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VERY LONG BASELINE INTERFEROMETRY (VLBI) APPLICATIONS TO SECULAR GEODYNAMICS AND EARTH STRAIN
 MEASUREMENT *

ABSTRACT

An instrumental technique from radio astronomy, known as Very Long Baseline Interferometry (VLBI) offers significant promise for the problem of accurate long distance, three dimensional surveying and determination of whole Earth geodynamical phenomena. The methods of VLBI make it possible for receiving stations to be independently operated at arbitrary separations using extragalactic radio sources at its frame of time invariant angular reference. Feasibility demonstrations at S-band (13 cm) wavelengths have been performed, and accuracies of a few centimetres for three-dimensional surveying over a short distance (16 km) have been demonstrated. VLBI operation on longer baselines (8400 km) have been performed between Goldstone, California, and Madrid, Spain in order to develop the capability for determination of Universal Time variations, in addition to the measurements of this intercontinental baseline. Systems analysis indicates that necessary calibrations can be developed so as to make possible the implementation of a transportable radio interferometer station concept. Using a transportable 9-m diameter dish antenna, operated in combination with a 64-m dish, receiving at X-band wavelengths (4 cm), it will be possible to measure the three-dimensional separation between antennas with a few cm accuracy for separations up to several hundred km. With simultaneous S- and X-band reception at each antenna, the transportable antenna could be operated at even intercontinental distances with 10 cm baseline accuracy. Earth platform parameters of Universal Time and polar motion could be calibrated to 0.25 msec and 10 cm, respectively, and radio source positions determined to 0.005 arcsec accuracies by S/X-band reception, using large antennas of the Deep Space Network in an extended synoptic observational mode.

The importance of accurate Earth parameter calibrations and the determination of secular appearing phenomena is extremely important, particularly in the light of recent geophysical theories. Continental plate tectonics and its resultant Earth crustal deformations (typically a few cm per year) in the zones of plate contact, appears to be intimately related with Earthquake occurrence on a local and global scale. In addition, recent research by Russian and American seismologists has led to a theory for earthquake prediction based on rock dilatancy. A consequence of the dilatancy models is that large areas (100's of km²) of the Earth's crust must undergo many cm of vertical uplift which is also precursory to earthquakes. Because the VLBI technique is capable of full three-dimensional baseline determinations, it offers great promise for both vertical crustal uplift detection as well as measurement of horizontal strain accumulation, and perhaps significantly contribute to the search for reliable earthquake prediction methods.

1. Historical Origins of VLBI

Historically, applications of interferometry have been primarily for astronomical purposes beginning with the work of A.A. Michelson and F.G. Pease in 1920. These early experiments used optical wavelengths to measure the angular diameters of stars. The method operated by combining star light received via two separate optical paths which had to be established and maintained at equal optical

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lengths (figure 1). This task proved to be extremely difficult and prevented the primary mirrors from being separable by more than 20 ft, mainly because of atmospheric dissimilarities in the two interferometer arms. A dissimilarity in optical path of only 0.2μ ($\frac{1}{2}$ an optical wavelength) is sufficient to destroy the interference pattern (or fringes) which is the output of any interferometer system.

With the emergence of radio astronomy as a discipline in the 1930's came the desire to create the analog of the Michelson/Pease stellar interferometer using radio waves instead of optical wavelengths. These early radio interferometers were the so-called "hard-wired" systems, because cables or some other phase stable communications link were needed to derive the first oscillator signals (figure 2). As with its optical forerunner, the radio paths must be stable to better than one-half an RF wavelength to maintain the fringe output of the interferometer. The practicality of laying cables has limited short baseline interferometers to about 1 km, whereas microwave relay links have allowed antenna separations up to about 100 km. Because the resolving power of an interferometer is dependent on the ratio of the wavelength to the antenna separation, there was the inevitable desire to move the antenna spacing to intercontinental distance, if possible. The breakthrough in achieving these very long baselines occurred in 1967 (BROTEN ET AL 1967; BARE ET AL 1967) because of improvements in quantum electronic frequency systems which afforded essentially identical performance of two or more separate devices for generating local oscillator signals. The improved frequency systems eliminated the need for a phase-stable link between the two receiving stations, making it possible for the stations to be separated by arbitrarily large distances limited only by the Earth's diameter. This, then was the origin of the radio astronomy technique of Very Long Baseline Interferometry (VLBI). Perhaps it would have been more apt to term the method independent station radio interferometry, so as not to imply that only very long baselines were allowed.

When the baselines are comparatively short, and phase stable communication links are available, the outputs of the heterodyne receivers are conveniently combined at a common site to produce fringes. However, on a very long baseline the output of the receivers must be handled differently. The only

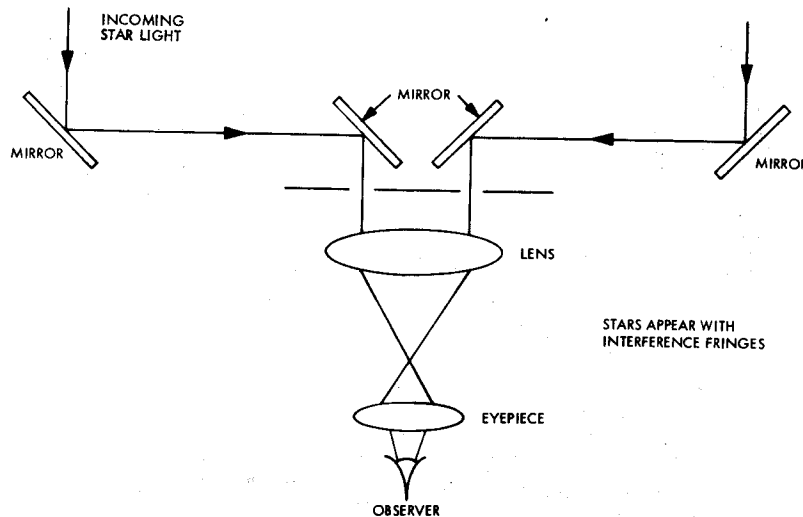


Figure 1. Michelson/Pease Stellar Interferometer

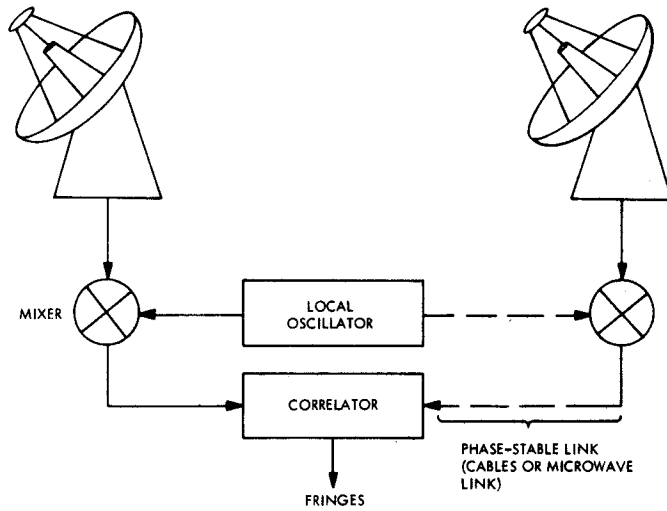


Figure 2. Conventional "Hard-Wired" Radio Interferometer

method so far demonstrated consists of recording receiver output on magnetic tapes along with time codes from each station. Two implementations exist in this type of recording:

- an analogue approach favoured by the Canadians; and
- a digital method used by virtually all US teams.

These magnetic tapes are brought together for cross-correlation processing usually several days to weeks after the time they were recorded. It is the cross-correlation process which yields the fringe response of the interferometer. A schematic diagram of the VLBI technique is given in figure 3.

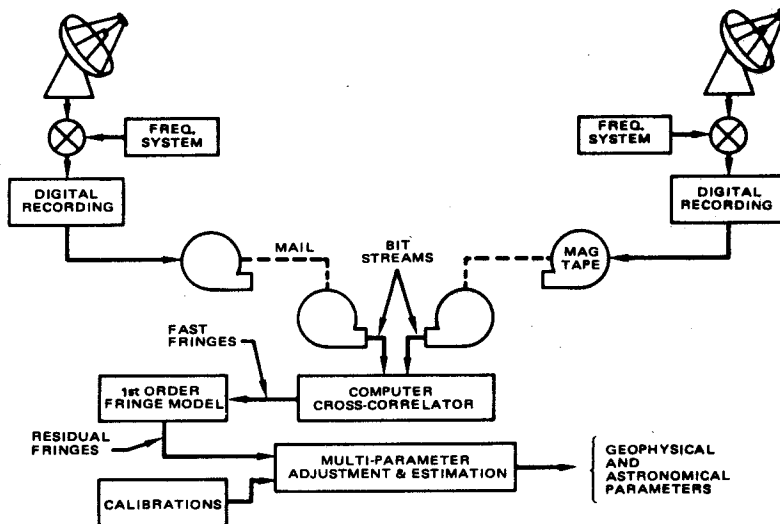


Figure 3. The VLBI Technique

Since the original experiment in 1920, interferometry has been used for astronomical applications and particularly for measuring the angular diameters of the source of the light, or radio waves. The early publications on VLBI however, correctly identified applications to geophysics (GOLD 1967; MACDONALD 1967) although the prediction of centimetre level measurements are yet to be realized over very long baselines.

