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PRECISION SURVEYING USING VERY LONG BASELINE INTERFEROMETRY

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Precision Surveying Using Very Long Baseline Interferometry

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ABSTRACT

Radio interferometry measurements have been used to measure the vector baselines between large microwave radio antennas. A 1.24 km baseline in Massachusetts between the 36 meter Haystack Observatory antenna and the 18 meter Westford antenna of Lincoln Laboratory has been measured with 5 mm repeatability in 12 separate experiments. Preliminary results from measurements of the 3928 km baseline between the Haystack antenna and the 40 meter antenna at the Owens Valley Radio Observatory in California are presented. The interferometric technique and comparison of the interferometrically determined baseline length with baseline lengths determined from conventional and satellite surveying methods will also be presented.

Precision Surveying Using Very Long Baseline Interferometry

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Very Long Base Line Interferometry, or VLBI as it is usually called, is one of the most promising tools now under development for making transcontinental and global scale geodetic measurements. It was, however, first developed by radio astronomers whose real desire was to synthesize extremely large radio telescopes. The VLBI group which I represent traces to 1968 when a group of researchers from M.I.T., Haystack Observatory, and Goddard Space Flight Center performed a VLBI experiment using the Haystack radio telescope in Massachusetts and the NRAO 140-foot antenna in Greenbank, West Virgina. In 1969 this group measured this baseline with an accuracy of 1 meter, which was quite accurate for that time. Since that time the technology of VLBI has advanced so far that I can confidently address you about determining transcontinental baselines with an accuracy of 5 cm.

What then is Very Long Baseline Interferometery?

The first figure shows the geometry of a VLBI experiment. Two widely separated radio telescopes observe radiation from some distant radio source - usually a quasar. Quasars are used because they are continuum sources, that is, they radiate energy at all frequencies over a broad range of frequencies from a few MegaHertz (MHz) to a few GigaHertz (GHz). Quasars also have two additional properties which make them useful for VLBI. They have small angular size; and their extreme distance from the earth - billons of light years - makes them for all practical purposes fixed points in the sky. To quantify that somewhat the angular diameter of the typical quasar used in our experiments is the same as

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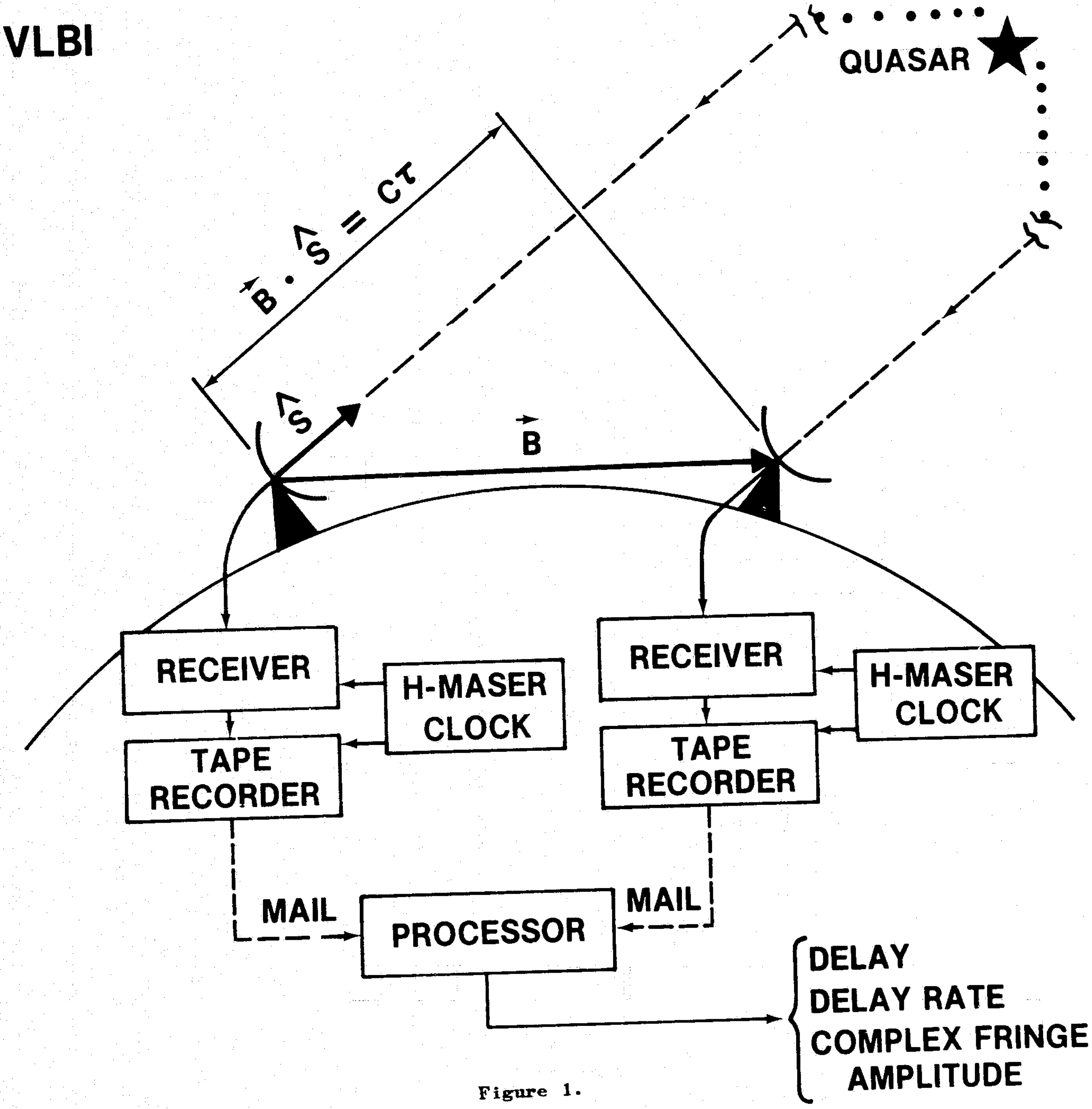
VLBI
QUASAR
$\vec{B} \cdot \hat{s} = c\tau$
$\hat{s}$
$\vec{B}$
RECEIVER
H-MASER CLOCK
TAPE RECORDER
RECEIVER
H-MASER CLOCK
TAPE RECORDER
MAIL
MAIL
PROCESSOR
DELAY
DELAY RATE
COMPLEX FRINGE AMPLITUDE

