GEODETIC LONG BASELINE INTERFEROMETRY RESEARCH IN CANADA

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ABSTRACT

Long baseline interferometry (LBI) has proved itself to be an invaluable geodetic tool. In this paper, the objectives and results of several studies using the Canadian LBI system will be presented. Radio telescopes at the Algonquin Radio Observatory (ARO), Lake Traverse, Ontario; the Owens Valley Radio Observatory (OVRO), Big Pine, California; and the Chilbolton Observatory (CHIL), Chilbolton, England, are being used to obtain precise positions of a number of extragalactic radio sources and to determine the components of the baselines connecting the radio telescopes with submeter precision. For example, the standard deviation of the weighted mean of the equatorial component of the ARO-CHIL baseline from five observing sessions between March 1973 and January 1978 is only 31 cm.

Since LBI is insensitive to the uncertainty in the geocentric gravitational constant, GM, it is a very useful technique for determining the scales of the coordinate systems used by other precise techniques. Beginning in May 1977, a number of LBI observing sessions were accompanied by simultaneous satellite Doppler observations. The baseline components obtained from the satellite Doppler observations were compared to the LBI values. The weighted mean scale bias of the NSWC 9Z-2 satellite Doppler coordinate system relative to the LBI system was found to be 0.42 ± 0.05 PPM. The weighted mean difference in the origin of longitude was found to be $0\overset{''}{.}87 \pm 0\overset{''}{.}01$ while the difference in declination origin was found to be $0\overset{''}{.}06 \pm 0\overset{''}{.}01$.

A pilot project to use LBI to make high-accuracy measurements of earth rotation parameters is also under way. The major innovation setting this system apart from other similar efforts is the inclusion of a scheme to accurately monitor local oscillator drifts using two-way transmissions through the Anik B communications satellite. The purpose of this innovation is to eliminate the troublesome possibility of mistakenly interpreting oscillator drifts as real geophysical effects.

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INTRODUCTION

Although originally designed for astrophysical purposes, the Canadian Long Baseline Interferometry (LBI) system has been used to obtain a number of geodetically useful results [Petrachenko, 1976; Cannon et al., 1979a; Langley et al., 1979]. In this paper, we present the results of further studies using this system and briefly discuss plans for a project to make high-accuracy measurements of earth rotation parameters using the Anik B communications satellite to accurately monitor local oscillator drifts.

VECTOR BASELINE AND SOURCE COORDINATE DETERMINATIONS

Between February 1975 and January 1978, seven LBI observing sessions were carried out using the 46m antenna at the Algonquin Radio Observatory (ARO), Lake Traverse, Ontario; the 40m antenna at the Owens Valley Radio Observatory (OVRO), Big Pine, California; and the 25m antenna at the Chilbolton Observatory (CHIL), Chilbolton, England. The dates on which observations were made and the frequencies used are listed in table 1. Thus far, only the data from the observing sessions of May 1977 and January 1978 (considered to be the best) have been analyzed for their geodetic and astrometric content.

Table 1
Dates of Observations

Observing Session	Frezuency (MHz)	Antenna		
		ARO	CHIL	OVRO
4 - 6 February 1975	10680	x	x	
21 - 25 June 1975	10680	x	x	x
13 - 16 May 1977	10680	x	x	x
15 - 18 July 1977	10680	x	x	x
15 - 18 September 1977	10660	x	x	x
9 - 13 November 1977	10660	x	x	x
17 - 20 January 1978	10660	x	x	x

A description of the Canadian LBI system, the observing strategy and the analysis technique has been given by Langley [1979]. Only a few of the details will be repeated here.

The observations were first corrected for the effect of the neutral atmosphere. Hopfield's model [Hopfield, 1971] was implemented using an extension of the algorithm of Yionoulis [1970]. Surface measurements of pressure, temperature, and relative humidity used as input to the model were taken at or near each of the stations during the observations. The observations were not corrected for the effect of the ionosphere. At the approximately 10 GHz observing frequency, the maximum contributions of the ionosphere to fringe frequency and delay are about 0.3 MHz and 1 ns respectively and that for most of the observations the contributions will be less than 0.1 MHz and 0.3 ns.

Since the standard deviations of the fringe frequency and delay residuals were expected to be about 2 MHz and 20 ns respectively, the ionospheric effect was considered to be fairly insignificant.

