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34

Total electron content of the ionosphere
north of Macquarie Island

Malcolm Lambert
Peter Jacklyn
E.A. Cohen

ANTARCTIC DIVISION
DEPARTMENT OF SCIENCE

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TOTAL ELECTRON CONTENT OF THE IONOSPHERE
NORTH OF MACQUARIE ISLAND

by

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ABSTRACT

The Faraday rotation/total electron content experiment operated on Macquarie Island from 28 December 1983 to 10 March 1985 is described. Faraday rotation theory is briefly reviewed and the format of digital data stored on hard disc and magnetic tape is described. Digital Faraday rotation data collected on Macquarie Island, is presented in graphical form.

STATE ELECTRIC COMPANY OF THE DISTRICT OF COLUMBIA
STATE OF MARYLAND

vs.

Wilson Jackson and Peter Jackson
Scientific Division
Department of Energy
Kingdom, Tennessee, Australia

and

D.A. Cohen
Division of Technical and Special Services
Lafayette University
Lafayette, Virginia, Australia

Plaintiff

The following is a copy of the original complaint captioned as above and filed in the District Court of the District of Columbia on or about the 15th day of August, 1983. The original complaint is captioned as above and is filed in the District Court of the District of Columbia on or about the 15th day of August, 1983. The original complaint is captioned as above and is filed in the District Court of the District of Columbia on or about the 15th day of August, 1983. The original complaint is captioned as above and is filed in the District Court of the District of Columbia on or about the 15th day of August, 1983.

1. THE FARADAY ROTATION TECHNIQUE

Temporal changes in the ionospheric total electron content (TEC) can be accurately determined by monitoring changes in the Faraday rotation of geostationary satellite beacon signals. As a linearly polarised VHF radio wave propagates through the Earth's ionosphere, its angle of polarisation is rotated. The ionosphere consists of a reasonably even distribution of free electrons and positive ions in a magnetic field. VHF radio waves propagating through this medium will be effectively split into two waves, circularly polarised in opposite senses. These are the characteristic waves. The Appleton equations show that the two characteristic waves experience slightly different refractive indices (Ratcliffe 1959). They therefore propagate at slightly different speeds. The differential propagation of the characteristic waves will cause the resultant linearly polarised wave to have its angle of polarisation rotated. The amount of rotation is proportional to the integrated free electron content and longitudinal magnetic field strength from the satellite to the receiver, (Davies 1969).

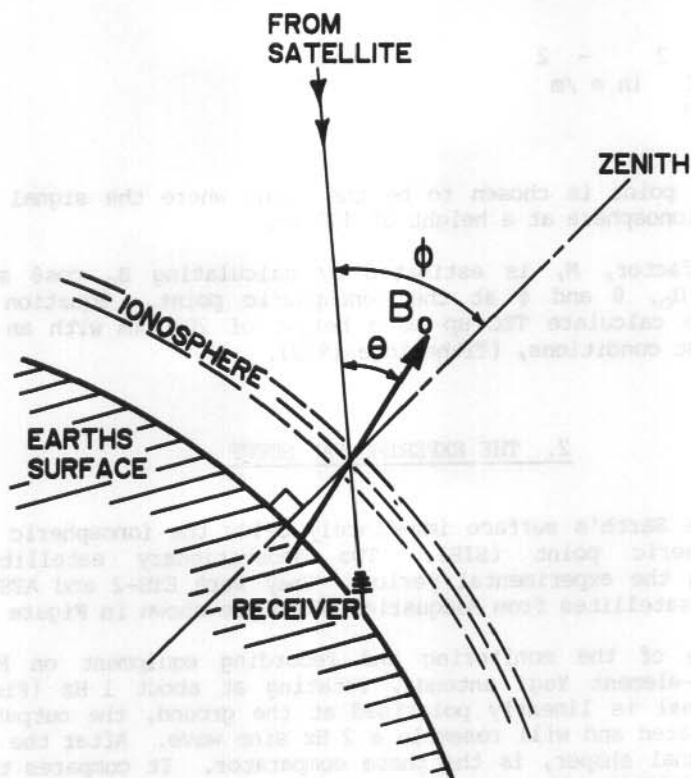


Figure 1. Geometry of the satellite to receiver ray path, and the magnetic field in the ionosphere.

TEC is generally measured as the number of electrons in a vertical column of area 1 m^2 . Slant TEC must be divided by the cosine of the zenith angle of the ray path in converting it to vertical TEC (Figure 1). A derivation of the relationship between Faraday rotation and TEC using the Appleton equation is given by Davies (1969). This relationship is as follows,

$$\Omega = \frac{K}{f^2} \int NB_0 \cos\theta \sec\phi \, dh$$

where

Ω = Faraday rotation in radians

$K = 2.365 \times 10^4$

f = wave frequency in Hz

N = electron density in e^-/m^3

B_0 = Earth's Magnetic Field strength in gauss

θ = angle between ray path and B_0

ϕ = zenith angle of ray path

h = vertical distance

If M equals the average value of $B_0 \cos \theta \sec \phi$, then

$$\text{TEC} = \int N dh \quad \frac{\Omega f}{KM} \quad \text{in } e^-/\text{m}$$

The ionospheric point is chosen to be the point where the signal ray path intersects the ionosphere at a height of 400 km.

The Faraday M-factor, M , is estimated by calculating $B_0 \cos\theta \sec\phi$ from the values of B_0 , θ and ϕ at the ionospheric point. Equation (2) can then be used to calculate TEC up to a height of 2000 km with an accuracy of $\pm 3\%$ under most conditions, (Titheridge 1972).

2. THE EXPERIMENTAL SETUP

The point on the Earth's surface immediately below the ionospheric point is the sub-ionospheric point (SIP). Two geostationary satellites were monitored during the experimental period. They were ETS-2 and ATS-1. The SIP's for these satellites from Macquarie Island are shown in Figure 2.

The first stage of the monitoring and recording equipment on Macquarie Island was a 5-element Yagi antenna, rotating at about 1 Hz (Figure 3). Because the signal is linearly polarised at the ground, the output of the antenna is modulated and will resemble a 2 Hz sine wave. After the pre-amp, receiver and signal shaper, is the phase comparator. It compares the phase of the wave modulating the signal with the phase of a locally produced modulator or reference wave. The changes in the output of the phase comparator are directly proportional to the changes in Faraday rotation which in turn are directly proportional to changes in TEC.

Table 1 gives various parameters for the satellites ETS-2 and ATS-1. Some values for ATS-1 are averaged as this satellite is not in a perfect geostationary orbit. It oscillates 11° either side of the equator with a period of one sidereal day.

Satellite	ETS-2	ATS-1
Position	130°E, 0°S	166°E, 0°S av.
Height	35 800 km	35 800 km
Frequency of beacon signal	136.112 MHz	137.35 MHz
Sub-ionospheric point	152.7°E, 48.3°S	160.0°E, 48.5°S av.
M-factor	0.67355	0.71362 av.
Δ TEC for	$37 \times 10^{15} e^-/m^2$	$35 \times 10^{15} e^-/m^2$ av.
$\Delta \Omega = \pi$ rad		
Elevation from Macquarie Is	20°	28° av.
Azimuth from Macquarie Is	326°	9° av.

Table 1. Various parameters for the geostationary satellites ETS-2 and ATS-1.

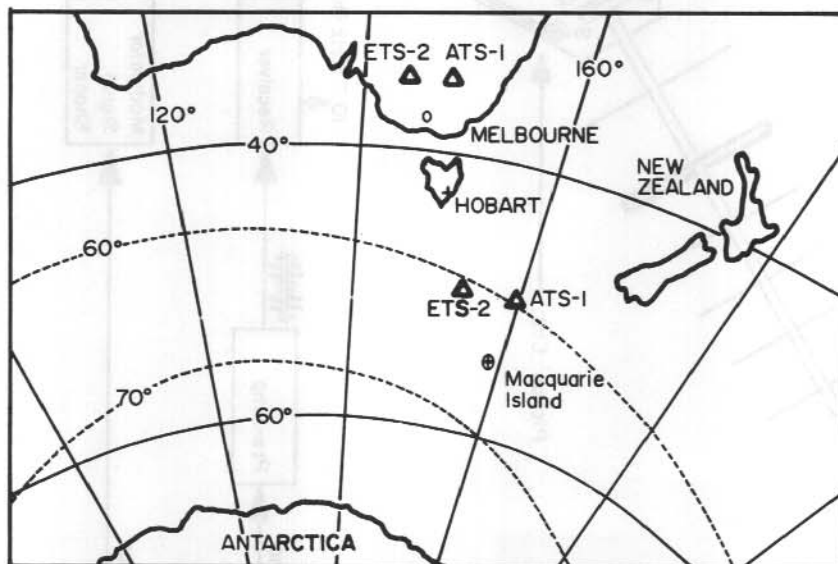


Figure 2. The location of the sub-ionospheric points (Δ) from Macquarie Island (lower pair) and from Melbourne. The dashed lines represent geomagnetic latitude.

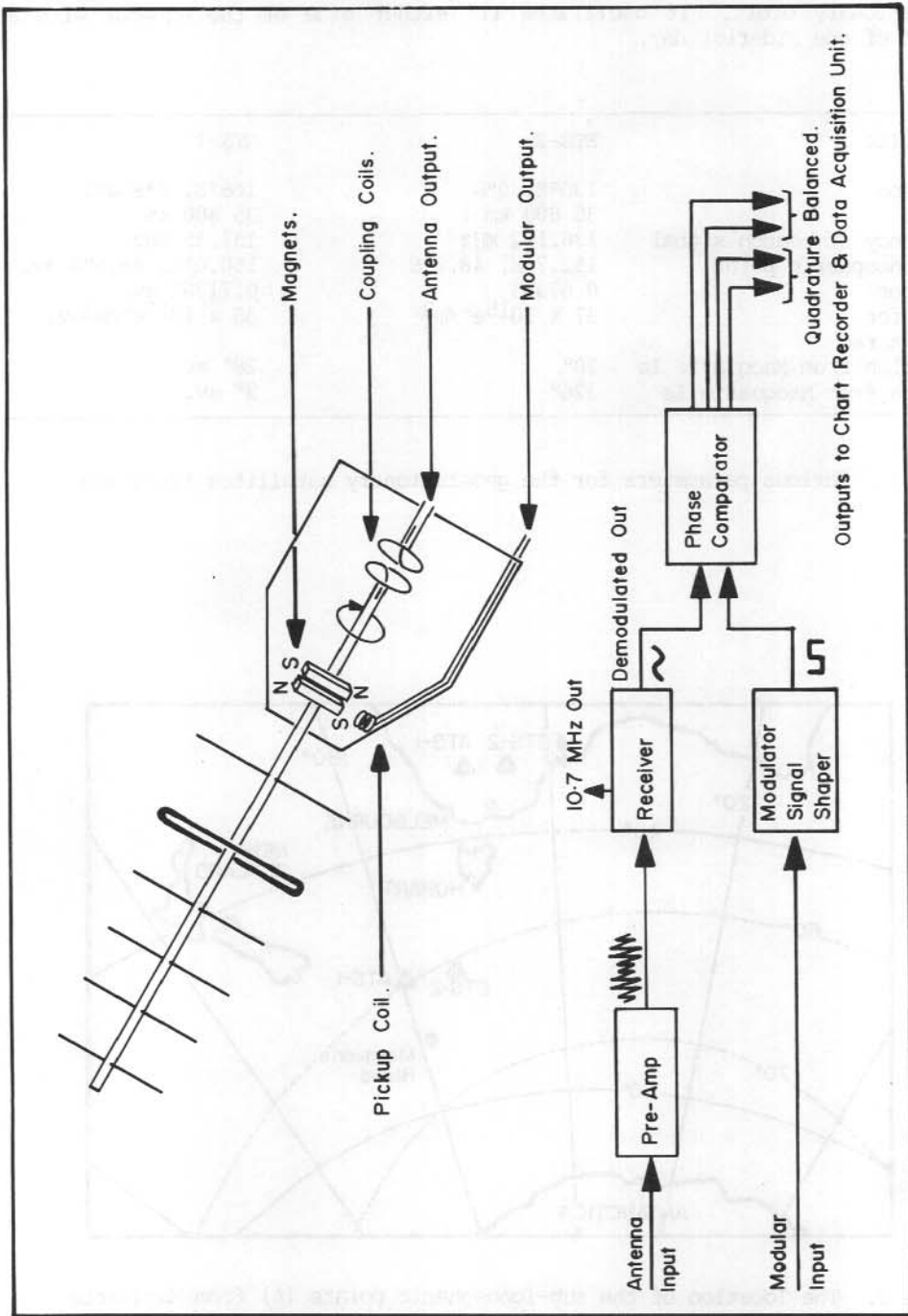


Figure 3. Schematic diagram of rotating antenna assembly and receiver components.

