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Results of the Australian Geodetic VLBI Experiment

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The 250-2500 km baseline vectors between radio telescopes located at Tidbinbilla (DSS43) near Canberra, Parkes, Fleurs (X3) near Sydney, Hobart and Alice Springs were determined from radio interferometric observations of extragalactic sources. The observations were made during two 24-hour sessions on 26 April and 3 May 1982, and one 12-hour night-time session on 28 April 1982. The 275 km Tidbinbilla – Parkes baseline was measured with an accuracy of ±6 cm. The remaining baselines were measured with accuracies ranging from 15 cm to 6 m. The higher accuracies were achieved for the better instrumented sites of Tidbinbilla, Parkes and Fleurs. The data reduction technique and results of the experiment are discussed in this paper.

I. The Australian Geodetic VLBI Experiment

The Australian Geodetic VLBI Experiment described by Stolz *et al.* (Ref. 1) has been completed and results obtained. Briefly, from 20 April to 3 May, 1982, five Australian radio telescopes were operated in synchronism to form a single radiotelescope. The five telescopes are sited at the NASA Deep Space Network (DSN) communications complex at Tidbinbilla near Canberra (DSS 43), the CSIRO Radio Observatory at Parkes, the University of Tasmania's Radio Observatory near Hobart, the University of Sydney's Fleurs Observatory near Sydney (X3), and the LANDSAT tracking station at Alice Springs (Fig. 1). The experiment was designed principally to provide high-resolution maps of distant quasars and galaxies. However, it also provided a means of making accurate geodetic measurements.

The antennas at Fleurs, Hobart and Alice Springs were instrumented at S-band (2.3 GHz) only, while those at Tidbinbilla and Parkes were instrumented at both X- (8.4 GHz) and S-band. Tidbinbilla was equipped with a Hydrogen maser and one was installed at Parkes especially for the experiment. Rubidium frequency standards were available at the other sites except Hobart where one was obtained on loan from the Division of National Mapping. The Mark II recording system was used (Refs. 2 and 3). Tidbinbilla, Parkes and Fleurs were instrumented with bandwidth synthesis (BWS) equipment to improve the accuracy of the VLBI observables. In this system a spanned bandwidth of 38 MHz is synthesized by sequential switching between two frequency channels. A single 2 MHz frequency channel was recorded at Hobart and Alice Springs.

The geodetic measurements were made during two 24-hour sessions on 26 April and 3 May, and one 12-hour night-time session on 28 April. Tidbinbilla and Parkes observed on 26 April and 3 May at both X- and S-bands, and on 28 April at S-band only. During the nights of 26 April, 28 April and 3 May, Fleurs, Hobart and Alice Springs were to observe at S-band. No observations were successful at Fleurs on 3 May. The Hobart antenna moved too slowly to observe all the scheduled sources, and those observed were spread over less than one half of the sky. On 28 April the Parkes maser failed and was replaced by a Rubidium frequency standard. The maser was back in operation on 3 May.

Twenty-three radio sources were successfully observed. The positions of 17 of these had been determined from intercontinental VLBI measurements using the DSN antennas (Ref. 4). The new sources were located south of -45° declination. Each radio source was observed for 10 minutes when all sites were observing, or 4 minutes when only Tidbinbilla and Parkes were observing. About 40 observations were made during a 12-hour session.

II. Data Reduction Technique

After the experiment the video tapes, on which the data were recorded at each station, were brought together for digital cross-correlation on the Mark II VLBI Processor at the California Institute of Technology. The post-correlation computer tapes, containing the highly compressed data, were then further processed at the Jet Propulsion Laboratory. Essentially, this involved extracting the phase as a function of time (phase tracking) to obtain the delay and delay rate observables. The ambiguities in BWS delays were then removed. The phase tracking and BWS techniques are described by Thomas (Ref. 3).

