Investigation of the polarization of 50 MHz signals via Sporadic-E reflection

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INVESTIGATION OF THE POLARISATION OF 50 MHZ SIGNALS VIA SPORADIC-E REFLECTION

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SUMMARY

Sporadic-E ('Es') layers in the ionosphere allow communication at much higher frequencies than would be possible via the background ionosphere, especially at solar cycle minimum. Es is created by a different mechanism from the background ionosphere and the creation process and structure are not fully understood. Similarly, the way that radio waves propagate via Es is not well characterised. Because of these factors, and particularly because of its intermittent nature, Es is difficult both to predict and to model. For these reasons Es is either represented very simplistically in ionospheric prediction models or it is not included at all.

This paper describes an experimental investigation of differential fading between orthogonal polarisations of 50 MHz signals propagated via Es at oblique angles, aimed at improving our understanding of the underlying mechanisms. Initial results indicate that cross-polarisation fading is frequently significant on a timescale from seconds to minutes.

1 INTRODUCTION

The ionosphere is a region of partially-ionised plasma embedded in the neutral atmosphere at heights from 50 km to 1000 km, although the zone involved in HF radio propagation only reaches up to around 350 km. The ionisation of what we here refer to as the 'background ionosphere' is due to photo-ionisation by solar extreme ultraviolet and X-rays, acting on nitrogen, oxygen and nitric oxide molecules and atomic oxygen. The mechanism for long-distance propagation of HF signals via the ionosphere is well established as magnetoionic refraction [1, 2].

Mid-latitude sporadic-E is an anomalous feature consisting of thin layers of dense but patchy ionisation which occur transiently in the lower ionosphere, at heights between 90 km and 130 km [3, 4]. The process of formation is distinct from that of the background ionosphere. The leading theory is that ions formed from metallic meteor debris (and the associated free electrons) are concentrated vertically by east-west wind shear, which generates a Lorentz force in the presence of the Earth's magnetic field [3, 4]. This can produce ionisation densities much greater than those of the background ionosphere.

Sporadic-E is important for VHF radio propagation because it can support beyond line-of-sight communication, albeit intermittently, at much higher frequencies than propagation via the normal E and F layers. VHF signals via sporadic-E propagation exhibit very rapid fading, much more so than equivalent HF signals via E or F propagation. It is likely that much of this fading is due to the limited size, non-uniform shape and rapid motion of the sporadic-E patches [3], but some studies have indicated that a significant proportion of the fading can be due to rapid polarisation changes [5]. Few systematic experimental studies of the polarisation of VHF waves by oblique Es reflection have been published and the results to date have been inconclusive [5, 6, 7].

In general, linearly-polarised electromagnetic waves cannot propagate in the ionosphere in the presence of the earth's magnetic field without changing their polarisation, because the free electrons in the plasma are constrained to rotate around the lines of magnetic flux. The interaction of an incident linearly-polarised wave with the free ionisation and the magnetic field forces the wave to decompose into 'Ordinary' and 'eXtraordinary' circularly-polarised components with opposite senses of rotation. Within the background ionosphere, the 'O' and 'X' waves travel at different velocities and follow significantly different paths; the polarisation of the downward wave exiting the ionosphere will be some combination of the 'O' and 'X' components, normally resulting in an elliptically polarised wave of variable angle and ellipticity [1, 2]

In principle, this magnetoionic double refraction applies equally to sporadic-E propagation but Es differs from the background ionosphere in a number of significant ways, from its process of formation to the physical characteristics of the ionised layer itself. The differences are summarised in Table 1. The fact that the differences are so dramatic suggests strongly that the received characteristics of radio waves which have been refracted/reflected by sporadic-E may be significantly different from those returned by the background ionosphere.

	Background ionosphere	**Sporadic-E**
Formed by	Ionisation of N_2, O_2, NO, O by solar EUV	Concentration of metallic ions by wind-shear
Horizontal extent	1000s of km	Few to 100s of km
Thickness	100s of km	Few km
Refractive index variation	Gradual	Rapid
Electron density	Smoothly varying	Very 'lumpy'
Mechanism of radio wave propagation	Mainly magnetoionic double refraction	Magnetoionic refraction? Specular? Scatter?
Path length within the ionised layer	Long	Short

Table 1: Summary of differences between sporadic-E and the background ionosphere

Although it is clear that at lower frequencies, radio wave propagation through the background ionosphere is primarily by magnetoionic double refraction, this has not been clearly demonstrated for Es propagation at VHF. The purpose of this research is to gain insight into whether VHF Es propagation exhibits the characteristics of specular reflection, magnetoionic double refraction, or scattering – or some combination of all three.