Between March 1984 and September 1984 the satellite ATS-1 drifted from 165.5°E to 166.5°E. This slight variation will not effect the results significantly.

Chart records of Faraday rotation started on 28 December 1983 and digital tape records commenced on 16 March 1984. During the first four months of operation there were many gaps in data collection due to antenna breakages and faults in the digital data acquisition unit. From 20 April 1984 to 4 March 1985 the few days of missing data were due to faulty cassettes, strong radio interference and short-term equipment failures. Most of the data were obtained by monitoring ETS-2. ATS-1 was monitored for a few weeks either side of the equinoxes because the transmitter on ETS-2 was turned off at that time of the year.

3. THE DIGITAL DATA

In the plots, the sample period is thirty seconds and the minimum step in the vertical direction is 1.125° or 1.964×10^{-2} radians. The zero point on the vertical axis is arbitrary and does not indicate the baseline of the data. The total number of rotations undergone by the signal from the satellite to the receiver can not be determined by monitoring the Faraday rotation alone. The baseline can be estimated by using the relationship which states that TEC is proportional to $(foF2)^2$. foF2 is the second critical frequency of the F-region ionosphere, as determined from the ordinary wave reflection, using an ionosonde. Preliminary analysis of the Macquarie Island Faraday rotation data and Macquarie Island ionosonde data suggests that the average night-time minima in total Faraday rotation is of the order of 1π radian.

On reducing the digital data to a presentable form, many false phase changes were removed. These were caused by interference from orbiting satellites. The interference generally lasted for five to ten minutes but could last for up to thirty minutes in some cases. In the digital data, the interference was replaced by a straight line of negative values. The absolute value of all the data was plotted. About 5% of the data were affected in this way.

During some night-time periods, data collection coincided with strong auroral activity near Macquarie Island. The rapid fluctuations in Faraday rotation on these nights rendered the data unreliable for periods of, from half an hour to up to three or four hours. Even the continuous chart records for these periods are difficult to interpret. As a consequence, care must be taken in using data from nights exhibiting strong Faraday rotation scintillations. The general form of the scintillations are accurate, but groups of, or individual peaks and troughs may be too high or too low by 1π radian, e.g. days 267, 292 and 306.

Data obtained by monitoring ATS-1 is uncorrected for the satellites daily oscillation over the equator. This motion will cause a continuously changing sub-ionospheric point and Faraday M-factor. It will not affect the interpretation of most features seen in the plots. Table 2 summarises the diurnal and annual variation of SIP and M-factor for ATS-1. These variations approximately follow sidereal time, so that for increasing dates, the times in Table 2 are decreased by about four minutes per day.

ATS-1 Latitude (Longitude \approx 166°E)	SIP Latitude (Longitude \approx 160°E)	M	Times of occurrence for	
			21/3/84	21/9/84
11°N	45.0°s	0.82	0855Z	2038Z
0°s	48.5°s	0.71	303Z and 15027Z	0242Z and 1444Z
11°s	50.5°s	0.65	1502Z	0836Z

Table 2. Summary of the diurnal and annual variation of the sub-ionospheric point and Faraday M-factor for ATS-1 from Macquarie Island.

The digital data presented in graphical form here has been stored in daily files on RLO2 hard disc and on magnetic tape in VAX/VMS BACKUP format. Each file consists of a string of integers, where the first thirteen integers contain date, time, etc. data. The rest of the integers to the end of the file are sequential data values, recorded at thirty second intervals. A one-unit change in the digital data represents a change in polarisation of 1.125°.

The following is an example of the beginning of a daily file:

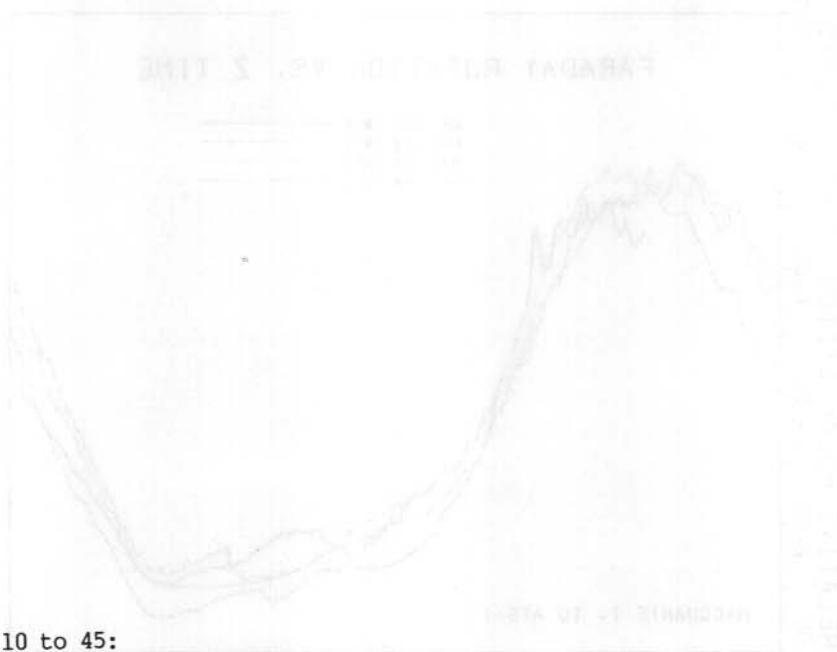
DATA	EXPLANATION
1	Hour Universal time and date of start of daily file =
31	Minutes 01:31:04Z
4	Seconds
6	Day
10	Month 6 October 1984
84	Year
0	Sample period in minutes = 0
30	Sample period in seconds = 30 seconds
2	Number of channels in original file (can be ignored).
2698	Number of samples in this file
2	Difference between beginning of this file and end of last file
4760	Minimum value in file
5239	Maximum value in file
5232	Data values to end of file
5234	
5235	
5233	
-5233	Section of data where
-5233	interference in original
-5232	data has now been replaced
-5232	by a straight line of
5231	negative numbers
5233	
5235	
.	
.	
.	
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Before plotting the data were smoothed using a sliding window. This was done to remove grassiness from the data. The window was nine units in width and averaged the data in the ratio 1:2:3:4:5:4:3:2:1.

Table 3 summarises the coverage of digital data collection during the experimental period.

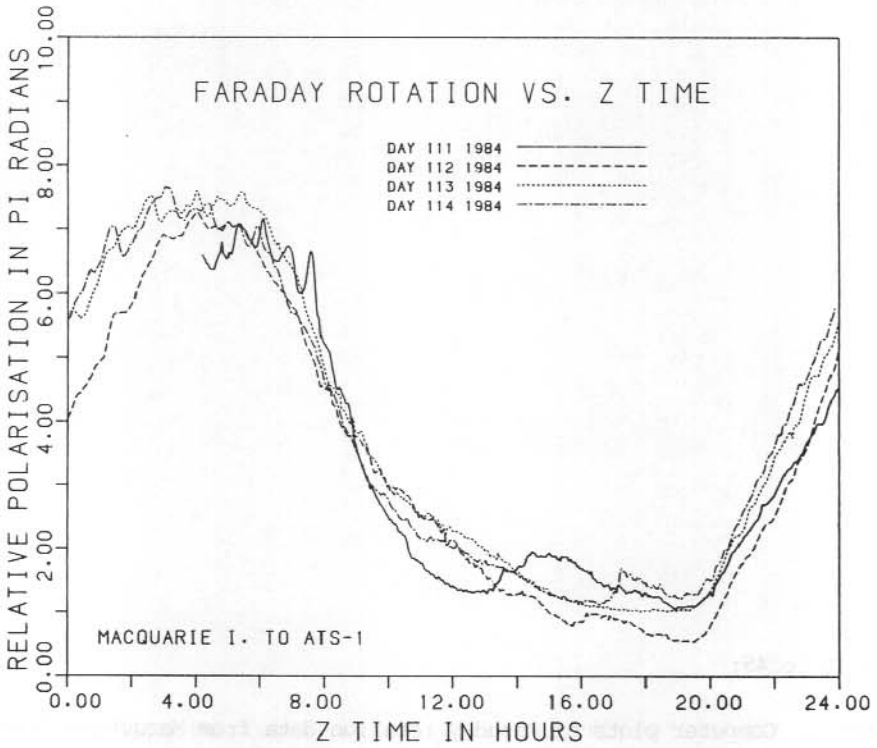
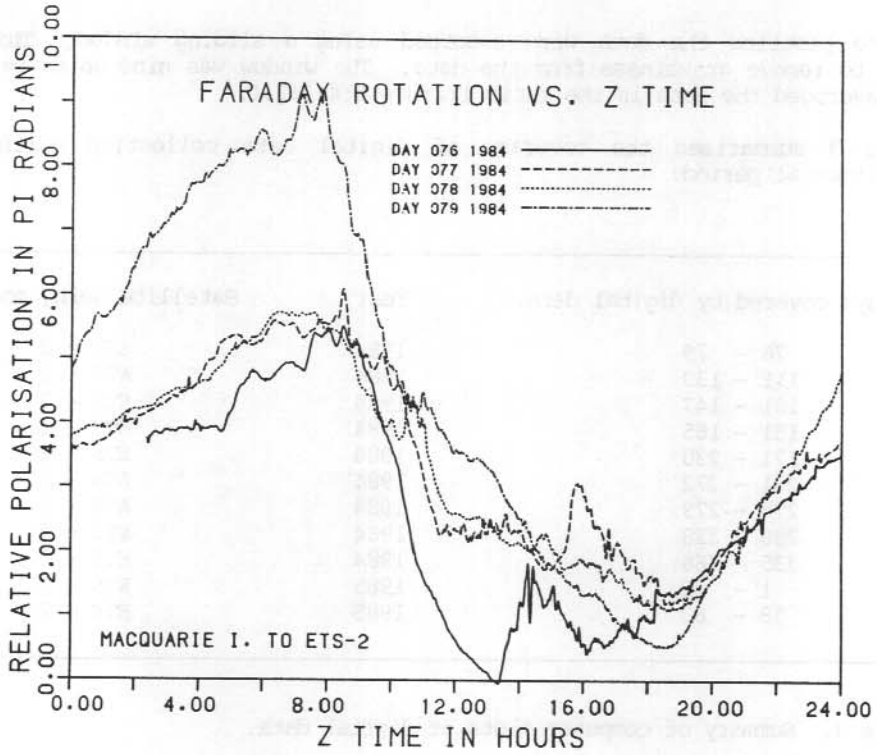
UT days covered by digital data	Year	Satellite being monitored
76 - 79	1984	ETS - 2
111 - 130	1984	ATS - 1
131 - 147	1984	ETS - 2
151 - 165	1984	ETS - 2
171 - 230	1984	ETS - 2
231 - 272	1984	ATS - 1
276 - 279	1984	ATS - 1
280 - 328	1984	ETS - 2
335 - 366	1984	ETS - 2
1 - 32	1985	ETS - 2
58 - 63	1985	ETS - 2

