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NOTE

Polarisers in the EISCAT System

by

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1. INTRODUCTION

The UHF antenna at Tromsø can transmit any chosen polarisation - linear, circular or elliptical. All three UHF antennas can receive signals with any polarisation. At Tromsø, however, the setting chosen for transmission will always determine the polarisation for reception, and until we have a reliable duplexer only circular polarisation will be used.

The choice of polarisation is based on several factors which determine the overall accuracy of our measurements. One factor is the signal-to-noise ratio at each station, which depends on the polarisation chosen. In addition, Faraday rotation in the ionosphere may introduce a systematic error, and this also depends on polarisation.

Unfortunately, the "optimum" polarisation will always be different for the three sites. For the moment our choice is restricted : at Tromsø we do not have an operating duplexer, and if we are to make monostatic measurements we must use circular polarisation. As it happens, circular polarisation is usually the optimum polarisation for measurements at Tromsø. The absence of insertion loss from the duplexer gives a better signal-to-noise ratio and measurements made at Tromsø with circular polarisation are immune from Faraday rotation. (Only if we wish to determine Faraday rotation would we choose to use linear polarisation for the sake of measurements made at Tromsø).

If in the future we have a reliable duplexer we will be able to transmit and receive linear polarisation at Tromsø, and although this may not be the optimum mode for Tromsø, it might be the optimum for Kiruna or Sodankylä. For a remote station the optimum mode is a linear polarisation perpendicular to the plane defined by the transmitter, the scattering volume and the receiving station, and in the extreme case when χ (the scattering angle) = 90°, this could give a signal-to-noise ratio double that possible with circular polarisation (see Figure 1).

But the polarisation that is optimum for Kiruna is not optimum for Sodankylä - especially for E-region observations made to the east of Tromsø (see Appendix 2). If, therefore, we decide to transmit linear polarisation we will have to choose some compromise between the two stations.

When we realise that the "optimum" compromise will itself depend on the parameter being measured - it will, for example, be different for remote measurements of ion composition than for measurements of the north-south electric field - we see that the choice of polarisation is a complicated matter. Perhaps we are fortunate that for the initial period of EISCAT operation we are restricted to circular polarisation!

2. ROLE OF THE POLARISERS IN THE EISCAT SYSTEM

The role of the polariser is different in Tromsø from the role in the remote stations, and I shall describe the two systems separately.

2.1 Polariser at Tromsø

In Tromsø the polariser has to handle a transmitted power as high as 2.10^{6} W as well as a received power weaker than 10^{-13} W. In order that the loss in the transmitted signal should not overheat the polariser, and in order that the system noise should not swamp the received signal, the loss in the polariser must be kept as small as possible, and so the polariser is constructed of waveguide.

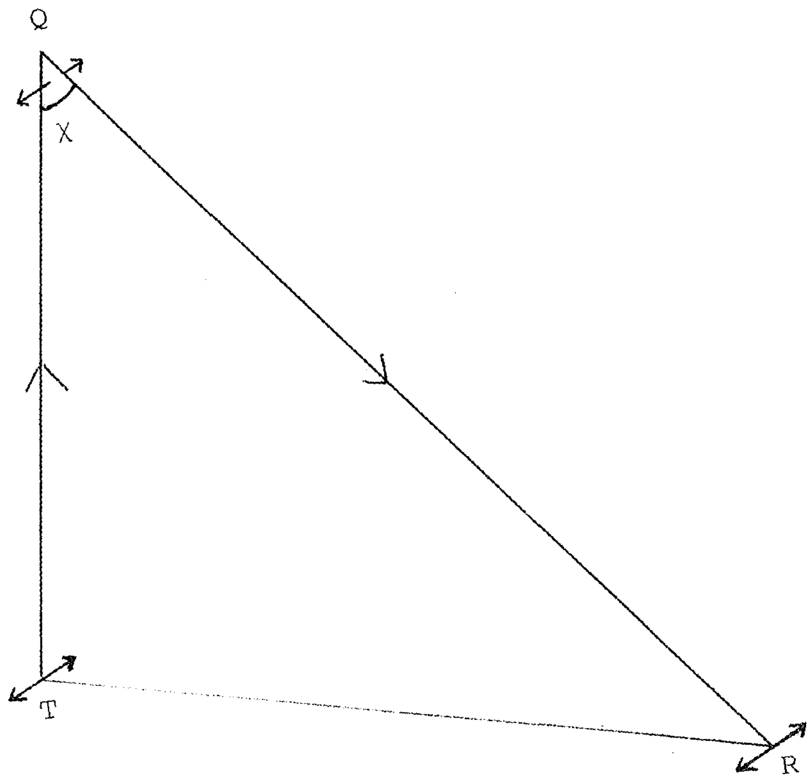

Figure 1 : Optimum Linear Polarisation for Reception at a Remote Station.

In order to protect the receiver from the transmitted signal, the polariser is placed between the antenna horn and the parametric amplifiers. A disadvantage of this is that the insertion loss of the polariser increases the overall system noise. An advantage is that it requires only one channel of the parametric amplifier to be used and this allows a true calibration of the receiver system to be made by inserting noise at the input of that channel.

The actual layout of the system at Tromsø depends on whether a duplexer is used or not : both versions are shown in Figures 2a and 2b.

The transmitter sends a signal through the waveguide to the transmitter port of the polariser. The "vertical" and "horizontal" † components emerge separately from two ports with an amplitude and phase determined by the setting of the polariser. E.g. for circular polarisation the amplitudes are equal but there is a 90° phase difference. The two components are finally combined in the horn to be transmitted to the ionosphere.

The return signal enters the horn and is separated into vertical and horizontal components which enter the polariser. If circular polarisation has been transmitted, the output appears entirely at the receiver port, where it enters one channel of the parametric amplifier.

If a duplexer is used, it will also be possible to use linear polarisation. In this case, in the absence of Faraday rotation, the output appears entirely at the transmitter port whence it passes through the duplexer and enters the other channel of the parametric amplifier.

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†The "horizontal" component is the component with electric field parallel to the horizontal axis of the antenna, and it is always horizontal. The "vertical" component is the component perpendicular to this, which is indeed vertical when the antenna points at the horizon, but otherwise is not!

