AT/23.4.1/003

PHASE (AND DATA) TRANSFER BY POINT-TO-POINT RADIO LINK

1. Introduction

Several different systems can be devised to transfer phase from point to point by radio link. In each case, however, the complexity of the schemes increases greatly once the separation of the points has increased sufficiently to require repeaters in the link system. A frequency-division-multiplexed (FDM) system employing the difference-tone method such as the one suggested for AUSSAT (AT/10.3/001) is superficially attractive since tone differences are unaffected by frequency translations in repeaters. However, it has been shown that the reciprocity of point-to point FDM systems is prejudiced under conditions of multipath propagation (Appendix). These conditions exist with significant probability throughout the year and are highly likely to degrade phase transfer to below acceptable limits.

The time-division-multiplexed (TDM) alternatives have been examined and the conclusions reached are that any one of four different TDM systems can transfer phase adequately but that only one of them requires little in-house effort to implement. It is also possible to utilise the unused capacity in this phase transfer system to carry astronomy data from the remote telescopes in a time-multiplexed form.

2. Phase transfer by time-multiplexed transmissions

Figure 1 is a schematic diagram of a primitive system which can measure the phase difference between two frequency standards which are physically separated. The phase differences, X and Y, between the standards are measured with respect to bi-directional transmissions between them. It is obvious that the difference X-Y determines the phase difference between the standards provided that the transmission path is reciprocal i.e. $\tau_{xy} = \tau_{yx}$. Unfortunately, it is not practical to transmit and receive simultaneously the same frequency in both directions over a lossy path. However, the frequency can be time shared between the two directions provided that both time comparisons are completed on a time scale shorter than the time scale for changes in path delay. Either a single-tone system or a difference-tone system can be employed. Two types of repeater can be used in phase transfer systems: ones in which there are net translations in frequency, or ones in which there are not. A frequency-translating repeater (FTR) can transmit and receive simultaneously whereas a non-frequency-translating repeater (NFTR) cannot, at least over hops with transmission loss greater than about 50 dB. A NFTR needs some means of storing the phase of the received signal until it can be retransmitted. A phase-locked oscillator (PLO) can perform this function, and separate PLO's are required for the outward transmission (from the master station) and for each return transmission through that repeater. A controller is also required to control the activities of the repeater. This sort of system is not available commercially and it would require a lot of development effort.

Similar remarks can be made about a FTR for a single-tone system which requires coherent frequency translation. On the other hand, a FTR for a difference-tone system has few non-standard functions. Only a simple controller is required to switch the direction of transmission at the appropriate times. Table 1 summarises the differences between the four major alternatives employing TDM transmissions. It can be seen that a difference-tone system with FTR's seems best since it requires least development effort.

Single-tone systems require significantly smaller signal-to-noise ratios than difference-tone systems because the tone frequency can be orders of magnitude greater than a difference tone. Nevertheless, the requirements for both systems can easily be met by commercial equipment as is shown in the next section.

3. Performance targets

It is assumed that 5% loss in fringe visibility due to imperfections in phase transfer is acceptable at an observing frequency of 22.3 GHz. This loss corresponds to a rms deviation of 0.32 radians of phase or 2.3 picoseconds of time over the fringe integration time. The acceptable rms time jitter in determining X and Y of Figure 1 is also 2.3 picoseconds. Figure 2 shows the rms time jitter of a rubidium standard as a function of integration time. It is obvious that it is necessary to make the phase comparison measurements and corrections about once per second in order to meet the 2.3 picoseconds target. The rms time jitter of 2.3 picoseconds is thus specified in 1 second integration time or, equivalently, in 1 Hz measurement bandwidth. Table 2 shows the signal-to-noise ratios and power levels that are required for a TDM system using a difference tone and frequency-translating repeaters. The requirements are easily met by commercial equipment.

4. A difference-tone system with frequency-translating repeaters

Figure 3 is a schematic diagram of a repeater for a difference-tone system using frequency-translating repeaters. The master station (Culgoora) is assumed to be to the left of the diagram and the remote telescope to the right. Frequency f_1 is used for transmission and reception on the hop to the left and f_2 on the hop to the right. It is envisaged that the whole repeater chain is open simultaneously between the master station and the remote telescope of vice versa. To achieve this, it is necessary that each repeater is synchronised to the master station. This can be done by transmitting some synchronising data down the chain from the master station. Each repeater must use these data to synchronise the outward and inward phases of activity. Of course, if the repeater loses synchronisation, it must force itself to receive from the master until it is resynchronised.

Apart from the addition of the controller, the only modifications to the link equipment that are required are those to gate off the transmitters at the appropriate times. How this is done depends upon the link equipment, but the addition of solid-state switches to the IF, LO or RF should not be too difficult, especially if the construction is of sub-modules connected by coax as is often the case.

