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PHASE SYNCHRONISATION OF WIDELY-SEPARATED FREQUENCY STANDARDS USING A SATELLITE-LINK

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1. INTRODUCTION

Increasing the long term stability of the independent frequency standards at VLBI telescopes is one of the essential steps required for a phase-coherent array (see ATDOC101). An effective means of achieving this stability is via a satellite link which compares the phases of the remote Rubidium standardswith that of the central Rubidium standard and generates corrections to be applied during the processing of the IF data.

The following sections briefly describe a link experiment in the Netherlands with the Orbital Test Satellite (OTS), an outline of the steps to be taken to make use of the Australian commercial satellite system, AUSSAT, for phase synchronisation of remote standards, and the costs of implementing the AUSSAT satellite-link. The report concludes with a series of recommendations for future action.

2. THE OTS EXPERIMENT

2.1 Results

Van Ardenne *et al.* (1981 a, b) carried out a phase comparison experiment with a two-way 14/11.5 GHz link through OTS. Their aim was to test the behaviour of the link system in isolation from the effects of independent clocks and the independent atmospheres above each ground station. Two pairs of sine waves (tones) 20 MHz apart were derived from one rubidium oscillator and transmitted from a single ground station, received again at the same ground station, and the relative phases of the tones then compared. The stability of the link expressed in terms of a 2-sample Allan variance as a function of integration time is shown in Figure 1, together with the stability curve for a rubidium oscillator. There is some indication from the field performance of Rb oscillators that their stability is better than depicted in Figure 1. It should therefore be borne in mind that the constraints on the link configuration discussed in this ATDOC may be eased in practice.

The link precision was found to be better than 10 psec over intervals from 10 to 1000 seconds. At these and longer timescales the link is more stable than a Rb standard. The equivalent fractional frequency stability was better than 10^{-14} in 1000 seconds and $< 10^{-15}$ over 24 hours. Improvements in the temperature stability of the measuring equipment and an increase in the frequency separation of the tones in a pair from 20 MHz to 100 MHz could be expected to lead to a stability of 10^{-15} in 1000 seconds and a few X 10^{-16} in 24 hours. The link performance on these timescales would then exceed that of a hydrogen maser oscillator between a few thousand and ten thousand seconds.

In a VLBI network equipped with Rb oscillators linked Van Ardenne *et al.*-wise via satellite, the phase of the "field" Rb's should be corrected with respect to that of the "central" Rb at intervals of ~ 6 seconds. This is the averaging interval at which the stability curves of the link and Rb cross (Figure 1). The rms time error of the field Rb will then remain at ~ 10 psec as a function of averaging time instead of increasing as shown in Figure 1, thus increasing the effective stability of the field Rb for the longer coherent integrations performed in astronomical data reduction. Because the central station is also equipped with a Rb, the rms time error of the Rb-Rb combinations is likely to be ~ 14 psec (or 25° phase at 5 GHz).

The performance of a rubidium oscillator for high observing frequencies can be seen with the aid of Figure 2. Figure 2 shows the relative decrease in the correlation coefficient of a long baseline interferometer as a function of coherent integration time for three frequencies for Rb-Rb and combinations and four frequencies for H-maser-H-maser combinations. A decrease of the normalised fringe amplitude to 0.8 implies a relative phase change between the oscillators of $\sim 40°$. At an observing frequency of 22 GHz, the Rb-Rb combination is likely to have suffered an amplitude decrease to 0.8 in only 10 seconds. In order to usefully correct the phase of one of the rubidiums, adjustments should be made at intervals of 2 or 3 seconds, which implies that the short term behaviour of the link would need to be improved. We return to this in section 3. At lower frequencies, corrections of the Rb phase can occur at 5 to 10 second intervals and allow tracking of the phase over long periods.

2.2 Method of phase comparison for two or more stations

Two tones are transmitted by each station through the satellite. At each remote station, the frequency difference between the tones from the central station (e.g. 20 MHz) is compared with a 20 MHz signal generated locally from the 5 MHz output of the frequency standard. The difference phase must then be subtracted from a similar difference phase measurement at the central station based on the tones received from the field station. This subtraction can occur in real-time by transmitting the difference phase at the field station back over the link to the central station, or by recording it on the second audio track of the video tape recorder at each field station and generating the phase corrections during correlation.

For a frequency difference of 20 MHz between tones in a pair, the required accuracy in phase measurement is $\lesssim 0°.04$ for a 10-second measurement.

2.3 Why two tones?

These are required to remove the common phase noise terms in the sine waves of a pair, such as from the satellite translation oscillator. This can be seen from the following simplified description of the link taken from Appendix 1 of van Ardenne *et al.* (1981 a).

Assume a reciprocal path A → B, B → A with time dependent but equal delays at each frequency. Its path delay is called τ which is the sum of the path delay from A to the satellite (η) and from the satellite to B (μ).

At station A the local standard generates the nominal basic frequency ω_A which has a phase at local time t_1

$$\Theta_A(t_1) = \omega_A t_1 + \phi_A(t_1) \qquad (1)$$

in which $\phi_A(t_1)$ includes offsets from the nominal frequency plus phase noise terms.

