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Phil. Trans. R. Soc. Lond. A 1977 **284**, 469-473
doi: 10.1098/rsta.1977.0022

Phil. Trans. R. Soc. Lond. A. **284**, 469–473 (1977) [469]
Printed in Great Britain

Applications of very-long-baseline interferometry to geodesy and geodynamics

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Very-long-baseline interferometry (v.l.b.i.) experiments can determine the separation between antennae many thousands of kilometres apart and can also determine the orientation of a baseline with respect to an extragalactic frame of reference. Shapiro *et al.* (1974) have used v.l.b.i. to determine the length of a 3900 km baseline with an accuracy of approximately 20 cm, and to estimate changes of universal time and the x component of polar motion which are in agreement with conventional optical determinations to within 3 ms and 1.3 m respectively. A significant improvement in accuracy is expected shortly. The technique and the limitations are reviewed.

Introduction

Very-long-baseline radio interferometry (v.l.b.i.) has been used for more than a decade by radio astronomers to study extragalactic radio sources. Techniques have now progressed to the point where submilliarcsecond angular resolution is routinely attained. Gold (1967) has pointed out that v.l.b.i. can usefully be applied to study terrestrial phenomena with respect to a reference frame defined by a set of extragalactic radio sources. For example, universal time, polar motion, solid Earth tides and continental drift can, in principle, be accurately determined by this method.

Gold has suggested that uncertainties of a few centimetres in several thousand kilometres can be attained. How well has practice matched prediction in this field? The purpose of this contribution is to attempt to answer that question.

The technique

Radio interferometry is basically a study of the degree of correlation of the signals from a radio source that are received by two or more spaced antennae. It is sufficient for astrometric, geodetic and geodynamic applications to consider only the phase of the correlation coefficient (provided that a substantially unresolved radio source is observed) since the phase depends solely on the length of the baseline and its orientation with respect to the source (see figure 1).

Unfortunately, instrumental effects and phase angle ambiguities make it impossible to use the phase for this purpose. The difference between the group delays and the difference between the phase-delay rates of the signals propagating from the source to each antenna can be determined, however, by existing systems with errors of approximately 0.15 ns and 0.1 ps s^{-1} respectively.

The major technical problem associated with v.l.b.i. is caused by the physical separation of the antennae which makes it impossible, at present, to correlate the signals in real time. It is necessary to record the signals at each antenna on magnetic tape along with time markers from very stable clocks. The group delay and phase delay rate differences can then be determined from a subsequent analysis of the recordings. These differences are affected by offsets and differential rates in the independent clocks used at each antenna. The observed differences are also affected by propagation of the wavefronts from the source through different regions of the troposphere and the ionosphere to each antenna.

The ionospheric contribution to the path length to each antenna varies as $(\text{frequency})^{-2}$. The daytime path effect in the zenith is typically 8 cm at 8 GHz, and the difference in the effects in the two paths depends upon the separation of the antennae, and on spatial and temporal variations in the ionosphere. The ionospheric zenith path fluctuates widely between day and night, and also exhibits large small-scale spatial and temporal variations. It is possible to correct the ionospheric path effects by making simultaneous observations of a radio source at two widely spaced frequencies but this has not yet been done for this purpose.