5. Switching time scales

At least N+1 phases of activity are required to transfer phase in a TDM system from a master station to N telescopes: one for the master to talk to all N telescopes, and one for each of the N replies. The cycle time needs to be short enough that no significant changes in path delay can have occurred. There are two main causes of rapid variation in the delay of the link path, multipath effects and tower sway.

The effect of tower sway is the easier of the two to estimate. Tower movements at rates of more than a few centimetres per second seem highly unlikely. This is equivalent to a rate of change of delay of 10^{-10} . The rate of change of delay due to multipath effects is much harder to estimate. Amplitude fades of up to 30 dB per second are quoted in the literature but there are no comparable data for delay. However, the median duration of multipath fades, t_{50} , is quoted in Hall (1979) as being related to path length, d(Km), frequency, f(GHz), and fade depth, F(dB), by

$$t_{50} = 56.6\text{x}10^{-F/20} \text{ x } (d/f)^{1/2}$$

for fades deeper than 20 dB over paths in the USA. t_{50} is then about 20 seconds for fades of depth 20 dB over paths of length 60 Km at a frequency of 3.8 GHz. This can be converted to a differential phase swing between two paths of approximately 0.2 radians in 20 seconds. The resultant phasor swings through $(2\pi-0.2)/_2$ = 3 rads in 20 seconds which is equivalent to a delay rate of $1.3\text{x}10^{-11}$ at 3.8 GHz. A cycle time of about $2\text{x}10^{-2}$ seconds seems to be adequate to keep the phase error due to delay rates less than 2 picoseconds.

Another possibility that would allow longer cycle times is to use some simple form of interpolation in making the X-Y comparisons. Computer control is probably an essential part of the phase comparison system so that this would be relatively easy to implement. The comparisons would be averaged over one second and then used to correct fringe phase. By far the easiest and most reliable way of doing this would be by software in the computer which reads the data from the correlator.

6. Data Transfer

The scheme that is suggested for phase transfer is extremely wasteful in that it uses bi-directional wideband equipment to transmit what are essentially CW signals. It is therefore worthwhile to examine ways in which the wasted capacity can be used. One obvious possibiity is to combine control commands and data from Culgoora with the repeater synchronisation signals and transmit them in burst mode in the outward phase of the measurement cycle. With a duty ratio of about 0.25, a mean data rate of about 35 Mbs^{-1} is available, probably enough to satisfy requirements for a few years.

Another possibility is to make the difference tone the clock recovered by demodulation of 16 QAM on the return link. This would allow data to be transmitted in a burst-mode from remote telescopes to Culgoora. A total mean data rate of 105 Mbs^{-1} would be available from standard 140 Mbs^{-1} links and this could be subdivided in any way between the remote telescopes subject only to the need for the recovered clock to have sufficient signal-to-noise ratio for phase-transfer purposes. Of course, the data in a time multiplexed form is compressed before transmissions have to be stretched in time before fringes can be obtained between remote telescopes but the hardware that is required to compress and stretch the data in time is similar to that used for recirculation in the correlator so it does not require a large development effort.

7. Developmental activities

Assuming that the basic radio links can be obtained commercially, the following areas need development effort before the system that is described here can be implemented.

1. Phase measurement devices for Culgoora and the remote telescopes, and the related software.
2. Hardware to code and decode control data from Culgoora.
3. Controllers for the repeater stations.
4. Solid state switches to disable the transmitters at the repeater sites.
5. Data stretching and compressing hardware for the remote telescopes and Culgoora.
6. Modifications to the 16 QAM demodulators to allow TDM operation.

8. Conclusion

An integrated system for phase and data transfer by radio link has been outlined and shown to be feasible. It is believed to require the least effort of all the radio link solutions to develop but it should be compared with the satellite phase transfer/tape recording alternative from the point of view of effort, cost, performance and operational convenience.

A few areas need further investigation. For example, the regulatory authorities need to be consulted about bi-directional and TDM use of frequencies, the signal-to-noise ratio penalty for recovering the clock from 16 QAM signals needs to be determined, and what is involved in TDM use of 16 QAM demodulators should be examined.

Table 1. Comparisons for four TDM systems

Method	FTR or NFTR	PLO's Required	S/N Requirements	Commercial Availability	Development Effort
Single tone	FTR	Yes	V. Low	No	Large
Single tone	NFTR	Yes	Low	No	Large
Tone difference	FTR	No	High	Yes	Small
Tone difference	NFTR	Yes	V. High	Some	Medium/ Large

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Table 2. System Requirements

Requirements

Permissible one-way measurement jitter in 1 second or (1 Hz), τ_j	2.3 pS
Difference tone frequency f_t	30 MHz
Difference tone S/N = $-20 \log_{10}(2\pi f_t \tau_j)$	67.3 dB
Differencing loss	3.0 dB
Repeater loss (for 6 identical hops)	7.8 dB
TDM loss = $10 \log_{10}(2D^2)$ where D = 0.25 is the duty ratio	9.0 dB
S/N of each tone per hop	87.1 dBcHz^{-1}