For those interested in the general VLBI literature and its use in the study of spatial structure of celestial radio sources, general survey articles (KLEMPERER 1972; KELLERMAN 1971) will be found useful.

2. The VLBI Technique

In VLBI measurements, the radio signal produced by a distant source is recorded simultaneously at the two radio antennas. Because of a difference of ray paths, reception of the signal will be delayed in time at one antenna relative to the other. By cross-correlating the two signals, the time delay and/or its time derivative may be determined (THOMAS 1972a; THOMAS 1972b). When narrow-band recording equipment is used, only the time derivative of the time delay may be measured with adequate precision to be useful. If the radio signal is generated by an extra-galactic object, the radio source may be regarded as a fixed object because of its great distance.

The time variation of the time delay is due entirely to the Earth's motion, but depends, of course, on the source location and the baseline vector between the two antennas. In general, measurement of the derivative of the time delay for many natural sources can lead, by means of a least-squares analysis, to the determination of source locations, the baseline vector, and Earth-motion parameters, such as UT1 (Universal Time), and polar motion.

Figure 4 shows a schematic diagram of a radio interferometer station pair, while figure 5 gives the geometry of the situation. As these two antennas are separated by a distance $|\vec{D}|$, there will be a difference in the time of reception of the signal at the two antennas. This delay τ_g is given by

$$\tau_g = \frac{\vec{D}}{c} \cdot \hat{s} \quad (1),$$

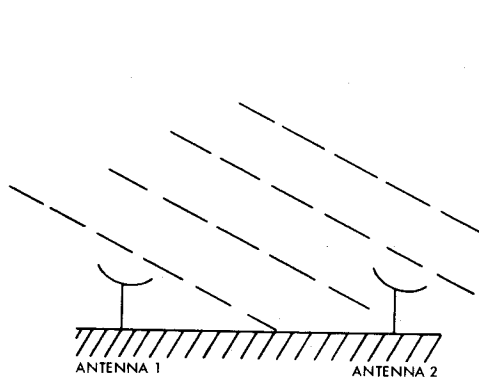


Figure 4. Interferometer Pair

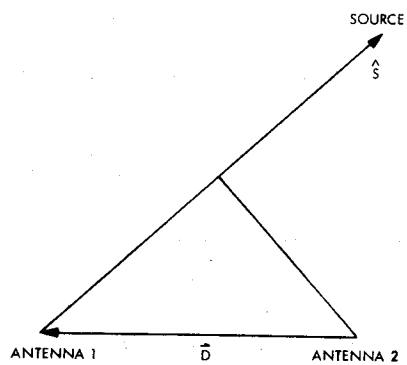


Figure 5. Interferometer Geometry

where c is the speed of light and \vec{s} is a unit vector opposite the direction of propagation of the wave front (assumed to be a plane for simplicity only). This time delay has a maximum possible value of (Earth's radius)/ c , or 0.021 sec. The quantity

$$v_F = \omega_o \frac{\partial \tau}{\partial t} \quad (2)$$

is known as the fringe rate, where ω_o is the received frequency and is just the negative of the Doppler shift between the two stations. In general, cross-correlation of the two data streams allows the time delay τ_g and the fringe rate v_F to be measured.

The dot product in equation 1 is most usefully expanded in terms of the equatorial co-ordinate system of date. In this system, the right ascension and declination of the source are given by α_s, δ_s while the equivalent quantities for the baseline vector D are α_b, δ_b .

Explicitly writing out the dot product in equation 1,

$$\begin{aligned} \tau_g &= \frac{|D|}{c} \left(\cos \delta_b \cos \alpha_b \cos \delta_s \cos \alpha_s + \cos \delta_b \sin \alpha_b \cos \delta_s \sin \alpha_s + \sin \delta_b \sin \delta_s \right) \\ &= \frac{|D|}{c} \left(\sin \delta_b \sin \delta_s + \cos \delta_b \cos \delta_s \cos(\alpha_b - \alpha_s) \right) \end{aligned} \quad (3),$$

the fringe rate - equation 2 - is then

$$v_F = - \frac{|D| \omega_o}{c} \left(\cos \delta_b \cos \delta_s \sin(\alpha_b - \alpha_s) \right) \frac{\partial}{\partial t} (\alpha_b - \alpha_s) \quad (4).$$

If the equatorial projection of $|D|$ is called r_b ,

$$r_b = |D| \cos \delta_b \quad (5),$$

since

$$\frac{\partial}{\partial t} (\alpha_b - \alpha_s) = \omega_e \quad (6),$$

where ω_e is the angular velocity of rotation of the Earth (0.73×10^{-4} rad sec $^{-1}$),

$$v_F = \frac{\omega_o r_b}{c} \omega_e \cos \delta_s \sin(\alpha_b - \alpha_s) \quad (7).$$

Equation 3 emphasizes the cylindrical co-ordinates are the natural units for this problem. The problem however, is also conveniently expressed in terms of a right handed Cartesian co-ordinate system fastened to the Earth with the x axis through Greenwich and the z axis along the instantaneous rotation axis. If $\alpha_G(t)$ is the right ascension of Greenwich, and λ_b is the longitude of the baseline in the Earth-fixed system, then

$$\lambda_b = \tan^{-1} \left(\frac{y_2 - y_1}{x_2 - x_1} \right) \quad (8),$$

where x_i, y_i, z_i refer to the Earth-fixed, geocentric co-ordinates of the i -th station, and the right ascension of the baseline vector becomes

$$\alpha_b(t) = \lambda_b + \alpha_G(t) \quad (9).$$

In a system fixed to the Earth,

$$X = |D| \cos \delta_b \cos \lambda_b ; \quad Y = |D| \cos \delta_b \sin \lambda_b \quad (10),$$

and

$$Z = |D| \sin \delta_b \quad (11),$$

where X, Y and Z are the projections of the baseline on the $x, y,$ and z axes. The geometry of a typical baseline is illustrated in figure 6.

Substituting equation 9 in equation 3, one can obtain

$$\tau_g = \frac{1}{c} \left\{ Z \sin \delta_s + \cos \delta_s \{ X \cos[\alpha_G(t) - \alpha_s] - Y \sin[\alpha_G(t) - \alpha_s] \} \right\} \quad (12),$$

and

$$v_F = - \frac{\omega_e \omega_o}{c} \left\{ \cos \delta_s \{ X \sin[\alpha_G(t) - \alpha_s] + Y \cos[\alpha_G(t) - \alpha_s] \} \right\} \quad (13).$$

3. Recent History of VLBI Geodetic Experiments

Various research teams have been active in the development of the VLBI technique for applications to geophysics. There has been considerable variety in instrumentation methods and lengths of baselines

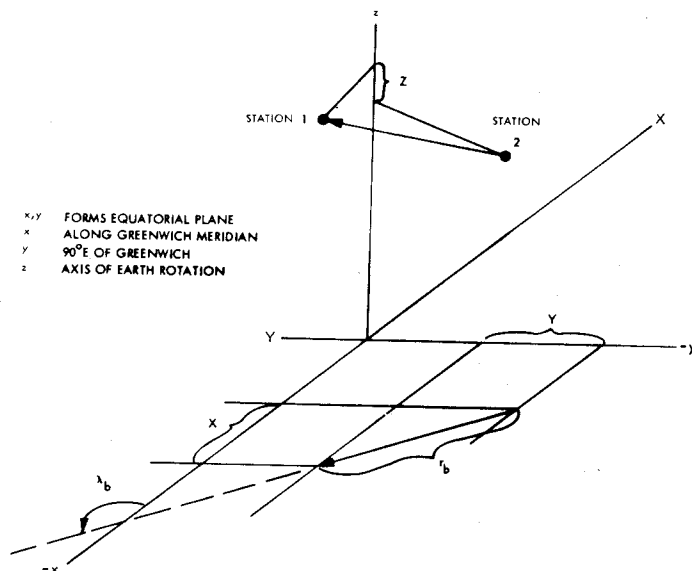


Figure 6. Intrinsic Co-ordinates of an Interferometer Baseline Vector

T a b l e 1
VLBI Geodetic Experiments Summary

Reporting Date	Group	Baseline	Length (km)	Reference
April 1970	MIT	Haystack / Greenbank	845	HINTEREGGER ET AL 1970
September 1971	GSFC	Rosman / Mojave	3000	RAMASASTRY ET AL 1973
October 1971	JPL	Goldstone only	16	FANSELOW ET AL 1972a
April 1972	GSFC/SAO	Agassiz / OVRO	2900	RAMASASTRY ET AL 1973
October 1972	MIT/GSFC	Haystack / Greenbank	845	HINTEREGGER ET AL 1972
December 1972	JPL	Goldstone / Madrid	8400	FANSELOW ET AL 1972b
December 1972	JPL	Goldstone only	16	THOMAS ET AL 1972

which are illustrated in table 1.