To obtain the baseline vectors, the model parameters are adjusted by least squares. Initially, the observations were weighted according to system noise and a variance factor of one. However, this produced residuals which were larger than would be expected. The original error estimates were then increased until the weighted RMS of the residuals divided by the number of degrees of freedom in the adjustment approximately equalled one. The models for delay and delay rate comprise principally a geometric delay, instrumental delays, and transmission media delays. Stolz *et al.* (Ref. 1) describe some of the parameters required to model the geometric delay. In this experiment uncertainties in the geometric delay due to errors in the earth orientation parameters are small in comparison with other errors as discussed below. That is, these parameters have been obtained with sufficient accuracy by independent measurements so that they may be treated as known quantities. Therefore, only the components of the baselines and the source positions were regarded as "solve-for" parameters in the geometric delay. The instrumental delay can, in the ideal case, be modelled by a series of constant (clock offset) and linear drift (clock rate difference) terms, but often a more complicated form is necessary to account for frequency oscillator instabilities. We solved for clock terms at all sites except Tidbinbilla. The transmission media (ionosphere and troposphere) delays could not be reliably estimated from the data. On the short baselines they are highly correlated. On the long baselines other errors dominate. We corrected for the effect of the ionosphere by using S- and X-band data where available, and for the troposphere by using models and meteorological data (Ref. 1).

Observations at a single frequency produce baseline lengths which are too long and source positions which are distorted. To avoid this problem we obtained the results in three steps. First we solved for the three components of the Tidbinbilla-Parkes baseline, 11 clock parameters, and 45 source coordinates from 145 delay and 145 delay rate observations obtained on 26 April and 3 May, 1982. The right ascension of radio source 3C273 was held fixed at $12^h\ 26^m\ 33^s.2792$ (epoch 1950.0) to refer the source positions to the dynamical equinox (Ref. 5). We assigned a variance of 0.0009 arcsec^2 to each of the catalogue source positions. The catalogue variances are smaller. Our value represents an accuracy estimate. Covariance terms were not available. Second, we solved for the three coordinates of Fleurs and 18 clock parameters from the 185 delay and 185 delay rate S-band (BWS) observations acquired at Tidbinbilla, Parkes and Fleurs on 26 and 28 April. The coordinates of Parkes, the catalogue source positions, and the positions of the new sources, as obtained above, were held fixed. Third, we solved for the six coordinates of Alice Springs and Hobart and 23 clock parameters from the 217 delay and 217 delay rate S-band (single channel) observations at Tidbinbilla, Parkes, Hobart and Alice Springs on 26 and 28 April and 3 May. The coordinates of Parkes, the catalogue source positions, and the positions of the new sources, as obtained above, were again held fixed. We adopted a cylindrical reference coordinate system with axes parallel to those of the conventional system defined by the geocentre, the CIO pole, and the Greenwich Meridian. The coordinates of Tidbinbilla were held fixed to define the origin of the reference system and to relate our measurements to the global network of VLBI stations (Ref. 4).

III. Results and Discussion

The baseline measurements and their formal errors are summarized in Tables 1 and 2. The distance from Parkes to Tidbinbilla was measured with a precision of 3 cm (0.1 ppm). The remaining distances are all precise to better than 0.7 ppm except those to Hobart which are precise to about 4 ppm.

We estimated the accuracy of the results by solving for the baselines, the source positions and clock terms from portions of the data and by covariance analysis. Bounds for subjective aspects of the analysis (e.g. selecting the clock parameters) were also estimated. The estimated errors are summarized in Fig. 2.

The Parkes-Tidbinbilla data were partitioned as follows: (a) 26 April; (b) 3 May; (c) night-time on 26 April and 3 May; and (d) day-time on 26 April and 3 May. The Fleurs data were partitioned into that gathered on 26 April and on 28 April. The Alice Springs and Hobart data were partitioned into that gathered on 26 April and 28 April and that gathered on 28 April and 3 May. The baseline solutions from the partitioned data are summarized in Table 3. The corresponding lengths agree to better than twice their formal error. The site coordinates agree to better than three times their formal error except the Parkes longitude for the day-time solution. Radio source 3C273 could not be observed at day-time and another source was chosen as the origin of right ascension. This accounts for a significant portion of the latter discrepancy.