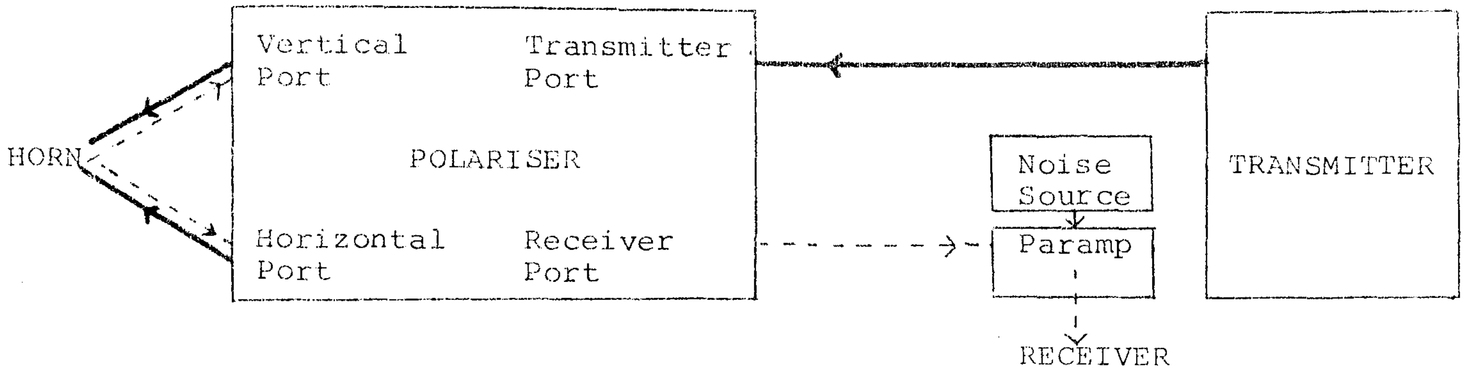


Figure 2a : Layout of the Polariser at Tromsø without Duplexer

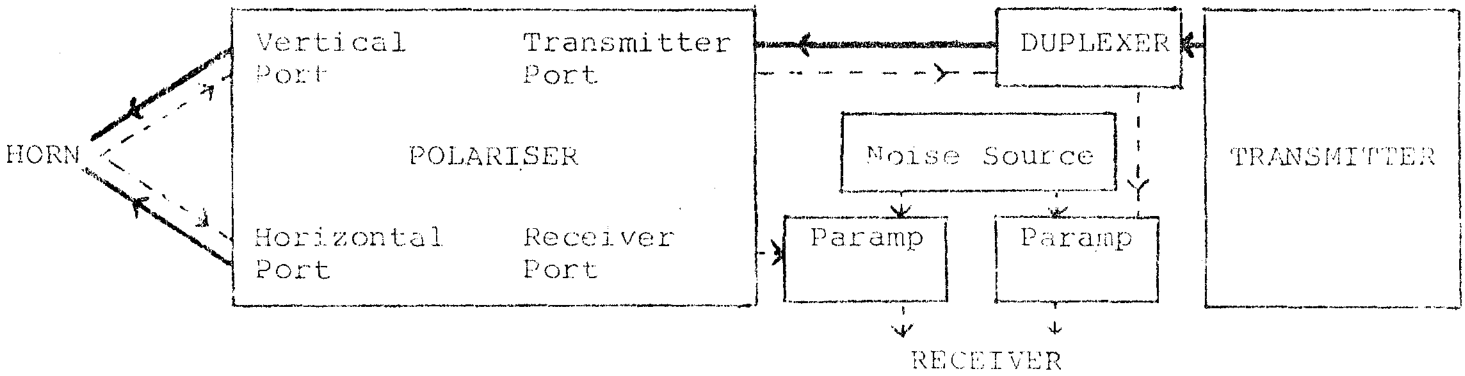


Figure 2b : Layout of the Polariser at Tromsø with Duplexer

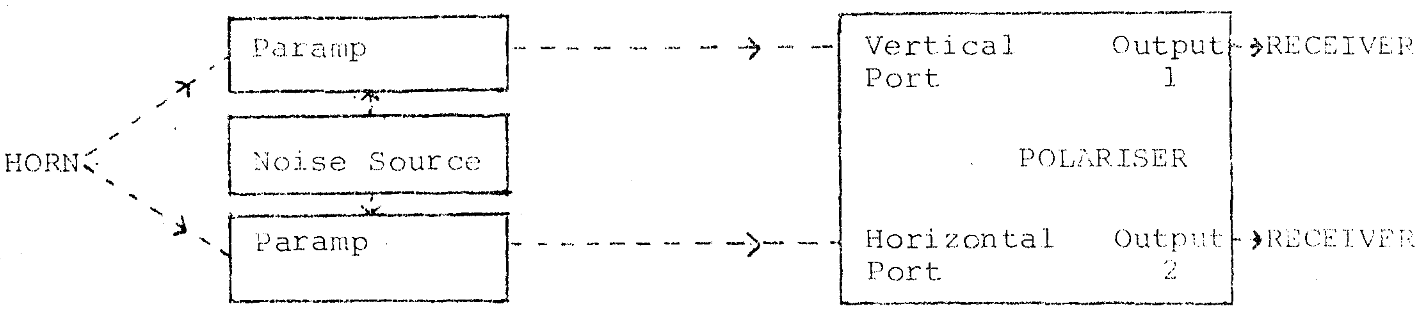
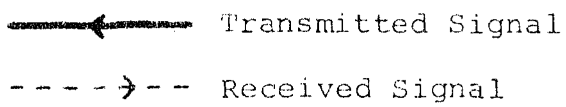


Figure 2c : Layout of the Polariser at Kiruna and Sodankylä



2.2 Polarisers at Kiruna and Sodankylä

In Kiruna and Sodankylä there is no need for the polariser to handle megawatts of power, nor is there such a need to protect the receiver. As a result, the vertical and horizontal components from the horn enter separate channels of the parametric amplifier directly and are amplified before entering the polariser, which is constructed of co-axial cable. An advantage of this arrangement is that the system noise is a minimum; it does mean, however, that the gain and noise temperature of the two channels of the parametric amplifier must be taken into account in setting the polariser. The layout of the system used at Kiruna and Sodankylä is shown in Figure 2c.

3. OPERATION OF THE POLARISER

3.1 Transmission from Tromsø

The operation of the polariser at Tromsø during transmission is illustrated in Figure 3a.

The transmitted signal, E cos(ωt), enters the first hybrid at the transmitter port T and is divided into two signals which emerge at ports 1.1 and 1.2. Note that because of the 180° in one arm of the hybrid, no signal at the fundamental frequency emerges at the receiver port R. This is not the case at harmonic frequencies.

The two signals then travel to the ports 2.1 and 2.2 of the second hybrid, and the path lengths are equal except for an extra ϕ_1 in path 1 introduced by phase-shifter 1.

The outputs from hybrid 2 then become the vertical and horizontal components of the transmitted signal. An extra ϕ_2 is inserted into the path of the vertical component by phase-shifter 2 and any other difference in the path lengths followed by the two components, ϕ_3, must be determined by calibration (see Section 5).

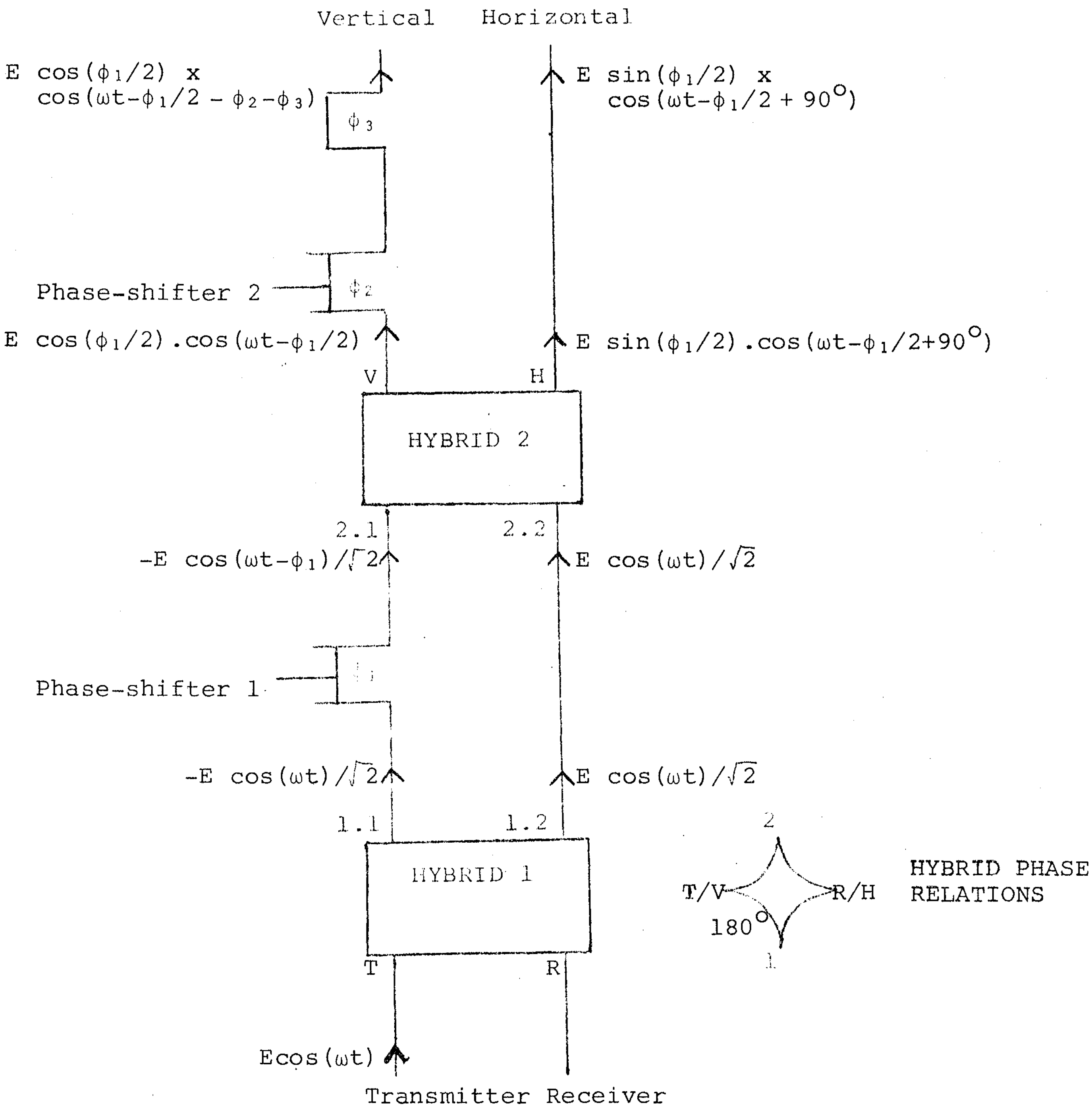


Figure 3a : Operational Principle of Polariser at Tromsø (Transmission)

Figure 3a shows how the field strengths of the signals finally transmitted are :-

Vertical : $E \cos(\phi_1/2) \cos(\omega t - \phi_1/2 - \phi_2 - \phi_3)$

Horizontal : $E \sin(\phi_1/2) \cos(\omega t - \phi_1/2 + 90^{\circ})$ (1)

i.e. R (the ratio of the amplitude of the vertical and horizontal components) = $E_V/E_H = \cot(\phi_1/2)$ and ϕ (the phase difference between the two components) = $\phi_V - \phi_H = -\phi_2 - \phi_3 - 90^{\circ}$. (2)

In other words, the first phase-shifter determines the relative amplitude of the transmitted signals, and the second phase-shifter determines the relative phase.