Figure 1.

that of a quarter held over Washington, D.C. as seen from San Francisco. The receivers at each of the telescopes pass a broad band of this radiation; the frequency output of an atomic clock is used to convert the received radiation to a much lower frequency where it is digitized and recorded on tape. To look at it another way the quasars can be thought of as raining on the earth a complicated random code. The VLBI observing scheme is simply a process of observing that code from various points on the surface of the earth, time tagging its arrival with respect to local clocks, and writing it to tape. The tapes from the two telescopes are sent to a central facility where they are cross-correlated. In an ideal case the two tapes would contain the identical random code but time tagged differently because the signals were received at different times. By sliding the bits on one tape relative to the bits on the other tape until they match, the time delay between the arrival of the code at the second site and the arrival at the first site can be easily found. In the real case the code on the two tapes is largely caused by noise in the receiver systems at the telescopes; also since the earth is rotating the time delay is continuously changing while the the bits are going on the tapes. So the real processing is rather more complicated than the ideal case I have described, but the underlying idea remains unchanged.

It is easy to see that delay measurements are sensitive to the position of the radio source in the sky, and this in turn makes them sensitive to the inertial coordinates of the source as well as the entire catalog of phenomena which affect the angular position of the earth relative to inertial space. Similarly it is easy to see that the delay is sensitive to relative positions of the two sites and in particular to the geophysically interesting baseline length and orientation. The final step in the VLBI process is the regression analysis to estimate these quantities from the observations. In this step hundreds to thousands of observations are combined in a statistical adjustment of the recoverable parameters. This adjustment usually includes the geodetic parameters, baseline length and orientation, source coordinates, and clock parameters.

What then are the limitations of VLBI? What is the state of the VLBI system presently in use by the Goddard/Haystack/MIT/SAO VLBI group, and where do we think that system is going in the immediate future?

Figure #2 displays the major error sources affecting VLBI. For each effect the bar shows the extent to which that effect limits our ability to recover baseline length accurately. In each case the upper bar shows the current state

TRANS-CONTINENTAL VLBI ERROR BUDGET (GSFC/HO/MIT PROGRAM)