In order to give some insight into the progression of such research, the following is a brief historical account of the experience at JPL.

VLBI Earth physics experiments began by using two stations of the Goldstone Deep Space Communications Complex (DSCC), the 64 m Mars and 26 m Echo antennas, separated by 16 km. In January 1971, a 30 cm two dimensional (equatorial components only) baseline measurement accuracy relative to a ground survey, was obtained by fringe frequency observations. Those fringe frequency measurements were disturbed by instabilities at the first local oscillator which were corrected for subsequent experiments by construction of a fixed frequency multiplier.

In the summer of 1971, a series of intercontinental baseline experiments were conducted between the 64 m Goldstone and 26 m Madrid stations of the Deep Space Network (DSN). The goals for the experiment were to measure variations in the Earth's rotational rate (UT1), the equatorial components of this inter-continental baseline (approximately 8400 km), and to begin the establishment of a catalogue of extragalactic radio sources. As reported by FANSELOW ET AL (1972b), each of these goals was achieved. The variations in UT1 were measured with a precision of the state of the art (2 msec) and found to be in agreement with those derived optically by the Bureau International de l'Heure (BIH), Paris, France. The equatorial baseline components were derived with an accuracy of 1.5 m and found to be within 2 m of the baseline derived by the DSN from doppler tracking of interplanetary spacecraft. A catalogue of ten extragalactic radio sources has been determined with a relative accuracy of 0.1 to 0.02 arcsec.

The experience gained from these Goldstone/Madrid measurements enabled a quantitative systems analysis to be made. The results indicate that a small antenna could be fielded for surveying over short, moderate or even intercontinental baselines. With the assistance of the geophysical community, particularly the Caltech Seismological Laboratory, sites of geophysical significance were suggested, and perhaps more importantly, the requirement for extremely high measurement accuracy was clearly established. It became recognized that the major geophysical contribution which a VLBI type measurement can make is the rate of Earth crustal strain taking place over hundreds of kilometres on either side of earthquake fault zones. However, in order to be of worth in the near term (within 5 years), measurements need to be made with 5 cm or better accuracy in three dimensions. Because the strain

rate can be at most about 6 cm yr^{-1} , and resolution of at least 2 cm yr^{-1} is required to adequately distinguish between various competing geophysical theories, a measurement accuracy of 5 cm would require 5 years to achieve a rate determination uncertainty of 2 cm yr^{-1} .

Since a radio interferometer has never achieved such high accuracies, it became necessary to conduct a series of feasibility demonstrations, and beginning in 1972, experiment emphasis returned to the Mars and Echo stations of the Goldstone DSCC. In April 1972, the first JPL test of two channel bandwidth synthesis was made with a channel spacing of 10 MHz. Bandwidth synthesis schemes were pioneered by MIT (ROGERS 1970) and allowed the measurement of the time delay interferometer function. The April experiment determined the third component of the baseline vector with an accuracy of 50 cm. Based on the April 1972 experiment, the radio system and computer software were redesigned to perform a synthesis over a 40 MHz channel separation. As reported by THOMAS ET AL (1972), the results of three experiments (16 August, 14 and 18 October 1972) are 5 cm, 4 cm and 4 cm in three dimensions, respectively. The comparison of the interferometer determinations with an existing ground survey indicates good agreement in the length of the baseline, within the 20 cm uncertainty of the horizontal geodetic control.

In August 1972, a surplus US Army transportable 9 m diameter satellite communications station was transferred to NASA/JPL to become a portable radio interferometer station.

4. Error Sources

4.1 Transmission Media

The most important of the VLBI error sources for geodynamic applications arises from the transmission media. Any interferometer is inherently a differential device, and thus the differential phase-delays in paths between the receiving antennas and the source are the important factors.

The transmission media consists mainly of the wet and dry components of the Earth's troposphere (the lower 11 km of our atmosphere) and the charged particles. Charged particles are mainly contributed by the Earth's ionosphere and space plasma. The general magnitude of the errors is given in table 2.

T a b l e 2
Transmission Media Corrections for Typical Very Long Baseline Observations at S-Band
(Elevation Angles Greater Than 10°)

	Troposphere	Ionosphere (S-band)	Space Plasma (S-band)
Delay	0 - 10 m	0 - 6 m	0 - 1 m
Fringe Frequency (f.f.) (S-band)	0 - 20 MHz	0 - 3 MHz	0 - 0.5 MHz
10 cm Fractional Correction	1% - delay 0.3% - f.f.	2% - delay 2% - f.f.	10% - delay 10% - f.f.

The transmission media are important error sources to VLBI because of their potential for introducing correlated or systematic errors in the observations. As the Earth rotates, the length traversed by the radio waves varies. At rise, when the radio source is first visible for a given station, the path through the ionosphere and the troposphere is longest. As the source apparently moves to higher elevation angles, the length through these media decreases, becoming a minimum at zenith and increasing as the source approaches set. Thus, the path length through the ionosphere and the troposphere has a diurnal variation. As was previously discussed, both the VLBI time-delay and fringe-frequency functions have diurnal signatures and thus diurnal phase-delay from the atmosphere will appear correlated with the VLBI data types (time delay and fringe frequency).

The fact that only the differential atmospheric delay enters as an error source is generally no help in eliminating the correlated effects. When the stations are far apart, the atmosphere above one station is essentially independent of that above another.

4.2 Frequency and Timing System

It is highly desirable, and perhaps mandatory, from a geophysical point of view, that VLBI baselines be ultimately measurable with 3 cm accuracy. Some data averaging will probably be done to achieve 3 cm, but averaging more than ten days of data is likely to be self-defeating because of correlated errors and the likelihood of washing out geophysically significant signatures. This implies that the accuracy of VLBI data from a single day should not be worse than 10 cm (0.3 nsec).

There is a necessity for observing extragalactic radio sources at widely separated declinations, in order to accomplish parameter separations in simultaneous solutions for geophysical, astronomical and instrumental effects. The requirement for the length-of-data arc is determined by the inherent information content of the interferometric observables for particular source declinations and baseline orientations. A VLBI "pass" on a particular source may be as short as 3 hours to as much as 12 hours.

A 0.3 nsec VLBI accuracy over a pass can be translated to a fractional frequency deviation ($\Delta f/f$) of between 3×10^{-14} (over 3 hours) to 7×10^{-15} (over 12 hours).

Performance at, and occasionally better than 7×10^{-15} has been demonstrated* in laboratory environments. However, extreme care must be taken when using the hydrogen maser outputs of 1, 5 or 100 MHz in multiplying these frequencies up to the local oscillator frequencies of S- and/or X-band. Apparently small phase shifts or rapid phase variations have destroyed many VLBI experiments in the past.

There are circumstances when a frequency system other than a hydrogen maser will suffice. One such case occurs when using the VLBI technique on short to moderate length baselines (< 1000 km). For baselines of such lengths, five or more radio sources can be rapidly (3 hours or less) observed over a wide range of declinations and hour angles, and a self-contained data set obtained from which it is possible to simultaneously solve for baseline and instrumental parameters. In this way it is possible to make use of $\Delta f/f = 1 \times 10^{-13}$ performance which can be obtained from rubidium frequency systems of modern design and still achieve baseline measurement accuracies of 5 cm or better.

* by hydrogen masers

5. Calibration of Transmission Media Errors

Interestingly, the largest single transmission media error, the dry component of the troposphere, is also the least difficult to correct. The dry component amounts to about 2 m at zenith and about 80 m at the horizon, but it is *a priori* predictable with centimetre accuracy for elevation angles larger than 15° using local meteorological data and empirical principles.

The next largest error source is the Earth's ionosphere. This error source varies between 0.5 m and 2 m of group delay at zenith for S-band (2 GHz). At X-band (8 GHz), the delay effects are lower by a factor of 16. The variability is due to solar illumination on the Earth's upper atmosphere, being smallest at night and largest at a little past local noon. Empirical models for the ionosphere are essentially useless for VLBI applications because of the considerable variability of the ionosphere on a day to day basis. Another approach is to use the indirect calibration procedure of VHF Faraday rotation (MULHALL ET AL 1970) to measure the columnar electron content along some particular fixed direction, and then to map that electron content to an arbitrary line of sight depending on the radio source being observed. Such indirect methods are now being employed for a UT1 experiment using DSN stations, and it appears that baseline accuracies better than 1 m are unlikely.