For each observing session, the corrected delays and fringe frequencies from all three baselines were simultaneously fitted to a model [Langley, 1979] for which the following parameters were estimated: the x, y, and z components of each baseline; the right ascension and declination of the sources observed (with the exception of 3C273B); and the coefficients of clock polynomials for fringe frequency and delay. The right ascension and declination of 3C273B were not estimated as they were used as a fiducial point for determining the coordinates of the other sources and, in part, the orientation of the baselines. It is usually the case when precise delay observations are available that only the right ascension of the fiducial source must be held fixed. However, when fringe frequency observations alone are used or when the fringe frequency observations dominate the delay observations when both types of observables are used (as in the present case), both the right ascension and declination of the fiducial source must be fixed [Cannon, 1978; Shapiro, 1976]. The coordinates adopted for 3C273B are those of Clark et al. [1976]. The estimated uncertainty in the position for 3C273B is $\pm 0\overset{s}{.}01$ and $\pm 0\overset{\prime\prime}{.}13$ for the right ascension and declination respectively.

The orientation of the LBI coordinate system was determined in part by the position of the earth's rotation pole and the differences UT1-UTC during the observing sessions as published *a posteriori* by the Bureau International de l'Heure (BIH) [1978a, 1978b]. These data are expressed in the 1968 BIH System.

The IAU system of astronomical constants that was introduced in 1968 was adhered to in the model including the value of the speed of light of 299 792.5 $\mathrm{km \cdot s^{-1}}$.

Because the Canadian LBI system has a relatively narrow recorded bandwidth (~4 MHz), the fringe frequency observations are much more sensitive to source position and the equatorial components of the baselines than are the delay observations. The fringe frequency observations therefore dominate the delay observations in the model fitting as far as these parameters are concerned. However, the fringe frequency observable is essentially insensitive to the z component of the baseline, and the delay observations provide the only information for estimating this component.

The weighted mean values of the source positions resulting from the model fits to the May 1977 and January 1978 data are shown in table 2. The weights used were the formal standard deviations derived from the post-fit residuals and the parameter variance-covariance matrix. Half of the sources were observed in only one of the observing sessions. For these sources, the single result from the individual model fit has been entered. The E-terms of annual aberration have been included in the coordinates in table 2. This conforms with normal cataloging procedures for the epoch 1950.0.

The baseline components from the individual fits are shown in tables 3 and 4, while the weighted mean values of the baseline components are shown in table 5. Again, the weights used were the formal standard deviations derived from the post-fit residuals and the parameter variance-covariance

Table 2
Weighted Mean Values of Source Positions from May 1977 and January 1978 Observing Sessions

Source	RA(1950.0)	DEC(1950.0)	No. Sol'n
0235 + 16	2^{h} 35^{m} $52\overset{s}{.}634 \pm 0\overset{s}{.}002$	$+16^{\circ}$ $24'$ $4\overset{''}{.}01 \pm 0\overset{''}{.}07$	1
NRAO150	3 55 45.261 ± 0.004	+50 49 20.29 ± 0.01	1
OJ287	8 51 57.253 ± 0.001	+20 17 58.38 ± 0.01	2
4C39.25	9 23 55.322 ± 0.002	+39 15 23.61 ± 0.03	1
3C273B*	12 26 33.248	+ 2 19 43.27	
3C345	16 41 17.610 ± 0.001	+39 54 10.83 ± 0.02	2
Bl Lac	22 0 39.366 ± 0.002	+42 2 8.58 ± 0.01	2
3C446	22 23 11.084 ± 0.003	- 5 12 17.60 ± 0.21	1

*3C273B was used as the fiducial source; see text

matrix. The standard deviations of the weighted mean z components of the baselines have anomalously small values, in light of the fact that the formal standard deviations of the individual determinations of the z components are of the order of 4m. No explanation is offered for the remarkable agreement between the values of the z components from the two observing sessions other than that supported by the (slim) odds of probability. It should be noted however that the agreement between the z components of the baselines of table 5 and those determined by satellite Doppler observations (to be discussed shortly) is about 1 to 2 m! Also, because the z components of the baselines are relatively small, the errors in z components do not contribute appreciably to the overall errors in the total lengths of the baselines.