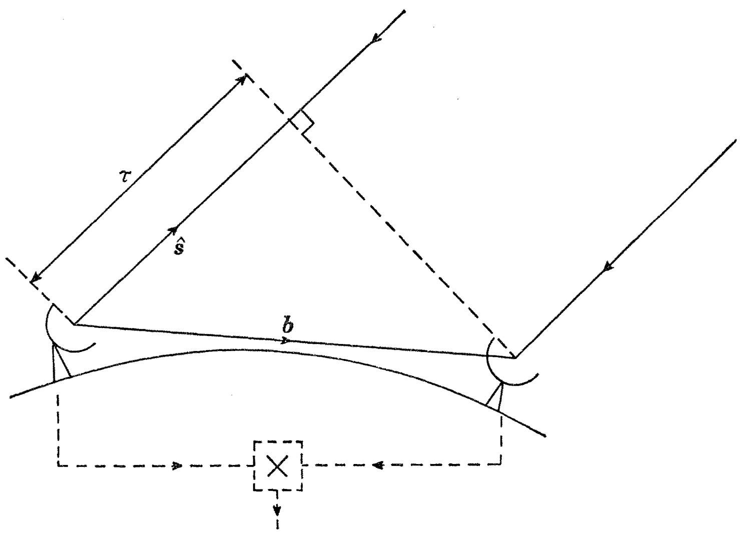

FIGURE 1. A schematic diagram of a very-long-baseline interferometer. The signal from the radio source arrives at the most distant antenna a time $\tau = (1/c)\, \boldsymbol{b}\cdot\hat{\boldsymbol{s}}$ later than at the nearest antenna.

The tropospheric contribution to the path length to each antenna is non-dispersive at radio frequencies. The effect is typically 2 m in the zenith of which about 40 cm is variable with time due mainly to variations of the water vapour content of the troposphere. The difference in the effects in the two paths depends upon the separation of the antennae, and on spatial and temporal variations in the troposphere. The tropospheric contribution does not correlate well with surface meteorological measurements because the water vapour content of the troposphere is not well mixed. It has been suggested that the amount of water vapour along the paths to the radio source can be determined by monitoring the radiation that the water vapour produces at 23 GHz, and Schaper, Staelin & Waters (1970) suggest that this can be used to reduce the tropospheric path uncertainty to approximately 1 cm. No experimental verification of this prediction has been reported yet.

The group delay difference that is observed is of the form

$$\Delta\tau = \Delta\tau_{\text{clock}} + (1/c)\,(\boldsymbol{b}\cdot\hat{\boldsymbol{s}} + \Delta l_i + \Delta l_t),$$

where $\Delta\tau_{\text{clock}}$ is the synchronization error of the clocks, c is the speed of light, $\boldsymbol{b}$ is the baseline vector, $\hat{\boldsymbol{s}}$ is a unit vector in the direction of the source, and Δl_i and Δl_t are the differences in the path lengths from the source to the antennae due to the ionosphere and the troposphere respectively.

The determination of the baseline from the expression for $\Delta\tau$ requires the separation of the various contributions. Counselmann (1973) has discussed how it is possible to do this. The path difference effects can be separated by fitting to $\Delta\tau$ the expected path corrections based on model ionospheres and tropospheres. The baseline, source positions and the clock error can be separated by making sequential observations of a set of at least three widely spaced radio sources provided that a set of observations can be made during the time for which the clock error is accurately modelled. Anything that affects the baseline on a time scale longer than a day can be determined by repeated observations, and anything that affects the baseline on a time scale shorter than a day, and which has a distinctive signature, can be fitted to the observations of $\Delta\tau$.

The uncertainties in the baseline parameters that are obtained are most likely dominated at present by the path effects. The residual uncertainties in Δl_i and Δl_t are difficult to estimate but the combined uncertainty is likely to be about 10 cm for baselines of several thousand kilometres at 8 GHz and correspondingly greater at lower frequencies.

Published results

V.l.b.i. observations with centimetric accuracy have only been made by a few groups working in the U.S.A., and only two reports of these observations have been published. Shapiro *et al.* (1974) have made observations at a frequency of 8 GHz with a baseline of almost 4000 km between antennae in Massachusetts and California, and a team at the Jet Propulsion Laboratory of the California Institute of Technology have determined a 308 m baseline by observations at 2.3 GHz (Ong *et al.* 1974). The latter baseline is not of geodetic interest but the J.P.L. team is now making observations with a 180 km baseline which spans the San Andreas fault in California. This baseline is determined with a precision of about 15 cm (P. F. MacDoran 1976, private communication).

Table 1. Summary of the results of determinations by v.l.b.i. (Shapiro *et al.* 1974)

baseline length	
v.l.b.i.	3 899 998.82 ± 0.16 m
survey – v.l.b.i.	– 1.6 m
U.T.1	
B.I.H. – v.l.b.i.	– 2.8 ± 2.9 ms
X component of polar motion	
B.I.H. – v.l.b.i.	– 0.2 ± 1.3 m

Table 1 shows the averaged results obtained by Shapiro *et al.* (1974) from observations made at intervals over a period of one year. The later observations in the series were made by an improved technique which yielded significantly reduced errors compared with the results of the earlier observations. The errors quoted in the combined results are therefore greater than could be obtained in a new set of observations. Shapiro *et al.* note that the residuals of the data in the fitting process were reduced by 14 % if the data were corrected for the solid Earth tidal effects predicted by a model.