What is needed is a direct calibration approach. Such an approach is to make VLBI measurements of radio sources (e.g., quasars and radio galaxies) simultaneously at two frequencies, S-band and X-band for example. Such an observing mode would afford the opportunity of exploiting the physical phenomenon of electromagnetic dispersion. Charged particle dispersion causes group delay effects which are inversely proportional to the square of the radio frequency being observed. Thus, X-band is less affected by charged particles than S-band. By differencing VLBI time-delay measurements at S- and X-band, a direct measurement of the differential columnar charged-particle content between the two Earth-based stations and the extragalactic radio source being observed, is obtained. This technique measures the aggregate differential charged particles contributed by the ionosphere, solar wind, interstellar and intergalactic media. Given a direct calibration capability of this S-/X-band type, it should be possible to calibrate the total charged particle problem with an accuracy of 10 cm or better.

Having calibrated the dry troposphere and charged particles, the only remaining significant transmission media error is the wet component of the troposphere. This error varies between 5 and 30 cm depending upon the time of the year. Published analytic studies on this topic (SCHAPER ET AL 1970) have shown that even in relatively humid areas, the zenith phase delay of tropospheric water vapour is predictable to 4 cm, given extensive past radiosonde balloon weather data; with water vapour radiometry and local surface weather data, the zenith water vapour delay can be ascertained to within 1 cm. The question of what accuracies will exist when no large body of historic radiosonde data is available for an arbitrary station location is receiving further study. However, the achievement of a 5 cm or better calibration using historical precipitable water data and surface weather from each station, appears reasonable (ONG ET AL 1973).

6. Phenomena to Which VLBI is Sensitive

6.1 Universal Time

Universal Time can be thought of as the time integration of the Earth rotation rate. The term UT1

is used to denote the instantaneous angular position of the Greenwich meridian with respect to the mean sun. Variations in UT1 exhibit a pronounced seasonal dependence and are thought to be at least in part the result of atmospheric transport, altering the Earth's moment of inertia (MUNK & MACDONALD 1960). There is also considerable randomness in UT1, which is unexplained.

Data on UT1 are obtained principally from the US Naval Observatory (USNO) and the Bureau International de l'Heure (BIH), Paris, France. Both of these UT1 services employ optical methods, either photographic zenith tubes (PZT) or transit circles. Both instruments possess msec (of time) resolution limits. It is the reliance on optical stars, however, which imposes the fundamental limit on accuracy.

Problems arise from two sources:

- . refractive effects of the atmosphere above the observatory; and
- . proper motion effects of the stars in the catalogue.

Ideally, the observatory would view the stars through a layered atmosphere at normal incidence. However, the atmosphere is not sufficiently layered in parallel planes nor free from random effects to allow uncorrupted observations; observations on a given night are likely to have individual standard deviations of 30 msec. It is only by taking 20 or more stars that the formal standard deviation can be reduced to about 7 msec.

The standard deviations of five day measurements of UT1 are approximately 3 msec, and the two time services (USNO and BIH) in the past have been in substantial disagreement regarding UT1.

A more subtle problem results from the stars themselves. There is a need for the stars in the catalogue to be sufficiently bright (brighter than eighth magnitude) to be measured with precision. However, bright stars are also likely to be local stars (0.1 to 1 kpc^{*}) having larger proper motions. Random errors in proper motions are large. Furthermore, these stars are a part of our own galaxy and are undergoing a rotation which imparts a systematic catalogue drift, the uncertainty of which is about an arcsec per century (0.01" per year). Thus proper motion and rotation corrections for the individual catalogue stars must be derived from the observations so that UT1 will not drift at a rate of 30 cm per year. The method of solving for the proper motions of the catalogue from the UT1 observations themselves is difficult at best.

The VLBI resolution potential can be extremely high: a fraction of the wavelength/baseline ratio. For a 10,000 km baseline at X-band ($\lambda = 3$ cm), the resolution could be smaller than 6×10^{-4} arcsec or 0.04 msec of UT1, however, the accuracy of the UT1 will probably be 0.5 msec or about one order of magnitude improvement in the state of the art.

6.2 Polar Motion

The phenomenon of polar motion (PM) is the movement of the Earth's crust with respect to the axis of rotation. These motions are conventionally decomposed into rotations about three Cartesian axes. The x and y components are in the equatorial plane, while z is the spin axis; x points to the Greenwich meridian. Strictly speaking, only the rotational motions about the x and y axes are categorized as polar motion; rotations about the z axis become part of the phenomenon of UT1. Polar motion data are conventionally obtained from the Bureau International de l'Heure (BIH), Paris, France, or the International Polar Motion Service (IPMS), Mizusawa, Japan. Both IPMS and BIH

* 1 kpc = 1000 parsec ; 1 parsec = 2×10^5 astronomical units

utilize observatories at various latitudes and observe stars at several declinations. As was discussed in the context of UT1 measurements, optical astrometric methods of this type suffer from limited instrument resolution, atmospheric refraction which is uncorrectable, and star catalogue drifts. Because of these common error sources, the PM measurement precisions are quite similar to those of UT1, approximately 1 m. Also, as in the case of UT1, the two sources of PM data occasionally disagree by as much as 5 m.

Polar motion is observable by VLBI because it changes the x and y projections of the baseline onto the equatorial plane. Maximum sensitivity to PM is obtained from a north-south oriented baseline (WILLIAMS 1970). Baseline measurement with 1 m accuracy should be achievable using a single frequency (S-band for example) and introducing external transmission media calibrations. A two-frequency (S- and X-band) wideband VLBI system with water-vapour radiometric tropospheric calibrations should allow PM to be measured with an accuracy of 20 cm or better from a single day of data. These observations are, of course, with respect to an extragalactic radio source (ERS) frame.

6.3 Earth Tides

In much the same way that the moon and sun deform the ocean surface to generate ocean tides, the solid land masses undergo tidal oscillations. Amplitudes of the Earth tides are typically less than 0.5 m with diurnal and longer period variations. *In situ* gravimeters possess more than sufficient sensitivity for measuring this effect; however, it is not possible to separate tidal deformations from changes in the gravity field of the Earth itself. Once VLBI accuracies are in the domain of 10 cm or better, Earth tides should be measurable interferometrically, allowing separation of the geometrical deformations from mass transport phenomena. It would therefore be desirable for gravimeters to be co-located with VLBI stations.

6.4 Continental Plate Tectonics and Regional Fault Monitoring

The theory of continental drift has had remarkable success in blending apparently diverse geophysical disciplines into a single model of the Earth's crust. The model consists of several large continental plates which are in relative motion, at least in the geological past. Some of these plates are undergoing collisions with one another and these collisions frequently result in seismically violent events. Any global understanding of earthquakes must certainly concern itself with the probable fact of continental drift.

The drifts of continental plates are generally small, less than 20 cm per year. These rates have been indirectly deduced from phenomena such as sea floor spreading data. However, no direct measurement of the relative motions of the major continental plates has been possible to date because operational global geodetic technology is currently at the 10 m accuracy level.

The potential of VLBI for measuring intercontinental separations with 10 cm accuracies clearly will have great impact on determining contemporary drift rates and developing more advanced models of global earthquake mechanisms.

The issue of regional fault monitoring is another area where VLBI can make a valuable contribution. Fault systems are frequently complex as discontinuities do not simply occur at some defineable interface. For example, locked portions of the San Andreas fault system of California are probably storing strain energy, and elastic deformations may be going on hundreds of kilometres from the fault. Thus, conventional high accuracy geodimeter point-to-point measurements across the "fault" will measure little or no change over a 20 km baseline, while over a several hundred km baseline, substantial strains may be occurring.

A point which is not widely appreciated is that state-of-the-art geodimeter measurements have high accuracy (1 part in 10^6) only in a horizon control sense (in only two dimensions). Vertical control is most accurately obtained by a method known as differential levelling. Levelling is explicitly dependent on local gravity as a reference and is therefore directionally sensitive to deflections of the vertical. These deflections make it difficult to distinguish geometric relationships from those of a geodetic nature which have been gravitationally affected. In addition, differential levelling is accomplished in 100 m increments, making frequent long distance surveys through rough terrain logistically difficult. Accurate vertical crustal uplift measurements are assuming a very important role in studying the earthquake mechanism (WHITCOMB ET AL 1973; ANDERSON & WHITCOMB 1973) and coupling that with the horizontal crustal deformations predicted by continental plate tectonics, there is a great need for highly accurate three dimensional Earth measuring methods.

Because VLBI is capable of determining three-dimensional station locations with 10 cm or better accuracies on baselines of arbitrary length (10 km to 10,000 km), operates virtually under all weather conditions, and makes its observations relative to an essentially time-invariant co-ordinate frame of extragalactic radio sources, its potential for defining earthquake strain fields is indeed great.

