 11.4 msec.

We have also gathered a large amount of data, which is still being analyzed, from our so-called four-element interferometers. As mentioned in EXPERIMENTS Section, we have employed for these experiments the 120'-diameter Haystack and 60'-diameter Westford telescopes in Massachusetts and two of the 85'-diameter telescopes at the National Radio Astronomy Observatory in West Virginia. One antenna at each end observes source "A" while the other observes source "B". Since the antennas at each end are interconnected with a phase-stable-link—typically buried coaxial cable—we may regard them as having identical local oscillators. Although the local-oscillator phase between the two ends is not known, the difference in phase from the fringes for the two sources is independent of the local oscillator phase. Use of this difference permits, in principle, a very accurate determination of the difference in positions of the two sources. There is only one major problem: The atmospheric contribution to the phase is different for the two sources and hence does not cancel out unless the sources are quite close on the sky. Unfortunately, we can not yet present source-position results from these experiments.

We have also attempted an experiment of this four-antenna type to measure the gravitational deflection of the signals from the quasar 3C279 as it is occulted by the sun—this measurement has become our annual Oktoberfest. In this case we used as a second source the quasar 3C273 which is only 10° away on the sky. The

Table 4

Source Coordinates from VLBI Observations*

Source	Right Ascension, α (1950.0)			Declination, δ (1950.0)		
	hr	min	sec	deg	min	sec
3C84	03	16	29.539	41	19	51.75
3C120	04	30	31.586 ±0.005	05	14	59.2 ±0.1
OJ287	08	51	57.232 ±0.005	20	17	58.45 ±0.1
4C39.25	09	23	55.296 ±0.004	39	15	23.73 ±0.04
3C273B	12	26	33.246**	02	19	43.2 ±0.1
3C279	12	53	35.831 ±0.004	-05	31	08.0 ±0.1
OQ208	14	04	45.626	28	41	29.4
3C345	16	41	17.634 ±0.004	39	54	11.00 ±0.07
PKS2134+00	21	34	05.222 ±0.005	00	28	25.2
VRO42.22.01	22	00	39.394 ±0.007	42	02	08.3 ±0.1
CTA102	22	30	07.82	11	28	22.8
3C454.3	22	51	29.530 ±0.009	15	52	54.24 ±0.03

*Coordinate determinations for which no uncertainties are quoted were based on only a single set of observations or had formal errors greater than 0."1; the errors in these coordinates are probably no more, and in some cases considerably less, than 0."5.

**Reference right ascension (Hazard et al., 1971); see text.

data were taken in September and October 1972. Although it is now a year later, the data are still being analyzed. It should be noted that the magnitude of the bending predicted by general relativity is 1.75"/R, where R is the distance of closest approach of the ray path to the sun, measured in solar radii. Our data were obtained at R $\gtrsim$ 20, implying a maximum deflection of 0.1". In Figure 2, we show the difference in fringe phases, with diurnal variation removed, for one day's observations. Note that 2π in phase (equivalent to one "fringe") equals 0."01. The major problem is to insure that the phase has no 2π "jumps" even where our highly-motivated, but lowly-paid, graduate-student tape hangers goofed and tapes were missed. The figure illustrates the ease with which we can bridge such gaps.