The results for Tidbinbilla-Parkes should not be significantly affected by incorrect modelling of the ionospheric delay since the measurements were made at both S- and X-bands (Ref. 1). We estimated the effect of the ionosphere on the results for Tidbinbilla-Fleurs and for Parkes-Fleurs by solving for the baseline vector between Tidbinbilla and Parkes from S/X-band night-time observations and from S-band night-time observations and taking the difference. The source positions were held fixed in both cases. Figure 2 shows that the baselines Tidbinbilla-Fleurs and Parkes-Fleurs are about 5 cm too long. The formal errors of the results are also larger than they would be if the ionospheric delay had been correctly modelled.

Errors in surface meteorological measurements and the models for the tropospheric delay sum to about 5 cm at the zenith (Ref. 6). Covariance analysis showed that this 5 cm systematic error produces a 4 mm error in the Tidbinbilla-Parkes baseline length. The effect on the baseline components is significant (Fig. 2). For instance, the height difference between Parkes and Tidbilbilla would be in error by about 10 cm.

The Love numbers h and ℓ, and the tidal phase lag were held fixed at 0.610, 0.085 and 0°.0 respectively, at all sites. Systematic errors of 0.05, 0.03 and 2° in h, ℓ and phase lag produced errors of less than 1 mm in the length and the components of the Tidbinbilla-Parkes baseline.

Errors in polar motion and UT1 do not affect baseline lengths; they do however affect baseline orientation. Errors of 30 cm and 0.001 sec in the adopted BIH values for polar motion and UT1 caused errors of less than 2 cm in baseline components (Fig. 2).

Results for Tidbinbilla-Parkes were also obtained by holding fixed the catalogue values of the source positions, and by assigning the variances given in the catalogue. In both cases the new results differ from those shown in Tables 1 and 2 by less than the corresponding formal errors.

The analyst decides which data points to delete from the solution, which clock parameters to solve for, what *a priori* weights to assign to the catalogue source positions, and what *a priori* variances to assign to the observations. We estimate the magnitude of these subjective errors on the Tidbinbilla-Parkes baseline length and components to be of the order 3–4 cm. The errors are significant. They can be reduced by using more stable clocks which require little or no modelling and increasing the observation rate so that there is greater redundancy, and by obtaining more reliable estimates of the accuracy of the data and the source positions.

IV. Comparison with Ground Survey

In addition to the VLBI measurements reported here, the baselines have also been determined by conventional survey techniques. We show the surveyed baselines in Table 2. They are preliminary results computed from coordinates of the 1983 adjustment of the Australian Geodetic Datum (J.S. Allman, 1983, private communication). Doppler data have not been included in the tabulated values. Table 2 shows that the differences between the VLBI and survey measurements are less than 3 ppm except for the baselines to Hobart. Both the VLBI and ground measurements to Hobart are of low quality. The ground measurements should be much improved when Doppler data are included in the adjustment.

V. Summary and Conclusions

The 275 km Tidbinbilla-Parkes baseline length has been determined with an accuracy of ±6 cm. The baseline components have been determined to better than ±15 cm. The 235 km Tidbinbilla-Fleurs and 250 km Parkes-Fleurs baseline lengths have each been determined with an accuracy of ±14 cm. The baseline components have been determined to ±45 cm. The Tidbinbilla-Alice Springs and Parkes-Alice Springs baseline lengths have been determined with accuracies of ±1.8 m and the components with accuracies of ±2.2 m. The Tidbinbilla-Hobart and Parkes-Hobart baseline lengths and components have been measured with accuracies of ±6.4 m and ±8 m respectively. The higher accuracies were achieved for the better instrumented sites of Tidbinbilla, Parkes and Fleurs.