If, for example, we choose $\phi_1 = 0$, we have 100% vertical polarisation, in which case the phase difference ϕ is irrelevant. Similarly, with $\phi_1 = 180^{\circ}$ we have 100% horizontal polarisation.

If, on the other hand, we choose $\phi_1 = 90^{\circ}$ we have equal amplitude components in the vertical and horizontal polarisations. With $\phi_2 + \phi_3 = 0^{\circ}$, the vertical component lags behind the horizontal by 90° and we have circular polarisation in the left-hand sense. If, however, $\phi_2 + \phi_3 = 90^{\circ}$, the vertical component lags by 180° and we have linear polarisation at an angle of 135°.

In general, if $R = E_V/E_H = \cot(\phi_1/2)$ and $\phi = \phi_V - \phi_H = -\phi_2 - \phi_3 - 90^{\circ}$, then we have elliptical polarisation with the tilt angle for the axes, β, given by :-

$$\tan(2\beta) = \frac{2\cos(\phi)}{R - 1/R} \qquad (3)$$

and with the ratio of the minor-to-major axes given by :-

$$(B/A)^2 = \frac{R\sin^2(\beta) + 1/R\cos^2(\beta) - 2\cos(\phi)\sin(\beta)\cos(\beta)}{R\cos^2(\beta) + 1/R\sin^2(\beta) - 2\cos(\phi)\sin(\beta)\cos(\beta)} \qquad (4)$$

(see Figure 4).

In setting the polariser, the power ratio is set in units of

1/4 dB so that the reading on the amplitude display, R', is given by :-

$$R' = 4 \times 10 \log(E_V^{\,2}/E_H^{\,2}) = 80 \log(\cot(\phi_1/2)). \qquad (5)$$

When R'is set in this way, ϕ_1 is automatically introduced into phase-shifter 1. ϕ_2 is set directly as indicated in the phase display. ϕ_3 must be determined by calibration (see Section 5).

Note. The above account differs from the account in the TIW manual with $\phi = -\phi_2-\phi_3-90^{\circ}$ rather than $\phi = -\phi_2$. In the TIW manual Figure 2.4 shows an extra 90° in the horizontal output : this does not seem to exist in the actual polariser and has been omitted. The addition of the ϕ_3 term allows for any small differences in path length.

3.2 Reception at Tromsø

Figure 3b illustrates the operation of the polariser at Tromsø during reception.

If a signal $E_V \cos(\omega t)$ enters the polariser at the vertical port, then a similar argument to that used in 3.1 shows that the output at the receiver port is $-E_V \sin(\phi_1/2)\sin(\omega t-\phi_1/2 - \phi_2-\phi_3)$ and at the transmitter port is $E_V \cos(\phi_1/2)\cos(\omega t-\phi_1/2 - \phi_2-\phi_3)$. Note that if we transmit vertical polarisation $\phi_1 = 0^{\circ}$ so that $\sin(\phi_1/2) = 0$ and $\cos(\phi_1/2) = 1$; i.e. if we transmit vertical polarisation, all the input signal at the vertical port emerges at the transmitter port.

If a signal $E_H \cos(\omega t)$ enters the polariser at the horizontal port the output at the receiver port is $E_H \cos(\phi_1/2)\cos(\omega t-\phi_1/2)$ and the output at the transmitter port $-E_H \sin(\phi_1/2)\sin(\omega t-\phi_1/2)$. Note that if we transmit horizontal polarisation, $\phi_1 = 180^{\circ}$ so that $\cos(\phi_1/2) = 0$ and $\sin(\phi_1/2) = 1$; i.e. if we transmit horizontal polarisation, all the input signal at the horizontal port emerges at the transmitter port.

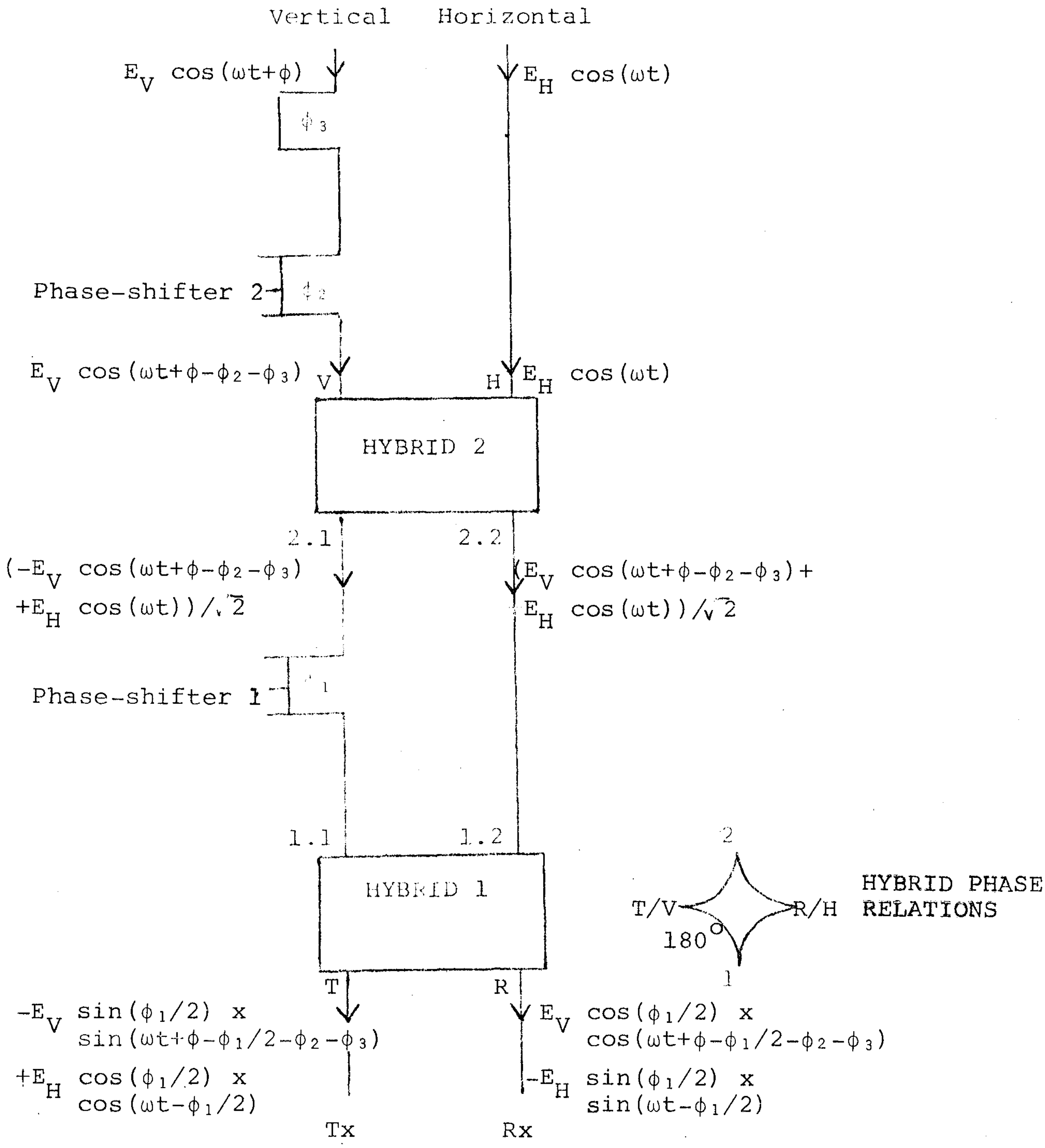


Figure 3b : Operational Principle of Polariser at Tromsø

(Reception)

<u>It follows that in the absence of Faraday rotation, all the received signal from a transmission with linear polarisation emerges at the transmitter port</u>. A measure of the signal emerging from the receiver port may, in fact, be a way of measuring Faraday rotation.

Using a similar argument it can be shown that if we transmit circular polarisation with $\phi_1 = 90^\circ$ and $\phi_2 + \phi_3 = 0^\circ$ then we also receive circular polarisation with the vertical component still lagging behind the horizontal component by 90°. The output at the receiver port is then $(E_V{}^2 + E_H{}^2)^{1/2} \cos(\omega t - \phi_1/2)$ and the output at the transmitter port is zero.

<u>It follows that all the signal from a transmission with circular polarisation emerges at the receiver port</u>. This result is independent of Faraday rotation. It is this that allows us to receive circular polarisation even without a duplexer. It also means that we need only use a single channel of the parametric amplifier and the setting of the polariser does not depend on the gain or noise temperature of the parametric amplifier.