6.5 The Extragalactic Radio Source (ERS) Frame

The co-ordinate system to which VLBI is sensitive is the frame of compact (emissions from regions less than 0.001 arcsec in diameter) extragalactic radio sources. These sources are primarily quasars, and are probably more than 10 to 100 Mpc away. Even if these sources have proper motions, they are not likely to accumulate the magnitude of errors encountered with local stars. For example, suppose a radio source 100 Mpc away was moving at one-tenth the speed of light perpendicular to the line of sight. Such a movement would be equivalent to 10^{-4} arcsec per year or about 3 mm per year drift in longitude. The issue of whether such motions actually exist, and whether they would be systematic, is far beyond the scope of this discussion. The current ERS catalogue for the 24 kHz recorded bandwidth system for VLBI Earth physics has about 50 objects suitable for use at S-band. With a future 2 MHz VLBI system, the catalogue of objects usable at both S- and X-band will remain at about 50. A catalogue of ten sources would serve well for a global geodynamics program.

7. Development Potential

7.1 Primary Network

The need for direct charged particle calibrations clearly indicates the desirability of simultaneous S/X-band VLBI as previously discussed. Given this type of calibration, the highly correlated errors due to the Earth's ionosphere can be effectively corrected to the 10 cm level or better. The wet component of the troposphere appears correctable given regional meteorological data and some type of direct calibrations such as water vapour radiometry at each antenna site.

Given these capabilities, impressive geodynamical measurements with the following accuracies should result:

$$\sigma_{\text{UT1}} = 0.5 \text{ msec (of time)} ; \quad \sigma_{\text{polar motion}} = 10 \text{ cm} ; \quad \sigma_{\text{Earth tides}} = 10 \text{ cm};$$

three dimensional station locations to 10 cm; extragalactic radio source catalogue to 0.005 arcsec.

The foregoing results should be attainable with a few days of data. Thus, in continental drift

regions of 10 cm per year, VLBI could provide definitive information on drift rates in 2 years or perhaps less.

7.2 Portable Applications *

The need for VLBI data from remote locations obviously suggests some type of portable VLBI station. Fortunately the physics of the situation lends itself readily to this type of portable station. The observation of extragalactic radio sources is possible because the interferometer performance is governed by the geometric mean of the antenna areas (SHAPIRO & KNIGHT 1970). Thus, if only a small diameter antenna (< 10 m) can be put into the field, the lack of its sensitivity can be mitigated by having a larger antenna serve as the other receiving element of the interferometer.

It is also possible to further reduce the data acquisition requirements on the portable station by having it operate as an adjunct to a primary VLBI network. The primary net would be responsible for measuring UT1, polar motion, and determining radio source positions. Thus, only five parameters directly connected with the portable station must be solved for;

- . the three co-ordinates for the station location;
- . the clock offset; and
- . the frequency offset.

Each radio source observed would provide three elements of information. Observing two sources, one at high declination and another at moderate low declination, would be sufficient to uniquely provide the portable station's location in three dimensions.

The particular implementation of received wavelengths would depend on the particular mission. For example, if data were desired on possible motions of some island in Japan, the portable station could be equipped for S/X-band simultaneous VLBI reception and a water vapour radiometer for tropospheric calibration. If this portable station had a 10 m diameter antenna and operated with a 26 m fixed station, five or more radio sources would be available, enabling the portable station to be located with a 10 cm accuracy, given only a few days data and operated in conjunction with a primary network.

For applications of regional tectonic monitoring, the situation is somewhat less complex. If a large fixed antenna is located in the approximate vicinity of a fault system, as is the case of the Goldstone antennas relative to the southern California portion of the San Andreas fault system, the baseline lengths can be limited to 1000 km or less. Having baselines of 1000 km or less enables a significant self-cancellation of the Earth's ionosphere, particularly the ionosphere's diurnal characteristic. If furthermore, the VLBI observations are made at X-band wavelengths, then the charged particle effects are essentially random at each station. This leaves only the tropospheric water vapour to be explicitly calibrated. Local meteorological data from the portable and fixed antennas, together with water-vapour radiometer measurements for each station should allow overall data accuracy of 7 cm from a single day of data. Four days of data from the portable station should allow a 3 to 5 cm accuracy in determining the station's location in three dimensions.

Such short to moderate length baselines tend to be insensitive to UT1, polar motion and source location; uncertainties of 3 msec in UT1 and 1 m in polar motion would amount to about 10 cm in the portable station location.

To operate portable stations at 1000 km separations from fixed stations would require primary

* Portable VLBI applications to earthquake research are being pursued under a concept name of ARIES (Astronomical Radio Interferometric Earth Surveying)

network performance equivalent to 0.005 arcsec. so that station locations would not have systematic errors above 3 cm from UT1, polar motion, and source location uncertainties.

Given a situation of no high-accuracy UT1, polar motion, and source locations, the portable stations could be designed to stand alone. That is, with moderately more sensitive receivers on the portable antennas, 10 m diameter stations could make up their own network, with station-to-station separation always less than about 200 km or with an observing program that makes sufficient observations to solve for the required UT1, polar motion, and source locations in a similar manner to that which would have been employed by the large antenna primary network.

8. Acknowledgments

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10. Discussion*

MELCHIOR: In the paper it is written that VLBI should allow the separation of geometrical deformations from mass transport phenomena. Does that mean you intend to directly measure the Love numbers h and l without mixing with k ?

ONG: Not at the moment.

MELCHIOR: The number h characterizes the ground variation directly. In the text it is said that it would therefore be desirable for gravimeters to be co-located with VLBI stations. In that use, gravimeters alone will not be sufficient. You should also have horizontal pendulums. Do you have an idea of the precision sought? For example, if you have a radial motion of 40 cm, should you, say, get 1% of that figure?

ONG: A precision of 5 - 10% of that figure is probably adequate.

MELCHIOR: Could you measure the deformations with a precision of 1%?

ONG: A precision of 1% of a 40 cm effect would amount to 4mm. At the present we can obtain 4 cm accuracy in all three components of short baselines. This is about 10% of the effect. Sub-cm precision for intercontinental baselines is beyond the present state of the art.

WERNER: An instrument of that size (radio telescope) should suffer from unexpected variations in position of the electrical centre; has the movement of the electrical centre been monitored relative to nearby marks to ascertain the size of this motion.

MACDORAN[†]: The electrical phase centre of the station is not the point of "antenna location" in a VLBI solution. The concept of a VLBI station location is at the intersection of antenna axes (i.e., the intersection of the elevation and azimuth axes). Such intersection of axes can be easily measured relative to a nearby geodetic control point. It is because of the method of multi-source simultaneous solution for baseline, astronomical and instrumental parameters that it naturally dictates the axes intersection to be the only spatially invariant point at each station.

GUBBAY: I believe there is a settling time for it and I believe movements have been noted at Tidbinbilla during the first six months of operation. Small movements, but they are being measured.

* Paper presented by K.M. ONG

† Post symposium written reply

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COMPARISON OF TWO INTERCONTINENTAL BASELINES BY VLBI

ABSTRACT

Compact components, $\leq .001$ arcsec, of several radio sources were observed in the course of VLBI observations at S-band between NASA-JPL Deep Space Stations located in South Africa, Australia, and California USA. During the southern summer of 1971-72, the stations were equipped with H-maser frequency standards of sufficiently high stability to allow phase coherent integration of the data, thus improving the system threshold and reducing the doppler fringe frequency reading error to better than 1 mHz.

The primary aim of the experiments was to monitor the secular behaviour of the fringe amplitude due to the compact components and consequently two successive observations were made on each source. However, the data were analysed to determine errors in the assumed baselines as well as the relative clock drifts and to improve the determination of source positions. There is some evidence for the existence of an error in the hour angle of both baselines of about $+ .07$ s. The error in the length of the projection of the trans-Pacific baseline on the equatorial plane was not significant. A present difficulty in determining this length for the southern VLBI and its solution is explained.

1. Introduction

During the southern summer of 1971-72, two stations of the NASA-JPL Deep Space Network, DSS 51 at Hartebeesthoek, South Africa and DSS 41 at Island Lagoon, South Australia, co-operated in a series of three interferometer experiments (see Table 1).

TABLE 1
 Interferometer experiments using independent
 H-maser frequency standards

Epoch	Western Station Designation	Eastern Station Designation
357-8 1971		
21 1972	DSS 51, Hartebeesthoek, near Johannesburg, South Africa	DSS 41, Island Lagoon, near Woomera, South Australia
44-5 1972		
52-3 1972	DSS 41	DSS 12, Goldstone, California United States of America

G. Nicolson and P. Harvey of the South African CSIR were responsible for the conduct of the experiments at the South African terminal. This series was followed within a few days by an experiment between DSS 12 near Goldstone in California and the Australian station, DSS 41. The three stations taking part in experiments across the two intercontinental baselines were equipped with 26 m antennae, maser front ends and Hydrogen maser frequency standards.