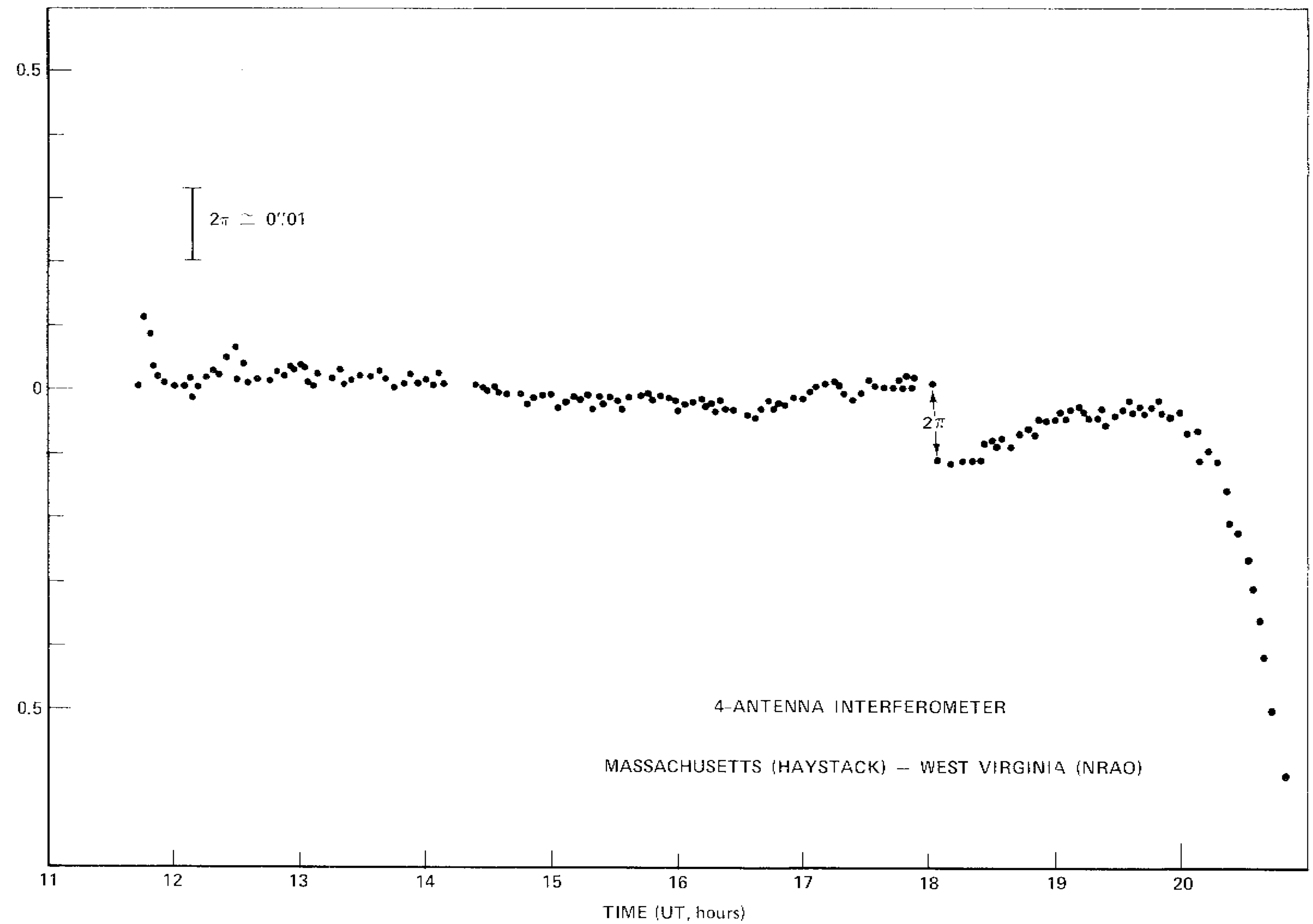

Figure 2. Fringe-Phase Differences: 3C279-3C273, 19 October 1972

THE FUTURE

We feel there are several obstacles to be overcome to achieve the significantly higher accuracy we require: instrumental calibration, which has been mostly lacking to date; calibration of the neutral atmosphere, which is currently modelled theoretically with a single parameter per day per site; and calibration of the ionosphere, less important at our 8 GHz frequency than at the $\simeq$2 GHz frequencies employed by others, but important for the achievement of centimeter-level accuracies.

At present we use only a simple solid-earth-tide model "grafted" onto the standard precession and nutation effects to represent the effects of the earth's deformation. Our next theoretical effort will involve development of a more accurate model for the earth's rotation, building, for example, on the work of McClure (GSFC Report, X-592-73-259, September 1973). We have also begun design studies on a system that will permit a 30-50 MHz bandwidth signal to be recorded instead of the currently available 360 kHz or 2 MHz. And we always seem to need more masers than are available in the world. In this connection, we wish to thank H. Peters, C. Wardrip and D. Kauffmann of GSFC, R. Sydnor of JPL, and R. Vessot of SAO for their continuing advancement of this field and for their frequent assistance in getting masers to obscure places around the world.

In conclusion, we feel pleased to have helped to bring VLBI to its current state of development and hope to continue this development and thereby to raise VLBI to its rightful place as the best measurement tool yet invented for clock synchronization, geodesy, and astrometry.

QUESTION AND ANSWER PERIOD

DR. CLARK:

Any questions?

DR. WINKLER:

Your comment about the clock synchronization on the West Coast prompts me to repeat something which we had announced last year, that there is now a Loran chain operational on the West Coast, with which one can make time synchronization experiments. I would like to encourage anyone who has requirements or interest to contact Mr. Lavanceau at the observatory.

DR. CLARK:

I appreciate your continued efforts in that area, too.

My comment was perhaps slightly wordy in that the Loran capability was not available at Goldstone during the time of those measurements.

Because of VLBI and delays in processing things, we always reported past history, in the past being typically two years back, and we speak of it as if it was now.