The results clearly demonstrate that long baselines in Australia can be measured by VLBI with an accuracy of a few centimeters in a matter of days. These accuracies are largely independent of baseline length. The accuracies can be improved upon by installing more sophisticated equipment such as the Mark III recording system which together with other instrument improvements will allow determinations of baseline measurements potentially accurate to 1 cm with modest size antennas.

Preliminary discussions have taken place to repeat the experiment described in this paper, to utilize the proposed $25 million Australia Telescope for geodetic VLBI measurements and to bring a highly mobile VLBI system to Australia, possibly as soon as 1984-1985. For the future experiments, we recommend

(1) that masers be installed at Fleurs, Hobart and Alice Springs so that measurements can be made at X-band;

(2) that BWS equipment be acquired at both Alice Springs and Hobart for improved delay measurements;

(3) that the slew rate of the Hobart antenna be increased;

(4) that the data acquisition rate be substantially increased; and

(5) that only about 15 well chosen sources be observed.

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Table 1. Site coordinates

Site	R^a, m		L^b, deg^c		Z^d, m	
Tidbinbilla (DSS 43)	5205 251.365		148.981 279 10		-3674 748.367	
Parkes	5354 918.85	±0.05	148.263 526 19	±0.02	-345[illegible] 035.80	±0.05
Fleurs (X3)	5302 029.34	±0.19	150.763 759 9	±0.06	-3533 527.69	±0.14
Alice Springs	5841 280.8	±0.8	133.882 357	±0.9	-2554 104.9	±2.0
Hobart	4683 738.3	±1.1	147.512 08	±1.4	-4314 838.7	±4.5

[a] Distance from the Z axis

[b] Longitude from the Greenwich meridian.

[c] The formal precisions of the longitudes are in metres.

[d] Distance from the equatorial plane.

Table 2. Baseline measurements and comparisons with survey

Baseline	VLBI, m		Survey, m	Difference ppm
Tidbinbilla-Parkes	274 751.78	±0.03	274 752.10	-1.2
Tidbinbilla-Fleurs	236 681.19	±0.07	236 681.46	-1.2
Parkes-Fleurs	251 340.46	±0.07	251 341.06	-2.4
Tidbinbilla-Alice Sp.	1938 997.1	±1.3	1938 994.8	1.2
Tidbinbilla-Hobart	835 297.0	±3.6	835 299.8	-3.4
Parkes-Alice Springs	1733 991.1	±1.2	1733 989.3	1.0
Parkes-Hobart	1093 516.8	±3.7	1093 520.3	-3.2
Hobart-Alice Springs	2445 610.4	±3.0	2445 610.9	-0.2
Fleurs-Hobart	1035 709.1	±3.7	1035 712.5	-3.3
Fleurs-Alice Springs	1979 707.5	±1.3	1979 705.5	0.5

Table 3. Repeatability

Baseline	26 April	28 April	3 May	Night-time	Day-time
	Length, m				
Tidbinbilla-Parkes	0.038		-0.049	[illegible]	0.009
Tidbinbilla-Fleurs	-0.027	0.035			
Parkes-Fleurs	0.029	-0.058			
	26 and 28 April		28 April and 3 May		
Tidbinbilla-Hobart	+1.1		-4.1		
Tidbinbilla-Alice Springs	0.0		+0.6		
Parkes-Hobart	+1.1		-4.0		
Parkes-Alice Springs	0.0		+0.6		
	Coordinates[a]				
Parkes R	-0.054		-0.095	0.000	-0.137
Parkes L	0.009		-0.017	0.061	-0.092
Parkes Z	0.014		0.001	-0.018	0.078
Fleurs R	0.37	-0.43			
Fleurs L	0.01	-0.02			
Fleurs Z	-0.31	0.38			
	26 and 28 April		28 April and 3 May		
Alice Springs R	+1.0		-0.3		
Alice Springs L	-0.1		-0.4		
Alice Springs Z	-0.8		+0.8		
Hobart R	+1.6		-0.3		
Hobart L	-1.5		+2.0		
Hobart Z	-2.6		+5.1		