Link parameters

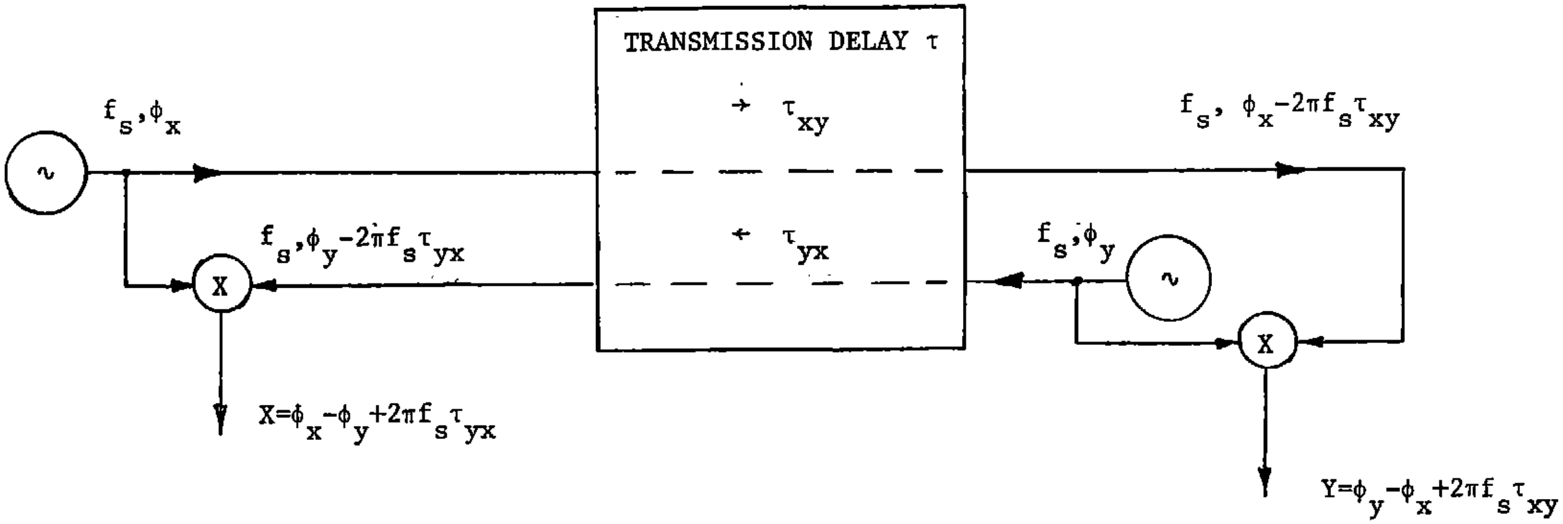
Transmission loss (3m diam. antennae, 3.8 GHz, 60 Km hop)	61.7 dB
Feeder loss	3.0 dB
Net loss	64.7 dB
Receiver noise (1000° K system)	-198.8 dBW Hz^{-1}

Transmitter power per tone (no margin for fading)

P_T = S/N + net transmission loss + RCVR noise

= 87.1 + 64.7 - 198.8 = - 47 dBW

Figure 1. A primitive system to measure phase offsets between separated frequency standards.



$$(X-Y)/2 = \phi_x - \phi_y + \pi f_s(\tau_{yx} - \tau_{xy})$$

Figure 2. The stability of a rubidium frequency standard as a function of integration time.