2 EXPERIMENTS

The incidence of radio propagation via mid-latitude sporadic-E is highly seasonal, with (in the Northern Hemisphere) a strong peak in the number and intensity of events between roughly May and August each year [3, 4]. The presence of 50 MHz radio signals propagated via Es between any two given points is normally short-lived, intermittent, and difficult to predict except in very general terms. For this reason, in order to be sure to gather enough useful data for analysis within a single summer 'Es season' it was decided to monitor multiple signal sources and take opportunities for data collection when Es events occur.

For these experiments amateur 50 MHz stations, including 24-hour beacons, were used as signal sources over ranges between 1,200 km and 2,500 km. Most amateur beacon stations transmit continuously with a power of a few watts into a single-element horizontal or vertical antenna. Other amateur stations typically use transmit power between 100W and 400W to horizontally-polarised Yagi antennas. Once general monitoring has identified a signal from a suitable station, detailed measurement recordings are initiated. To date, measurement campaigns have taken place between May and August in each of 2016, 2017 and 2018.

The receiving station is located in Churt in southern England (51.135 N, 0.784 W). Signals are monitored using a direct-sampling digital receiver with dual, phase-synchronous 16-bit ADCs, controlled by open-source PC-based software. This system gives the ability to make simultaneous horizontally- and vertically-polarised signal measurements at a rate much faster than any previously published study of sporadic-E.

The antenna consists of two identical seven-element LFA2 Yagis, one vertically oriented and the other horizontal, co-located on the same boom. The LFA2 antenna design was selected because of its low sidelobe level, which reduces the reception of local noise. The whole antenna is rotatable in azimuth to direct it towards the remote signal source and it is installed at three wavelengths (18m) above the ground, clear of buildings and trees, in order to isolate it from external influences.

It is necessary to compensate for differential ground gain between the two polarisations. Simulation using NEC-4 of the LFA2 Yagi at 18 m above average ground indicates that the ground gain excess for horizontal polarisation over vertical polarisation is less than 2.5 dB for all radiation angles below 8 degrees from the horizontal, which corresponds to Es reflection distances of 1,200 km or more at median Es layer heights [8]. To compensate for the residual difference in ground gain, a 2 dB correction is applied during data analysis.

Three phases of experiments are reported:

- Phase 1: received power measurements of single sources at 15 samples per second
- Phase 2: 13-second average received power measurements of multiple sources during a single sporadic-E event
- Phase 3: received power and phase measurements of single sources at 6000 – 24000 samples per second

2.1 PHASE 1 EXPERIMENT (May to August 2016)

Equipment for Phase 1 was an Apache Labs ANAN-100D direct sampling dual-channel receiver [9] controlled by PowerSDR OpenHPSDR mRX PC-based software [10] with other station details as described above. Each Yagi antenna was connected to a separate input channel of the receiver. Signal power data were collected using the 'Radio Astronomy' (RA) data logging module built into PowerSDR.

Each data collection run captured amplitude variations for a single signal source with a receiver bandwidth of between 500 Hz (beacons) and 2.7 kHz (SSB voice). Simultaneous measurements of horizontally polarised (H) and vertically polarised (V) signal power were captured at a rate of 15 samples per second, with each individual sample representing a 10 ms average. The difference in power calibration between the two receiver channels was measured to be less than 1dBm.

Measurements of receiver input power were converted to amplitude and then a pseudo polarisation angle was calculated from each H and V sample pair. As these power measurements do not contain phase information, zero phase difference between the H and V signals was assumed, although this may not be true in reality.

2.2 PHASE 2 EXPERIMENT (May to August 2017)

To provide a higher volume data collection facility, another technique was developed for Phase 2 to allow thousands of longer-period (approximately 13 second average) polarisation measurements of European amateur digital signals during a single Es event.

The same receiver and antennas were used as for Phase 1 but rather than using the PowerSDR RA facility, receiver audio was fed from PowerSDR to dual instances of JTDX digital communications software [11] which were used to decode amateur digital communications using the FT8 protocol [12]. Each individual FT8 signal has a bandwidth of 50 Hz, allowing many signals to be monitored simultaneously within an overall receiver bandwidth of 3 kHz.