The standard deviations of the post-fit fringe frequency and delay residuals for the May 1977 and January 1978 observing sessions are 2.0 MHz, 15.2 ns and 1.9 MHz, 13.1 ns respectively.

Preliminary results of the baseline and source position determinations from the May 1977 observing session alone have been published previously [Langley et al., 1979]. The results presented here differ slightly from the preliminary results for two reasons: (1) some (poor) observations of the source NRAO150 were used in the preliminary analysis but not in the final model fit for the May 1977 observations, and (2) the model used for the preliminary analysis did not include the effect of earth tides on the observations.

The equatorial components of the ARO-CHIL baseline obtained from the May 1977 and January 1978 observing sessions have been compared to values obtained from the analysis of three observing sessions in 1973 from which only fringe frequency data were obtained [Petrachenko, 1976]. The five values are shown in figure 1. The weighted mean of the five values is 5 251 087.68 m with a standard deviation of 0.31 m.

Table 3
Baseline Components from May 1977 Observing Session

Baseline Component	ARO - OVRO	ARO - CHIL	OVRO - CHIL
x component	-3 327 634.51 ± 0.40 m	3 090 274.92 ± 0.42 m	6 417 909.43 ± 0.90 m
y component	-132 217.46 ± 0.30 m	4 245 482.14 ± 0.41 m	4 377 699.57 ± 0.78 m
z component	-723 368.94 ± 3.91 m	381 826.14 ± 4.25 m	1 105 195.08 ± 5.23 m
equatorial component	3 330 260.19 ± 0.40 m	5 251 087.29 ± 0.41 m	7 768 771.78 ± 0.86 m
total length	3 407 916.60 ± 0.92 m	5 264 950.99 ± 0.51 m	7 846 991.21 ± 1.13 m
east longitude	182° 16′ 31.″245 ± 0.″019	53° 56′ 57.″223 ± 0.″016	34° 17′ 53.″389 ± 0.″022
declination	-12° 15′ 17.″660 ± 0.″231	4° 9′ 31.″933 ± 0.″166	8° 5′ 47.″902 ± 0.″136

Table 4
Baseline Components from January 1978 Observing Session

Baseline Component	ARO - OVRO	ARO - CHIL	OVRO - CHIL
x component	-3 327 635.05 ± 0.24 m	3 090 275.34 ± 0.42 m	6 417 910.44 ± 0.67 m
y component	-132 218.44 ± 0.28 m	4 245 482.88 ± 0.46 m	4 377 701.38 ± 0.70 m
z component	-723 369.31 ± 1.32 m	381 825.62 ± 3.80 m	1 105 194.92 ± 3.58 m
equatorial component	3 330 260.76 ± 0.24 m	5 251 088.13 ± 0.45 m	7 768 773.64 ± 0.68 m
total length	3 407 917.24 ± 0.36 m	5 264 951.79 ± 0.53 m	7 846 993.03 ± 0.84 m
east longitude	182° 16′ 31″.304 ± 0″.017	53° 56′ 57″.227 ± 0″.017	34° 17′ 53″.414 ± 0″.018
declination	-12° 15′ 17″.674 ± 0″.078	4° 9′ 31″.911 ± 0″.149	8° 5′ 47″.891 ± 0″.093

Table 5
Weighted Mean Values of Baseline Components from May 1977
and January 1978 Observing Sessions

Baseline Component	ARO - OVRO	ARO - CHIL	OVRO - CHIL
x component	-3 317 634.91 ± 0.27 m	3 090 275.13 ± 0.21 m	6 417 910.08 ± 0.51 m
y component	-132 217.98 ± 0.49 m	4 245 482.47 ± 0.37 m	4 377 700.57 ± 0.90 m
z component	-723 369.27 ± 0.18 m	381 825.85 ± 0.26 m	1 105 194.97 ± 0.08 m
equatorial component	3 330 260.61 ± 0.29 m	5 251 087.67 ± 0.42 m	7 768 772.92 ± 0.93 m
total length	3 407 917.16 ± 0.32 m	5 264 951.37 ± 0.40 m	7 846 992.38 ± 0.91 m
east longitude	182° 16′ 31″.278 ± 0″.030	53° 56′ 57″.225 ± 0″.002	34° 17′ 53″.404 ± 0″.013
declination	-12° 15′ 17″.673 ± 0″.007	4° 9′ 31″.921 ± 0″.011	8° 5′ 47″.895 ± 0″.005