The trans-Pacific experiment was conducted in conjunction with A. T. Moffet and D. Shaffer of the California Institute of Technology and D. Spitzmesser of the Jet Propulsion Laboratory. The only significant difference in equipment configuration from that adopted for the southern baseline experiments was the substitution of the S-band synthesizer by a multiplier chain at one station.

Cohen and Shaffer 1971 took the results of a survey for compact components using a trans-Pacific baseline between the 64 m telescope at Goldstone, California and the 26 m telescope at Tidbinbilla, Australia, to determine the position of compact components. Their position determinations were among the first using VLBI techniques with independent local oscillators. The accuracy of these positions was limited by the stability of the station rubidium frequency standards and by the single parameter atmospheric model adopted.

In our experiments, both ionospheric and atmospheric contributions to the phase path were taken into account. The ionospheric model adopted for computing corrections to the observed doppler difference frequency was that given by ONDRASIK & MULHALL (1969). Here the real ionosphere is replaced by a curved slab of ionization with the same vertical total electron content. Stanford University and F. Hibberd of the University of Armidale supplied values of total electron content for the American and Australian observations respectively. These values were obtained by measurements of Faraday rotation using signals from geostationary satellites. No total electron content information was available from South Africa. Values for this site were inferred from locally obtained F-region critical-frequencies (supplied by the South African CSIR Telecommunication Group) using the method described by MULHALL, ONDRASIK & THULEEN (1970) together with scale heights calculated from the Armidale data.

The atmospheric contribution to phase path was calculated using a standard US atmosphere for a latitude of 35° and an average water vapour content. The height of the observing telescope above sea level was the significant parameter in producing differences between observing sites.

2. Description of Method

If \vec{B} represents the retarded baseline vector (NASA LS35 station solution) and $\vec{\ell}$ the unit vector in the direction of an extragalactic source and c the velocity of light, then T , the time lapse between the arrival of corresponding segments of the waveform at the respective stations can be expressed

$$T = \frac{1}{c} \vec{B} \cdot \vec{\ell}$$

The bandwidth of the data is only 14.3 kHz and therefore T cannot be determined to better than about 0.5 microsec. This is equivalent to an uncertainty of about 150 m in the projection of the baseline in the direction of the source. Due to the rotation of the earth $\vec{\omega}$ however, the angle between \vec{B} and $\vec{\ell}$ varies continuously and the time derivative of the lapse time, i.e. the doppler difference frequency ν , divided by the observing frequency F , becomes

$$\frac{v}{F} = \frac{dT}{dt} = \frac{1}{c} \vec{\omega} \times \vec{B} \cdot \vec{l}$$

The difference S , between the observed frequency ν_o , and the expected ν_p , is given by

$$S = \frac{1}{\Delta T} \int_0^{\Delta T} (\nu_o - \nu_p) dt = \frac{\phi}{\Delta T} \quad (1)$$

where ϕ is the total phase accumulated over the integration time ΔT , and can be determined to approximately 0.1 cycle. The hydrogen maser frequency standards used at the stations were sufficiently stable to allow phase coherent integration over the whole data record of 660s, giving an accuracy of ± 0.15 mHz in the measurement of S . This is equivalent to an intrinsic error in the equatorial component of the baseline distance of about 0.3m, assuming that there are no other sources of error. Contributions to S arise from:

- 1) errors in right ascension of source
- 2) errors in declination of source
- 3) possible error in baseline length, and
- 4) possible errors in frequency standards or "bias".

There are other possible contributions to S , such as the atmosphere and the ionosphere, but for the moment let us restrict ourselves to these four sources of error.

Errors 3 and 4 are common to all sources, although in the case of 3 the contribution to S of a constant error in baseline length will be different for different sources. Suppose we observe n sources twice each. This provides $2n$ values of S and we have $2n + 2$ unknowns.

Let a_m and b_m be the errors in the assumed values of right ascension and declination of the m th source. Let e be the error in the length of the projection of the baseline on the equatorial plane ($=R$), and let d be the frequency difference between the two station frequency standards or "bias". Then for the $2n$ values of S obtained there are n sets of dual equations of the form:

$$S_{2m-1} = a_m \frac{\delta S_{2m-1}}{\delta(RA)} + b_m \frac{\delta S_{2m-1}}{\delta(DEC)} + e \frac{\delta S_{2m-1}}{\delta R} + d \quad (2)$$

$$S_{2m} = a_m \frac{\delta S_{2m}}{\delta(RA)} + b_m \frac{\delta S_{2m}}{\delta(DEC)} + e \frac{\delta S_{2m}}{\delta R} + d \quad (3)$$

Referring to equation 2, S_p depends upon errors in right ascension, declination, R , and the bias d . Therefore, if S_p is plotted against $\frac{\delta S}{\delta R}$, the scatter of the points from a best fit line will depend upon the errors in right ascension and declination.

The best fit line will have a gradient equal to e and the value of S given by this line when $\frac{\delta S}{\delta R}$ equals zero will be d . Using these values of e and d in equations 2 and 3 the right ascensions and declinations of the n individual sources can be readily calculated from the n pairs of equations.

To find the best fit line, the assumption has been made that the population of sources is large enough to be regarded as having a normal distribution in right ascension and declination errors, i.e. the assumption that the following equation is valid.

$$\sum_{2n} \left\{ \frac{S_p - (d + e \frac{\delta S}{\delta R})}{W_p} \right\}^2 = \text{Minimum} \quad (4)$$

e and d are found by differentiating this equation with respect to e and d . The two resulting equations can then be solved for e and d . W_p is a weighting factor depending upon the derivation of the reference source positions.

The weight to be attached to an observation when determining the best fit line is a function of the ionospheric and tropospheric contributions to S . The contribution of these regions to S is proportional to the electrical length of the path through them but the models used for these regions are imperfect. The path length is a function of the right ascension and declination of the star so that the weighting factor W_p will also be a function of the position of the star.

The weight is also a function of the errors in the reference positions of the stars. The Kristian and Sandage optical positions are taken to have an accuracy of ~ 0.5 arcsec. The contribution to S due to a position error is also a function of the position of the star.

We have therefore defined the weighting factor W_p to be

$$W_p = \left\{ \left(0.5 \frac{\delta S_p}{\delta(RA)}\right)^2 + \left(0.5 \frac{\delta S_p}{\delta(DEC)}\right)^2 + \left(\frac{1}{20} T_p\right)^2 + \left(\frac{1}{10} I_p\right)^2 \right\}^{\frac{1}{2}} \quad (4)$$

where RA and DEC are the right ascension and declination of the star used for the p^{th} observation and T and I are the corrections to S due to the troposphere and ionosphere. The factors of $\frac{1}{20}$ and $\frac{1}{10}$ reflect the confidence that we have in our models for the two regions. The possibility of the optical and radio positions being different would give an additional contribution to W_p . We have no quantitative data about this, so are unable to include it.

3. Results

Figure 1 represents the trans-Pacific results. The reference positions for the sources are those of the optical counterparts of each source. The best fit line gives $e = -5.3$ and $d = -0.1$ see Table 2. The points in figure 2 are obtained when the reference positions are VLBI determinations either by NASA/JPL or MIT. In this case W_p consists only of the terms representing the relative likely error in the atmospheric correction.

Figure 3 displays the results obtained using the Southern VLBI, South Africa to Australia. The baseline and bias errors are assumed unchanged for the three experiments and the results are plotted together. The reference positions have been determined optically and the weighting factors W corresponding to the optical case have been adopted to obtain the best fit line. The outstanding feature of this plot is that the points cover a very narrow range in $\frac{\delta S}{\delta R}$ because no accurate high declination optical determinations were available. The wide range in the value of $\frac{\delta S}{\delta R}$ within the declination viewing limits would otherwise allow better baseline and bias solutions in this case than

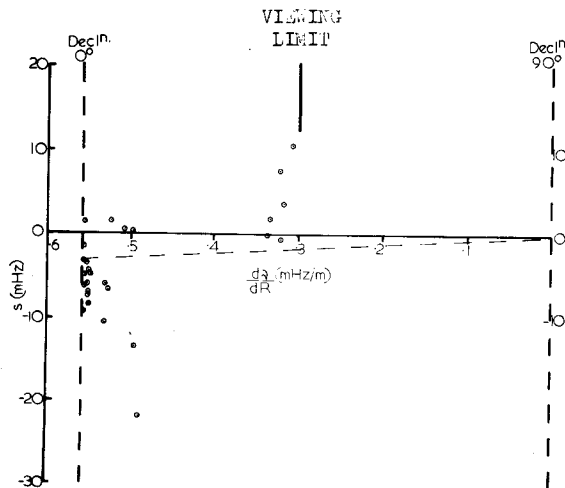


Figure 1. Trans-Pacific results

Plot of frequency residuals against the effect in mHz of an error of +1m in equatorial distance R
Reference positions were determined optically
(KRISTIAN & SANDAGE 1970)

TABLE 2

Baseline	Reference Sources	Figure	Error in Equatorial Projection e(m)	Bias d(mHz)
Trans-Pacific	Optical	1	-5.3	-0.1
Trans-Pacific	VLBI	2	-0.5	-3.9
Southern	Optical	3	11.8	-16.6
Southern	Various	4	-67.9	26.4

for the trans-Pacific interferometer.