3.3 <u>Reception at Kiruna and Sodankylä</u>

Figure 3c illustrates the operation of the polariser at the remote stations. There are two main differences from the operation of the polariser at Tromsø during reception. In the first place the setting of the polariser at a remote station can be independent of the setting used for transmission, and so we can arrange for the receiving system to be "matched" to any polarisation. Secondly at the remote stations the vertical and horizontal components are first amplified by separate channels of the parametric amplifier and then enter the polariser. It follows that the gain and the noise temperature of each channel must be considered in choosing the optimum setting of the polariser.

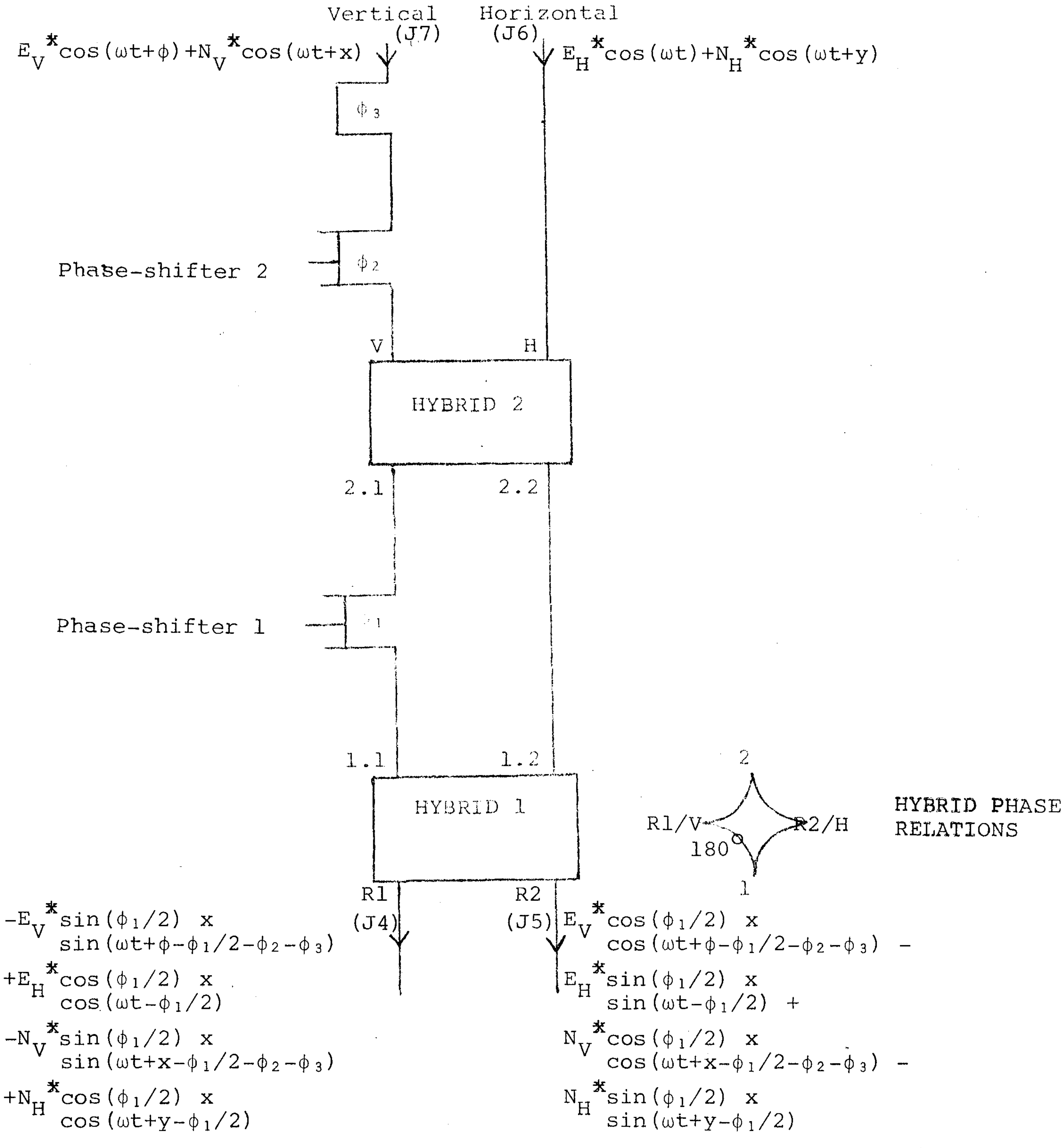


Figure 3c : Operational Principle of Polariser at Kiruna and Sodankylä.

In general a component enters the polariser at both ports having been amplified by a voltage gain G. Therefore let $E_V^{*} = E_V.G_V$ and $E_H^{*} = E_H.G_H$. At the same time, the system noise in each channel is amplified so that the noise voltages have amplitudes represented by $N_V^{*} = N_V.G_V$ and $N_H^{*} = N_H.G_H$.

The phase difference between the two components on entering the horn, ϕ, is determined by the polarisation of the transmitted signal and the geometry of the path from Tromsø to the remote station (see Section 4). The phases of the two noise components are random and are not related to each other. This can be represented by adding x and y to the phase expression in each case respectively, where x and y are random, independent of each other and vary with time.

It can be seen in Figure 3c that the output voltage at the receiver port 1 is given by the following expression :-

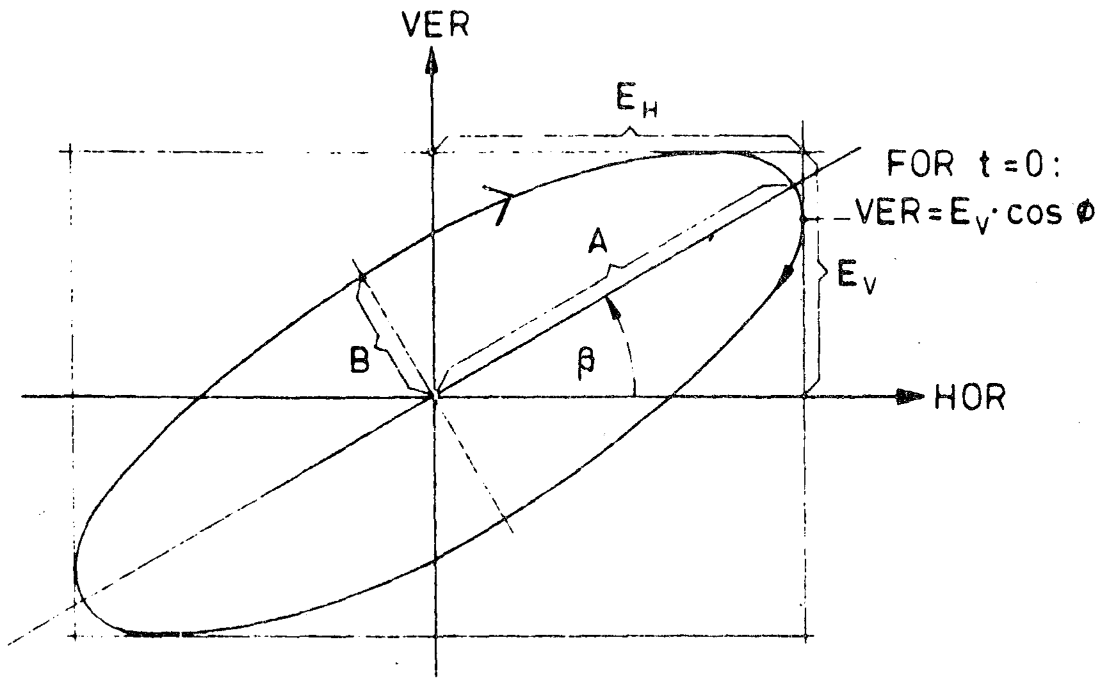
$$\begin{aligned} V_1 = & -E_V^{*}\sin(\phi_1/2)\sin(\omega t+\phi-\phi_1/2-\phi_2-\phi_3) + E_H^{*}\cos(\phi_1/2)\cos(\omega t-\phi_1/2) \\ & -N_V^{*}\sin(\phi_1/2)\sin(\omega t+x-\phi_1/2-\phi_2-\phi_3) + N_H^{*}\cos(\phi_1/2)\cos(\omega t+y-\phi_1/2) \end{aligned} \tag{6}$$

while the output voltage at the receiver port 2 is given by :-

$$\begin{aligned} V_2 = & \ E_V^{*}\cos(\phi_1/2)\cos(\omega t+\phi-\phi_1/2-\phi_2-\phi_3) - E_H^{*}\sin(\phi_1/2)\sin(\omega t-\phi_1/2) \\ & +N_V^{*}\cos(\phi_1/2)\cos(\omega t+x-\phi_1/2-\phi_2-\phi_3) - N_H^{*}\sin(\phi_1/2)\sin(\omega t+y-\phi_1/2) \end{aligned} \tag{7}$$