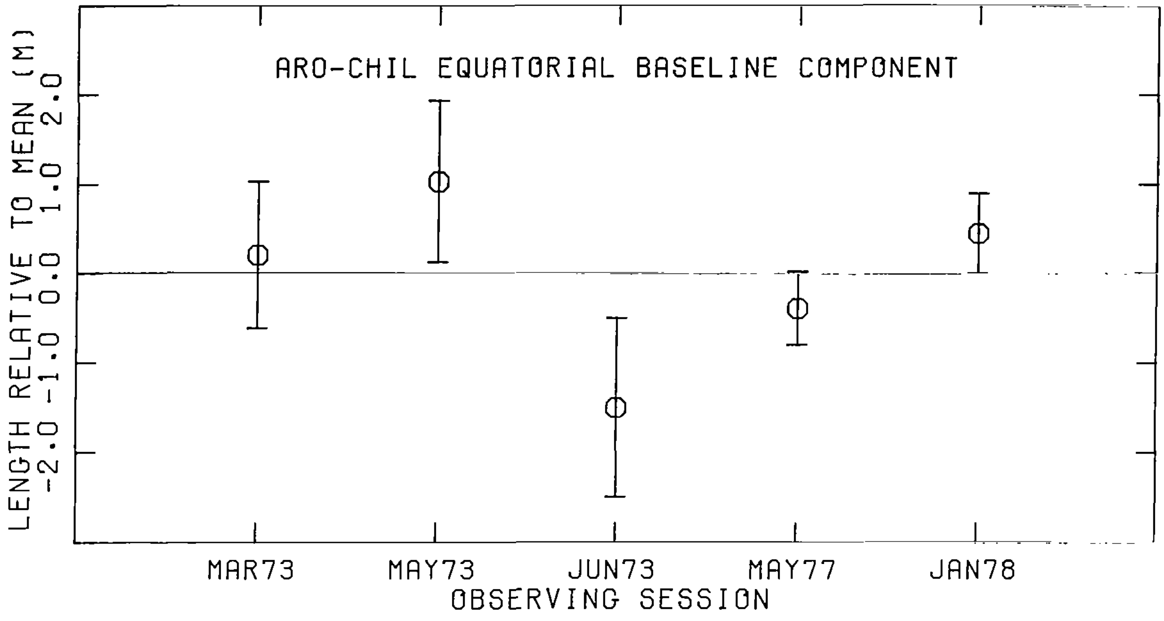

Figure 1. Five determinations of the equatorial component of the ARO-CHIL baseline. The weighted mean is 5 251 087.68 ± 0.31 m.

COMPARISON OF LBI BASELINE DETERMINATIONS WITH SATELLITE DOPPLER RESULTS

During the May 1977 and January 1978 observing sessions, satellite Doppler receiving stations were set up near the antennas used for the LBI observations. The object of these simultaneous LBI-satellite Doppler observing sessions was to compare the determinations of the vector baselines between each of the LBI antennas by the two techniques; hence, to derive the differences in scale and orientation of the coordinate systems employed.

For the May 1977 observing session, satellite Doppler receivers were installed within about 100m of the LBI antennas at each of the observatories. For the January 1978 observing session, there was no satellite Doppler receiver at the Chilbolton Observatory. However, for both observing sessions, satellite Doppler observations were available from the TRANET permanent tracking station at Barton Stacey which is only a few kilometers away from the Chilbolton Observatory.

The satellite Doppler observations were conducted between May 9 and 15, 1977, and between January 16 and 21, 1978. The observations at ARO were made by the Geodetic Survey of Canada, those at OVRO by the National Geodetic Survey of the U. S. Department of Commerce, and those at CHIL by the University of Nottingham and the Ordnance Survey of Great Britain. The TRANET station is operated by the Directorate of Military Survey of the United Kingdom.

The satellite Doppler observations were reduced by Jan Kouba of the Earth Physics Branch of the Department of Energy, Mines, and Resources using the GEODOP computer program [Kouba and Boal, 1976] and a precise ephemeris supplied by the U.S. Defense Mapping Agency Topographic Center (DMATC). The number of satellite passes used to obtain the satellite Doppler station positions varied from 25 for the May 1977 observations at the Barton Stacey TRANET station to 48 for the May 1977 observations at ARO and OVRO. Although as many as five TRANSIT satellites were observed at each station, only the observations of satellites 68 and 77 were used in the data reduction.