The same condition obtains in Figure 4 where the reference positions include any available positions determined by long or short baseline radio interferometers or by optical means that are accurate to about a second of arc or better. The common sky of the southern interferometer does not extend to declinations above $+16^\circ$ and the positions of the high declination southern sources observed, P0332-40, P0438-43, and P0537-441 are not sufficiently well known yet. Consequently the best fit solutions for figures 3 and 4 are of very little value. However, accurate optical positions for these sources are being determined by B. Peterson at Mt Stromlo.

Figure 5 compares the distribution in right ascension error among the sources observed across the Pacific and for the southern interferometer respectively. The error in the hour angle of the baseline is taken to be the value of the mode of the distribution to avoid the effect of "rogue" values. The error in the hour angle of the two baselines appears to be similar and in the same sense.

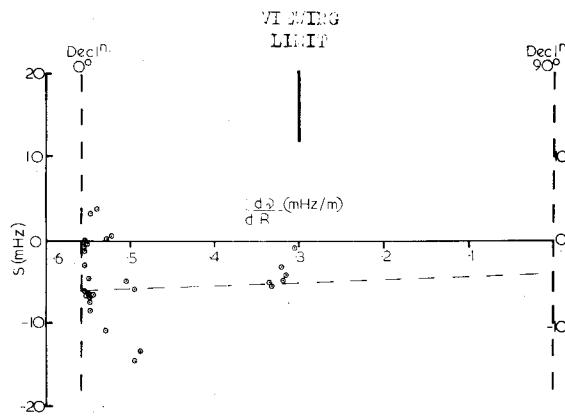


Figure 2. Trans-Pacific results

Plot of frequency residuals against the effect in mHz of an error of +1m in equatorial distance R
Reference positions were determined by VLBI
(JPL and MIT results)

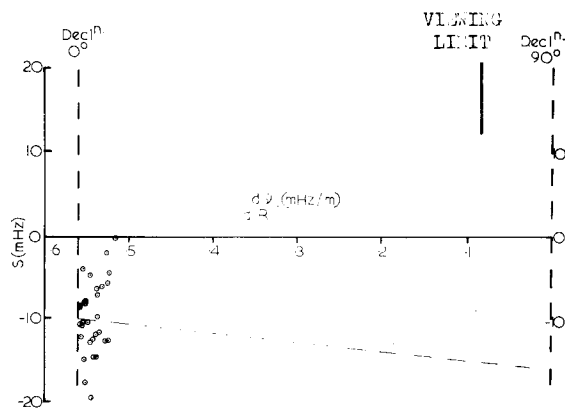


Figure 3. Trans-Indian results

Plot of frequency residuals against the effect in mHz of an error of +1m in equatorial distance R
Reference positions were determined optically
(KRISTIAN & SANDAGE 1970)

Faraday rotation observations are available in Australia and in California on a continuing basis and will probably soon become available in South Africa. However, X-band receivers will be available at the NASA-JPL stations in Australia and at this observing frequency the effect of the ionosphere is negligible. Dual frequency observations would yield optimum results.

Our experiments were not designed for the purpose of geodetics, but they have yielded some geodetic

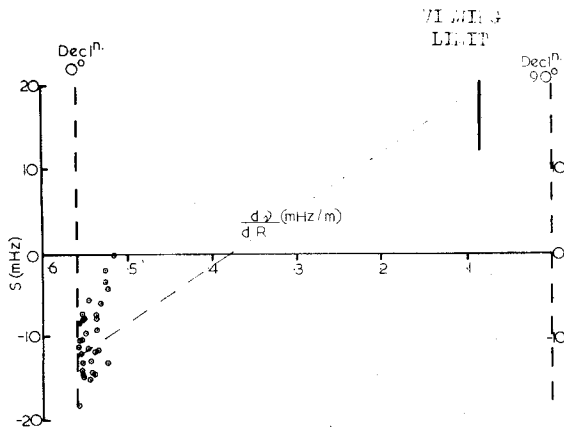


Figure 4. Trans-Indian results

Plot of frequency residuals against the effect in mHz of an error of +1m in equatorial distance R
Reference positions were determined by various techniques

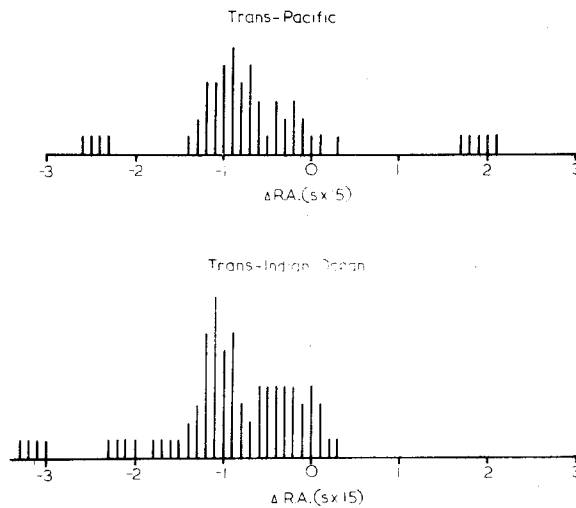


Figure 5. Frequency distribution of right ascension errors (arcsec)

information. The length of the projection of the trans Pacific baseline on the equatorial plane, R , seems to be accurate, but there is a significant error in the hour angle of this baseline. To obtain the true baseline therefore, the assumed baseline must be rotated eastwards. There is some evidence that this also applies to the southern baseline.

A VLBI experiment, or series of experiments, could be designed to yield a baseline accuracy of about 1m in R and an accuracy in baseline hour angle of .01 s. A sampling rate of 1 to 2M bits/sec would be required to provide a corresponding accuracy in the determination of the component of the baseline along the earth's axis.

Short-baseline connected-element interferometry can provide positions of the required degree of accuracy but the centroid of the object thus observed at low resolution does not appear to correspond to the VLBI objects. The position for P0438-43 obtained by Wade in 1973 using the NRAO interferometer would be consistent with an intercontinental baseline error of a few hundred meters.

Two pairs of trans-Pacific observations were taken on 3C279 and each pair was treated independently. The observations were not successive in this instance, the first and third and the second and fourth forming the two pairs. The agreement between the two positions obtained for 3C279 was better than 0.1". The discrepancy between the two values of declination and the MIT value was also within this limit but the right ascensions differed from the MIT value by $-.07$ s. This is probably due to an error in the hour angle of the assumed baseline which has been discussed. Table 3 sets out the difference between our trans-Pacific positions of several sources and those determined by FANSELOW et al (1973), of JPL, or by ROGERS et al (1973), of MIT and in one case, the position of the optical component given by KRISTIAN & SANDAGE (1970).

TABLE 3
TRANS-PACIFIC RESULTS (OF FIGURE 2)
POSITION SOLUTION MINUS REFERENCE POSITION

Source	RA Err (S ^{*15})	Dec Err (arcsec)	References
NRA0190	-1.230	23.16	JPL
P2134+00.4	-2.407	7.608	JPL
P0106+01	0.504	-5.456	JPL
P1055+01	-1.157	-2.204	JPL
3C273	-0.881	-0.576	MIT
P1741-3.8	-0.292	-1.160	JPL
3C279	-1.008	-0.052	MIT
3C279	-1.003	-0.002	MIT
P1510-08	-0.739	-1.050	K&S
3C454.3	-0.750	-0.7374	JPL
P2345-16	-0.294	0.513	JPL
3C345	0.858	0.950	JPL
4C39.25	0.008	0.171	JPL
VR042.22.1	1.883	1.593	JPL

4. Conclusions

Although our series of observations was designed to study temporal variations of quasar components of angular diameter $\leq .001$ arcsec., useful geodetic and source-positional information has been obtained. This was in spite of the fact that individual observations were made sequentially rather than being spaced so as to cover a reasonable range of hour angle.

It is by no means certain that when one component dies and another is born that the new one will

occupy the same position as the old one. Accuracies of the order of 0.01 arcsec are on the horizon and one will soon be able to detect such differences in position of successive components, if they exist.

For an inertial reference system for geodetic purposes one will need a population of extra galactic sources so that these small differences will average to zero.