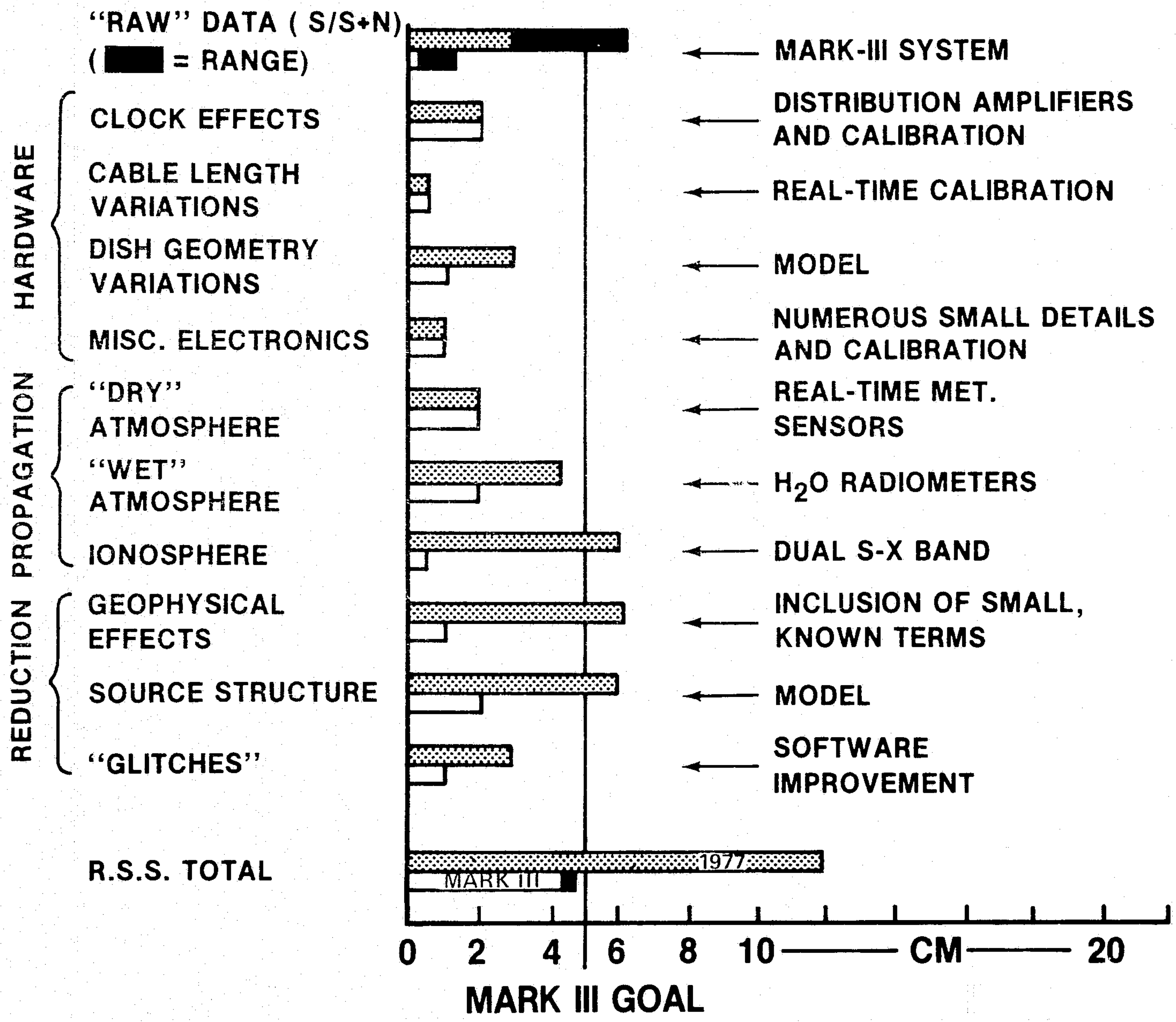

Figure 2.

of our system, and the lower bar shows the planned state after our new system, the MARK III system, is fully implemented. The MARK III system is the all consuming task which the group that I represent is presently pursuing.

These error sources can first be divided into two groups: those which are random and those which are systematic. The random noise effects can be overcome by simply acquiring more data; the systematic effects are not so easily defeated.

Random effects are all covered in the first line of the bar chart - the line labeled "RAW" DATA. The noise effects are specified almost exclusively by four parameters of the VLBI observing system - the instantaneous recorded bandwidth, the total spanned bandwith, the diameters of the antennas, and the receiver noise. The total spanned bandwidth refers to the frequency window through which the source noise is received. The width of this window is determined by the pass-bands of the antenna feeds, parametric amplifiers, and receivers employed in the telescopes. Our current experiments employ new MARK III equipment which operates in the X-band region of the spectrum - near 8.4 GHz - and has a 400 MHz wide passband. This equipment has only been employed for the last year. Using current technology it is impractical to record a 400 MHz wide signal, so our system samples the spectrum in discrete frequency windows. The width of these smaller windows, the instantaneous recorded bandwidth, is determined by the record capability of the tape recorders. It is in the tape recorders that our new system will make its most significant improvement over all existing VLBI systems. Presently we use the MARK I tape recorder system, which has a recording rate of 720 kilo-bits per second and which has remained virtually unchanged since it was first introduced in 1969. We are about to introduce the MARK III recorder, which will have a record capability of 4 Megabits per second in each of 28 channels for a total record rate in excess of 100 Megabits per second. To put this rate into perspective a standard television channel could be recorded on each of the twenty-eight channels. Televison used to be thought of as a very broad band signal, and it was not until the 1960's that it was possible to record even one televison channel on tape. The third parameter which characterizes the noise is the size of the telescopes - the smaller the antenna, the weaker the signal. In addition, the accuracy of the antenna surface, i.e., how smoothly it approaches a perfect conic section, affects the efficiency with which the signals can be collected. The final parameter specifying noise is the receiver noise temperature. The new MARK III receivers will minimize this source. They are good, but not cryogenic, receivers.