In setting the polariser there are two criteria we could adopt. The simplest criterion would be to choose ϕ_1 and ϕ_2 so that all the signal power emerges at one port, say receiver port 1. It can then be shown that this is the case if we choose ϕ_1 so that $E_V^{*}/E_H^{*} = \tan(\phi_1/2)$ and choose ϕ_2 so that $\phi - \phi_2 - \phi_3 = -90^{\circ}$. (8)

This result is obvious if we imagine that the only effect of the parametric amplifiers is to amplify the scales of the vertical and horizontal components as shown in Figure 4. This result is independent of the noise temperatures of the two channels of the parametric amplifier.



$$HOR = E_H \cdot \cos wt$$
$$VER = E_V \cdot \cos(wt+\Phi)$$
$$R = \frac{E_V}{E_H}\ ;\quad \Phi = \Phi_{VER} - \Phi_{HOR}$$

$$\tan 2\beta = \frac{2\cdot\cos\Phi}{R - 1/R}$$ β = TILT ANGLE FOR MAJOR OR MINOR AXIS

$$\left(\frac{B}{A}\right)^2 = \frac{R\cdot\sin^2\beta + 1/R\cdot\cos^2\beta - 2\cdot\cos\Phi\cdot\sin\beta\cdot\cos\beta}{R\cdot\cos^2\beta + 1/R\cdot\sin^2\beta + 2\cdot\cos\Phi\cdot\sin\beta\cdot\cos\beta}$$

Setting	R	Φ	β	B/A	POLARIZATION
-127	≅ 0	0°	0°	0	HORIZONTAL
+127	∞	0°	0°	0	VERTICAL
0	1	90°	-	1	RIGHT CIRCULAR
0	1	-90°	-	1	LEFT CIRCULAR

FIG 4 ,DESCRIPTION OF THE POLARIZATION ELLIPSE

If, however, we take account of the system noise in each channel, then a better criterion would be to choose ϕ_1 and ϕ_2 so that the signal-to-noise ratio in the output from one port is a maximum. In simple statistical terms it is clear that we should reduce the contribution of the channel with the highest system noise. If we carry out the calculation in full, we find that when we set ϕ_2 as before, then ϕ_1 is given by the expression:-

$$\tan(\phi_1/2) = \frac{E_V^{*}.N_H^{*\,2}}{E_H^{*}.N_V^{*\,2}} = \frac{E_V.G_H.N_H^2}{E_H.G_V.N_V^2} \qquad (9)$$

As we would expect, when $N_V^* = N_H^*$ the criterion is the same in both cases, but in practice we would expect to have differences in gain of at least 1 dB, and differences in system noise of at least 25% so the two criteria do give different settings of ϕ_1 and it is recommended that careful measurements of G_V, G_H, $\langle N_V^2\rangle$ and $\langle N_H^2\rangle$ should be made at intervals so that the best signal-to-noise should be used. (see Appendix 1).

4. THE POLARISATION RECEIVED AT A REMOTE STATION

In simple monostatic backscatter, the scattered signal has the same polarisation as the transmitted signal so that if a linear mode is transmitted a linear mode is received, and if a circular mode is transmitted a circular mode is received.

In bistatic scatter, however, this is not the case. If, for example, the Tromsø station transmits a circularly-polarised signal vertically upwards, the signal received at one of the remote antennas is elliptically polarised with the major axis horizontal and the minor axis vertical. The ratio of major-to-minor axes = 1 : cos(χ) where χ is the scattering angle TQR (see Figure 1).

If now the Tromsø beam is scanned off the vertical, in general the axes of the ellipse will rotate by an angle β with respect to the polarisation axes of the receiving antenna.

Figure 5 is stereographic projection of a hemisphere which shows how the value of β can be calculated for any given scattering volume.

Imagine that one of the remote stations is at the centre of the sphere, and that the directions T, Q and Z are the directions of the Tromsø station, the scattering volume and the zenith respectively. If we now consider the spherical triangle TQZ, then ZT is a constant ($= 90.89^\circ$ for Kiruna and 91.75° for Sodankylä); ZQ is the zenith angle of the receiving antenna when pointing at Q ($= 90^\circ$ - elevation);
and $T\hat{Z}Q$ is the difference in the azimuth of Tromsø, Az^T, and the azimuth of Q, Az^Q ($= 346.31^\circ - Az^Q$ for Kiruna and $312.68^\circ - Az^Q$ for Sodankylä).

Solving the spherical triangle TQZ we have :-

$$\cos(TQ) = \cos(ZT)\sin(\text{elevation}) + \sin(ZT)\cos(\text{elevation})\cos(Az^T - Az^Q);$$

$$\sin(T\hat{Q}Z) = \sin(Az^T - Az^Q)\sin(ZT)/\sin(TQ). \qquad (10)$$

Note that in solving the second equation the usual care must be taken to distinguish values of $T\hat{Q}Z > 90^\circ$ from values $< 90^\circ$. +

Now $T\hat{Q}Z$ is the angle between the plane defined by the directions Z and Q (i.e. the plane in which the receiving antenna moves in elevation and hence the plane of the vertical polarisation) and the plane defined by the directions T and Q (i.e. the plane which passes through the Tromsø station, the scattering volume and the remote station and hence the plane in which the circular polarisation of the transmitted signal is "foreshortened" to become an ellipse). When we remember that the remote station is at the centre of the sphere, then it is clear that $T\hat{Q}Z$ is, in fact, $180^\circ - \beta$, where β is the tilt-angle of the polarisation ellipse (anticlockwise positive).

+ See Appendix II.

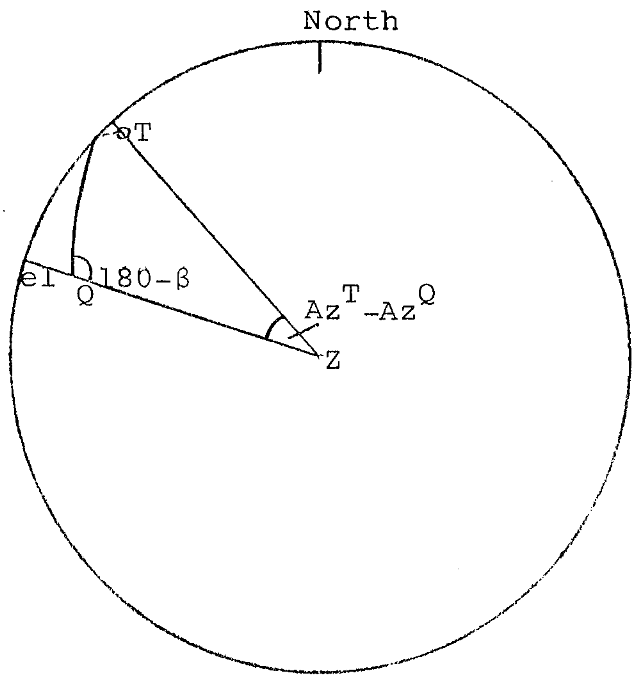


Figure 5 : Geometry of the Scattering of a Signal from Tromsø to a Remote Station

Knowing χ and hence the ratio of major-to-minor axes $(1 : \cos\chi)$, and knowing β we can determine R and ϕ :-

$$R = E_V/E_H = \left\{\frac{\sin^2(\beta) + \cos^2(\beta)\cos^2(\chi)}{\cos^2(\beta) + \sin^2(\beta)\cos^2(\chi)}\right\}^{1/2} \tag{11}$$

$$\text{and } \cos(\phi) = \frac{-\sin(\beta)\cos(\beta)\sin^2(\chi)}{\{(\sin^2(\beta)+\cos^2(\beta)\cos^2(\chi))(\cos^2(\beta)+\sin^2(\beta)\cos^2(\chi))\}^{1/2}} \tag{12}$$

In this way we can predict the polarisation of the received signal for any specified scattering volume when circular polarisation is transmitted. The only error in this prediction will be due to any Faraday rotation of the ellipse, and under most conditions this will be very small.

5. CALIBRATION OF THE POLARISERS

In calibrating the polariser we need to confirm that $E_V/E_H = \cot(\phi_1/2) = \text{antilog}_{10}(R'/80)$; we need to confirm the set values of ϕ_2; and we need to easure ϕ_3.

5.1 Calibration of Polariser at Tromsø.

At Tromsø calibration can be carried out by transmitting a signal from the RF Exciter (i.e. a signal of about 50 W) and measuring the vertical and horizontal components at one of two locations:-

The transmitted signal passes through the horn where it can be measured for both vertical and horizontal polarisations using the 60 dB directional couplers mounted in the waveguide, a suitable detector (e.g. HP423A Crystal Detector) and a voltmeter. These measurements are easily made and as both couplers are mounted at the same point in the waveguide the measurements should be reliable both for amplitude ratio and for phase difference.