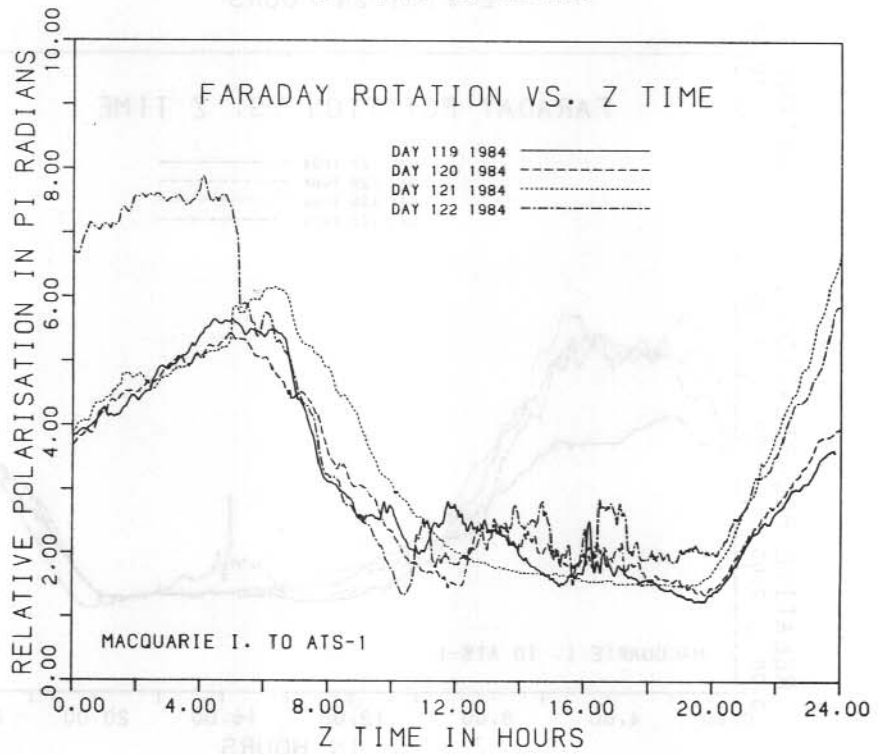
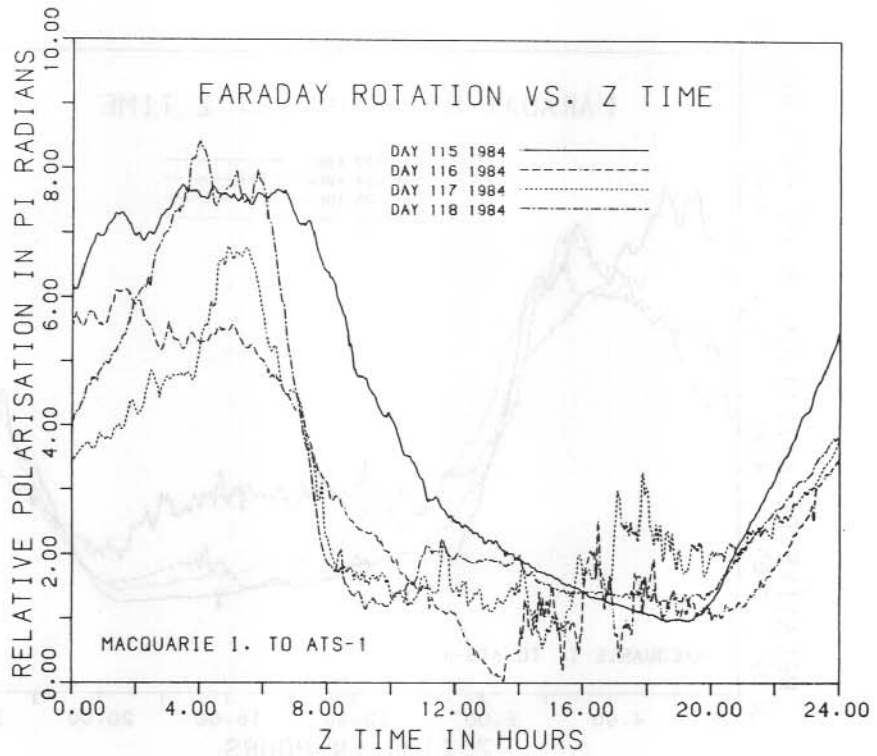
Table 3. Summary of computer plots of digital data.

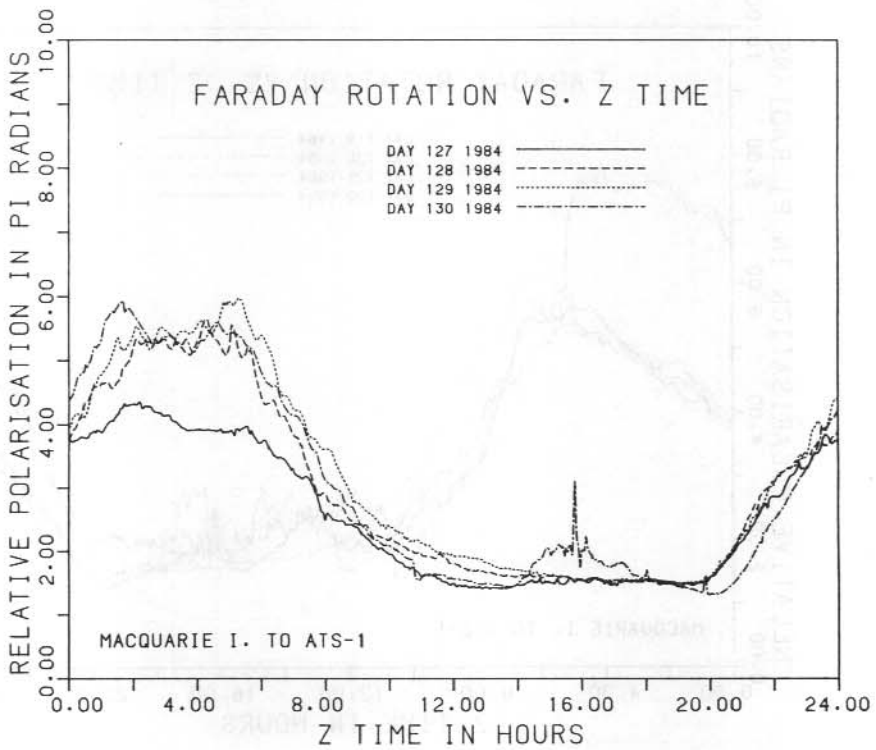
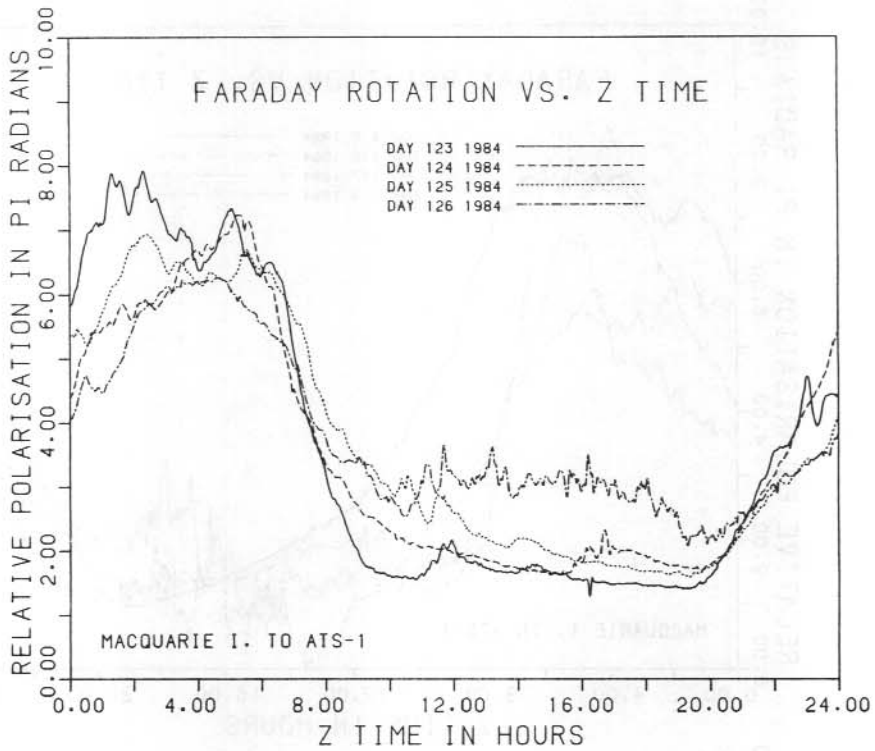