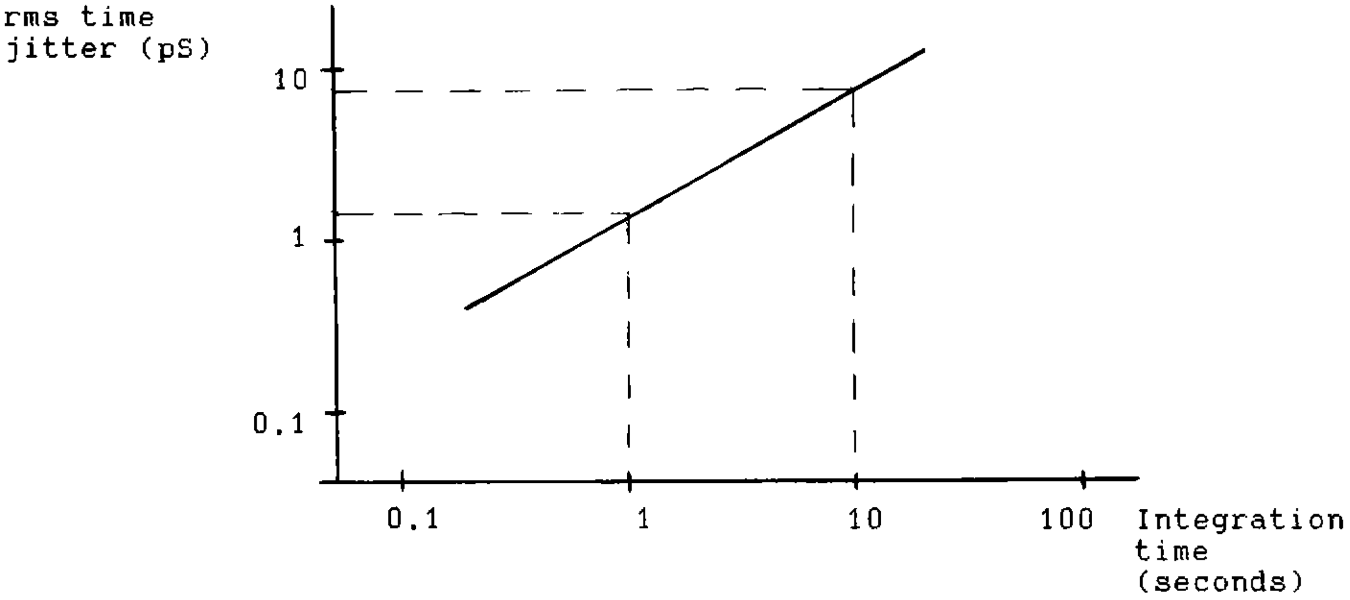
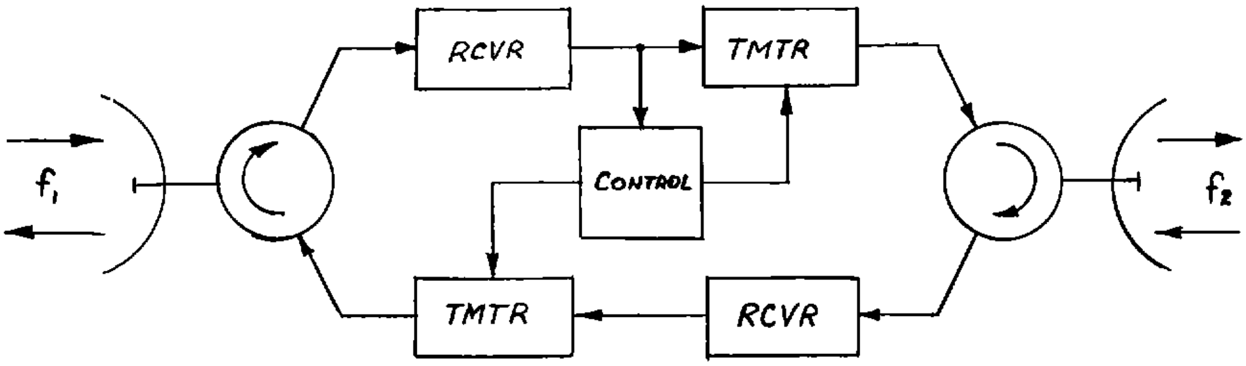


Figure 3. A frequency translating repeater for TDM, difference tone signals.



APPENDIX

The Effects of Multipath Propagation on Phase Transfer by Terrestrial Radio Links using the Difference Tone Method

1. Introduction

One possible implementation of the LBA element of the AT transfers data and phase by terrestrial, point-to-point radio links. The supposition has been that phase transfer can be accomplished by using a frequency-multiplexed, two-way, difference-tone method similar to that used with a satellite by van Ardenne et al. (1981, 1983). It is shown here that the accuracy of phase transfer by this method is severely prejudiced when multipath conditions exist, even though the signals themselves are not deeply faded. Data from the literature and from measurements made by David Swan show that multipath conditions may be present in excess of 20% of the time. The times when multipath conditions are almost certainly not present are during the afternoon.

2. The 2-way difference-tone method of phase transfer

The essentials of this method are illustrated in Figure 1. It is a useful method for phase transfer through frequency translating repeaters since frequency translations common to a pair of tones do not affect the phase difference between them. It can be seen that the results of the phase comparisons can be combined to give the offset in phase between the two frequency standards provided that the transmission system has equal group delays for transmissions in opposite directions i.e. $\tau_{xy} = \tau_{yx}$.

The next section shows that τ_{xy} is not equal to τ_{yx} in the presence of multipath propagation if the transmission frequencies in opposite directions are not the same, i.e. if $f_x \neq f_y$.

3. The effects of multipath propagation

Assume that transmission at frequency f between two sites can occur through two different paths with phase delays τ_1 and τ_2, and with amplitude ratio β. The resultant received amplitude can be represented by R (Figure 2) where

$$R = \exp(-j2\pi f\tau_1) + \beta\exp(-j2\pi f\tau_2)$$

$$= Z\exp[-j(2\pi f\tau_1 + \alpha)] \; ,$$

$$Z = [1 + \beta^2 + 2\beta\cos\{2\pi f(\tau_2 - \tau_1)\}]^{1/2} \; ,$$

$$\text{and } \alpha = \tan^{-1}\frac{[\beta\sin\{2\pi f(\tau_2 - \tau_1)\}]}{[1 + \beta\cos\{2\pi f(\tau_2 - \tau_1)\}]}$$

Figure 3 shows how α varies as a function of $2\pi f(\tau_2-\tau_1)$ for several values of β. It is obvious that the group delay, τ, given by

$$\tau = \tau_1 + \frac{1}{2\pi}\frac{d\alpha}{df}$$

is a function of f and $\tau_2-\tau_1$. Reciprocity will not apply to the transmissions in opposite directions over such a path unless the transmissions are at the same frequency.