FT8 transmissions operate on a 15 second transmit/15 second receive cycle. JTDX calculates and records an estimated signal to noise ratio (SNR) for each decoded signal, effectively representing a 13-second average value. A pseudo polarisation angle was calculated using the same technique as in Phase 1, with the addition of the calculation of a derived signal power based on the recorded SNR and measured receiver noise levels from the horizontal and vertical antennas. The difference in receiver noise level between the two antennas at the chosen azimuth was less than 1dBm.

2.3 PHASE 3 EXPERIMENT (May to August 2018)

The techniques used in Phase 1 and Phase 2 capture differential amplitude fading but do not measure the phase difference between the horizontally and vertically polarised components of the received signal**.** The true shape and orientation of the polarisation ellipse is directly related to the phase difference between the orthogonally-polarised components; knowledge of the relative phase is also necessary to distinguish between right-hand and left-hand circular/elliptical polarisation.

Equipment for Phase 3 was an Apache Labs ANAN-8000DLE direct sampling dual channel receiver [9] with other station details as described above. In order to be able to fully characterise the polarisation of the received signals, simultaneous real-time digital IQ samples were recorded direct from PowerSDR for both H and V polarisations, at between 6000 and 24000 samples per second.

3 EXPERIMENTAL RESULTS

3.1 PHASE 1 RESULTS (May to August 2016)

Observations were captured during twenty Es openings across a range of distances and azimuths. Representative samples are shown in Figures 1 to 3.

Figure 1 shows the amplitudes of the horizontal and vertical polarisation components of an Es signal from a station in Sardinia, at a range of 1,515 km. Figure 2 shows the calculated pseudo polarisation angle for the same signal. It can be seen that the received polarisation apparently changes from 45 degrees, to close to horizontal, then close to vertical, and again back to horizontal over a period of about 200 seconds. The transmitted polarisation was horizontal [13].

Figure 3 shows the calculated pseudo polarisation angle for a single-hop Es signal from a beacon station in Rome, at a distance of 1,448 km. Note the expanded timescale v/s Figures 1 and 2. It can be seen that the received polarisation is continuously changing on a period of a few seconds, from nearly vertical to nearly horizontal and back again.