DR. BLACK:

Harold Black, APL.

I notice you solve for the zenith distance at each site. I would surmise that those are individually rather poorly determined, but that the differential zenith height is well determined. Is my surmise correct?

DR. CLARK:

Yes, the zenith thickness of the atmosphere amounts to a couple of meters of path length thickness. Well, it is no more than a couple of meters in thickness. When we are only doing geodesy in the couple of meter level, it is not that critical.

We do find that we are able to come up with fairly good bits for the neutral atmosphere. We wish we were able to calibrate it. We have some ideas in mind on how to calibrate it, but we just haven't gotten there yet.

Remember that these stations are quite widely separated, and typically just because of the fact that the Earth is curved and not flat, we are observing at rather different zenith distances. We are observing on the East Coast through the humidity and smog, and on the West Coast through their nice, dry climate.

There is absolutely no correlation between the atmosphere in California and the atmosphere in Massachusetts.

So, the differential atmosphere is really just as poorly determined as the individual site atmosphere.

QUESTION:

My comment is -- well, it is really a question. What do you feel is going to be the fundamental limitation on VLBI positions? It looks to me as though the atmosphere is finally going to close in on us, and stop us at about a part in 10 to the 15th or so. So is there a future need for better frequency standards in VLBI? The best standards today were used on the two antenna experiment, does one need that good a frequency standard?

DR. CLARK:

Well, there are a couple of types of experiments to do source positions, which could use far better frequency standards. Ones which would essentially remove the atmospheric bias very easily.

If you could merely count the total number of fringes during a day, even if you missed by a couple of fringes because the atmosphere today was different from the atmosphere of yesterday, merely counting the total number of fringes during the day would give us a very good position.

Now, that would require stability of a fraction of the fringe per day, which is down in parts to 10 to the 16th or 17th level, which is certainly past the state of our frequency standards.

As of right now, we are on the hairy edge between whether it is the frequency standards that are dominating our determination, or the atmosphere.

We need to calibrate the atmosphere better, and at that point we will be exploiting the frequency standards even more fully.

Parts in 10 to the 14th, or so, for the same reasons that were mentioned in the previous talk, are adequate for most of the determinations, but it is sure nice to have a part in 10 to the 15th, if you can get it.

MR. RYAN:

Jim Ryan, Goddard.

It sounds like you have solved for just about every parameter that could give you problems. I am wondering, typically, how many parameters are you solving for, and what feeling of confidence do you have that you have been able to eliminate the correlations?

DR. CLARK:

In all cases, it is less than the number of data points. That is my first look, and it is never any more than we absolutely have to have. It varies from experiment to experiment, depending on how many transient glitches occurred in clocks, how bad the atmosphere was, do we need to parameterize it on a sub day basis, things of that form.

A typical number is, oh, perhaps 30 or 40 parameters for 150 observations, something in that order, for a given day.

We do keep careful track of the correlations between these terms in our post processing program and this is one of the things that bothers us, and one of the reasons why we have been very conservative in some of our claims on error bars.

We do have the ability in our program to apply a priori covariance matrices to the data, so that we can essentially change the weighting in these different parameters, too. But we very seldom use that.

MR. MERRION:

My name is Art Merrion. I am from the Defense Mapping Agency.

I have a question -- perhaps I am asking the wrong person.

I can see when you finish your work, you are going to have a result, just the same as, say, for instance, Dr. Weber did at the University of Maryland. He had a result.

But after he finished and published and so forth, then they started experiments in other parts of the world.

Are you or anybody else performing a similar type experiment over the PLATE movement, similar to what you are doing between the Pacific and the North

American PLATE movement? Is there something like this going on right now somewhere else in the world?

DR. CLARK:

Well, we have the one which is going across the Atlantic right now, a continuing program using the telescope at Onsala, Sweden.

I believe, that later on, you will hear the other VLBI group at Goddard report on one of their proposed programs, which will involve just this type of measurement.

We are always on the lookout for new stations, and we, just philosophically and historically, are a very low budget group that have just joined together because we find the problem scientifically interesting.

As a result, we are particularly constrained to use those telescopes that already exist, that we can beg, borrow or steal observing time on. Hence these results use existing telescopes. We don't move telescopes around. We are striving for the best sensitivity, in order to give all of these programs simultaneously.

So, we have concentrated on a relatively small set of baselines to develop the techniques.

Really, I think what you should hear, the main summary point that I would like to make, what we are trying to do is to get the techniques developed so that VLBI can be turned into this operational tool at the centimeter level. And I feel that it can be in the future.

DR. KLEPCZYNSKI:

Thank you very much.