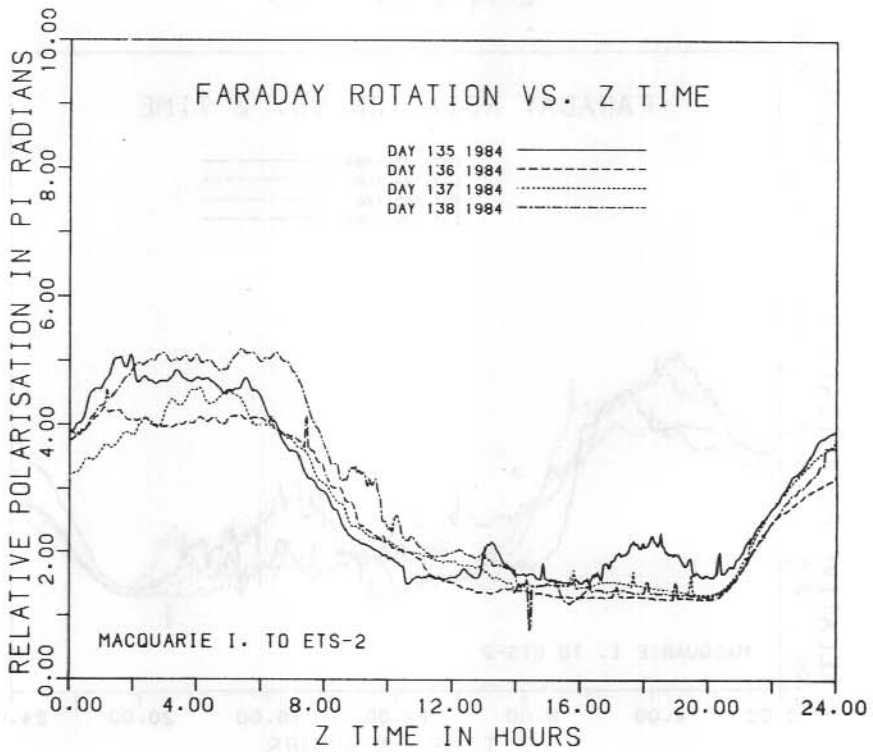
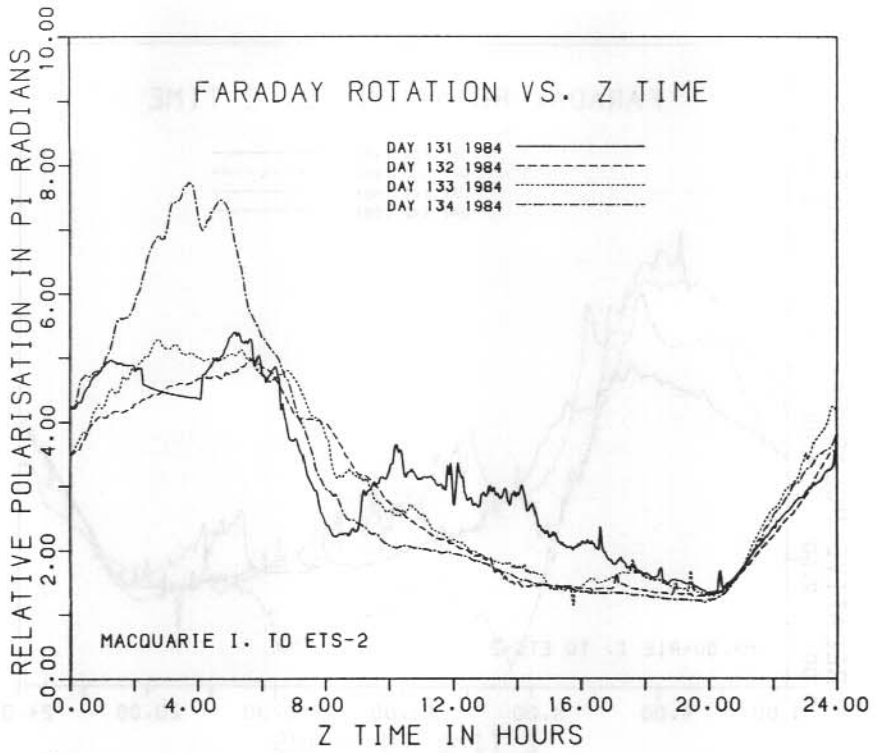
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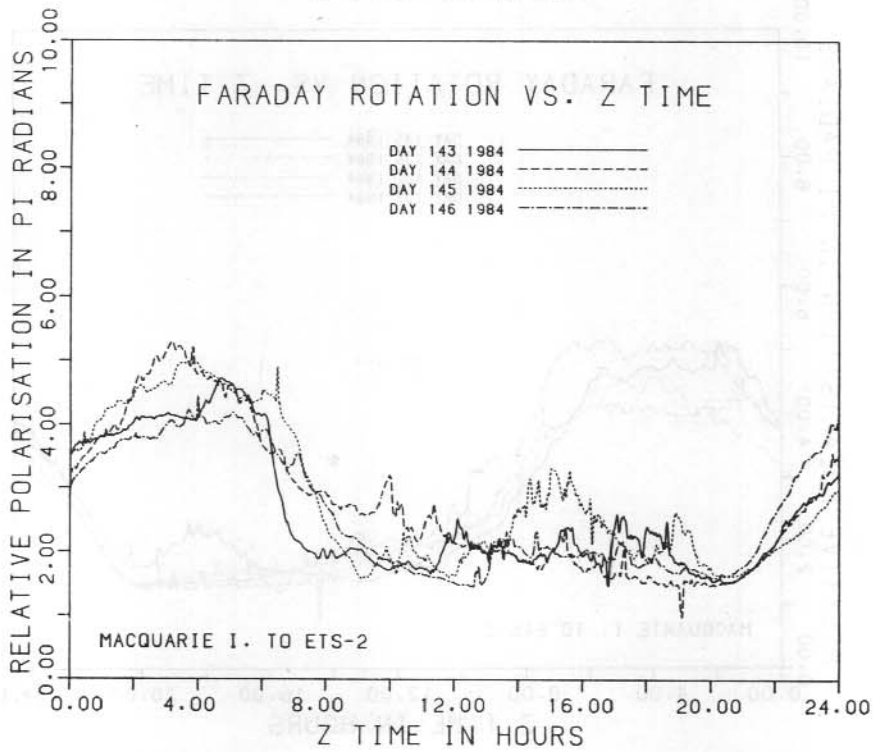
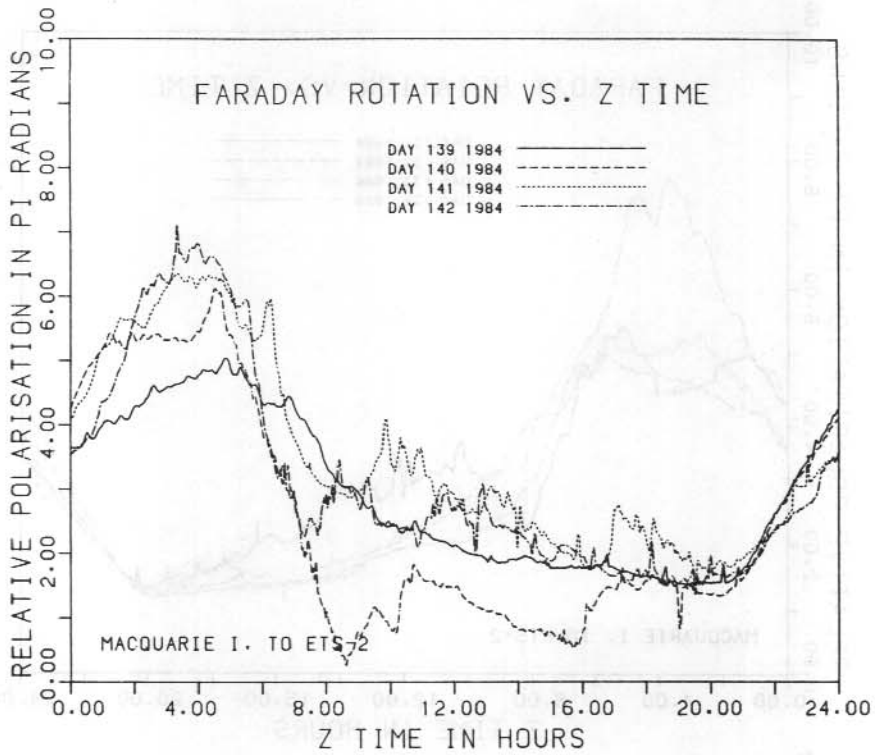
Figure 4. Computer plots of Faraday rotation data from Macquarie Island.

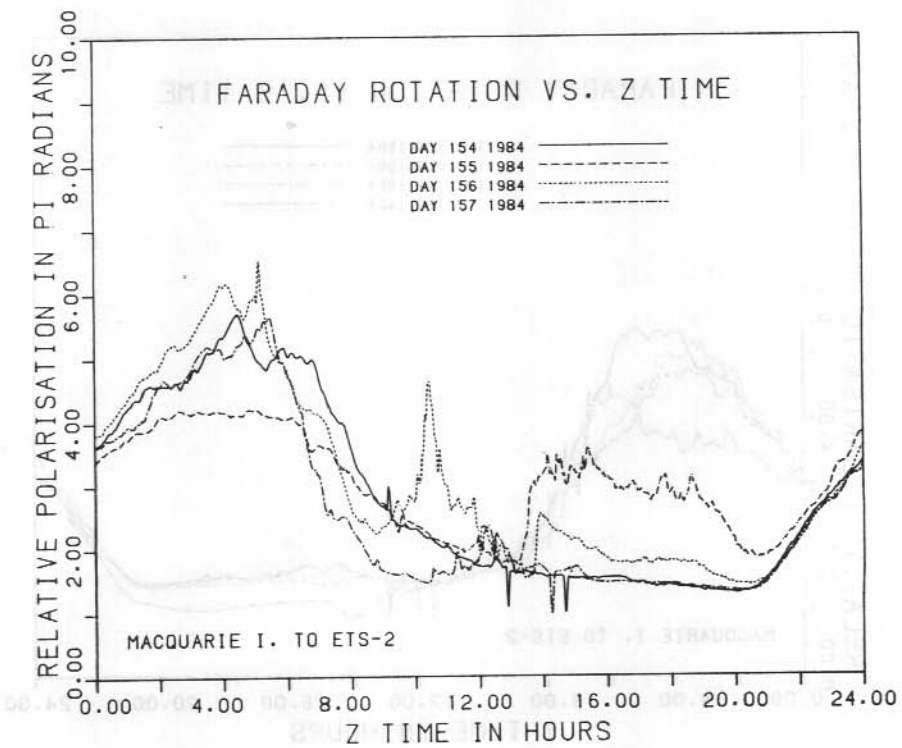
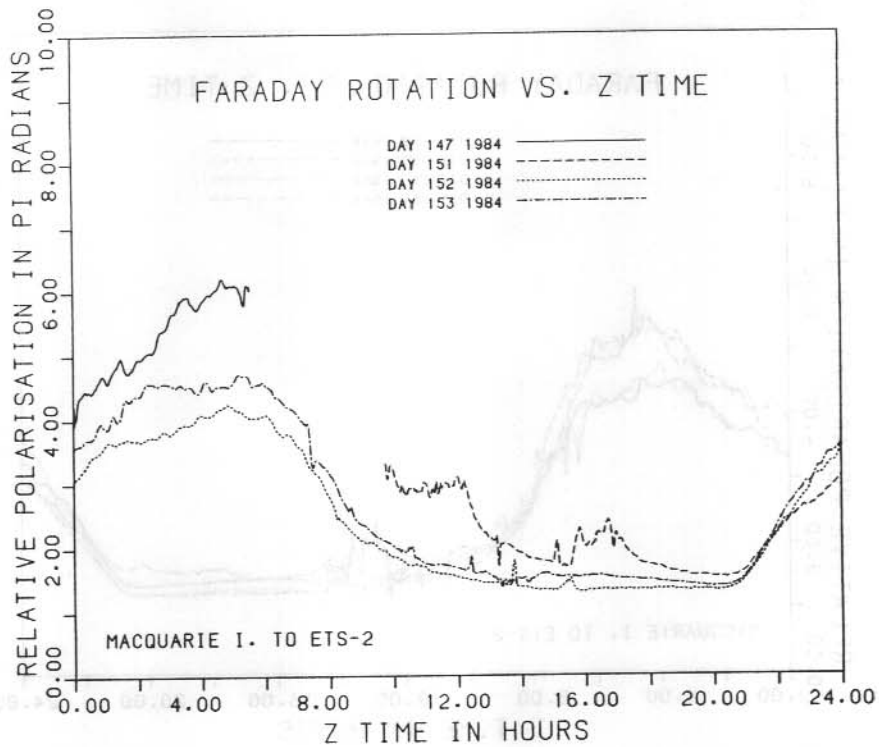


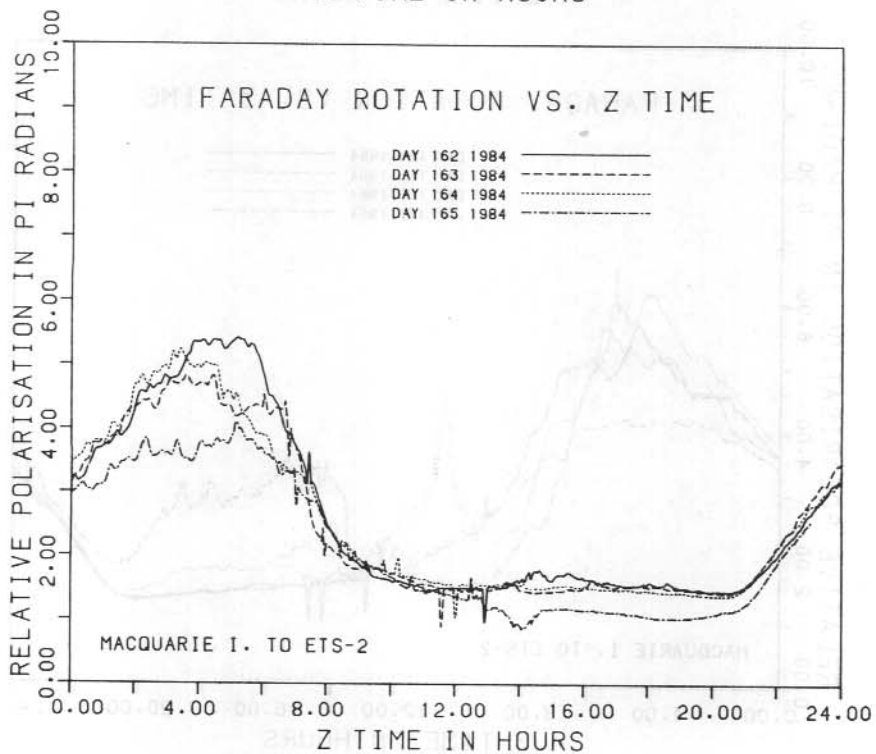
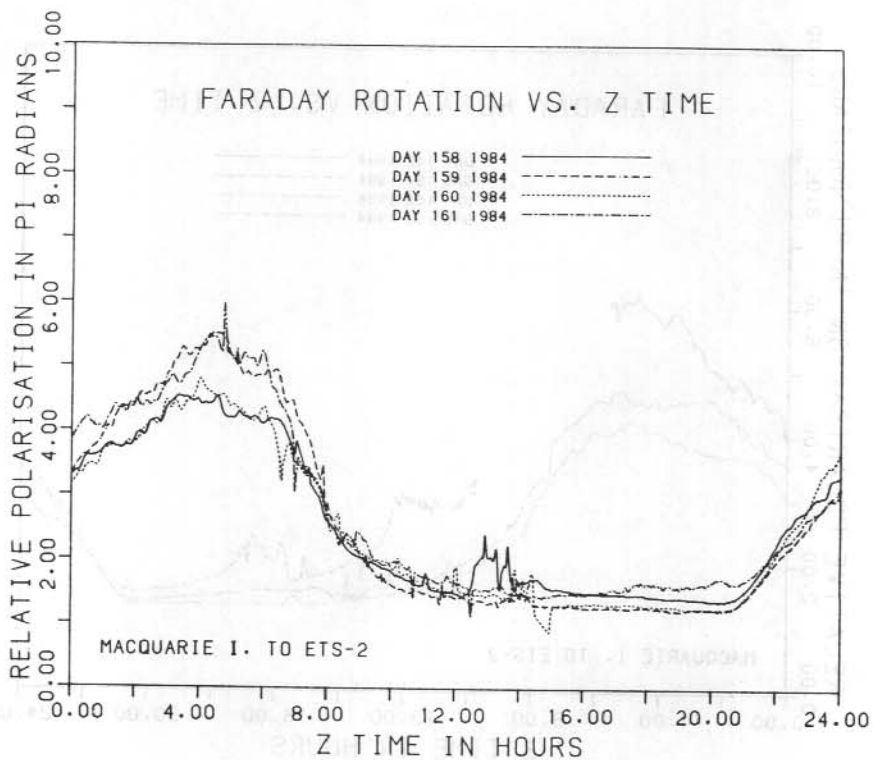