In the same way at station B at local time t_2

$$\Theta_B(t_2) = \omega_B t_2 + \phi_B(t_2) \qquad (2)$$

At local time t_1, at station A, the received phases from B at the nominal frequencies ω_2 and ω_4 (derived from the clock at B) are

$$\Theta_{2A}(t_1) = \frac{\omega_2}{\omega_B} \cdot \Theta_B(t_1-\tau(t_1)) - \Theta_S(t_1-\eta(t_1)) + n_2(t_1) \tag{3}$$

$$\Theta_{4A}(t_1) = \frac{\omega_4}{\omega_B} \cdot \Theta_B(t_1-\tau(t_1)) - \Theta_S(t_1-\eta(t_1)) + n_4(t_1) \tag{4}$$

in which $\Theta_S(t_1)$ represents the satellite translation oscillator and $n_1(t_1), n_2(t_1)$ are independent, band limited white phase noise terms due to the finite S/N ratio of the link.

The phase difference between these two sine waves at A at time t_1 is given by

$$\Delta\Theta_{24A}(t_1) = \frac{\omega_2-\omega_4}{\omega_B} \cdot \Theta_B(t_1-\tau(t_1)) + n_{24}(t_1) \tag{5}$$

from which the effects of the satellite transponder and any other frequency converting oscillator common to the tones of a pair are clearly removed completely. The sum of the white phase noise terms is represented by $n_{24}(t_1)$. By means of (1), the phase difference can be written as

$$\Delta\Theta_{24A}(t_1)=(\omega_2-\omega_4)t_1 - (\omega_2-\omega_4).\tau(t_1) + \frac{\omega_2-\omega_4}{\omega_B}.\phi_B(t_1-\tau(t_1))+n_{24}(t_1) \tag{6}$$

Similarly at station B, the phase difference due to nominal frequencies ω_1 and ω_3 at local time t_2 can be written as

$$\Delta\Theta_{13B}(t_2)=(\omega_1-\omega_3)t_2-(\omega_1-\omega_3)\tau(t_2) + \frac{\omega_1-\omega_3}{\omega_A}\cdot\phi_A(t_2-\tau(t_2)) +n_{13}(t_2) \tag{7}$$

The fast varying terms $(\omega_2-\omega_4)t_1$ and $(\omega_1-\omega_3)t_2$ can be removed by subtracting the same nominal frequency derived from the home frequency standard. Difference frequency components including phase noise are then incorporated in the difference of the "phase noise" terms (see next expression). Assuming the same nominal frequencies $\omega_A=\omega_B=\omega_C$ and $\omega_1-\omega_3=\omega_2-\omega_4=\Delta\omega$, this subtraction results in

at A : $$\Delta\Theta_{AB}(t_1)=\Delta\omega\cdot\tau(t_1)+\frac{\Delta\omega}{\omega_C}\cdot\left[\phi_B(t_1-\tau(t_1))-\phi_A(t_1)\right] + n_{24}(t_1) \tag{8}$$

at B : $$\Delta\Theta_{BA}(t_2)=\Delta\omega\cdot\tau(t_2)+\frac{\Delta\omega}{\omega_C}\cdot\left[\phi_A(t_2-\tau(t_2))-\phi_B(t_2)\right] + n_{13}(t_2) \tag{9}$$

From this it is clear that the first term directly indicates any delay changes, weighted by the frequency difference $\Delta\omega$. The second term is the one which carries the information about the phase difference between the standards.

In a two-station experiment, the phase difference $\Delta\Theta_{BA}(t_2)$ measured at the "remote" station B, is coded and sent via the link to the central station A, or recorded on tape, for comparison with the phase difference $\Delta\Theta_{AB}(t_1)$. The comparison would result in a residual phase difference given by

$$\Delta\Theta(t_1,t_2)=\Delta\omega(\tau(t_1)-\tau(t_2))+\frac{\Delta\omega}{\omega_C}\left[\phi_B(t_1-\tau(t_1))+\phi_B(t_2)-\phi_A(t_1)-\phi_A(t_2-\tau(t_2))\right]+$$

$$+\ n_{24}(t_1)+n_{13}(t_2) \qquad (10)$$

The first term in Equation (10) is sensitive to residual phase delay differences between the pairs of sine waves (see next section), while the second term is the one of interest for the phase difference between the frequency standards. If the phase noise terms remain relatively constant as a function of bandwidth, then it is advantageous to have as wide a separation of sine waves in a pair as possible, e.g. $\Delta\omega$=100 MHz, in order to increase the magnitude of the phase difference to be measured. But there is then the concurrent problem of magnifying the residual phase delay terms. We return to this in Sections 3.2 and 3.3.

2.4 Why two path?

There are two reasons for this: (1) to remove atmospheric phase terms which differ in the two paths, and (2) to remove phase terms caused by satellite motion.

Consider the first term in Equation (10). If the delay paths from central station to field station and vice versa are identical, the first term is zero. If equation (8) or (9) had been used to compare clocks instead of (10), i.e., a one-way link, the first term would dominate the whole expression and any small changes in the delay would mask the phase differences between the clocks.

The effect of satellite motion, different atmospheric paths between ground station and satellite,and the ground station-satellite geometry means that signals transmitted at the same instant at the two stations arrive at different times at the satellite (see Figure 3). The satellite, moving at up to 0.5m/s, changes position between these arrival times so the total delay in the signal path going one way is not the same as in the reverse. Subtraction via the first term in equation (10) leaves you with a non-zero phase delay.