Alternatively, these measurements can be made using the two Yagi aerials at the top of the ionosonde mast, one mounted in the horizontal plane and one in the vertical plane, and both pointing directly at the UHF antenna. At this site (about 400 m. from the antenna) the Yagis are well within the range of Fresnel diffraction but if they lie along the axis of the UHF antenna then the measurements are valid. To ensure that they do lie on axis, the UHF antenna can be scanned carefully in azimuth and elevation until the detected signal is a maximum (az. reading 199.77; el. reading 4.84).

It is more difficult to make measurements at the top of the ionosonde mast, and there is a greater error in the exact mounting of the Yagis, but these measurements do represent signals that have actually been transmitted from the antenna.

Whether we make our measurements via the directional couplers or via the Yagis, the principle is the same.

To calibrate ϕ_1, the detected voltages for the signals in both polarisations are measured for different values of ϕ_1. Table I suggests suitable values of R' and the corresponding values of power predicted for the two polarisations.

Table I

R	ϕ_1	Predicted Values (relative) E_V^2	E_H^2
+127	003	0.999	0.001
070	015	0.982	0.017
046	030	0.934	0.066
031	045	0.854	0.144
019	060	0.749	0.251
009	075	0.627	0.373
000	090	0.500	0.500
-009	105	0.373	0.627
-019	120	0.251	0.749
-031	135	0.144	0.854
-046	150	0.066	0.934
-070	165	0.017	0.982
-127	177	0.001	0.999

If the detector is carefully calibrated, the voltage recorded can be converted into the actual power detected in vertical and horizontal polarisation and these values can be plotted against the predicted values for the different values of ϕ_1. If both sets of points lie on the same straight line, then the values of ϕ_1 are confirmed.

As a quick check, it may be sufficient to make three spot measurements :-

i) when R' = +127 (ϕ_1 = 003^O) only a vertically polarised signal should be transmitted; this can be confirmed and the signal stength, S , measured;

ii) when R' = 000 (ϕ_1 = 090^O) equal power should be transmitted in the vertical and horizontal polarisations; this can be confirmed and the signal power should be S/2 in each case;

iii) when R' = -127 (ϕ_1 = 177^O) only a horizontally polarised signal should be transmitted; this can be confirmed and the the signal strength should again be S.

If the calibration of ϕ_1 has confirmed that R' = 000 gives equal power in the vertical and horizontal polarisations, then R' should be set at 000 to confirm the set values of ϕ_2 and to measure ϕ_3.

The two outputs at vertical and horizontal polarisation should be combined using a 2:1 junction with arms of equal length, and the combined output detected as before while ϕ_2 is stepped systematically from 000^O to 360^O in regular steps of 20^O.

If the detected power of the combined output is plotted against the set value of ϕ_2, the result should be a sine-curve with a minimum value of zero and a period of 360^O.

Let the observed minimum be at a phase setting of $\phi_2 = \phi_m$. If we now plot $S(\phi_2)$ against $\sin(\{\phi_2 - \phi_m\}/360)$ the result should be a straight line through zero if, in fact, the actual variation of ϕ_2 follows the set value.

Finally, at ϕ_m the signal at vertical and horizontal polarisation are 180° out of phase. We can therefore set $(-\phi_m - \phi_3)$ equal to $90^\circ \pm 180^\circ$ i.e. $\phi_3 = 90^\circ - \phi_m$. (13)

Note that if this measurements is made by Yagis feeding an unbalanced line, care must be taken that the driver elements in the two Yagis are in the same direction as the probes feeding the two couplers in the horn. Otherwise there will be a 180° error in ϕ_3 as measured by the Yagis.

5.2 Calibration of Polarisers at Kiruna and Sodankylä

To calibrate the polarisers at the remote stations, a single Yagi can be mounted at a remote site within line-of-sight of the antenna and fed with a signal. The site should be at as high an elevation as possible, but measurements at Sodankylä have proved successful at an elevation of 0.6°.

With the Yagi mounted vertically, the antenna is pointed directly at the source. The value of R' is set at the values listed in Table I and the signal received is amplified by the receiver chain, detected and recorded. The power measured for a given value of R' is plotted against the predicted value and once again a straight line confirms the value of ϕ_1.

The calibration can be repeated using the Yagi in the horizontal plane. Once again the plot of detected power versus predicted power should lie on a straight line, but the slope may be different because of the different gains in the two channels of the parametric amplifiers (G_V and G_H).

To calibrate ϕ_2 and ϕ_3 , the Yagi can be set at an angle of 45° so that the transmitted signal is equal in amplitude and phase in the two polarisations. ϕ_2 is stepped through all values between 0° and 360° and when the detected power is plotted against ϕ_2 , the minimum value ϕ_m corresponds to a phase difference of 180° between the two polarisations.

Once again the curve of detected power versus ϕ_2 should be a sine curve so that if we plot power versus $\sin(\{\phi_2-\phi_m\}/360)$ the results should lie on a straight line to confirm the variation of ϕ_2. ϕ_3 can then be determined from the equation :-

$$\phi_m + \phi_3 = 90^{\circ}. \tag{14}$$

Note that in looking at the transmitting source from the antenna the rotation of 45° should set the Yagi into the plane that bisects the two probe outputs from the waveguide, as shown in Figure 6b.

5.3 Final Check

The proof of the pudding is in the eating! The final check in each case is to compare the theoretical setting of the polariser for a given observation, as predicted from the calibration, with the setting that gives the maximum signal-to-noise in practice. This check should be carried out when the strength of the echo from the ionosphere is very strong. After subtracting the background noise, the power in the incoherent-scatter spectrum (i.e. the zero-lag of the ACF) can be measured while R' and ϕ_2 are varied. If we maximise first on one and then on the other we should quickly derive the optimum setting.

When this was done at Tromsø it confirmed the setting of R' and confirmed the value of ϕ_3 with an uncertainty of $\pm 10^{\circ}$.

In Kiruna and Sodankylä it confirmed the value of R' and confirmed the value of ϕ_3 to within 10°.

By using the correct polarisation at Sodankylä, the signal-to-noise was improved by 1.7 dB. (see Appendix 3B).

Although small errors still remain they are of very little significance. Fortunately trigonometric functions are very non-linear, and small deviations around the correct settings make very little difference as the signal-to-noise ratio has a very flat maximum.

6. CONCLUSION

For measurements at the remote stations a useful improvement in signal-to-noise ratio can be obtained by always using the correct polarisation. The correct setting could be built into the EROS system to set the polarisers automatically, assuming a left-handed circular polarisation is transmitted from Tromsø. This could be done by performing the whole calculation in EROS, or by calculating the parameters in advance and including them in the specification of the observation.

One problem may arise in certain cases. The polarisers are slow to set and there may be cases where the change in polarisation takes longer than the antenna scan-time. In such cases we might have to choose between i) taking a compromise value of the polariser setting for several positions; ii) or making as much change as possible in the time allowed; or iii) continuing to run the polariser while observations are being made. As the polariser at the remote stations occurs <u>after</u> the parametric amplifiers it may be possible to choose option iii) without affecting the signal-to-noise ratio.

APPENDIX I

OPTIMUM SETTING OF POLARISER AT A REMOTE STATION

In following a signal with components $E_V\cos(\omega t)$ and $E_H\cos(\omega t+\phi)$ through the two channels of the parametric amplifier and the polariser at a remote station, we have at each stage in Figue 3c the following signals :-

V	H
$E_V^*\cos(\omega t+\phi)+N_V^*\cos(\omega t+x)$	$E_H^*\cos(\omega t)+N_H^*\cos(\omega t+y)$
2V	2H
$E_V^*\cos(\omega t+\phi-\phi_2-\phi_3)+$ $N_V^*\cos(\omega t+x-\phi_2-\phi_3)$	$E_H^*\cos(\omega t)+$ $N_H^*\cos(\omega t+y)$
2.1	2.2
$\{-E_V^*\cos(\omega t+\phi-\phi_2-\phi_3)+E_H^*\cos(\omega t)$ $-N_V^*\cos(\omega t+x-\phi_2-\phi_3)+N_H^*\cos(\omega t+y)\}$ $\times 0.707$	$\{E_V^*\cos(\omega t+\phi-\phi_2-\phi_3)+E_H^*\cos(\omega t)$ $+N_V^*\cos(\omega t+x-\phi_2-\phi_3)+N_H^*\cos(\omega t+y)\}$ $\times 0.707$
1.1	1.2
$\{-E_V^*\cos(\omega t+\phi-\phi_1-\phi_2-\phi_3)$ $+E_H^*\cos(\omega t-\phi_1)$ $-N_V^*\cos(\omega t+x-\phi_1-\phi_2-\phi_3)$ $+N_H^*\cos(\omega t+y-\phi_1)\}\times 0.707$	$\{E_V^*\cos(\omega t+\phi-\phi_2-\phi_3)$ $+E_H^*\cos(\omega t)$ $+N_V^*\cos(\omega t+x-\phi_2-\phi_3)$ $+N_H^*\cos(\omega t+y)\}\times 0.707$
R1	R2
$-E_V^*\sin(\omega t+\phi-\phi_2-\phi_3-\phi_1/2)\sin(\phi_1/2)$ $+E_H^*\cos(\omega t-\phi_1/2)\cos(\phi_1/2)$ $-N_V^*\sin(\omega t+x-\phi_2-\phi_3-\phi_1/2)\sin(\phi_1/2)$ $+N_H^*\cos(\omega t+y-\phi_1/2)\cos(\phi_1/2)$	$E_V^*\cos(\omega t+\phi-\phi_2-\phi_3-\phi_1/2)\cos(\phi_1/2)$ $-E_H^*\sin(\omega t-\phi_1/2)\sin(\phi_1/2)$ $+N_V^*\cos(\omega t+x-\phi_2-\phi_3-\phi_1/2)\cos(\phi_1/2)$ $-N_H^*\sin(\omega t+y-\phi_1/2)\sin(\phi_1/2)$