The satellite Doppler and LBI observations refer to different positions. The satellite Doppler reference point is the electrical center of the Doppler antenna. The LBI reference point is the point where the azimuth axis of the LBI antenna intersects the horizontal plane in which the altitude axis rotates. The differences in the reference points for each observing site were determined by conventional surveys.

The derived Doppler station positions were combined with the survey differences to obtain the baseline components for the LBI antennas. These are presented separately for each observing session in tables 6 and 7. The components are expressed in the NSWC 9Z-2 coordinate system. The first entry in table 6 for each component of the ARO-CHIL and OVRO-CHIL baselines was derived from the observations at the Chilbolton Observatory station. The second entry was derived from the observations at the Barton Stacey TRANET station; only the least significant figures are given. In each case, the two results for the baseline components of the ARO-CHIL and OVRO-CHIL baselines are within the estimated accuracies.

The differences between the LBI-derived baseline components and those derived from the combination of satellite Doppler and ground surveys are presented in tables 8 and 9. The differences are given in the sense: LBI result minus satellite Doppler result. The accuracy estimates were obtained by combining the uncertainties of the LBI results with the uncertainties of the satellite Doppler results.

The scale bias of the NSWC 9Z-2 coordinate system as determined from the total baseline lengths is given in table 10 for each baseline from both observing sessions together with the differences in east longitude and declination.

The scale difference ranges from 0.26 ± 0.17 to 0.70 ± 0.41 PPM with a weighted mean of 0.42 ± 0.05 PPM

The differences in the east longitudes of the baselines, which can be interpreted as a difference in definition of the longitude origins of the coordinate systems, have a weighted mean of $0.''87 \pm 0.''01$. This is in agreement with a previous result [Cannon et al., 1979a].

The differences in the declinations of the baselines as determined by the two techniques have a weighted mean of $0.''06 \pm 0.''01$. This small difference between the two techniques may, in part, be due to the adopted declination of source 3C273B which defines the declination origin of the LBI

Table 6
Baseline Components Obtained from May 1977 Satellite Doppler Observations and Ground Surveys

Baseline Component	ARO - OVRO	ARO - CHIL	OVRO - CHIL
equatorial component	3 330 262.77 ± 1.0 m	5 251 089.08 ± 1.0 m 090.03 ± 1.0 m	7 768 775.57 ± 1.0 m 776.41 ± 1.0 m
total length	3 407 918.98 ± 1.0 m	5 264 952.72 ± 1.0 m 953.60 ± 1.0 m	7 846 994.82 ± 1.0 m 995.53 ± 1.0 m
east longitude	182° 16′ 30″.338 ± 0″.06	53° 56′ 56″.362 ± 0″.04 56″.367 ± 0″.04	34° 17′ 52″.503 ± 0″.03 52″.514 ± 0″.03
declination	-12° 15′ 17″.605 ± 0″.06	4° 9′ 31″.904 ± 0″.04 31″.867 ± 0″.04	8° 5′ 47″.862 ± 0″.03 47″.836 ± 0″.03

Table 7
Baseline Components Obtained from January 1978 Satellite Doppler Observations and Ground Surveys

Baseline Component	ARO - OVRO	ARO - CHIL	OVRO - CHIL
equatorial component	3 330 262.49 ± 1.0 m	5 251 090.21 ± 1.0 m	7 768 776.00 ± 1.0 m
total length	3 407 918.79 ± 1.0 m	5 264 953.74 ± 1.0 m	7 846 995.06 ± 1.0 m
east longitude	182° 16′ 30″.372 ± 0″.06	53° 56′ 56″.407 ± 0″.04	34° 17′ 52″.546 ± 0″.03
declination	-12° 15′ 17″.615 ± 0″.06	4° 9′ 31″.844 ± 0″.04	8° 5′ 47″.826 ± 0″.03