Various trade-offs could be made among these error sources, but there is one which we intend to exploit extensively. The effects of decreasing antenna size can be largely offset by increasing tape recorder capability. The rationale for developing the MARK III recorder was to provide for achieving centimeter level VLBI results using relatively small antennas. In figure #2 the upper bar for the line labeled "RAW" DATA, which terminates in a range from three to six centimeters, characterizes a system using MARK I recorders and telescopes ranging in sizes upward from thirty meters. The lower bar is for a system using the MARK III recorder and antennas only a few meters in diameter.

Now I will discuss the list of systematic error sources.

Clock effects refer to the stabilities of the system clocks for periods ranging from a few minutes to a few days. We are currently using hydrogen maser clocks that are stable to a few parts in ten to the minus fourteen. They are the best clocks available and are likely to remains so for some time.

Cable length variations refer to the fact that while the signal is received and time tagged at the feed horn in the center of the antenna, the pulses which are used to do the tagging are generated on the ground and must travel a length of coaxial cable to the feed horn. Any stretching of that cable or changes in its dielectric constant will cause anomalous time delay. We have implemented a system to calibrate this effect by continuously monitoring the electrical length of this cable.

Dish geometery variations result because radio telescopes are large steel structures which to some extent deform under wind and gravitational loading and differential heating. We know that the deformation cannot be more than a few millimeters because if it were the telescopes could not focus X-band signals, which have a wave length of less than three centimeters.

I will pass over miscellaneous electronics, which is a very small error source and which would require discussion of a large number of individual circuits within the system.

Propagation media effects refer to the fact that once the signal from the radio source enters the earth's atmosphere it no longer travels at vacuum light speed. In the ionosphere the signal is retarded by charged particles and at lower altitudes by the neutral atmosphere. The total anomalous delay caused by the neutral atmosphere is about seven nanoseconds overhead, that is, about two meters. The anomalous delay scales roughly by the cosecant of elevation for lower elevations and, for example, is eighty nanoseconds at five degrees elevation. The neutral atmosphere can be resolved into two parts - 'dry component' caused by the total mass of air along the signal path, and a 'wet' component caused by a special effect of the water vapor. We calibrate the 'dry component' by measuring the atmospheric pressure at the telescopes, and this can be used to compute the total mass of air to a few percent. The 'wet component' can be calibrated by measuring the humidity, temperature, and pressure at the telescopes; but this is not a fully satisfactory method since the humidity at the telescope often is not well correlated with the water vapor along the ray path. To achieve a better calibration of the 'wet component' we are instrumenting the telescope sites with water vapor radiometers which measure the microwave brightness in the vicinity of the 23 GHz water vapor emission line. Tests have shown that this brightness is well correlated with total water vapor along the ray path.

The ionosphere is a much smaller effect than the neutral atmosphere, having a worst case effect of 30 cm overhead for X-band signals. We are attacking the ionosphere through the fact that it is dispersive - the anomalous delay for a given frequency is inversely proportional to the square of that frequency. With the MARK III system we will simultaneously observe at X-band (8.4 GHz) and at S-band (2.3 GHz). The ionospheric delay in the S-band will be 13 times larger than in the X-band. Therefore by suitably comparing the simultaneous S- and X-band observations the ionosphere can be recovered.

Geophysical effects include a host of small terms. One of the principal geophysical effects is the solid earth tide. This is a response of the solid earth to the same forces which give rise to ocean tides. The main solid earth tide effect is a semi-diurnal change in the altitude of the telescope with a maximum amplitude of fifteen centimeters. We intend to remove the effects of earth tides by mathematically modelling them in our data analysis and by solving for the parameters of the model. Other geophysical effects include ocean loading, polar motion, and UT-1. Ocean loading is the depression of the solid earth in the vicinity of the seashore as a result the inflow of ocean tides. It has been observed with local scale measurement systems such as tilt meters and strain gauges but never with any global scale measurement system. I will go into polar motion and UT-1 below.

Source structure refers to the fact that while we like to think of the quasars as idealized points in the sky, they are in fact on some very small angular scale diffuse objects. As a result the centroid of brightness, which is the source position that VLBI 'sees' at any instant, varies throughout the day and is different for different baselines. We intend to calibrate this effect by carefully modelling the structure of the sources. This is a standard radio astronomy technique, and in fact the source structure models are in themselves extremely interesting scientific results.

The final error source, "glitches", is a recognition that no hardware or software system developed by human beings is ever perfect. This is our estimate of the effects we have overlooked and the software inadequacies remaining. The improvement from three centimeters to one centimeter reflects the continual review and upgrading of our computer programs.

In summary, based on an analysis of the details of our system we believe we can today deliver baseline length with an accuracy of better than fifteen centimenters, and when the MARK III is fully implemented an accuracy of five centimeters.