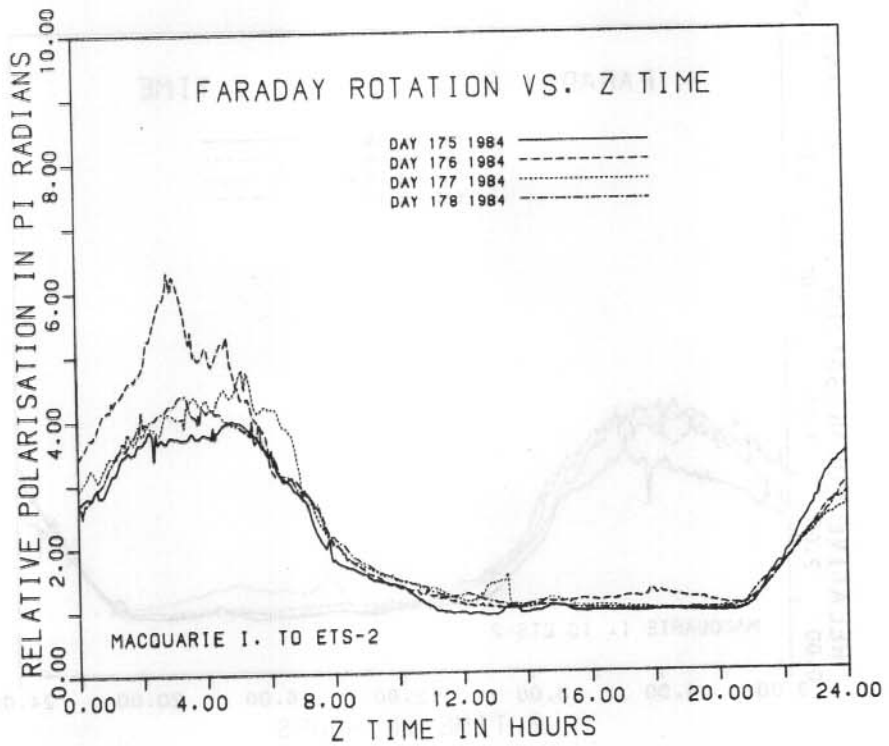
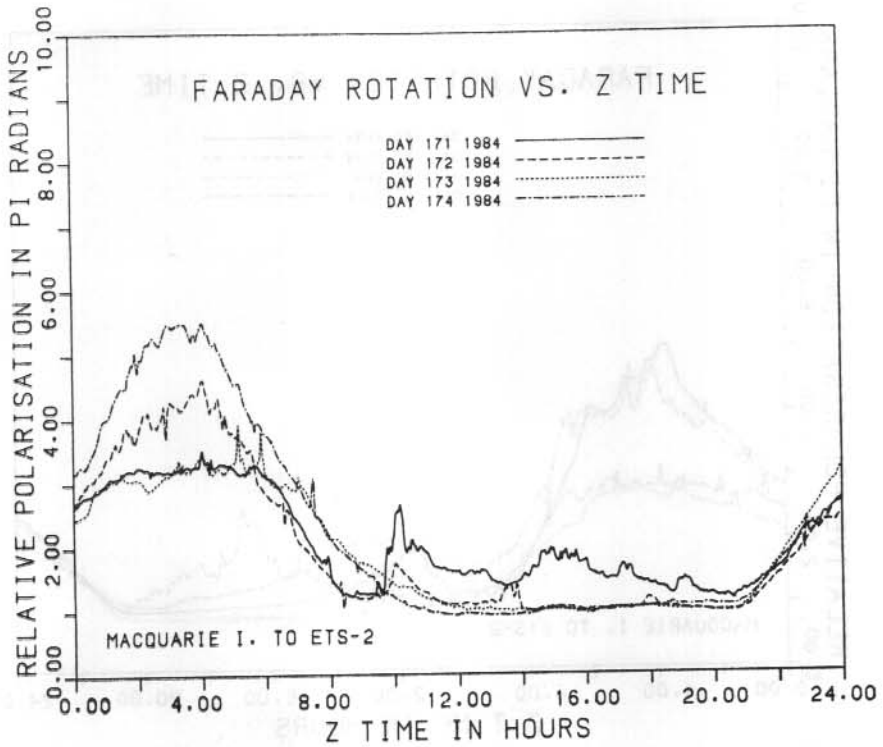


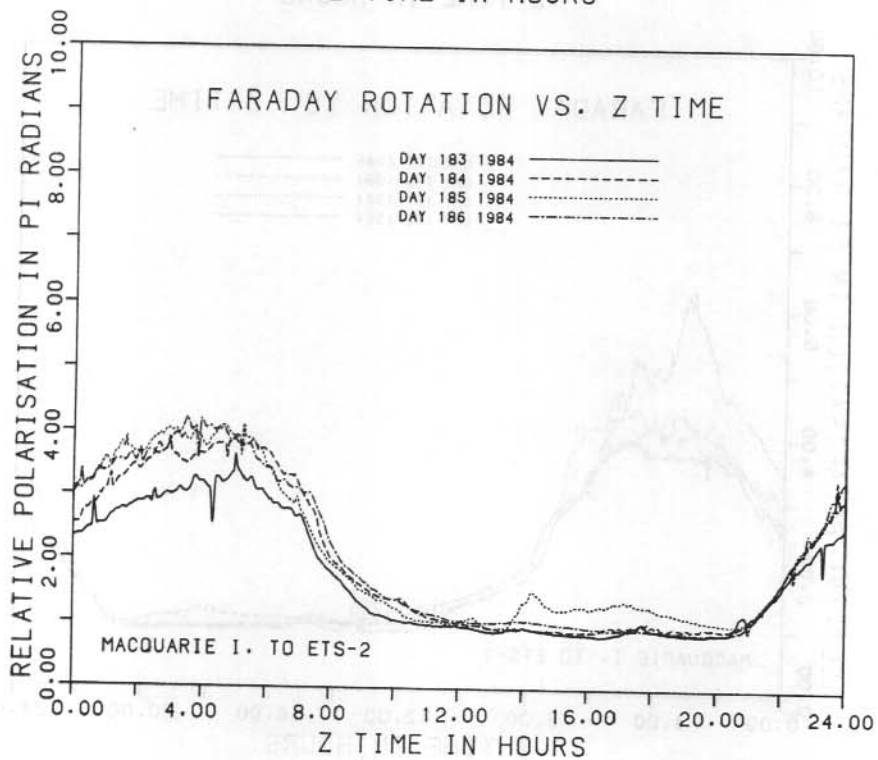
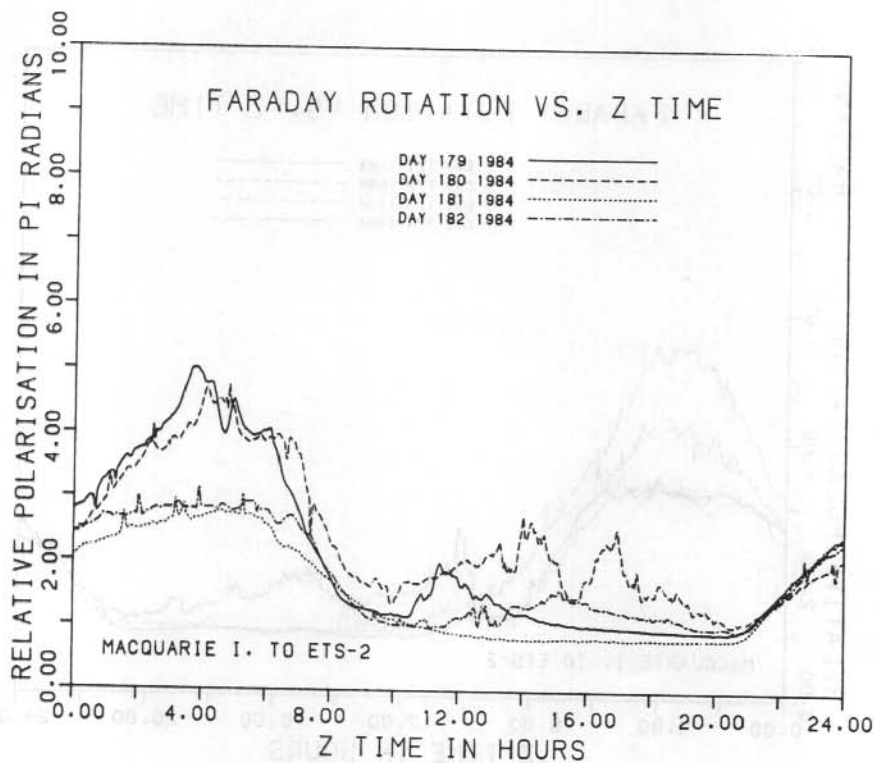