Standard practice for bi-directional radio links is to leave at least one empty channel between the channels used for outgoing and incoming signals in order to avoid mutual interference. On the assumption that this practice would be followed, Figure 4 shows a plausible disposition of tones and data, and Figure 5 shows the non-reciprocal phase error

$$\Delta\alpha = \alpha(f_x+f_s)-\alpha(f_x)-\alpha(f_y+f_s)+\alpha(f_y)$$

$$= 2\pi f_s(\tau_{xy}-\tau_{yx})$$

plotted as a function of $\tau_2-\tau_1$ (phase delay difference)

for f_s = 40 MHz, f_x = 2.00 GHz, f_y = 1.92 GHz

and several values of β(multipath amplitude ratio)

For convenience, a steady slope has been removed from two of the curves and arbitrary fixed offsets added to them. Note that the magnitude of the wobbles in $\Delta\alpha$ grow with increasing $(\tau_2-\tau_1)$ and that plausible values of $(\tau_2-\tau_1)$ for paths >30 km are greater than those plotted. Even away from the differential delays which give the deepest fades (0.25, 0.75, 1.25, ... ns), there are significant slopes on the curves. Since f_s needs to be multiplied by a factor of over 500 for interometry at 22 GHz, it is obvious that variations in $(\tau_2-\tau_1)$ are likely to cause large perturbations in the transferred phase.

4. Anomalous atmospheric refraction

The most troublesome form of multipath propagation is caused by the anomalous refraction in the lower atmosphere associated with temperature inversion, i.e. where atmospheric temperature rises with height. This, along with rain attenuation, is responsible for most of the fading of microwave links.

Temperature inversions usually form overnight whenever the sky is clear and wind velocities are low. In areas with high daytime humidity, ground mist or fog often forms under these conditions. The inversion can persist for a significant fraction of a day and reform day after day until the weather patterns shift. At least in the U.K. this sort of weather is associated with high pressure regions and the absence of local fronts and troughs. It is most prevalent near the autumnal equinox although the conditions can occur at any time of year. Unfortunately, this sort of weather is otherwise very good for all sorts of astronomical observations.

Some local weather input is obviously desirable.

5. The probability of occurrence of multipath conditions compared with the probability of fading to a certain depth

It is possible that local fading statistics might be available from, for example, Telecom. These can be converted into a lower limit to the fraction of the time that multipath conditions exist by multiplication by an appropriate factor.

For deep fading to occur, the amplitudes over the 2 paths must be closely the same. Therefore assume that $\beta=1$. The condition for a fade to at least ΛdB below the normal signal level is the condition that

$$Z \leqslant 10^{(-\Lambda/20)}$$

which is equivalent to

$$\cos\{2\pi f(\tau_2-\tau_1)\} \leqslant -(1-Z^2/2) \qquad (\beta=1)$$

or, if $Z \ll 1$, then

$$\pi-Z \leqslant 2\pi f(\tau_2-\tau_1) \leqslant \pi+Z$$

If all values of $2\pi f(\tau_2-\tau_1)$ are a priori equally probable, then the probability of fading to a depth of at least Λ(dB) when $\beta=1$ is just Z/π. Plausible values of $(\tau_2-\tau_1)$ for hops longer than 30 km encompass several waveform periods at 2 GHz so that assumption is reasonably valid. Values of β differing from 1 are possible and hence reduce the probability of a deep fade occurring. Therefore, the conclusion is that the probability of multipath conditions existing is $>\pi/10^{(-\Lambda/20)}$ times the probability of a fade to a depth of at least ΛdB ($\Lambda \gg 1$).

Fading statistics are available for several geographical areas. For average rolling terrain in Europe, the percentage of the time for which a fading depth of 20 dB is exceeded is about 0.5% over a 100 km path at 4 GHz during the worst month of the year (Hall 1979). This suggests that multipath conditions must be present for more than 16% of the time. David Swan has monitored received signal strength on two links operating in the 2 GHz band between Mounts Canobolas and Bodangora, and Mount Bodangora and Cenn Cruaich. Both paths are about 100 km long. The fractions of the time for which multipath conditions were estimated to exist have been averaged over monthly intervals. The results vary between 19.5% for February/March to 48% in June. Averaged between mid-February and mid-July, multipath conditions exist for 39% of the time. The times when multipath conditions were almost guaranteed not to be present were during the afternoon when observations are most likely to be disturbed by the ionosphere.