Figure #3 shows how well we believe the MARK III will determine other important parameters. The baseline between the telescopes can be determined by VLBI as a vector in a geocentric crust-fixed coordinate system. With one 24 hour observing session we will determine the equatorial components of the baseline to five centimeters and the polar component to eight centimeters. Polar motion is the movement of the geographic pole of the earth, which is fixed on the earth's crust, relative to the spin axis of the earth. UT-1 is the angular position of the earth as it spins about its axis relative to the inertial reference frame defined by the fixed stars. VLBI can determine the parameters characterizing both these effects. We expect to determine polar motion to 10 cm, and variations in UT-1 to 0.15 milliseconds of time.

This review of our system is instructive. But, in fact, does our system actually deliver these levels of precision and accuracy in the field? This is not an easy question to answer - when you claim to have the best system available to do a job there are no absolute standards against which you can test yourself. We can, however, do a number of things which partially answer that question. We can design experiments which will isolate specific elements of our system. We can determine the precision of our results - how closely do our answers repeat when we redetermine an invariant parameter. We can compare our results with the results of other high accuracy systems. This will

MEASUREMENT ACCURACY GOALS FOR THE MARK III SYSTEM FOR 24 HOUR VLBI OBSERVATION

EQUATORIAL BASELINE COMPONENTS	5 CM
POLAR BASELINE COMPONENTS	8 CM
POLAR MOTION	10 CM
VARIATIONS IN UT. 1	0.15 MS

calibrate the accuracy of our system at some very high level but not the ultimate accuracy which we claim.

Figure #4 presents the results of a system test performed on the 1.24 kilometer baseline between the Haystack and Westford antennas, both of which are located near Boston. On this baseline all hardware error sources are fully effective, but the environmental error sources are not. The proximity of the antennas causes the effects of the neutral atmosphere, the ionosphere, and geophysical phenomena to largely cancel. We can then see precisely how the remaining portions of our system, chiefly the hardware elements, are performing. Twelve VLBI experiments were carried out on this baseline between October 1976 and May 1977. The experiments ranged in duration from five to twenty hours. The rms scatter of the length was 3 mm. The scatter for the vector components, which is not shown on this figure, was 7 mm in the vertical components, and 5 and 3 mm in the two horizontal components. To give some idea of the accuracy of this result the length was compared to a determination from a conventional ground survey. The quoted uncertainty in the ground survey was 20 mm in length, and the difference between this survey and our result was 8 mm. These results certainly support our error budget. In fact they are quite a bit better than our error budget would predict. One of the reasons for this is that on the short baseline we were able to use an added technique called 'phase delay resolution', which was not taken into account in the error budget. This improved resolution enabled us to determine that the instrumental systematic error sources in the measurements are less than our target values in the error budget.

For the past year we have been performing experiments on a 4000 km baseline between Haystack and the Owens Valley Radio Observatory telescope near Big Pine, California. The hardware system employed was the one characterized by the upper bars on the error budget figure. It contained MARK III front end equipment, that is, parametric amplifiers and receivers; but used the MARK I back end. Based on the error budget it should have been capable of delivering 15 cm baseline length results. Figure #5 shows nine separate baseline length determinations spanning a period from September 1976 to March 1977. The vertical lines for each point show the formal uncertainty for each point. These formal uncertainies are a product of the least-squares analysis which is used to extract the recovered parameters. The actual root-mean-square scatter about the mean value is 7 cm - well within the error budget. In fact the spread between the two outliers is only 20 cm.

HAYSTACK-WESTFORD BASELINE
INDIVIDUAL EXPERIMENT CORD LENGTH
LESS MEAN CORD LENGTH VERSUS TIME

(MEAN CORD LENGTH 1,239,393.9 ± 3.1 mm)