Van Ardenne *et al.* (1981a, Appendix 10) show that this can be analysed to eliminate the satellite motion since the motion has a clear signature (Figure 4). The atmospheric effects, particularly from the ionosphere, are harder to keep track of since they are independently variable in each path and, furthermore, are a function of the carrier frequency of each tone which differs in the up- and down-path.

An expression for the excess phase in the radio path due to the ionosphere can be given as (van Ardenne *et al.*, App.9, equation 18):

$$\Delta\phi = \frac{40.5}{C} \cdot D_\tau(t) \cdot \Delta\omega \cdot \left[\frac{1}{f_{1_{up}}^{\;2}} - \frac{1}{f_{2_{down}}^{\;2}} \right] \tag{11}$$

where $D_\tau(t)$ is the integrated electron content along the radio path through the ionosphere, typically 10^{17} electrons/m^2, $\Delta\omega$ = separation in frequency of tones in a pair, $f_{1_{up}}, f_{2_{down}}$ = up- and down-link carrier frequencies for the two pairs of tones. Variations in $D_\tau(t)$ are the problem for the link precision. They occur most dramatically at sunrise and sunset, and during solar maximum; factors of 8 to 10 increase over 3 to 4 hours can be experienced. Upper limits to $\Delta D_\tau(t)$ of 10^{18} electrons/m^2 can be given, leading to a maximum residual time difference $(\Delta\phi/\Delta\omega)$ of $\sim$ 350 psec. In the VLBI situation this is serious because stations can experience sunrise or sunset at times differing by several hours. Travelling ionospheric disturbances (TIDs) are also a source of concern, since they modulate $D_\tau(t)$ by a few percent or $\lesssim$ 10 psec on timescales of 10 to 20 minutes.

There are means to estimate the electron content along the paths to the satellite and thereby eliminate or substantially reduce the problem of the ionosphere. If the satellite carries beacon packages at frequencies at either end of the band then measuring the relative phase or delay of the beacon signals can give $D_\tau(t)$ via equation (16) of Appendix 9. Using a single beacon signal and measuring its Doppler shift and Faraday rotation can also give estimates of $D_\tau(t)$. It is also possible to use ionosonde measurements on other transmission paths coupled with models of the ionosphere.

Apart from sunrise-sunset, the ionosphere can be relatively stable over many hours, particularly at night, with phase variations an order of magnitude smaller. During solar minimum, sunrise-sunset ΔD_τ can be $\sim 10^{17}$ electons/m^2 which further reduces the problem.

Van Ardenne *et al.* calculate that the effect of the troposphere on the link precision for frequencies up to 30 GHz amounts to residual time difference errors of $\sim$ 1 psec on timescales of a few thousand seconds. Even the effects of rain are negligible in comparison to those from the ionosphere.

3. THE AUSTRALIA TELESCOPE AND AUSSAT

AUSSAT can, in principle, be used for a phase comparison link for the VLBI segment of the AT. Ground stations would be required at Culgoora (central station), Tidbinbilla, Fleurs, Hobart, Alice Springs, Carnarvon and any other site to be used for VLBI. It is assumed that Parkes and Siding Spring are connected to Culgoora via radio link and the phase excursions of frequency standards at these two stations monitored at Culgoora. If Tidbinbilla were also to be radio linked into the system, its phase excursions could be monitored similarly.

3.1 AUSSAT

AUSSAT is the name given to Australia's domestic communication satellite system. Two satellites are due to be launched in 1985 into positions on the geostationary orbit at 156° and 164° east longitude. Uplink signals to the satellites will be in the 14.0 to 14.5 GHz band, and downlink signals in the 12.25 to 12.75 GHz band. Both spacecraft have 15 transponders, each 45 MHz wide; 8 of the 15 respond to one sense of polarisation, the remaining 7 to the other. Transponders of the same polarisation are all based on the same translation oscillation. A total of 8 transponders in each satellite is connected to the national beam.

Station-keeping in orbit is accurate to 0°.05. Figure 5 depicts one of the spacecraft in relation to Australia.

The tones required for the VLBI phase synchronisation could be accommodated in separate channels in one (or more) of the medium-rate data-transmission transponders, or perhaps in the wings of a TV transponder. Ten tones are required for four field stations plus the central station on the Van Ardenne *et al.* scheme. Detailed plans for the location of the tones in frequency space will need to be developed to avoid intermodulation products.

AUSSAT transmits beacon signals at each end of the link frequency band but these are not phase coherent with the translation oscillators used for the transponders. The beacon signals cannot therefore be used to replace one of the tones in the pairs.

Clark (1982) has considered generating copies of the translation oscillator frequency at the central and field ground-stations as a means of reducing the number of tones by half. This requires accurate measurement of the translation oscillator frequency and of the position of the spacecraft. We have not pursued this method further in this document, but it deserves consideration.

In the following sub-section, we develop a preliminary link budget for a single carrier (tone).

3.2 Link budget

3.2.1 Introduction

Link budgets for this system have been calculated using the specifications for the Australian Domestic Satellite System national beam coverage. These specifications call for three values of saturated carrier flux densities (SCFD) at the satellite, -90, -85 and -80 dbW/m^2, a satellite receiver system $G/_T$ of -3db/°K, and a down-link EIRP of 36dbW from the satellite via the national beam.