In order that all the signal should come out at the receiver port :-

$$E_V^*\cos(\omega t+\phi-\phi_2-\phi_3-\phi_1/2)\cos(\phi_1/2)=E_H^*\sin(\omega t-\phi_1/2)\sin(\phi_1/2)$$

Therefore if $\phi-\phi_2-\phi_3 = -90^\circ$ and if $E_V^*/E_H^* = \tan(\phi_1/2)$ out of the signal channel we get :-

$$\{E_V^*\sin(\phi_1/2)+E_H^*\cos(\phi_1/2)\}\cos(\omega t-\phi_1/2)$$
$$+N_V^*\cos(\omega t+x')\sin(\phi_1/2)+N_H^*\cos(\omega t+y')\cos(\phi_1/2)$$

and so the ratio of signal power to noise power, S/N, =

$$\frac{(E_V^{*\,2}\sin^2(\phi_1/2)+E_H^{*\,2}\cos^2(\phi_1/2)+2.E_V^*.E_H^*\cos(\phi_1/2)\sin(\phi_1/2)}{(N_V^{*\,2}\sin^2(\phi_1/2)+N_H^{*\,2}\cos^2(\phi_1/2))}$$

For all the signal to come out of this channel we now have $E_V^*/E_H^* = \tan(\phi_1/2)$

If, however, we wish to maximise the signal-to-noise ratio out of this channel, we must maximise S/N by equating :-

$$\frac{\partial}{\partial\phi_1}\{\frac{S}{N}\} = 0$$

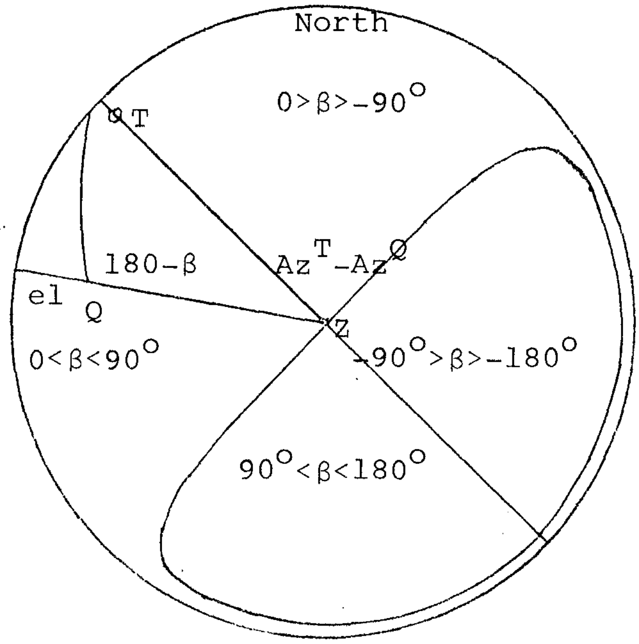
When we do this we have the expression :-

$$\frac{E_V^*N_H^{*\,2}}{E_H^*N_V^{*\,2}} = \tan(\phi_1/2)$$

APPENDIX II

Spherical Geometry of Scattering of a Signal to a Remote Station

i. Transmission of Circular Polarisation from Tromsø



Solving the spherical triangle TQZ we have :-

$$\cos(TQ) = \cos(ZT)\sin(el) + \sin(ZT)\cos(el)\cos(Az^T-Az^Q);$$

$$\sin(T\hat{Q}Z) = \sin(Az^T-Az^Q)\sin(ZT)/\sin(TQ)$$

$T\hat{Q}Z = 180^\circ - \beta$, where β is measured anti-clockwise as in Figure 4.

If a remote station R is looking at a scattering volume directly above Tromsø then $\beta = 0$, and TQR defines a vertical plane.
If the scattering volume is then moved slightly to the south of the vertical plane (i.e. Az^T-Az^Q positive) then the major axis of the polarisation ellipse moves anticlockwise (i.e. β positive).
As $\sin(Az^T-Az^Q)/\sin(TQ)$ increases, β also increases until it reaches a value of 90°. It is possible on the stereogram to define a boundary on which β is always 90°. This boundary is defined by considering a right-angled spherical triangle TQZ where $T\hat{Q}Z = 90^\circ$.
If the scattering volume moves over this boundary, then $T\hat{Q}Z \nless 90^\circ$ and so $\beta \ngtr 90^0$. (i.e. if $(Az^T-Az^Q) > \cos^{-1}\{\cot(ZT)\cot(el)\}$ then $\beta > 90^\circ$).
The opposite applies if the scattering volume moves north of the vertical plane, as shown in the diagram above.

APPENDIX IIIA

Calibration of Polariser at Tromsø

i. Detected Signal from Couplers in Horn for different settings of R'.

R'	Vertical		Horizontal	
	V_D/mV	Power (arbitrary)	V_D/mV	Power (arbitrary)
127	310		000	00.0
080	310		015	01.7
064	308		030	03.5
052	307		048	06.6
040	300		072	11.3
028	287		108	21.1
024	280		123	25.7
019	271		145	
012	255		170	
000	215		220	
-12	170		265	
-19	141		280	
-24	121	25.1	292	
-28	106	20.6	300	
-40	0-0	11.1	312	
-52	042	05.5	318	
-64	025	02.9	320	
-80	013	01.4	320	

The detectors were only calibrated accurately over a limited range but over that range the power detected in each channel was proportional to the power predicted. The calibration also confirmed :-

a) when R'=+127 only vertical polarisation was detected;

b) when R'=-127 only horizontal polarisation was detected;

c) when R'= 000 the vertical and horizontal polarisations were almost equal.

ii. Detected Signal from Couplers in Horn after combining in 2:1.

Phase	V_D/mV	Power (arbitrary)	(R'=000)
000	325		
020	230		
040	130	29.5	
060	060	09.0	
070	035	04.4	
080	027	03.1	
090	045	06.2	
100	070	11.1	
120	160		
140	250		
160	345		
180	435		
210	575		
240	637		
270	637		
300	487		

The detectors were only calibrated accurately over a limited range but by measuring carefully over that range it was clear that the minimum signal from the 2:1, corresponding to the vertical and horizontal polarisations being 180° out of phase, occurred with a polariser phase setting of 78°. (i.e. $\phi_3 = 12^{\circ}$.) See Figure 7b.