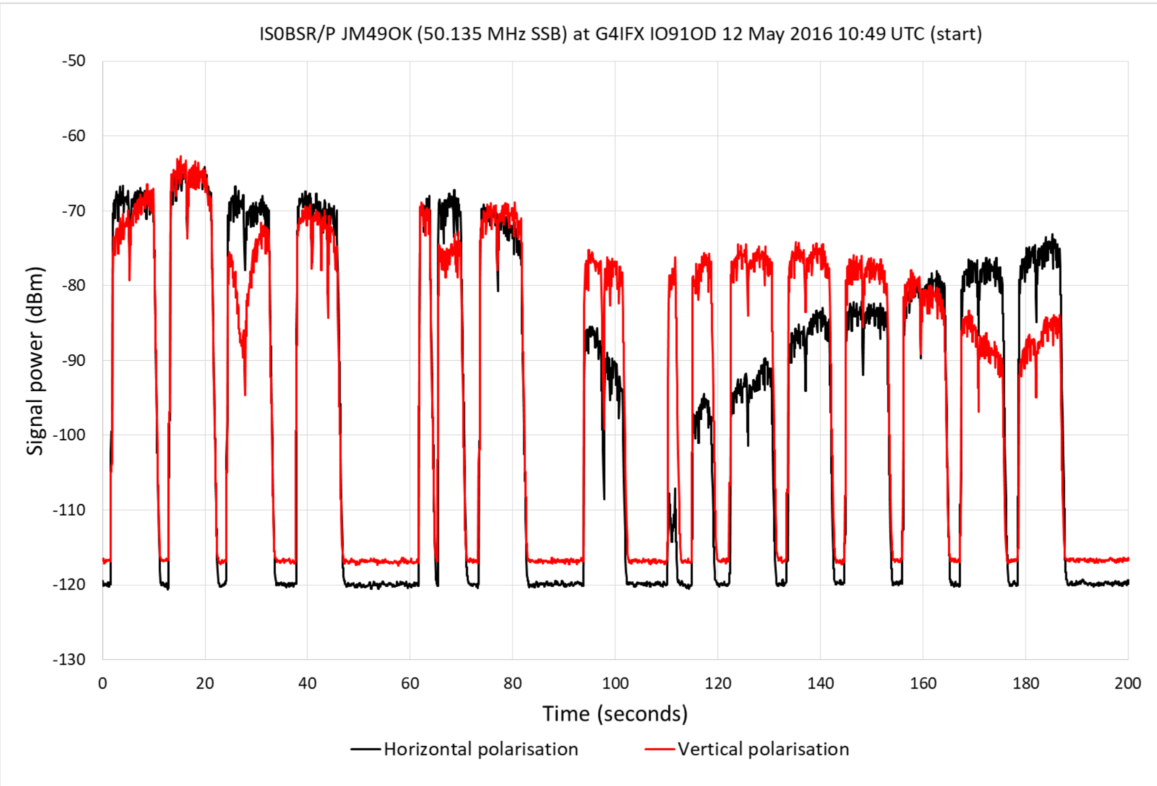

Figure 1: Signal power v/s time, Sardinia to UK 12 May 2016 – 1,515 km. Single-hop Es.
SSB voice transmission. Transmitted polarisation: horizontal.

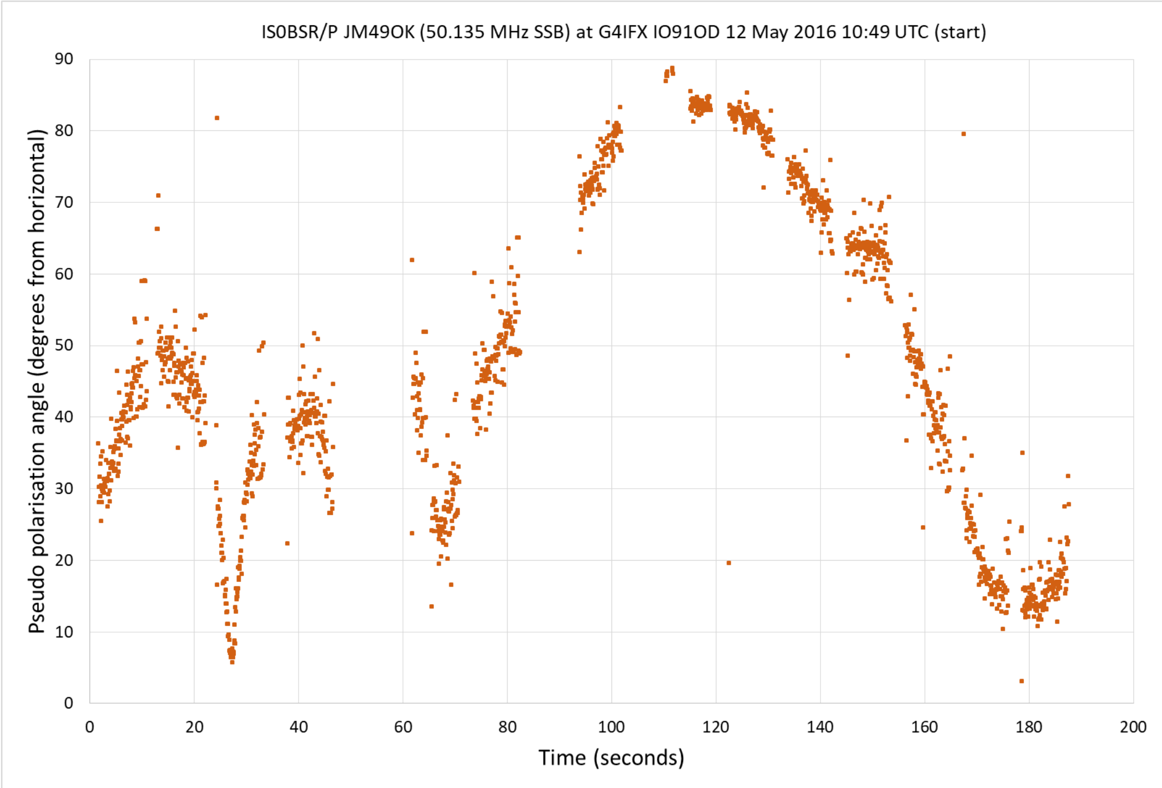

Figure 2: Calculated pseudo polarisation angle (0 degrees = horizontal) for the record in Figure 1.
Transmitted polarisation: horizontal.