[a] See Table 1

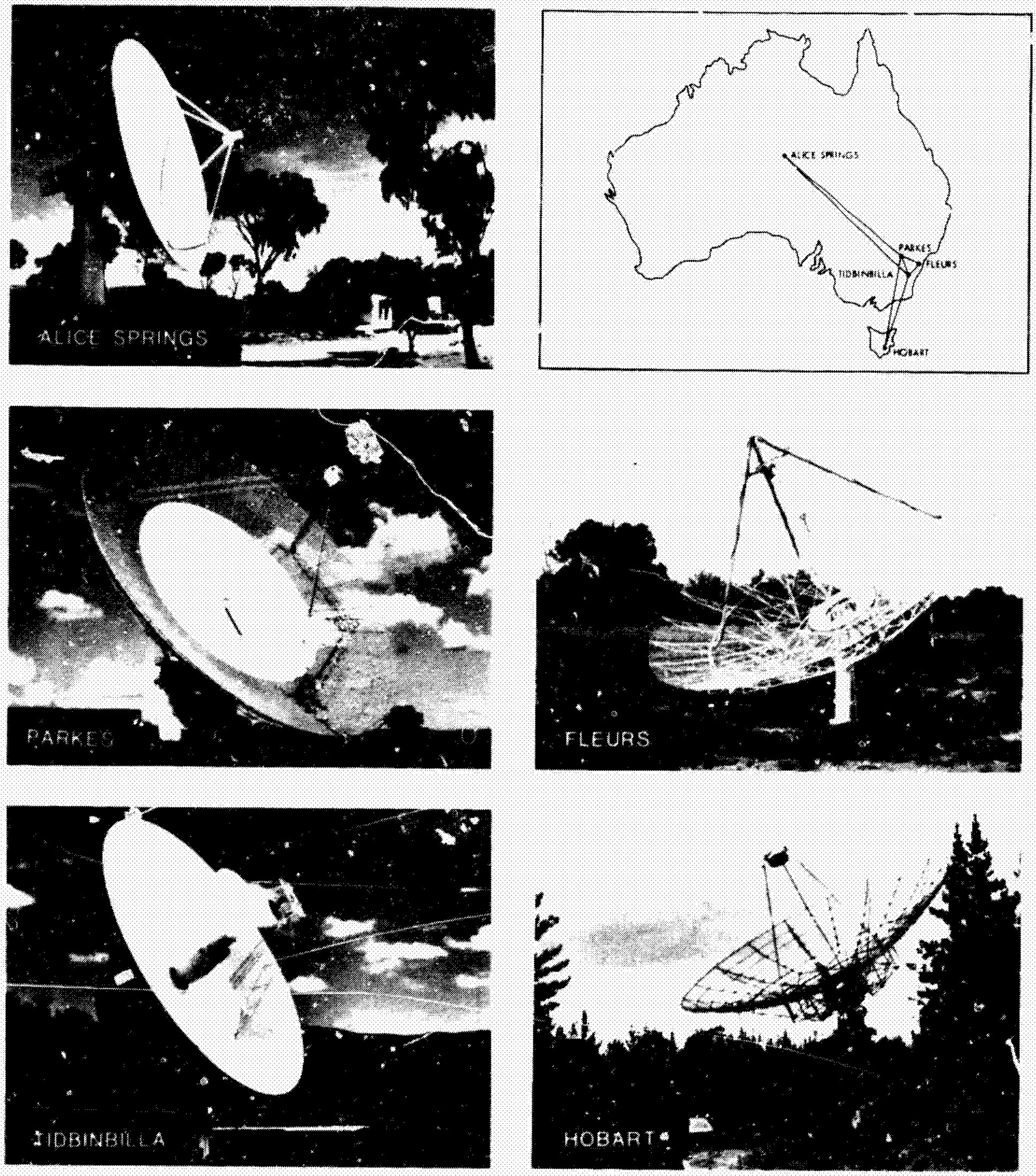

Fig. 1. Australian VLBI geodesy network, 1982