Table 8
Baseline Differences from May 1977 Observations: LBI – Satellite Doppler

Baseline Component	ARO – OVRO	ARO – CHIL	OVRO – CHIL
equatorial component	−2.58 ± 1.1 m	−1.79 ± 1.1 m −2.74 ± 1.1 m	−3.79 ± 1.3 m −4.63 ± 1.3 m
total length	−2.38 ± 1.4 m	−1.73 ± 1.1 m −2.61 ± 1.1 m	−3.61 ± 1.5 m −4.32 ± 1.5 m
east longitude	+0.″907 ± 0.″06	+0.″861 ± 0.″04 +0.″856 ± 0.″04	+0.″886 ± 0.″04 +0.″875 ± 0.″04
declination	+0.″055 ± 0.″24	+0.″029 ± 0.″17 +0.″066 ± 0.″17	+0.″040 ± 0.″14 +0.″066 ± 0.″14

Table 9
Baseline Differences from January 1978 Observations: LBI - Satellite Doppler

Baseline Component	ARO - OVRO	ARO - CHIL	OVRO - CHIL
equatorial component	-1.73 ± 1.0 m	-2.08 ± 1.1 m	-2.36 ± 1.2 m
total length	-1.55 ± 1.1 m	-1.95 ± 1.1 m	-2.03 ± 1.3 m
east longitude	+0.″932 ± 0.″06	+0.″820 ± 0.″04	+0.″868 ± 0.″03
declination	+0.″059 ± 0.″10	+0.″067 ± 0.″15	+0.″065 ± 0.″10

Table 10
Scale, Longitude, and Declination Differences

Baseline	Scale (PPM)	East Longitude (″)	Declination (″)
May 1977			
ARO-OVRO	0.70 ± 0.41	0.907 ± 0.06	0.055 ± 0.24
ARO-CHIL	0.33 ± 0.21	0.861 ± 0.04	0.029 ± 0.17
ARO-CHIL*	0.50 ± 0.21	0.856 ± 0.04	0.066 ± 0.17
OVRO-CHIL	0.46 ± 0.19	0.886 ± 0.04	0.040 ± 0.14
OVRO-CHIL*	0.55 ± 0.19	0.875 ± 0.04	0.066 ± 0.14
Jan 1978			
ARO-OVRO	0.45 ± 0.32	0.932 ± 0.06	0.059 ± 0.10
ARO-CHIL	0.37 ± 0.32	0.820 ± 0.04	0.067 ± 0.15
OVRO-CHIL	0.26 ± 0.17	0.868 ± 0.03	0.065 ± 0.10
Weighted Mean	0.42 ± 0.05	0.87 ± 0.01	0.06 ± 0.01

*Based on satellite Doppler observations at Barton Stacey.

coordinate system and the difference between the BIH pole position values used in the analysis of the LBI data and the DMATC pole position values used in the analysis of satellite Doppler data.

EARTH ROTATION MEASUREMENTS BY SATELLITE LINK LBI

A program to investigate the ability of a long baseline interferometer to measure UT1, pole position, and precession-nutation has recently been undertaken. This program is discussed in detail by Cannon et al. [1979b], and only a brief overview will be given here.

UT1, pole position, and precession-nutation have traditionally been monitored using optical instruments such as photographic zenith tubes (PZTs) and polar telescopes. Recently, the optical methods have been supplemented by more modern techniques. Of these techniques, satellite Doppler is currently the most widely used. Satellite Doppler pole positions are now routinely determined. Although of higher precision than the optical pole positions they are unfortunately tied to the reference frame of the satellite orbits which slowly drift with respect to an inertial reference frame. Furthermore, satellite Doppler data are relatively insensitive to UT1. Due to these deficiencies in the satellite Doppler technique, LBI is being considered as an alternative technique for supplying accurate pole position and UT1 measurements.

In Canada, the Earth Physics Branch of the Department of Energy, Mines, and Resources is responsible for the measurement of UT1 and pole position. It contributes both PZT and satellite data to the BIH determinations of these quantities. In March 1978, the Earth Physics Branch entered into a contract with a group of researchers including J. L. Yen of the University of Toronto, J. A. Galt of the Dominion Radio Astrophysical Observatory, S. K. Knowles and W. B. Waltman of the U. S. Naval Research Laboratory, and W. H. Cannon and W. T. Petrachenko of York University, with the collaboration of the Herzberg Institute of Astrophysics of the National Research Council of Canada. The terms of the contract require the coinvestigators to use a long baseline interferometer to measure UT1 with an accuracy at least equal to the accuracy of the best PZTs in existence; i.e., 2-3 ms. Potential for improvement is also expected to be shown along with an evaluation of the ability of a long baseline interferometer to measure pole position.