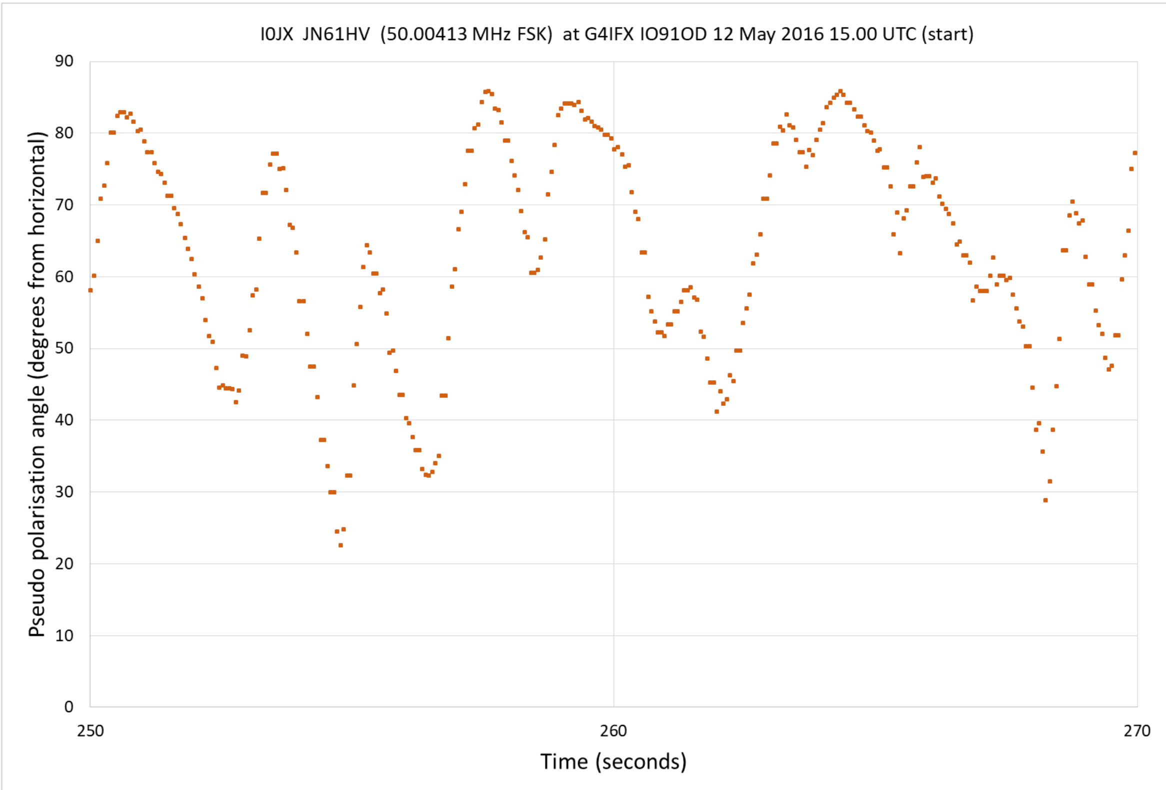

Figure 3: Calculated pseudo polarisation angle (0 degrees = horizontal) vs time for a single-hop Es signal from Rome, received in the UK (1,448km) on 12 May 2016.
Transmitted polarisation: vertical. Receiver bandwidth 600Hz. Note the expanded timescale.

Overall, the Phase 1 measurements indicate clearly that, once common-mode amplitude fading has been factored out, significant differential-mode fading remains between the two received linear polarisations.

As the pseudo polarisation angle was calculated without information on the phase difference between the H and V signals, the actual polarisation angle may differ from the values shown. However, the results clearly show that polarisation fading does occur, over timescales which range from seconds to minutes.

3.2 PHASE 2 RESULTS (May to August 2017)

Figure 4 shows a histogram of calculated pseudo polarisation for a long sporadic-E event in July 2017. 1,975 13-second-average data points are plotted, from 94 different stations at ranges between 1,200 km and 2,500 km in a roughly easterly direction from the UK.

These results indicate that over the whole duration of this Es event, the average pseudo polarisation angle, calculated as before, was about 45 degrees to the horizontal, albeit with a broad spread. Signals for which only the H or V component was decoded have been excluded, hence there are no results at the extremes either side of the mean. To ensure that this effect has not biased the results, alternative scenarios were investigated whereby the noise floor was artificially raised to remove weaker signals from the analysis. As expected, the spread of polarisations was reduced in such cases but the basic shape of a Gaussian distribution with a mean of about 45 degrees was maintained. This indicates that the inevitable presence of a signal detection threshold does not fundamentally change the nature of the result.