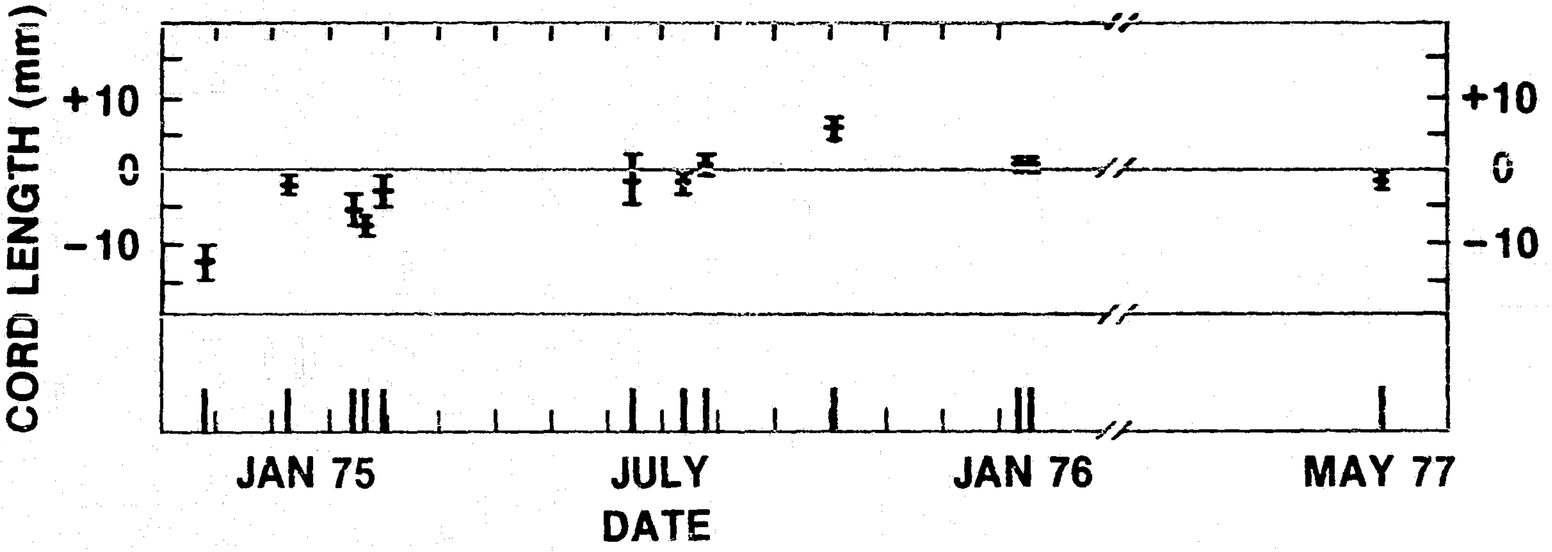

Figure 4.

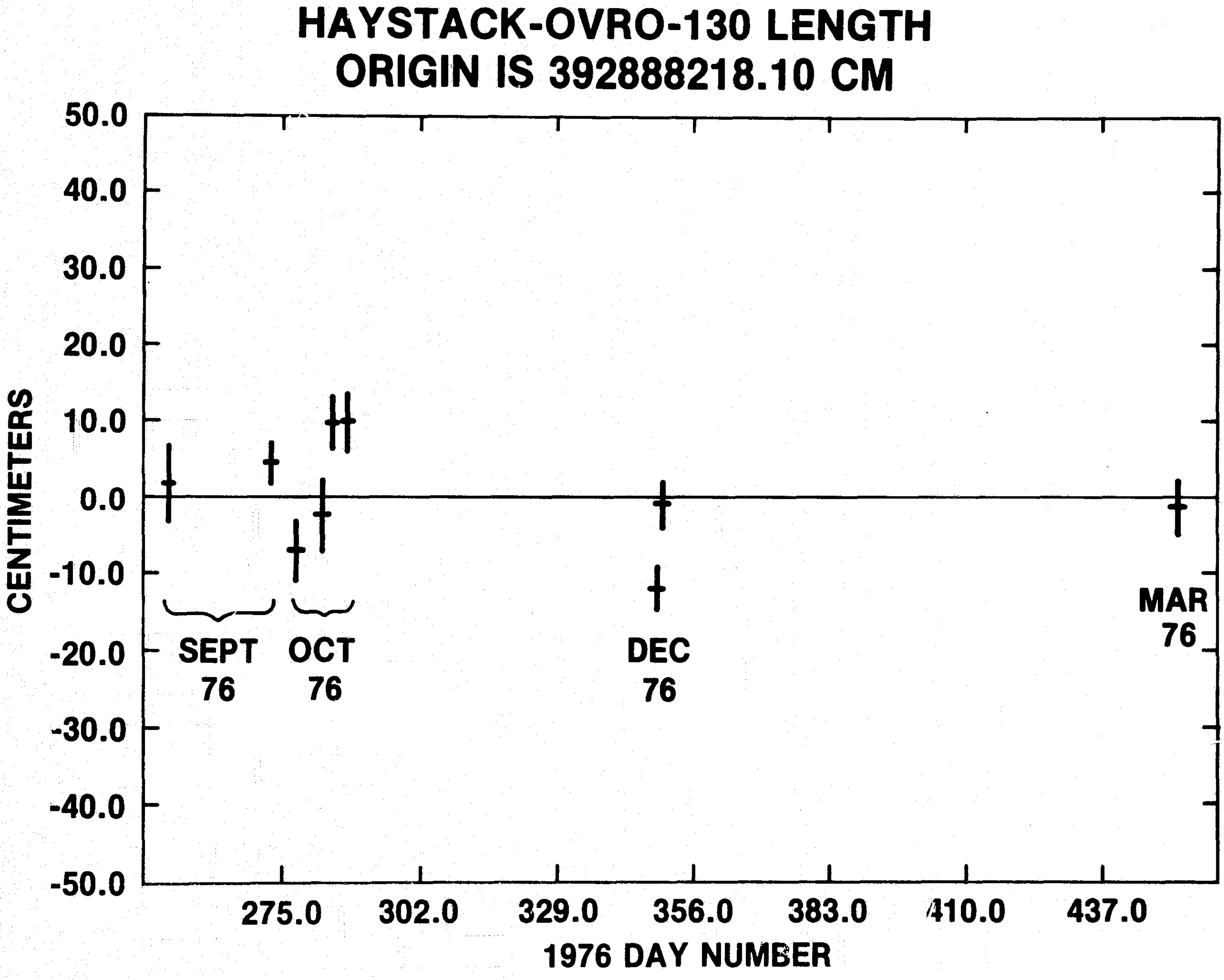
HAYSTACK-OVRO-130 LENGTH
ORIGIN IS 392888218.10 CM
CENTIMETERS
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
SEPT 76
OCT 76
DEC 76
MAR 76
275.0
302.0
329.0
356.0
383.0
410.0
437.0
1976 DAY NUMBER