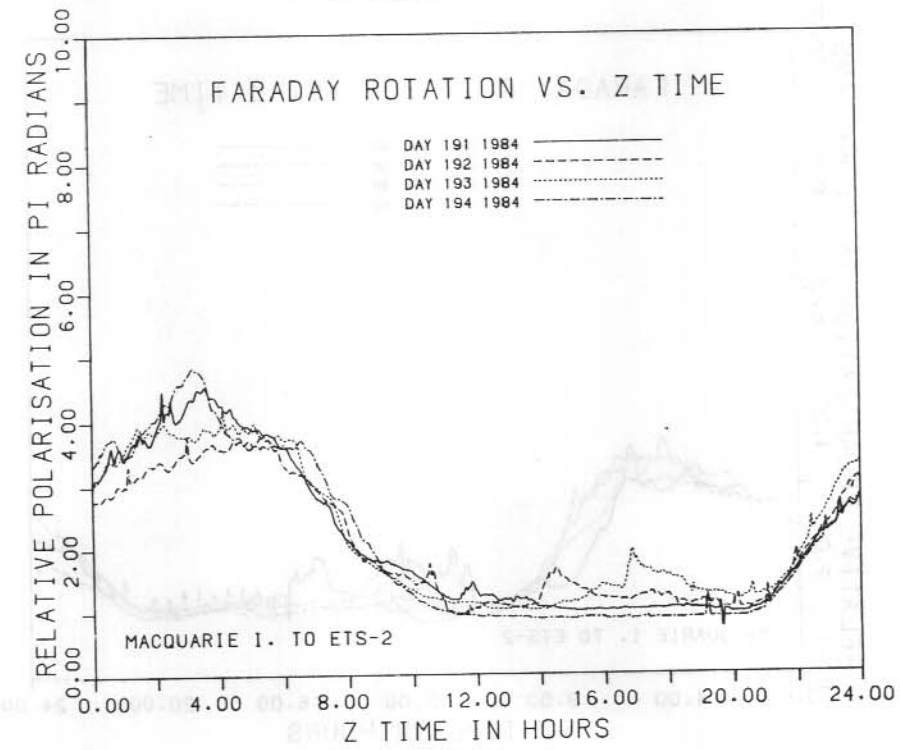
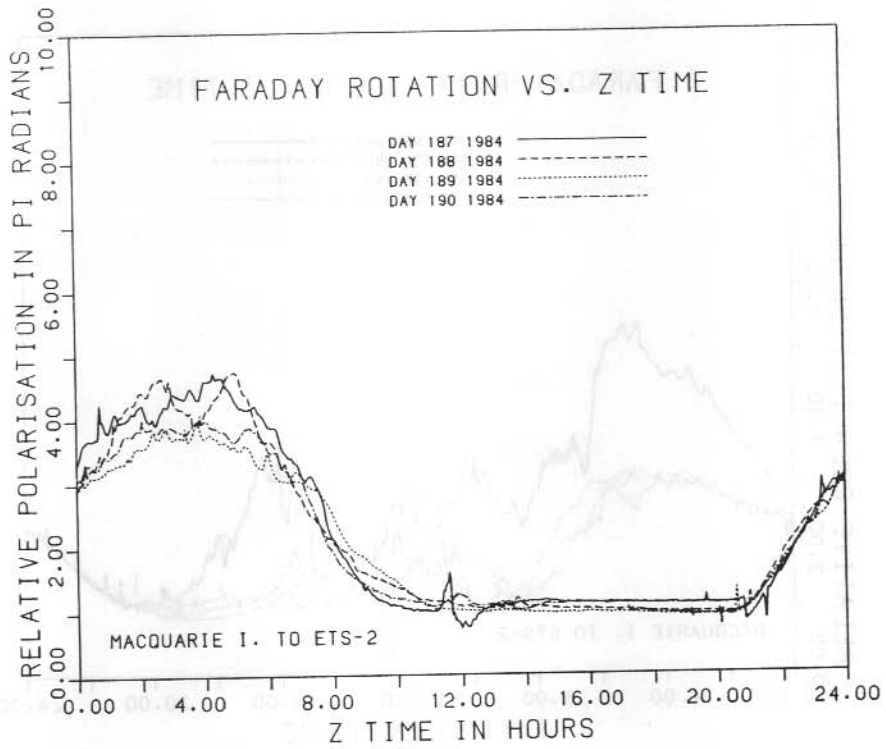


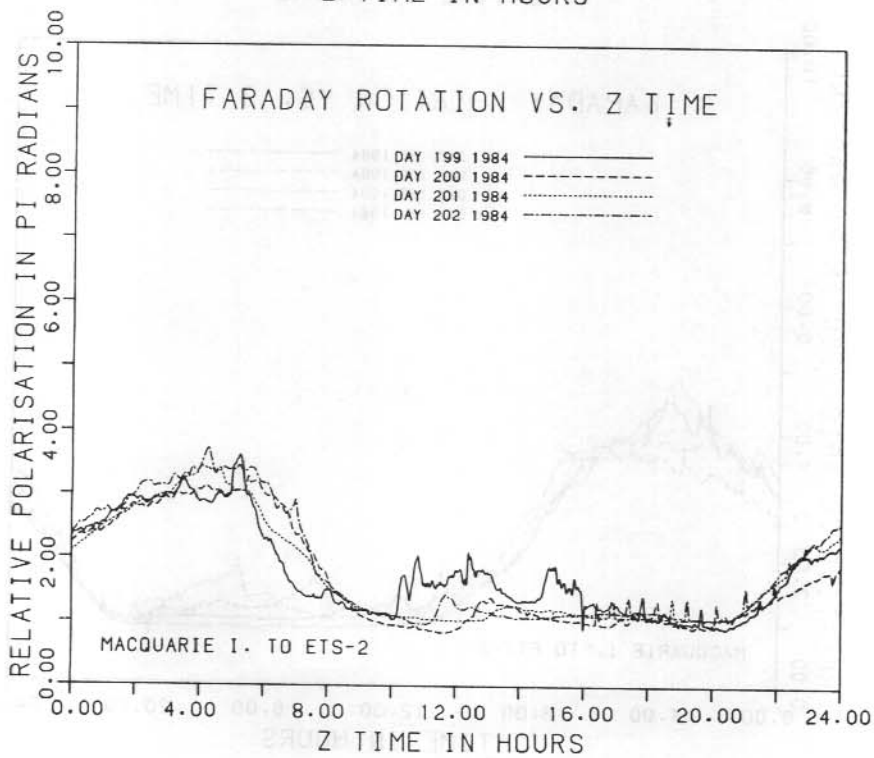
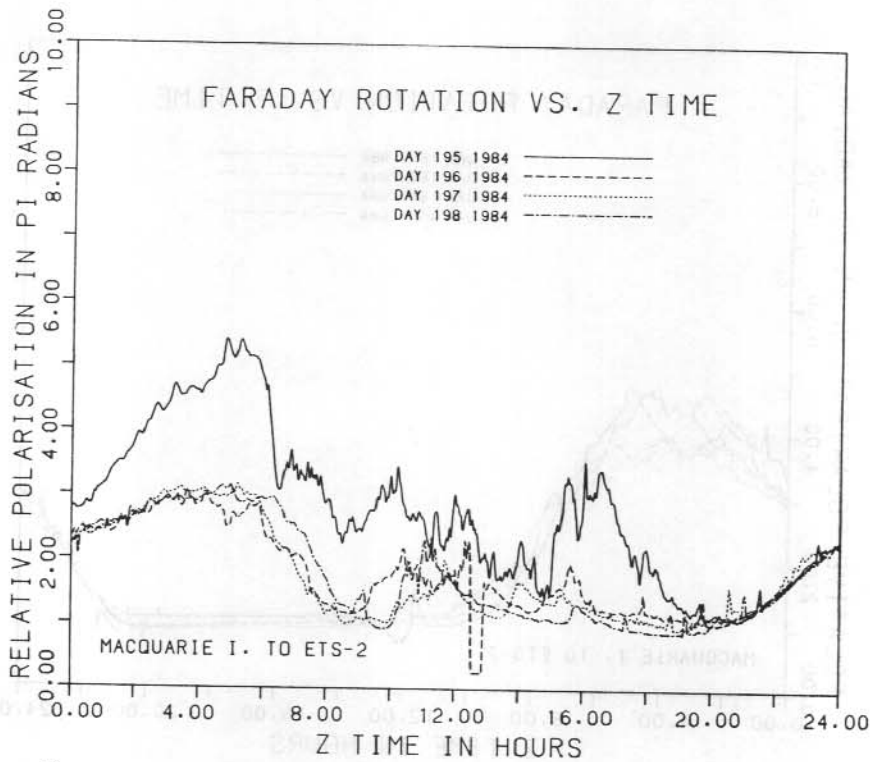


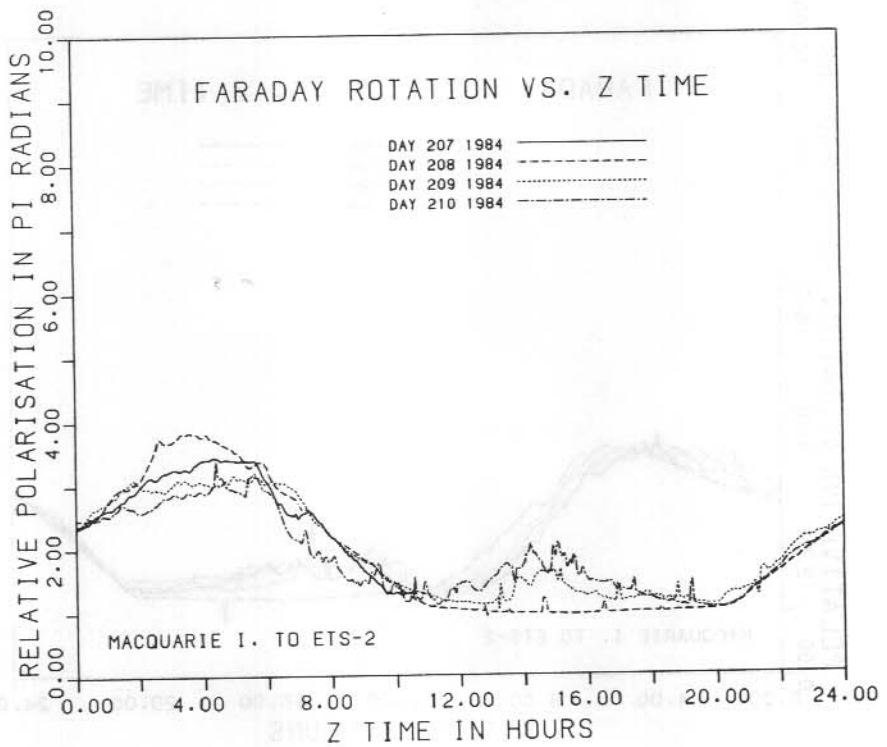
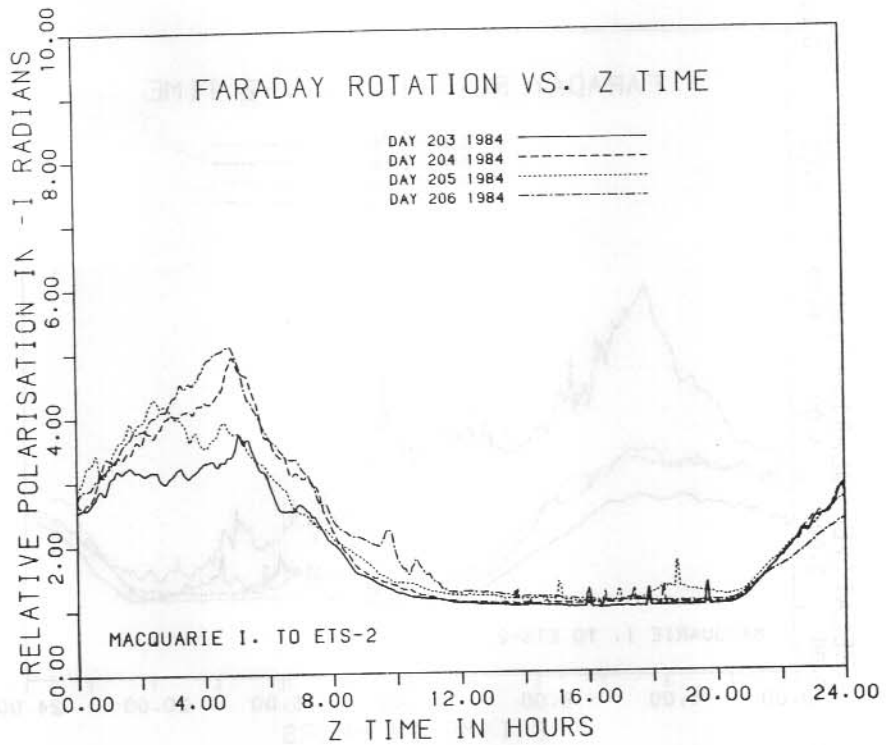