5. References

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6. Discussion

- ROBERTS: When you are able to observe the source for many hours, is it not possible to solve for both the baseline and the position of the source?
- GUBBAY: Yes, and we will, eventually, but can't do it at present because the hydrogen masers have left as they were in Australia only for the Mariner Mars experiment. For good geodetic work, I would certainly favour hydrogen masers although in the last paper there was some reference to modern caesium systems. Maybe our chairman (HIBBARD) could differentiate between the older caesium systems we use, and which have very poor short term stability like the old rubidium, and the modern caesium system.
- HIBBARD: There is a new Hewlett Packard caesium standard not yet available in Australia which is ten to a hundred times better in general short term stability and a little better in absolute frequency. We are referring to seven parts in 10^{12} in absolute frequency, and it is suggested this stability is more like a part in 10^{13} over some hundreds of seconds. This is extremely good and when these are scattered around the stations, you'll find a lot more work can be done. There will be no abundance of hydrogen masers.
- ANON: Could the caesium tube be shortened? Is it a problem of epoch? MACDORAN's paper stated that a caesium tube is satisfactory over a short baseline and not a long baseline.
- ONG: It is mainly that over a short baseline, you could make a more rapid measurement of sources during a three hour period. You would avoid using a caesium standard for over three hours. It would drift too much.
- MARKOWITZ: The table in your paper gives comparisons of baselines in terms of frequency. What is required for geodetic applications are lengths. Will you be expressing these comparisons in terms of length?

GUBBAY: What I have done is to express a comparison in right ascension. As far as the baseline is concerned, I can only say that I am comparing not the baseline but the quality of the results. In the case of the trans-Pacific line we can get some kind of an answer, i.e., less than ± 5 m. The LS35 solution is pretty accurate. I agree we should come out with errors in metres. Less than a metre (0.3 m) for the trans-Pacific line for the equatorial distance. In the case of the trans-Indian, the results are not trustworthy. Table 2, column 4, lists the respective errors in equatorial projection in metres; column 5 shows the corresponding relative clock drifts in mHz.

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ON THE SCALE AND ORIENTATION OF GEODETIC REFERENCE SYSTEMS FROM VLBI

ABSTRACT

Since all points on the Earth's surface must be considered to be in motion relative to one another, the optimum strategy is to hold one station fixed and refer the motion of all points on the Earth to this station. The next step is to use the current technologies to measure the vector between pairs of geodetic stations within the instantaneous reference system. The final step is to relate the instantaneous reference systems to one another and then extract the data on earth dynamics.

Given an acceptable geodetic reference system for long term studies of the Earth, the problem then becomes one of adding scale and orientation to the network of geodetic stations. This paper examines the *method* by which these goals can be achieved and the possible *consequences* on the extracted information, using the technique of VLBI.

1. Introduction

For long term studies in earth physics a Geodetic Reference System should be such that it is possible to relate observations directly to it and to have secular variations in position simply related to changes in co-ordinates between epochs. An example of a convenient system is given by (MATHER 1973):

1. At any epoch replacing earth by an instantaneous rigid body model;
2. Adopting a three-dimensional cartesian system centred at the geocentre;
3. Letting x_3 axis coincide with the axis of rotation;
4. Letting x_1x_3 plane contain the axis of rotation and one point on the earth's surface.

Ideally, this one point on the earth's surface should be the only fixed station, to which the motion of all other points is referred. Then provided that the instantaneous reference systems can be related to one another, earth dynamic studies require the high precision measurements of the vector between pairs of geodetic stations within the instantaneous reference system.

VLBI observations can define the vector between the optical centres of the two radio telescopes within the co-ordinate system of the observed radio sources, to resolutions approaching 10 cm (HINTEREGGER ET AL 1972). Then provided the many parameters involved in the transformation to the instantaneous reference system can be evaluated, we have our requirements apparently fulfilled (LLOYD 1973). However, the *scale* and *orientation* for the baseline within the reference system is indeterminate from observations on unknown sources. So that, while VLBI can relate points on the earth's surface to one another to very high precision within an arbitrary reference system at any instant, external observations are required to define the scale and absolute orientation with respect to the accepted geodetic reference system.

2. The Basic Problem

The measured quantities in the VLBI technique are the time delay and the fringe frequency, where the time delay can be considered to be the time difference taken for the radio wavefront to reach the two radio antennae from the source, and the fringe frequency is the difference between the doppler frequencies at the two antennae. Hence, the measurements are differential quantities and VLBI can be considered as a geometrical device relating parameters of the baseline vector and source vectors. An analogy can be made with the measurements of directions by a theodolite in a triangulation net where each observed quantity is related to the position of the observer and that of the target. In the case of the theodolite measurements an arbitrary adjustment can be made which is completely consistent within itself but which does not yield the practical co-ordinates required (called a free net adjustment). To obtain the answer which we want from the triangulation adjustment in terms of real co-ordinates, the co-ordinate system must be uniquely defined. For directions reduced to a projection plane two points are held fixed or one point plus an externally observed azimuth (giving orientation to the net) and one observed distance (giving scale) are held fixed during the adjustment. Similarly, with VLBI observations, either internal control or external observations or conditions are required to obtain an unambiguous solution for the parameters with respect to the reference system.

The basic problem can now be summarised. In an adjustment of VLBI observations to distant radio sources, internal control must come from holding several source co-ordinates fixed. But these co-ordinates can only be estimated from earth-based VLBI which assumes a known baseline vector. But of course, baseline vectors are really the unknowns and also, by fixing the source positions, errors will be introduced into the extracted earth dynamic parameters, due to the proper motions of the sources.

3. Discussion

While a network of VLBI baselines cannot be tied to the geodetic reference system by VLBI observations alone, it can form an internally consistent arrangement fixed to two observed sources. Therefore, since geophysicists are really more interested in relative movements on the earth, rather than absolute distances between points on the earth's surface, it might appear attractive to perform experiments and holding the two sources fixed at their best known values. The error here would be in assuming that the two fixed sources had negligible proper motions over several years, at about the 0.001 arc second level, an assumption which is without justification.

It can be said that for unambiguous results in earth dynamics, besides VLBI observations, external observations or measurements using a different principle appear essential. These observations are required to scale the space, introduce orientation of the geodetic net with respect to the geodetic reference system, and isolate the proper motions of the sources.

It appears that accurate scaling observations over more than one VLBI baseline, besides introducing the unknown scale to the space, can also isolate the proper motion of the sources. This is because, while accurate scaling will show a change in the chord distance between the two earth points due to plate tectonics, the change in distance as recorded by VLBI will also include the proper motion effects of the fixed source parameters. An example of a very accurate scaling device is laser ranging to artificial earth satellites.

The observation of absolute orientation need only be made at one location, such as the reference point through which the x_1x_3 plane is defined, but the measurement must have precision equivalent to that of

VLBI and scaling. As a minimum requirement it must be possible to measure at different epochs either the direction of one baseline, or one source within the reference system. A suitable technique is not available at the moment.

4. Conclusion

The goal of modern geodesy is to relate points on the earth's surface to one another within a geodetic reference system. VLBI could be considered as the workhorse within such a programme relating geodetic stations within an arbitrary reference system. However, to obtain parameters within the defined reference system will require observations of scale (with respect to the velocity of light) and of absolute orientation, by means of different observing techniques. The combination of VLBI observations and laser ranging observations would be an exciting venture and a step towards the achievement of this requirement.

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6. Discussion

GUBBAY: I think it is a little severe to state that VLBI has no means of finding its own reference system; because without knowing anything about baselines, either its length or orientation, we can determine the declination of a source in this way. Let us consider a thought experiment where your sources are spread through the whole range of $\pm 90^\circ$; if we had sufficient time to observe all sources, then that source with the greatest peak fringe frequency lies on the equator. The peak frequency of the other sources are related through declination only. If you get the peak frequency of one source and compare it with the maximum ...

LLOYD: You get the source closest to the equator.

GUBBAY: You have a continuous spread

LLOYD: You have a line of sources separated by nothing; but you don't have this line in reality.

GUBBAY: This was a thought experiment; in practice the relation between them is $\cos(\text{Decl}^n A)/\cos(\text{Decl}^n B)$

LLOYD: Yes; but this is not practical at all. What you do is make observations on discrete sources. Set up parametric equations and there is no way of putting in control internally to give absolute values.

ANGUS-LEPPAN: Is this reference system you propose consistent with reference systems for other types of observations?

LLOYD: I did not mention a reference system specifically as this can apply to any reference system. Ideally we'd like a reference system such as that pointed out by MATHER which has various

properties, one of which is that observations should be directly related to the reference system. Secondly the parameters you are after should be easily extracted from this system. I am in full agreement with the system he quotes.

I showed a Cartesian system here but I did not say how it was defined. The system defined by MATHER where the z-axis coincides with the instantaneous rotation axis, the origin coincides with the instantaneous geocentre and the x-axis is defined in the following manner. The x-z plane contains one Earth fixed point. And that is very suitable for VLBI observations. Unfortunately we have to fix the co-ordinates of one or two extra-terrestrial sources. The only way this can be done is to combine several different types of observational techniques and bring them together. The problem is one of establishing an absolute orientation with a few cm precision.