The satellite transponders which will be available have a 200 channel frequency plan, so that the carrier power per channel will be reduced by this factor.

It is assumed that the satellite used is parked in the 156° East longitude orbit, this position being used to calculate the slant range from the satellite to Sydney of 37,273 km which in turn is used to determine the path attenuation between isotropic antennas of 207 db at 14.25 GHz and 205.8 db at 12.5 GHz.

The carrier to noise margin in a 1Hz band can then be estimated for the up and down links once a receive $G/_T$ is assumed.

3.2.2 Link margin calculations

The link margin is calculated first for a basic earth station (2.5m antenna, 300K receive system temp.) operating via a standard $-90dbW/m^2$ SCFD transponder. Various other improvements such as increased transponder input levels (-85 and $-80dbW/m^2$) and improved earth station $G/_T$, were examined and the improvement in link margins noted. Table 1 is a summary of this.

Uplink : f = 14.25 GHz; λ = 2.1 cm

Saturated carrier flux density (SCFD)	:	$-90dbW/m^2$ (at satellite)
Surface area at satellite range (in db)	:	162.4db
∴ Saturated EIRP	:	72.4db W
Back-off	:	-6.0db (reduction of intermodulation)
Per carrier power dividing factor (200)	:	-23.0db
∴ EIRP/carrier	:	43.4dbW/carrier
Path attenuation	:	-207db
Atmospheric margin	:	-1db
Received power/carrier	:	-164.6dbW (into the satellite antenna)
Satellite receive $G/_T$	:	-3db/°K
$C/_T$	:	-167.6db/°K
∴ $C/_{No} = C/_{kT}$ (k = -228.6 dbJ/°K)	:	61.0db Hz

Downlink: f = 12.5 GHz ; Tsystem = 300°K (280 + 20)°K ≡ ($T_R + T_A$); $G/_T$ = 23 db/°K
λ = 2.4 cm

Transmit EIRP	:	36 dbW
Back-off	:	-3 db
Power dividing factor	:	-23 db (200 carriers/transponder)
∴ EIRP/Carrier	:	10 dbW/carrier

Path attenuation	:	-205.8 db
Atmospheric margin	:	-1 db
Antenna gain	:	47.7 db (assuming η = .55)
∴ Received power/carrier	:	-149.1 dbW/carrier
System noise temperature	:	-24.7 db°K (300°K)
Received C/T	:	-173.8 db/°K
∴ C/No = C/kT	:	54.8 db Hz

The overall link margin is thus:

$$\frac{1}{C/No}\text{ (overall)} = \frac{1}{C/No}\text{ (up)} + \frac{1}{C/No}\text{ (down)}$$

$$= \frac{1}{61.0\text{ db}} + \frac{1}{54.8\text{ db}}$$

∴ C/No (overall) = <u>53.9 db Hz</u>

The following table gives a summary of the overall link margins after various link improvements.

<u>Table 1</u>

	C/No (overall) db Hz					
G/Ts \ S.C.F.D.	d=2.5m Ts=300°K	d=3.0m Ts=300°K	d=4.7m Ts=300°K	d=2.5m Ts=70°K	d=3.0m Ts=70°K	d=4.7m Ts=70°K
-90dbW/m^2	53.9	55.1	57.6	58.0	58.7	60.0
-85dbW/m^2	54.5	55.9	59.3	59.8	61.0	63.2
-80dbW/m^2	54.7	56.3	59.9	60.6	62.0	65.2

Note that the only improvements possible to the link as it stands involve increasing the uplink saturated carrier flux density (SCFD) or the downlink receive station G/T. The available SCFD depends upon the transponder allocated to the link by OTC. The receive station G/T can be improved by increasing the antenna diameter up to 4.7m, (any larger involves higher cost factors and may introduce pointing problems) and/or by reducing the receive station system temperature to about 70°K. This latter course would need a cryogenically cooled LNA.

It is interesting to note that to reproduce the link margin obtained in the van Ardenne *et al.* experiment (61.0 db Hz) we would require a -85 dbW/m^2 transponder, a 3 metre receive station antenna and a cooled LNA giving a Tsystem = 70°K. However the link performance of van Ardenne *et al.* (± 10 psec in 5 to 10 seconds integration time) could be reproduced in an AUSSAT system by increasing the tone separation to 45 MHz and using a 2.5 m antenna and a 300K receive system. (The effects of increasing the tone separation are discussed in section 3.3). This configuration will be referred to later as the minimum performance link.

3.2.3 Transmitter requirements

The EIRP/carrier of the uplink system is estimated to be 43.4 db W. For a 2 tone system per station the total EIRP would then be (43.4+3) db W = 46.4 db W.

Taking a range of transmit antenna diameters ranging from 1 metre up to 4.7 metre we can estimate the power requirements for the transmit high power amplifier. Table 2 gives an indication of these requirements.