Conclusion

It has been shown that the anomalous refraction form of multipath propagation has deleterious effects on phase transfer by the frequency multiplexed version of the two-way, difference-tone method. These propagation conditions can persist for significant periods of time. Time multiplexed phase-transfer method are less susceptible to multipath propagation degradation and are worth further investigation.

References

van Ardenne, O'Sullivan, and Buiter (1981), NFRA Note 341.

van Ardenne, O'Sullivan, and de Dianous (1983) IEEE TRANSIM-32, pp 370-376.

Hall "Effects of the troposphere on radio communication" Peter Peregimus Ltd./IEE 1979.

Figures

1. Schematic diagram of a 2-way, difference-tone phase transfer system.

2. Phasor diagram.

3. The phase shift, α, of the resultant versus the differential over the two paths with delays τ_1 and τ_2 respectively.

4. Possible link frequency assignments.

5. Phase transfer error, $\Delta\alpha$ $(\tau_2 - \tau_1)$ for 3 values of the amplitude ratio β.

Figure 1

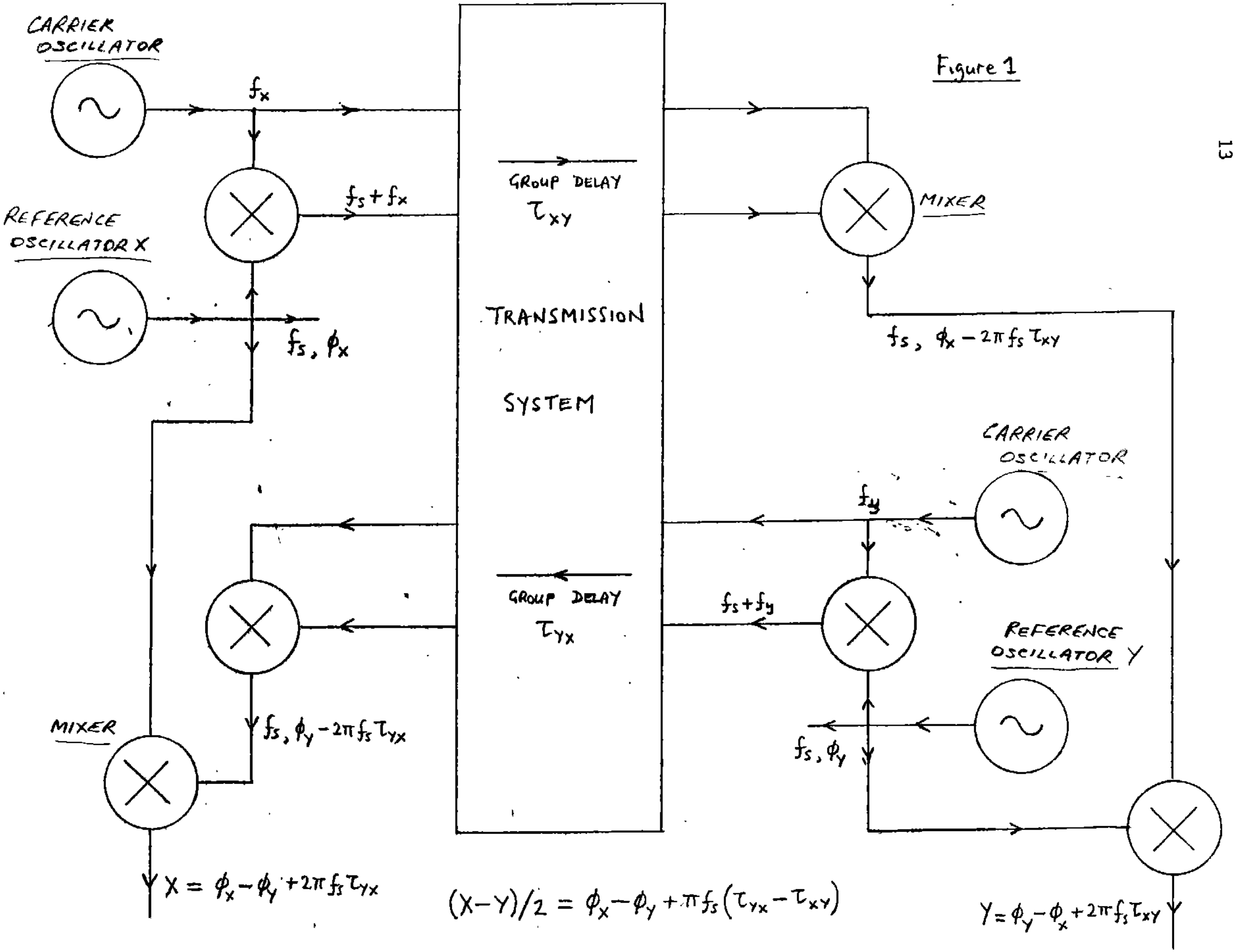
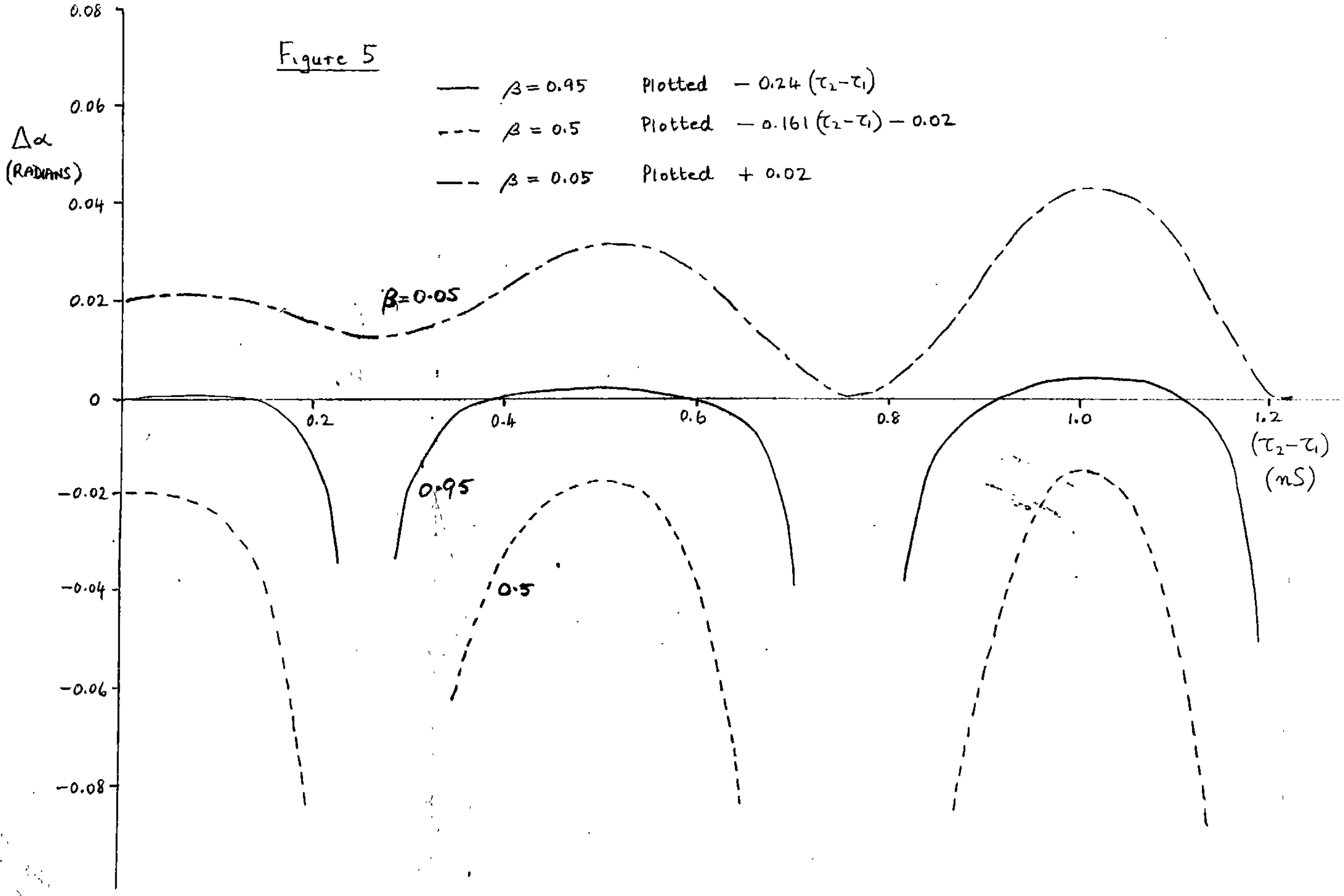

CARRIER OSCILLATOR
f_x
REFERENCE OSCILLATOR X
$f_s + f_x$
f_s, ϕ_x
GROUP DELAY τ_{xy}
TRANSMISSION SYSTEM
GROUP DELAY τ_{yx}
MIXER
$f_s, \phi_x - 2\pi f_s \tau_{xy}$
CARRIER OSCILLATOR
f_y
$f_s + f_y$
REFERENCE OSCILLATOR Y
f_s, ϕ_y
MIXER
$f_s, \phi_y - 2\pi f_s \tau_{yx}$
$X = \phi_x - \phi_y + 2\pi f_s \tau_{yx}$
$(X-Y)/2 = \phi_x - \phi_y + \pi f_s (\tau_{yx} - \tau_{xy})$
$Y = \phi_y - \phi_x + 2\pi f_s \tau_{xy}$