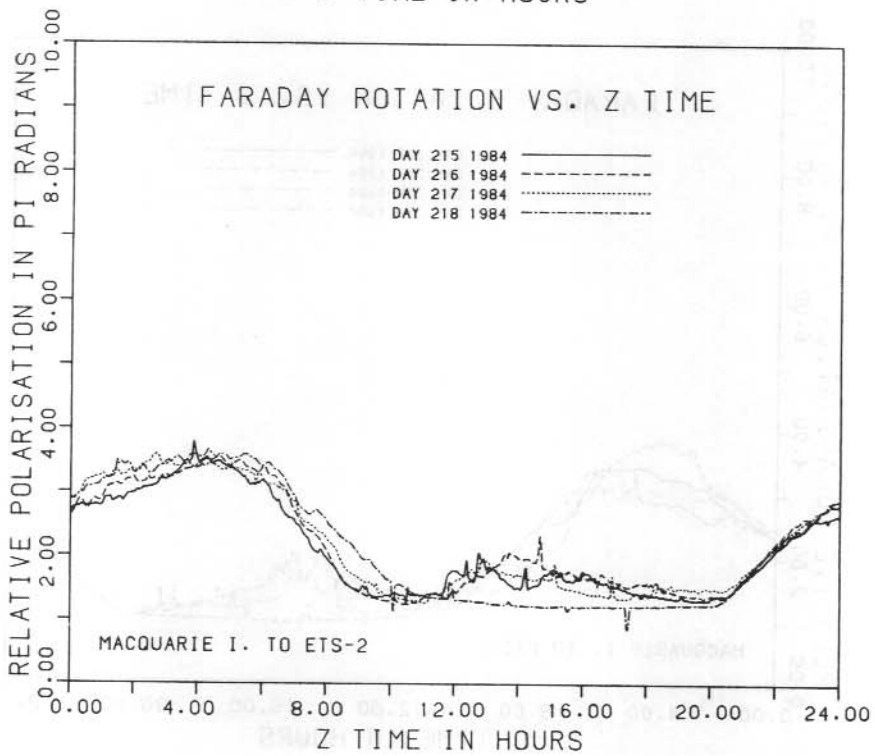
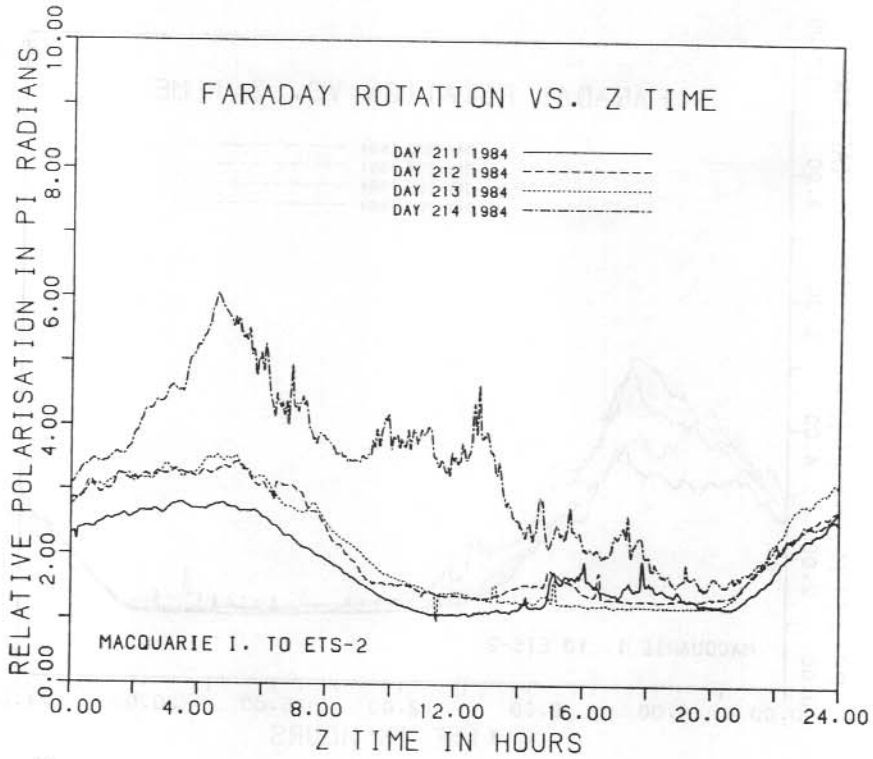


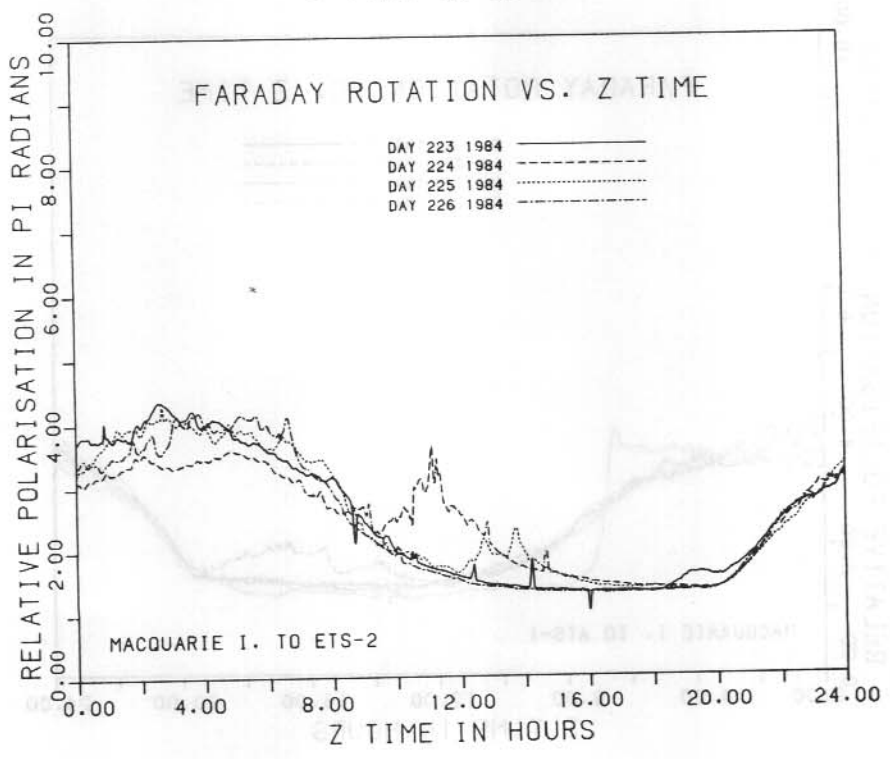
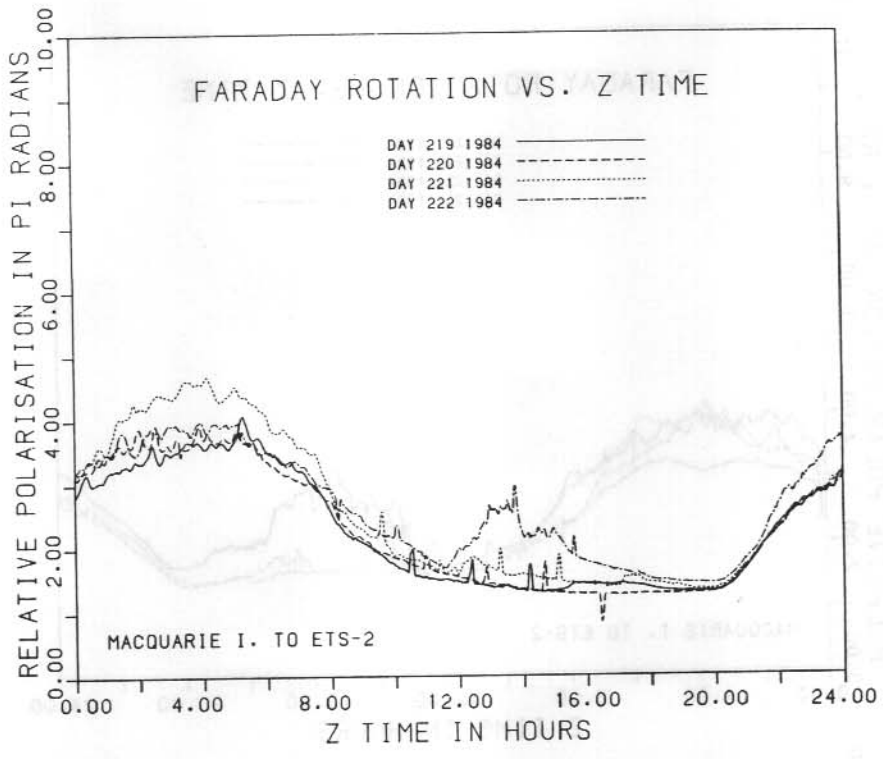


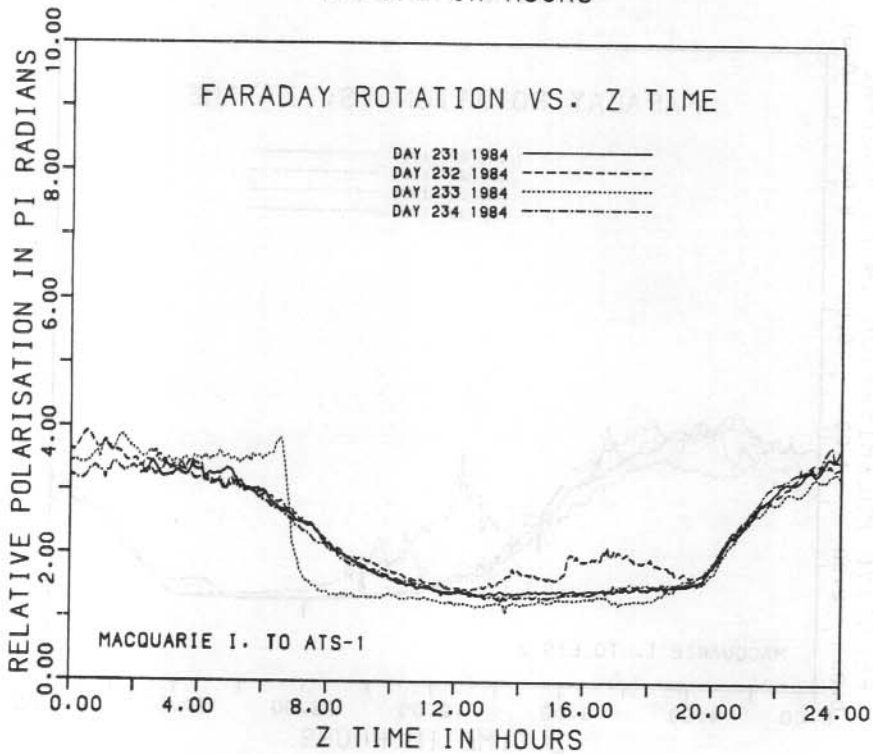
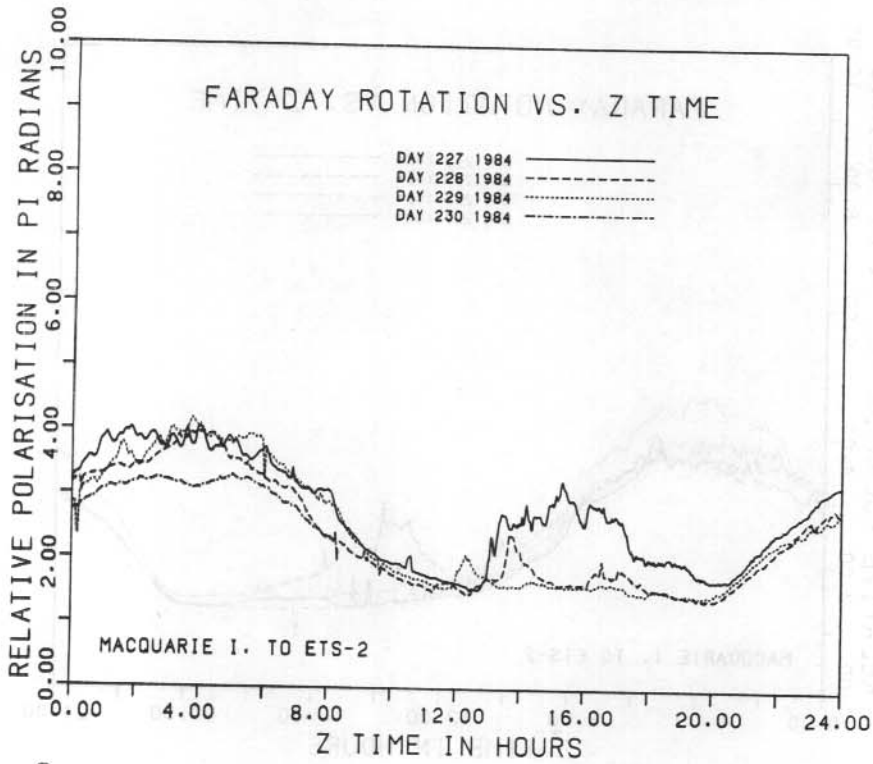