Table 2

Antenna Diameter m	Antenna Gain db	Power Amplifier Operating Output db W	Power Amplifier Saturated Output db W	Max Power watts
1	40.9	+5.5	+11.5	14.1
2.5	48.8	-2.4	+3.6	2.3
3.0	50.4	-4.0	+2.0	1.6
4.7	54.3	-7.9	-1.9	0.6

3.3 Improvements to the OTS link precision

As mentioned previously the link precision (Δt) is dependent on the sine wave separation ($\Delta\omega$) and the link margin ($C/_{No}$) and the integration time (τ) as follows:

$$\Delta t \; \alpha \; (\Delta\omega)^{-1} . (\frac{C}{No} . \tau)^{-\frac{1}{2}}$$

Clearly, Δt can be reduced markedly by a larger $\Delta\omega$ provided other factors such as residual delay terms do not grow too rapidly. The provisional frequency plan for the AUSSAT indicates that if the two sine-waves of a pair were routed through different FSS (fixed satellite service) transponders a separation of 320 MHz could be achieved. This would give a factor 16 improvement for the same $C/_{No}$ and τ. If at the same time these transponders were set at an SCFD of -85 dbW/m^2 and ground station receive system of 4.7m diameter and T_{system} = 70 K was used giving $C/_{No}$ = 63.2 db Hz, then the link precision is given by curve (c) in Figure 1.

Factors limiting the precision of the link system as the tone separation is increased are:

(i) differential group delay variations at the two tone frequencies caused by the group delay characteristics of the ground station electronics. According to van Ardenne *et al.* (1981a, Appendix 9) these must be kept to $<$ 1 psec.

(ii) differential ionospheric effects over the frequency range spanned by the tones, particularly at sunrise and sunset. These could amount to ± 10 psec for a tone separation of 320 MHz.

If this link is not limited by these other factors and is used to lock Rb standards then a factor 5 improvement should result (2 psec). This would seem to represent the maximum performance possible in a Rb-satellite system since the lock times (~ 0.4 sec) are now comparable with the return transit time to the satellite (~ 0.25 sec).

This improvement from 10 psec rms (giving 8° phase error at 2.3 GHz or 30° at 8.2 GHz) to 2 psec lifts the maximum usable frequency to 43 GHz (30° phase error or 0.85 coherence).

Alternatively, if this high frequency performance is not required then the 10 psec precision of the van Ardenne experiment is likely to be satisfactory. This can be simply achieved with the 2.5m/300K receive system mentioned in the link budget as the minimum performance link, if the tone separation is increased to the maximum 45 MHz bandwidth of one transponder. The SCFD required would be -90 dbW/m^2.

3.4 Costs

3.4.1 Capital investment ($K)

The capital investment required is tabulated below for field and central stations for two cases:

(a) to achieve the OTS experiment performance (45 MHz tone separation) - see curve (a) Figure 1.

(b) to achieve a performance better than the OTS experiment (tone separation 320 MHz) - see curve (c) Figure 1.

(1) Field station

Item	(a)	(b)
antenna	3 (2.5m)	10 (4.7m)
mount	1	2
transmitter	10	10
receiver + IF	10	35 (cooled)
building	5	5
phase comparison electronics	5	5
Rb oscillator	15	15
Total:	$49K	$82K

(2) Central station

antenna etc. + building	24 (2.5m)	62 (4.7m + cooled)
phase comparison electronics	25	25
Rb oscillator	15	15
Total:	$64K	$102K

For a satellite link coupling four field stations to a central station, the total capital costs are:

(a) for minimum performance link $260K

(b) for high performance link $430K

3.4.2 Engineering costs

A test phase of 1 man-year (½ engineer, ½ tech. officer) should be allowed for, to repeat and improve the performance of the van Ardenne *et al.* experiment. Subsequently 8 man-years (1 engineer, 3 tech. officer, 4 tech. assistant) would be required to bring the full system into operation. One man-year would be required for software development.

If the high performance link is implemented, one man-year (¼ engineer, ¾ tech. officer) will be required for the building of cooled receiver systems.

Total manpower costs: (a) \$330K (min. performance link)
(b) \$370K (high performance link)

3.4.3 Operating costs per annum

(i) satellite usage

10 tones at \$10K per tone (channel)/year (50% usage)	\$50K

(ii) ground stations

approx. 5% of capital costs for equipment replacement and operating manpower	\$15K
Total:	\$65K p.a.

4. CONCLUSIONS

(1) Following the experience in the Netherlands with OTS, we conclude that a satellite-linked local oscillator system should be feasible with AUSSAT.

(2) The capital investment and manpower costs are estimated to be at least \$260K and \$330K (10 man-years) respectively for a minimum performance link. For a high performance link, the costs are \$430K and \$370K (11 man-years) respectively.

(3) The operating costs are estimated to be \$65K per annum assuming 10 channels (tones) are used. Reduction of the number of tones, by time sharing (TDMA) the two satellite channels used for the return path amongst the 4 field stations, may well reduce the operating costs at the expense of a small (?) increase in capital costs for TDMA equipment, and at the expense of SNR. The latter consequence may preclude phase correction at high observing frequencies for the minimum performance link.

5. RECOMMENDATIONS

If it is decided to proceed with a satellite-link, we have the following recommendations to make:

(1) Repeat the single station test of van Ardenne *et al.* in the first year of operation of AUSSAT (1985?) or even earlier with INTELSAT. It may be possible to borrow the Dutch equipment. The test should include evaluation of larger tone separations than the 20 MHz used in the OTS experiment.