The use of a long baseline interferometer to measure earth rotation parameters is not a new idea. This potential usage was recognized even before the first successful implementation of LBI in 1967. However, technical problems have delayed the realization of this anticipated use. Since 1967, most of these technical problems have been solved, but the fact that in the operation of a long baseline interferometer, separate oscillators must be used at the ends of the baselines leads to the troublesome possibility of mistakenly interpreting oscillator drifts as real geophysical effects. In order to eliminate the effect of the drifting oscillators, it has been proposed that for this project, the phases of the oscillators be continuously compared via a satellite link. This is a new and significant innovation setting this system apart from other LBI systems attempting to measure earth rotation parameters.

Over the past year, phase link experiments have been performed using the Hermes Communications Technology Satellite. The results of these experiments were encouraging. It was apparent that the major corrupting effect, the satellite Doppler shift, had been reduced below the level of detection. However, small residual phase drifts presently under study still remain. Over measurement periods of about 1 day, these drifts limit the performance of the phase link to approximately the level of a rubidium clock.

On December 15, 1978, Anik B was launched. This is the satellite to be used during the forthcoming experiment to measure UT1. The satellite is now fully operational and the first phase link tests have just been performed (June 1979). Monthly shakedown experiments will follow over the next 3 months, with the first simultaneous use of the phase link with a long baseline interferometer taking place later this year. The interferometer will consist of stations at the Maryland Point Observatory, Maryland Point, Maryland; the Algonquin Radio Observatory, Lake Traverse, Ontario; and the Dominion Radio Astrophysical Observatory, Penticton, British Columbia.

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REFERENCES

Bureau International de l'Heure, Circular D, Paris, 1978a.

Bureau International de l'Heure, Rapport Annuel pour 1977, Paris, 1978b.

Cannon, W. H., "The Classical Analysis of the Response of a Long Baseline Radio Interferometer," Geophysical Journal of the Royal Astronomical Society, 53, 503-530, 1978.

Cannon, W. H., R. B. Langley, W. T. Petrachenko and J. Kouba, "Geodesy and Astrometry by Transatlantic Long Base Line Interferometry," Journal of Geophysical Research, 84, 229-236, 1979a.

Cannon, W. H., J. Galt, S. H. Knowles, W. T. Petrachenko, J. A. Popelar, W. B. Waltman, and J. L. Yen, "Plans for Phase Coherent VLBI for Geophysical Applications Using the ANIK-B Satellite," these proceedings, 1979b.

Clark, T. A., L. K. Hutton, G. E. Marandino, C. C. Counselman, D. S. Robertson, I. I. Shapiro, J. J. Wittels, H. F. Hinteregger, C. A. Knight, A. E. E. Rogers, A. R. Whitney, B. O. Rönnäng and D. E. H. Rydbeck, "Radio Source Positions from Very-Long-Baseline Interferometry Observations," Astronomical Journal, 81, 599-603, 1976.

Hopfield, H. S. "Tropospheric Effect on Electromagnetically Measured Range: Prediction from Surface Weather Data," Radio Science, 6, 357-367, 1971.

Kouba, J. and J. D. Boal, Program GEODOP, Department of Energy, Mines and Resources, Ottawa, April 1976.

Langley, R. B., "Precision Geodesy and Astrometry with a Three Station Long Baseline Interferometer," Ph.D. Thesis, York University, Toronto, 1979.

Langley, R. B., W. H. Cannon, W. T. Petrachenko and J. Kouba, "LBI and Satellite Doppler: Baseline Comparisons," Proceedings of the 2nd International Geodetic Symposium on Satellite Doppler Positioning, Austin, Texas, 1979.

Petrachenko, W. T., "Geodetic and Astrometric Analysis of Fringe Frequency Data at 2.8 cm Wavelength from the Algonquin-Chilbolton Long Baseline Interferometer," M.Sc. Thesis, York University, Toronto, 1976.

Shapiro, I. I., "Estimation of Astrometric and Geodetic Parameters," in Methods in Experimental Physics, Vol. 12, part C, ed. M. L. Meeks, Academic Press, New York, 1976.

Yionoulis, S. M., "Algorithm to Compute Tropospheric Refraction Effects on Range Measurements," Journal of Geophysical Research, 75, 7636-7637, 1970.