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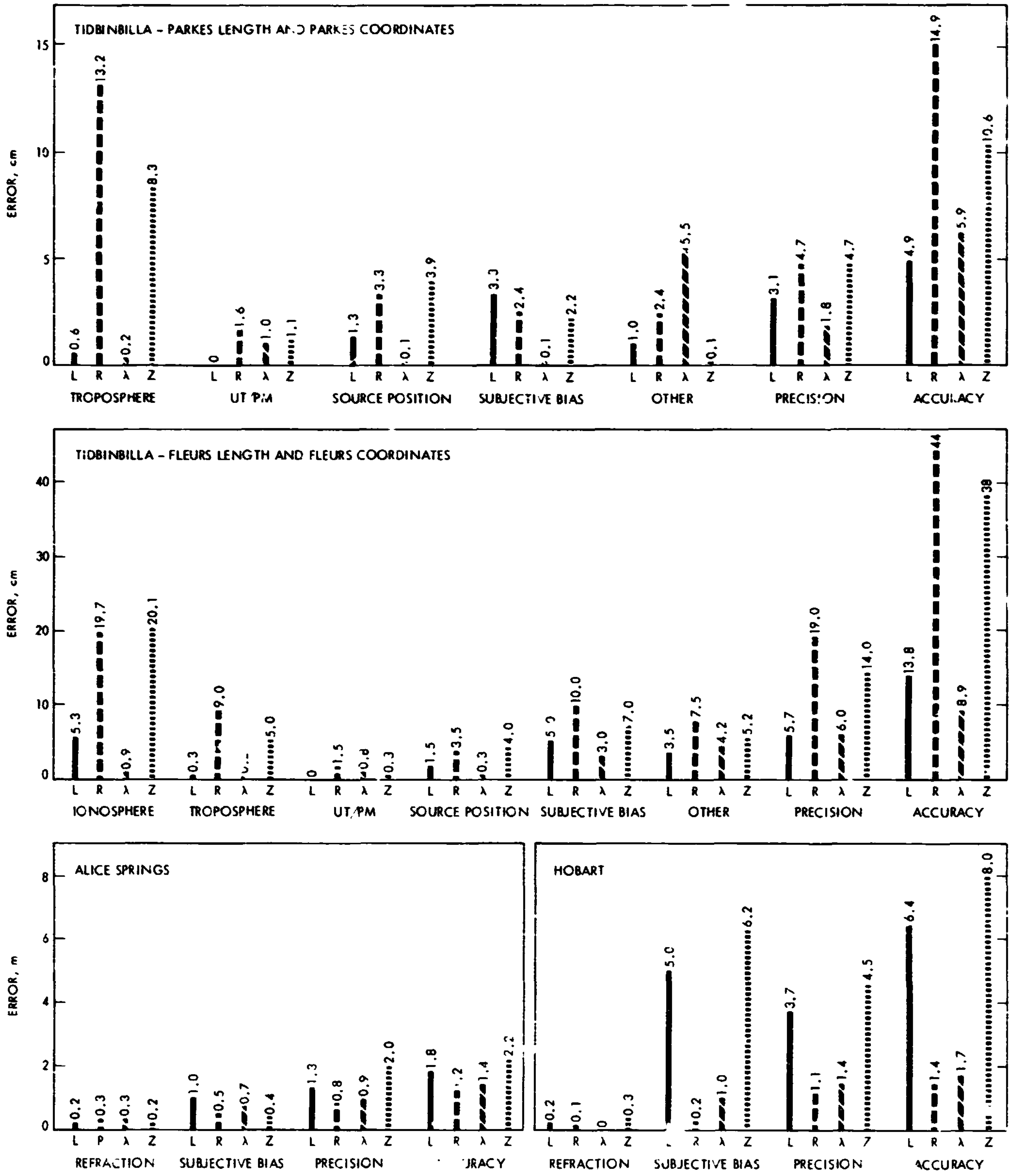

Fig. 2. Error budgets