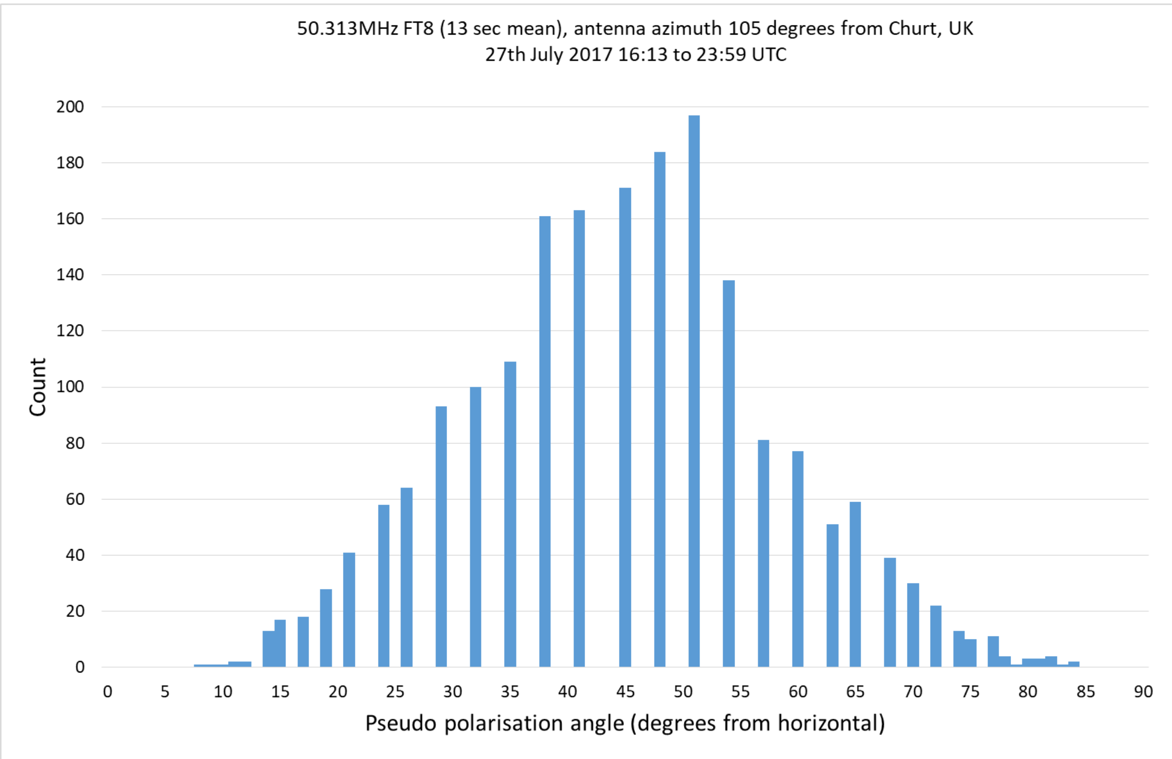

Figure 4: Histogram of calculated pseudo polarisation angle of signals received (0 degrees = horizontal) during a long Es opening from 16:13 to 23:59 UTC on 27 July 2017. Based on 13-second averages. Incorporates 1,975 data points from 94 different stations, 1200km - 2500km range. Transmitted polarisation: assumed horizontal.

3.3 PHASE 3 RESULTS (May to August 2018)

Twenty recordings, totalling over 13 hours duration, were made of signals via Es from nine different amateur beacon stations during Phase 3. Analysis is still underway but initial indications are that at least some received signals are strongly elliptically polarised (rather than linearly polarised) for periods of minutes at a time.

4 DISCUSSION

In summary, these experiments indicate that 50 MHz signals reflected/refracted via sporadic-E tend to exhibit a strong axis of polarisation which rotates over periods of seconds or minutes. Averaged over longer periods and over a range of different paths during a long Es event, the average pseudo polarisation angle (ignoring phase) has been shown to tend to about 45 degrees to the horizontal. The results are consistent with Es signals being strongly elliptically polarised with a rotating major axis, suggesting that a significant proportion of the fading observed in VHF Es signals is from that cause.

As the techniques used in phases 1 and 2 do not measure the phase difference between the horizontally and vertically polarised components of the received signal, they do not completely characterise signal polarisation. Initial analysis of some of the Phase 3 measurements, which do include differential amplitude and phase, indicates that received signals are indeed at least sometimes elliptically polarised.

While the rapid polarisation variations observed in Phases 1 and 2 are believed to be real, the results can only be regarded as indicative so far. This is now the subject of further work, alongside ray trace modelling to compare theory with experiment.

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