Figure 5.

We have used this set of experiments to monitor the changes in the X component of polar motion since October 1976. The X component of polar motion is the displacement of the earth's spin axis relative to a defined geographic pole in the plane of the Greenwich meridian. Figure #6 is a plot of the difference between our determination of the displacement and that determined by the standard international service for polar motion, the Bureau International de l'Heure in Paris (BIH). This figure also shows a simillar difference plot for pole determinations made by the Defense Mapping Agency using the Doppler Satellite System. Without absolute a priori knowledge of the baseline orientation VLBI measurements are not sensitive to absolute pole position, but only to its changes with time. As a result we have accepted as defined the BIH pole position on October 4, 1977; as you can see we and the BIH are coincident on that date. The plot shows a steady divergence between our results and those of the BIH until in March of this year the difference had reached approximately two meters. This is inconsistent with the claimed accuracies of both the BIH and our VLBI system. However, the Doppler Satellite System shows the same trend. In fact had we adopted the Doppler value of the pole for October 4th the difference between our results and the Doppler results would have been near the uncertainty in the Doppler results. So it appears that the discrepancy between our resutls and those of thr BIH is due to an error in the BIH results. The BIH pole positions are based primarily on a mass of optical astronomy data taken by observatories all over the world. It seems now that space developed technology is about to cause a revolution in the way the earth's pole is tracked.

What can we say about the accuracy of our transcontinental length determinations?

It is impossible to answer that question in a fully satisfactory way - there is no comparable yardstick. There are at least three systems now being developed which have claimed accuracies in the vicinity of the VLBI accuracies and which can be used for intercomparisons with varying degrees of difficulty. They are the satellite laser systems, the lunar laser system, and the Doppler Satellite System. While we have plans to intercompare with all these systems, to date we have been only able to intercompare with the Doppler Satellite System results. This is testimony to the flexibility and reponsiveness of the Doppler Satellite System. Figure #7 shows length comparisons for three baselines. The Haystack to Goldstone, California and Haystack to Owens Vally (OVRO) baselines are both 4000 km; the Haystack to Greenbank, West Virgina baseline is 800 km. The VLBI results for the Haystack-Goldstone and Haystack-Greenbank baselines are