(2) Develop a frequency plan for the 10 tones.

(3) Investigate the detailed feasibility of TDMA for reducing the number of tones.

(4) Investigate the detailed feasibility (frequency plan, cost) of shared use of one of the ABC's TV transponders.

(5) Investigate means of reducing the end-to-end SNR requirements for the full system, in particular by improving the OTS phase-locking electronics and the overall temperature stabilisation.

(6) Design the software for application of the phase data from both the satellite link and the ground link (Parkes and Siding Spring to Culgoora) to correct the interferometer phase data.

(7) Consider the feasibility of using a similar phase lock scheme for the microwave relay link sections of the AT.

References:

van Ardenne A., O'Sullivan, J.D. and Buiter, J. (1981a): NFRA, Note 341, February 1981.

van Ardenne A., O'Sullivan, J.D. and de Dianous, A. (1981b): submitted to IEEE Transactions on Instrumentation and Measurements.

Clark, B.G.: VLB Array Memo 30, August 1981.

Rogers, A.E.E. and Moran, J. (1981): IEEE Trans. Instr. and Meas., IM-30, 283.

Figures:

1. The residual rms time error of (a) the OTS satellite-link, (b) a commercial Rb standard, (c) a theoretical satellite-link, and (d) a hydrogen maser, determined from the Allan variance and plotted as a function of integration time. [(a) and (b) are taken from van Ardenne *et al.* 1981b].

2. Coherence estimates for Rb and maser frequency standards as a function of frequency and integration time (taken from the proposal for a US VLB Array and based on data given by Rogers and Moran 1981).

3. Schematic diagram of the effects of satellite motion on path length differences.

4. The rate of delay change in the OTS experiment as a function of UTC, as measured from the phase difference between the tones in a pair 20 MHz apart. The satellite velocity with respect to the ground station corresponds to half this rate. It can be determined with a few mm/sec accuracy within any 10 second integration time. (Taken from van Ardenne *et al.* 1981b).

5. AUSSAT coverage of Australia.

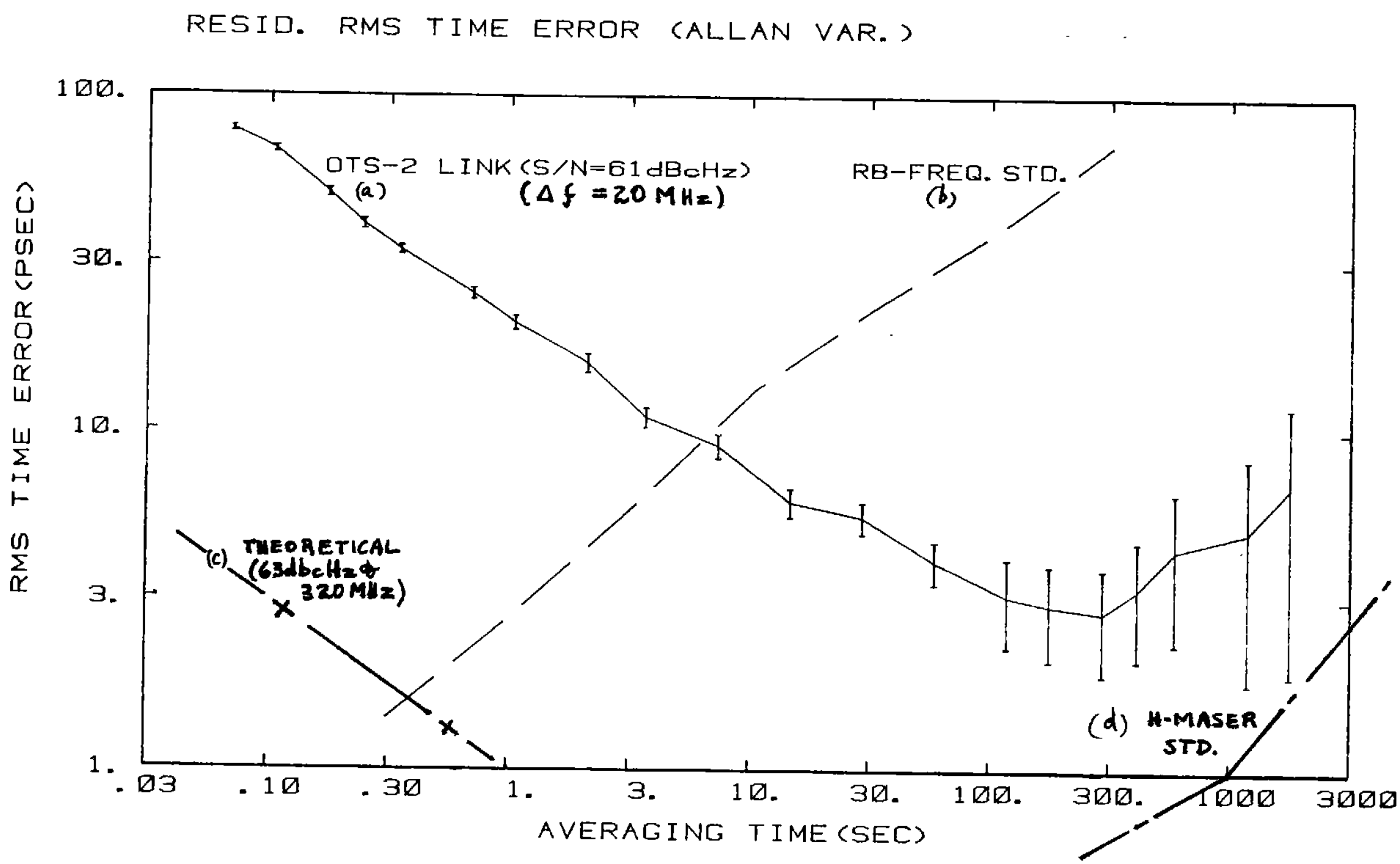
RESID. RMS TIME ERROR (ALLAN VAR.)
RMS TIME ERROR (PSEC)
100.
30.
10.
3.
1.
.03
.10
.30
1.
3.
10.
30.
100.
300.
1000
3000
AVERAGING TIME (SEC)
OTS-2 LINK (S/N=61dBcHz) (a)
(Δf =20 MHz)
RB-FREQ. STD. (b)
(c) THEORETICAL (63dbcHz @ 320 MHz)
(d) H-MASER STD.