Figure 5



$\beta = 0.95$ Plotted $-0.24(\tau_2-\tau_1)$
$\beta = 0.5$ Plotted $-0.161(\tau_2-\tau_1) - 0.02$
$\beta = 0.05$ Plotted $+0.02$
$\Delta\alpha$ (RADIANS)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0.2
0.4
0.6
0.8
1.0
1.2
$(\tau_2-\tau_1)$ (nS)
β=0·05
0·95
0·5

Figure 2

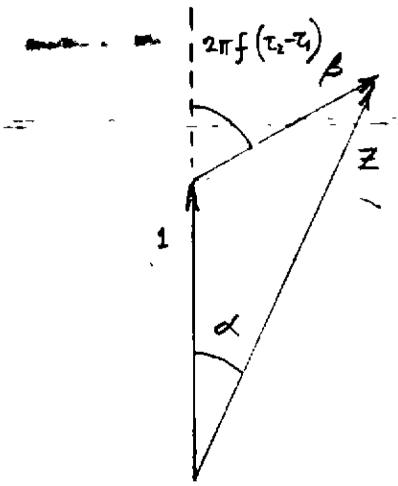


Figure 3

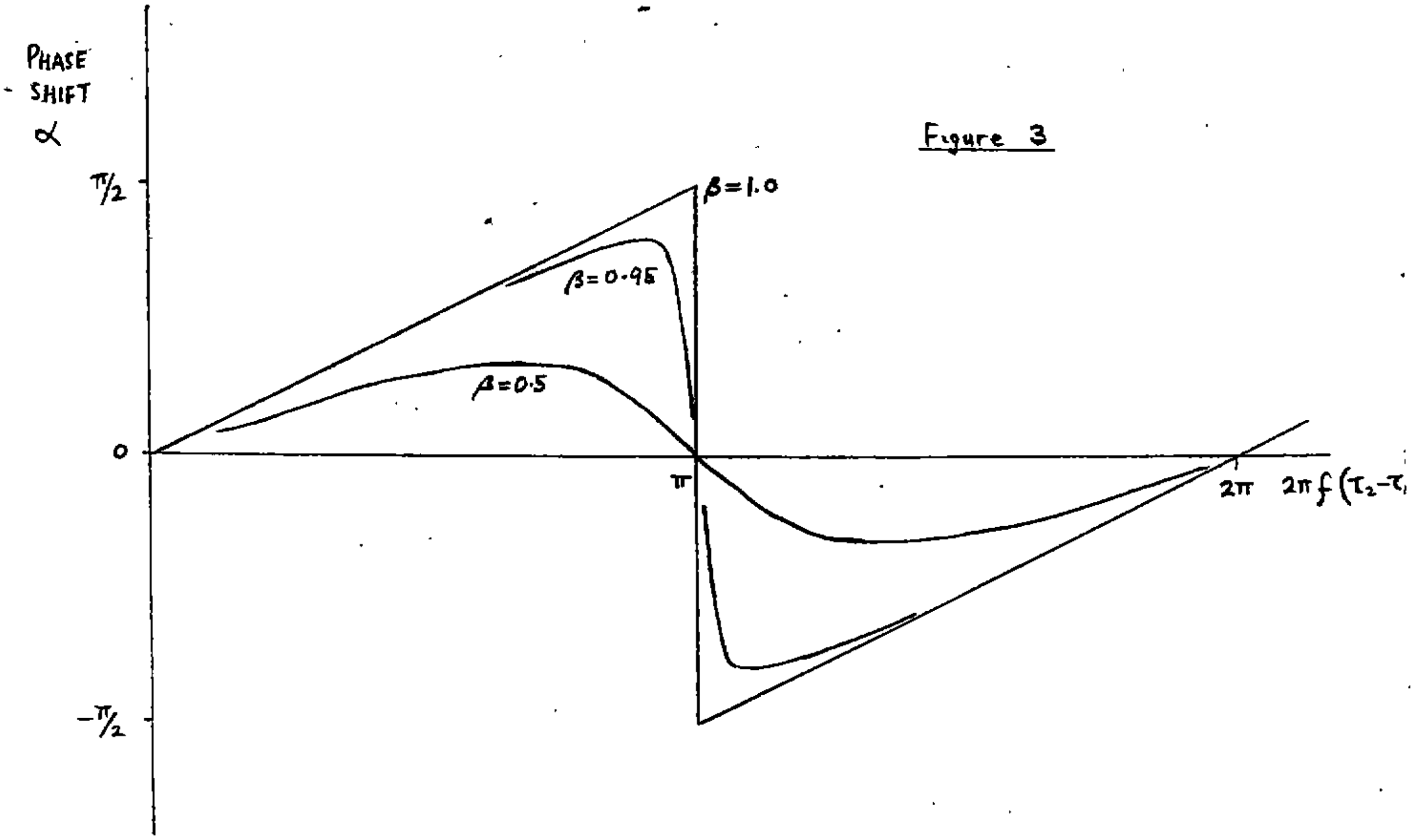


Figure 4