Potential improvements in accuracy

It has been demonstrated by observations made over a 1.24 km baseline using v.l.b.i. equipment and processing that the instrumental contribution to baseline uncertainty can be kept below 1 cm (I. I. Shapiro 1976, private communication). The accuracies of the baseline determinations that have been made are therefore most probably limited by the uncertainties of the tropospheric and ionospheric path corrections.

The path corrections can probably be determined to centimetre accuracy by the techniques outlined previously so that overall baseline accuracies of a few centimetres should soon be available. At this level, it will be necessary to question the implicit assumptions that have been made about the radio sources.

The radio sources that are suitable to define a reference frame are all of extremely small angular diameter, they are generally quasars, and they appear to be at great distances. Their great distances make it unlikely that they will exhibit proper motion in time intervals of less than tens of years. However, all compact objects of this type seem to be variable in intensity on time scales ranging from one week and upwards, and their angular structures are also time dependent (see, for example, Kellermann *et al.* 1974). It has been suggested that these sources can be modelled as either a centre of activity which generates and shoots out radio components at irregular intervals, or as a compact cluster of many centres of activity which generate radio components independently at irregular intervals. In both cases, the radio components expand with time, become less intense, and are resolved by or are too weak to be seen by the interferometer after a time interval of approximately 0.5–2 years.

The instantaneous positions of these sources can vary with time by several milliarcseconds. The reference frame that is defined by the ensemble average of the source positions may be variable or uncertain at the milliarcsecond level which means that U.T. determinations by v.l.b.i. may be limited in accuracy to about 0.5 ms

It is impossible to separate the many factors of geodetic and geodynamic interest from observations made at only two sites. A world-wide, and therefore three dimensional, network of observing sites is most desirable for this purpose. Radio astronomers are already making simultaneous observations of radio sources with several widely spaced antennae and it would seem to be only a matter of time before similar observations are made for geodetic and geodynamic reasons. It is here that what might be a disadvantage of v.l.b.i. compared with alternative methods becomes apparent.

Interferometric observations are made between pairs of antennae. A network of N antennae can make $N(N-1)/2$ independent interferometric observations. The time taken to process these observations is proportional to $N(N-1)/2$ if the combinations are taken in pairs at a time. The processing time becomes formidable when N is large. In practice, not all combinations may be taken and this can save considerable processing time. Facilities which can simultaneously process the three combinations between three antennae are also coming into operation thus giving a further reduction in processing time.

Conclusion

V.l.b.i. systems can currently make baseline determinations with precisions of about 15 cm, and should soon approach precisions of a few centimetres. It seems unlikely that an international network of antennae will be established solely for geodetic and geodynamic purposes so that the production of comprehensive data for the geophysicist will come from the cooperative efforts of existing radio observatories and communications facilities with the necessary equipment. The data produced by v.l.b.i. would seem to be of comparable precision to those produced by lunar laser ranging techniques and to be complementary to them.

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Discussion

J. A. Weightman (*Geodetic Office, Elmwood Avenue, Feltham, Middlesex*). If two v.l.b.i. stations are indeed separated by 11 000 km, or almost an Earth diameter, then would not the component $\boldsymbol{b}\cdot\hat{\boldsymbol{s}}$ of the baseline vector in the direction of the source be very small to the detriment of the final result? Moreover would not the angle of elevation of the signal be very low, with a correspondingly long path through the Earth's atmosphere?

B. Anderson. The baseline can always be determined, in principle, if sources with widely differing positions are observed. UTI is not determined accurately however unless the baseline has a significant projection in the equatorial plane of the Earth. The use of a baseline longer than an Earth radius would lead to a decrease in accuracy due to the increase in tropospheric and ionospheric path corrections and the decrease in the time for which a source is mutually visible by the antennae. It is always possible to span the whole Earth by combining observations made with more moderate baselines.

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