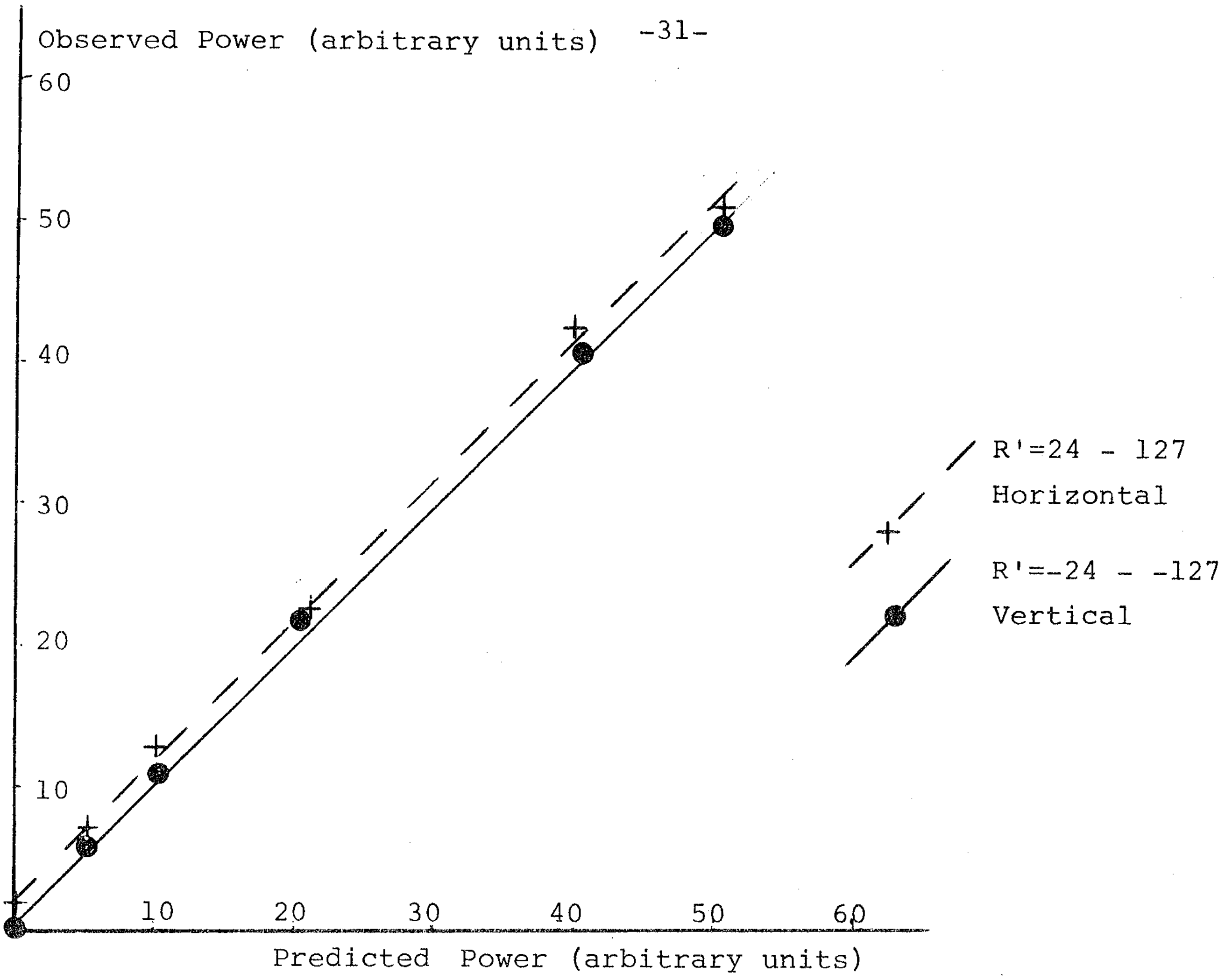


Figure 7a : Detected Signal from Coupler in Horn.

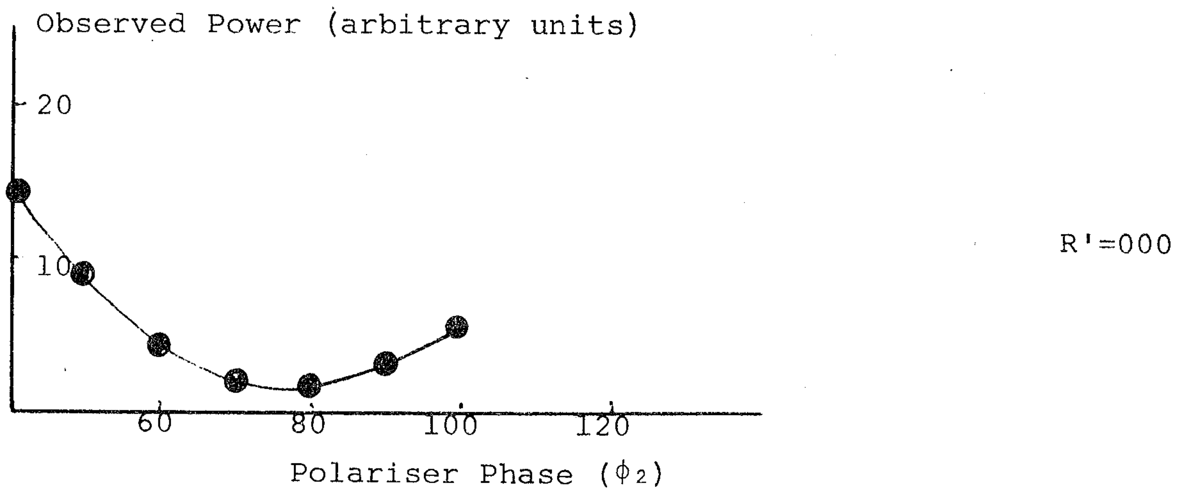


Figure 7b : Detected Power from Horn after combining in 2:1.

APPENDIX 3B

Calibration of Polariser at Sodankylä

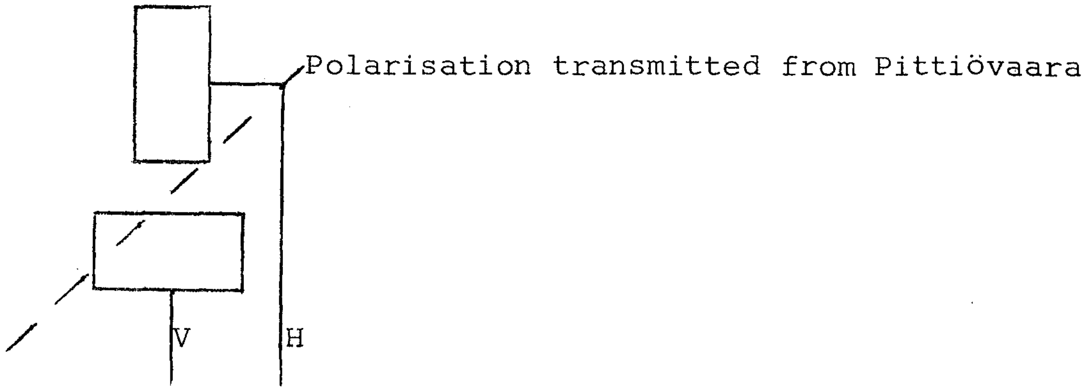


Figure 8 : Looking at Pittiövaara Transmitter from Hub-room at Sodankylä.

Transmissions were made from a site about 10 km from Sodankylä.
With the Yagi mounted horizontally, maximum signal was received in Channel 1 (J4) for a polariser setting of -127.
With the Yagi mounted vertically, maximum signal was received with the polariser setting of +127.
With the Yagi mounted at approximately 45° (as shown above) equal outputs in both Channels were obtained for a polariser setting of +003. The small difference in sensitivity at the two polarisations corresponded to the approximate setting of the Yagi and differences in gain in the two channels of the parametric amplifier.
These measurements gave a satisfactory "spot-check" for the amplitude ratio set by the polariser.
The measurements with the Yagi set at 45° were also used to determine ϕ_3. Note that while the Yagi was set in the conventional position for +45°, and while the horizontal probe from the waveguide was set in the conventional positive sense, the probe from the vertical branch was set in the conventional negative sense, so the vertical signal must be changed in sign in Equations 6 and 7.

Therefore, output from J4 (Channel 1)

$= \quad E_V^* \sin(\phi_1/2)\sin(\omega t-\phi_1/2-\phi_2-\phi_3) + E_H^* \cos(\phi_1/2)\cos(\omega t-\phi_1/2)$

For equal strength signals in the two channels, and for equal phase, we can simplify this to :

$K\{\cos(\omega t) + \cos(\omega t-\phi_2-\phi_3-90^\circ)\}$

Therefore the output = 0 for $-\phi_2-\phi_3-90^\circ = -180^\circ$.

The observed zero is given by $\phi_2 = 280^\circ$ (see Figure 7)

Therefore $\phi_3 = -190^\circ$.

When left-handed circular polarisation is transmitted from Tromsø at azimuth 180.5 and elevation 77.2°, we would expect to receive at Sodankylä from a height of 300 km a right-handed elliptical polarisation, with $E_V/E_H = 0.61$ and $\phi = 105^\circ$

We would therefore expect to receive all the signal in Channel 1 if $R' = -17$ and $\phi_2 = \phi-\phi_3+90^\circ = 25^\circ$

On observing left-handed circular polarisation transmitted from Tromsø at azimuth 180.5 and elevation 77.2 from a height of 300 km, the values of R' and ϕ_2 were adjusted to give a maximum signal in Channel 1. The values derived were $R' = -17$ and $\phi_2 = 33^\circ$. In other words, actual radar observations confirmed the calibration to within the accuracy of measurement for R' and to within 8° for ϕ_2.

By using the optimum polarisation rather than horizontal polarisation, the signal-to-noise ratio in Channel 1 was improved by 1.7 dB. This was better than expected, and corresponded to the fact that the noise temperature on the horizontal channel is higher than on the vertical channel.

Similar measurements were made at Kiruna.

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