FIGURE 1

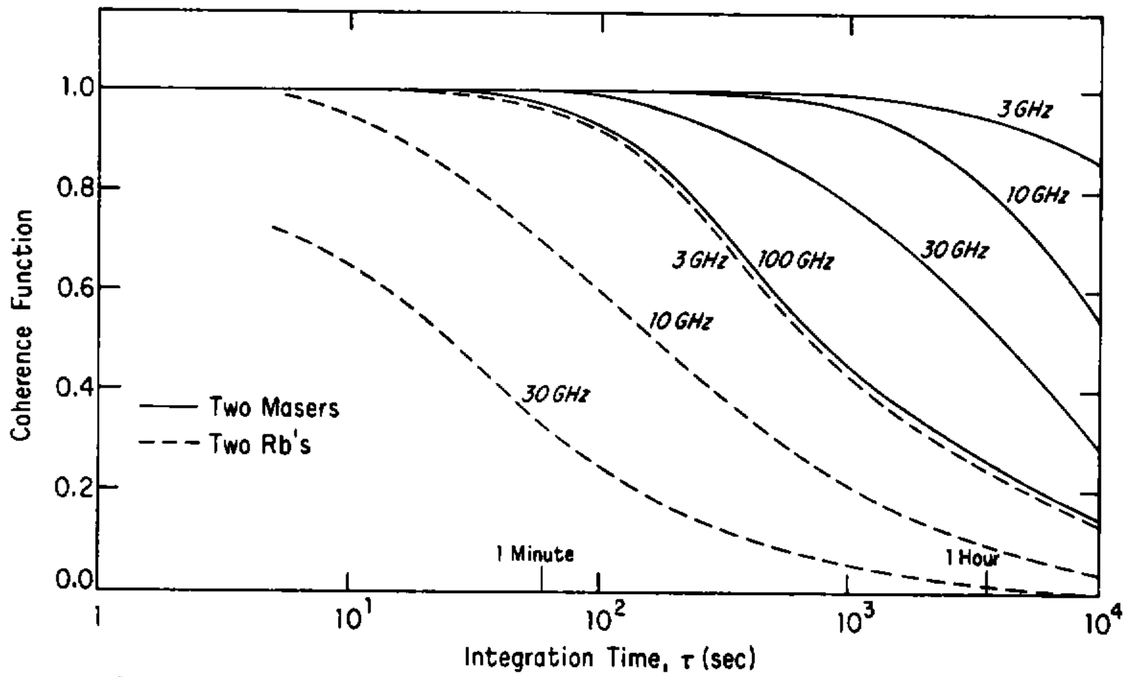

FIGURE 2

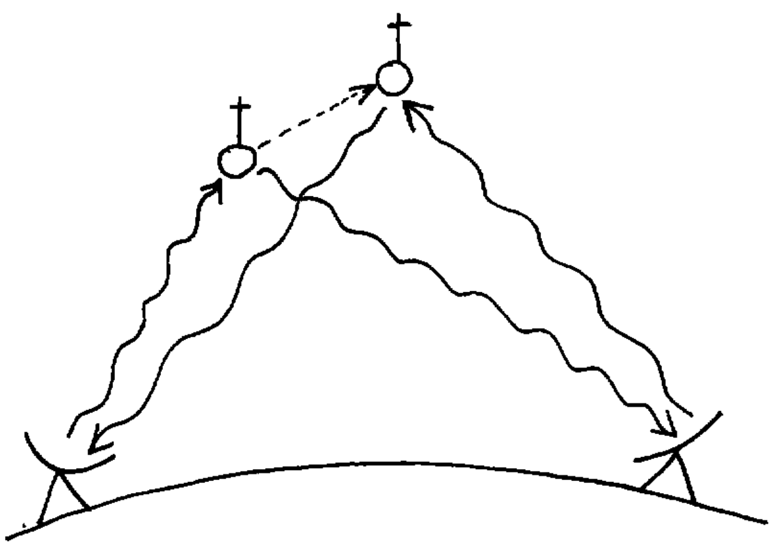