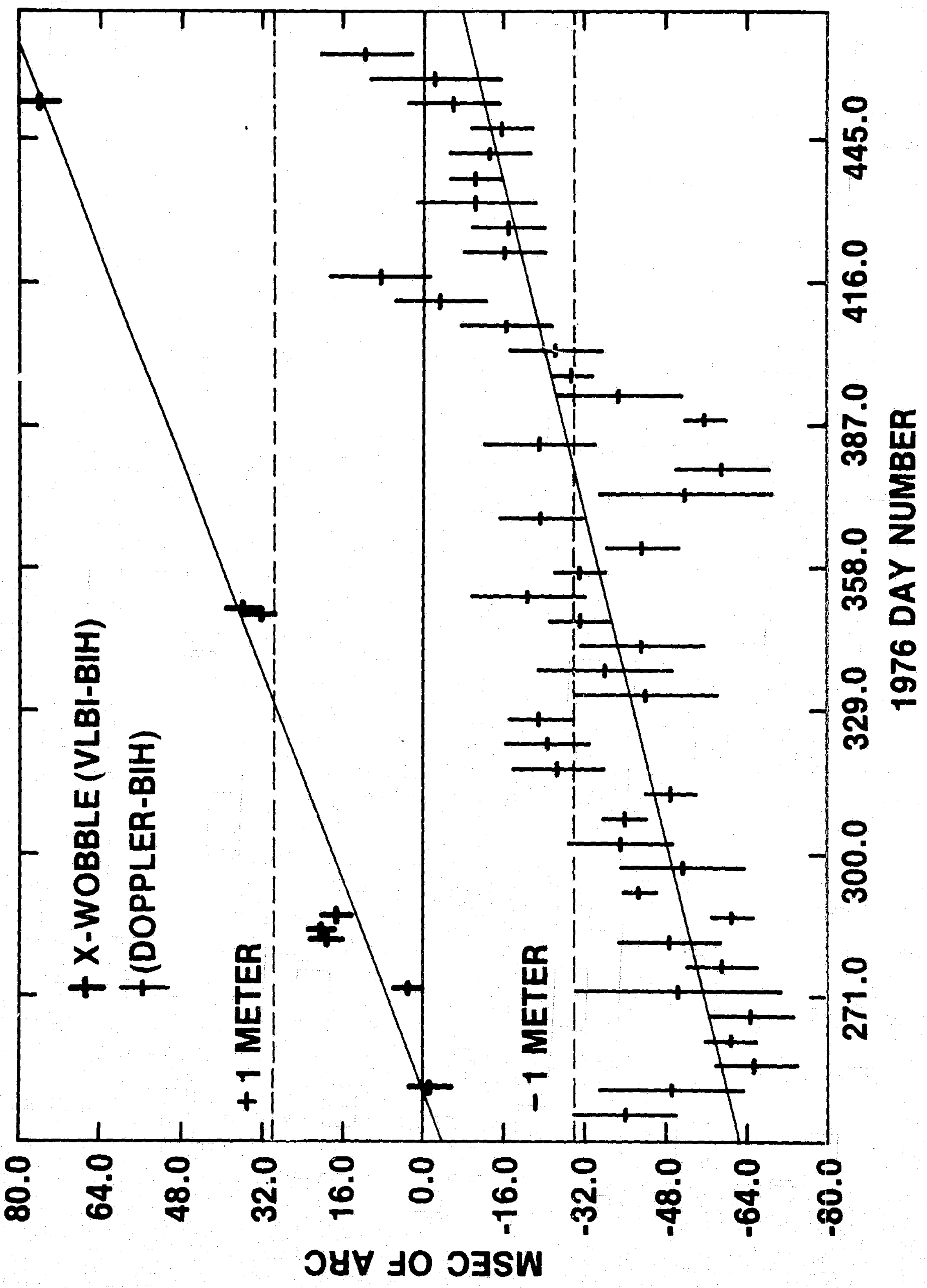
X-WOBBLE (VLBI-BIH)
(DOPPLER-BIH)
+1 METER
−1 METER
80.0
64.0
48.0
32.0
16.0
0.0
-16.0
-32.0
-48.0
-64.0
-80.0
MSEC OF ARC
271.0
300.0
329.0
358.0
387.0
416.0
445.0
1976 DAY NUMBER

Figure 6.

INTERCOMPARISONS
DOPPLER SATELLITE WITH VLBI
(PRELIMINARY)

STATIONS		CHORD DISTANCE		
FROM	TO	DOPPLER (M)	VLBI (M)	DIFF (CM)
HAYSTACK	GOLDSTONE	3899998.42	3899998.34	+ 8
HAYSTACK	OVRO	3928881.82	3928881.63	+19
HAYSTACK	GREENBANK	845130.14	845129.90	+24

DOPPLER RESULTS FROM L. HOTHEM OF N.G.S.

Figure 7.

actually a few years old and were determined with a system which is less accurate than that described in the error budget. The Haystack-Owens Valley result is new. The claimed uncertainties in the Doppler satellite length determinations is in all cases 0.5 meters. The difference on the Haystack-Goldstone baseline, which is only 8 centimeters, is fortuitously good. The differences on the other two baselines is well within the uncertainty of the Doppler Satellite results. At least to the half meter level these results confirm our claims.

I have made a case that we are about to produce a system capable of making transcontinental length measurements with 5 cm accuracies and making measurements of UT-1 and polar motion to comparable accuracies. If we succeed what will we have done? Is this anything more than a technological tour de force?

To answer this question the following is a partial list of the scientifically interesting phenomena which the MARK III VLBI system will measure usefully:

UT-1,
long term polar motion,
diurnal polar motion,
precession,
nutation,
solid earth tides,
ocean loading,
local crustal motions,
and tectonic plate motions.

This last phenomenon has potential for profound results. Currently geophysicists believe that the crust of the earth is made up of a small number of rigid plates. These plates move about relative to one another, and motion along the plate boundaries causes the great earthquakes. This theory predicts that the plates are moving today with speeds of as much as 10 cm per year, but the theory is based on data which averages the plate motion over hundreds of thousands to millions of years. There is no hard, direct evidence that the plates are in motion now; perhaps the motion is episodic - no one knows. A few years of 5 cm level VLBI measurements will provide direct evidence as to whether the plates are in motion today.

Finally, geophysicists also speculate that variations in polar motion and UT1 are related to a variety of interesting phenomena including, but not limited to, earthquakes, aseismic tectonic motion, core-mantle interactions, and meteorological phenomena. A detailed resolution of these effects will require the increased spatial and temporal resolution which VLBI measurements can provide. To this end NASA and the National Geodetic Survey have under consideration a joint program to set up and run an operational polar motion service based on the MARK III technology.