FIGURE 3

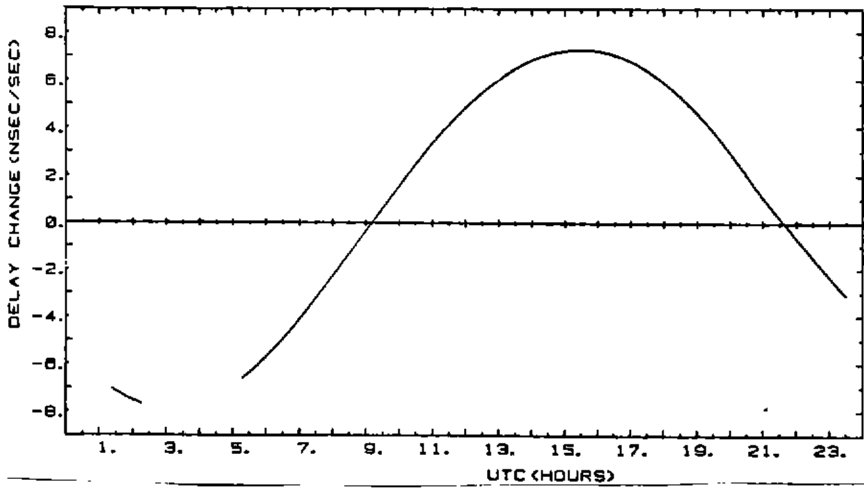

FIGURE 4

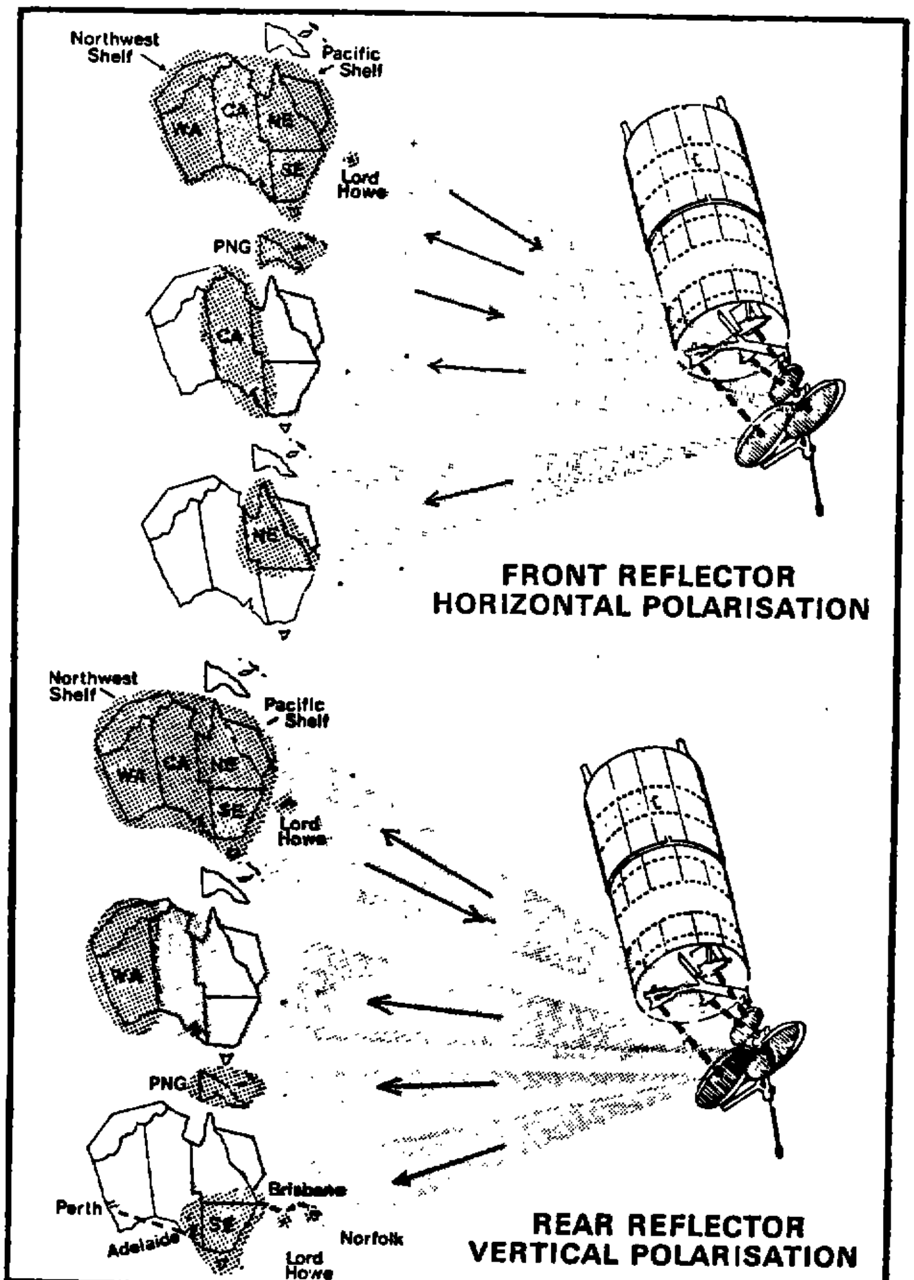

FIGURE 5