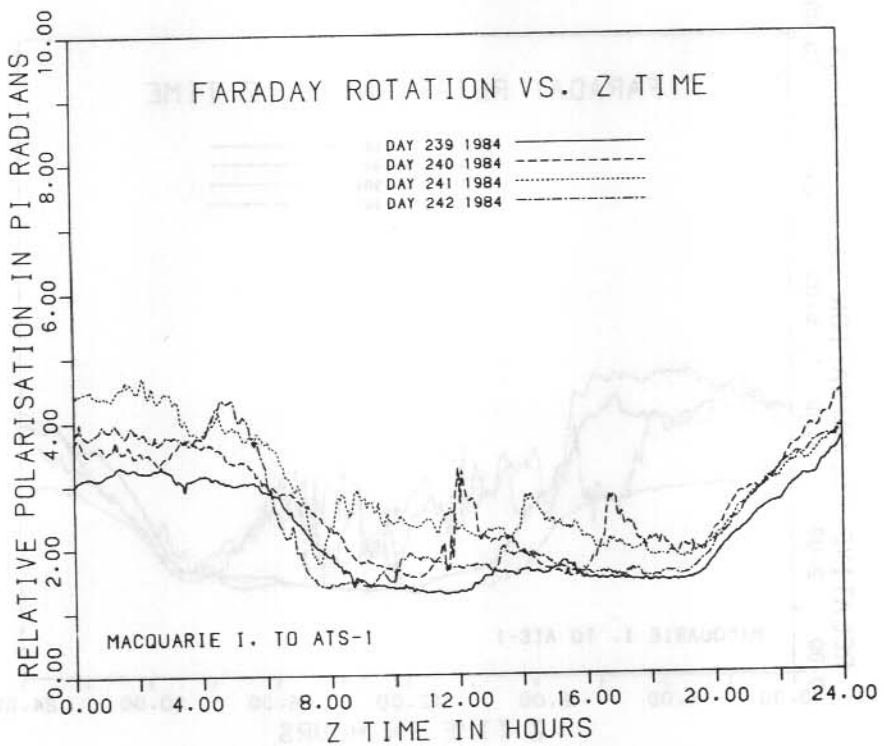
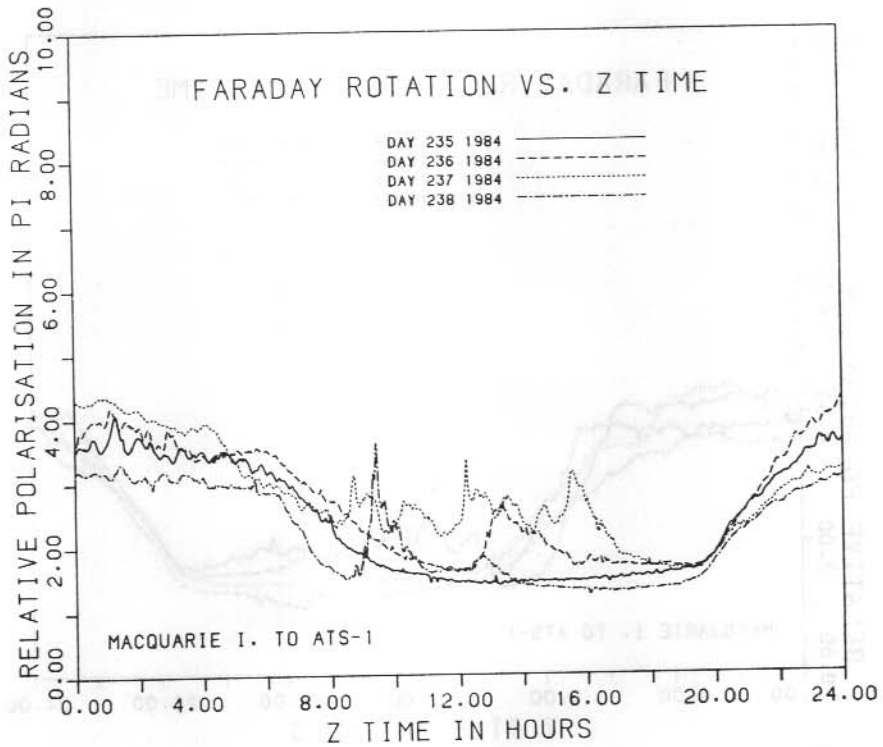


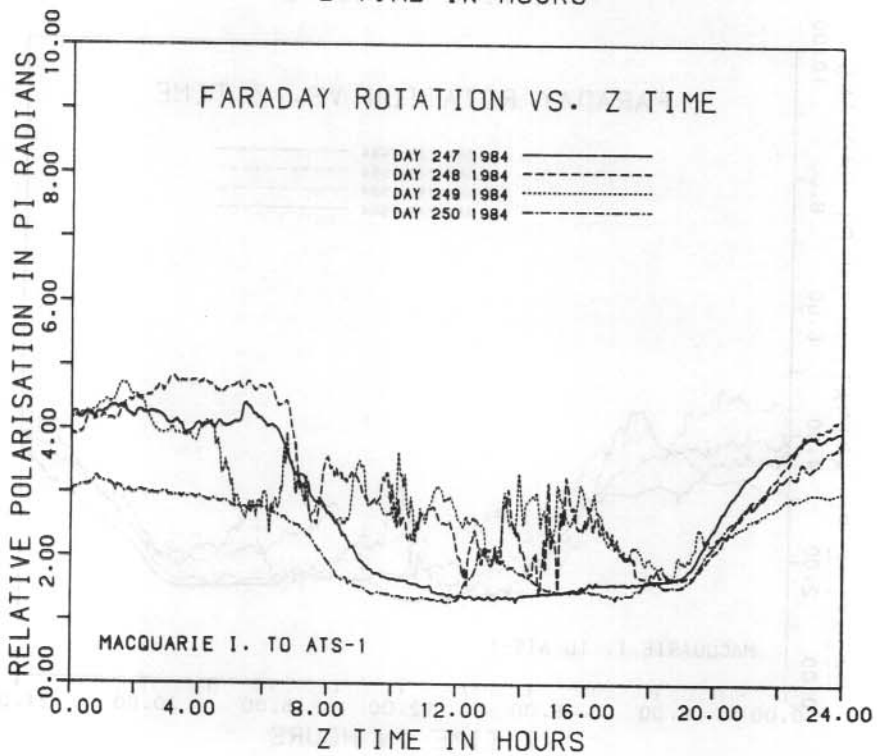
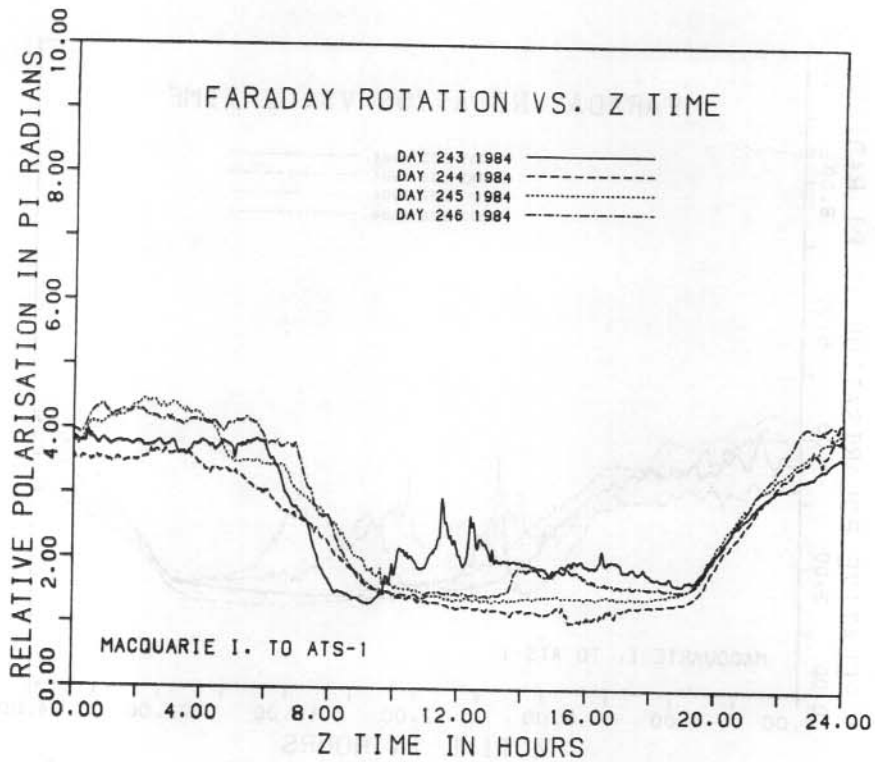


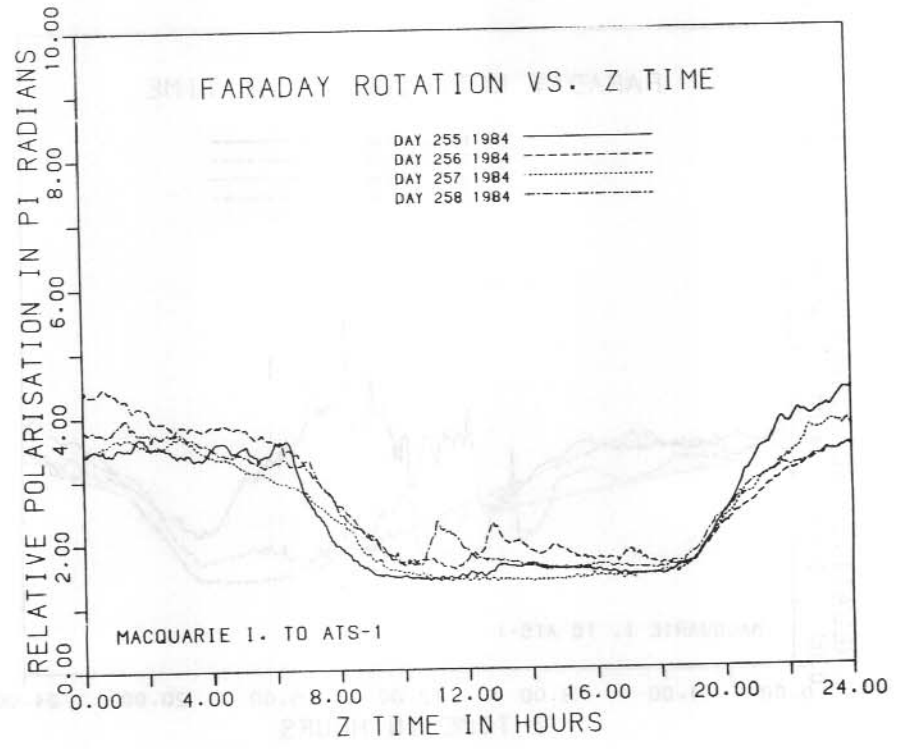
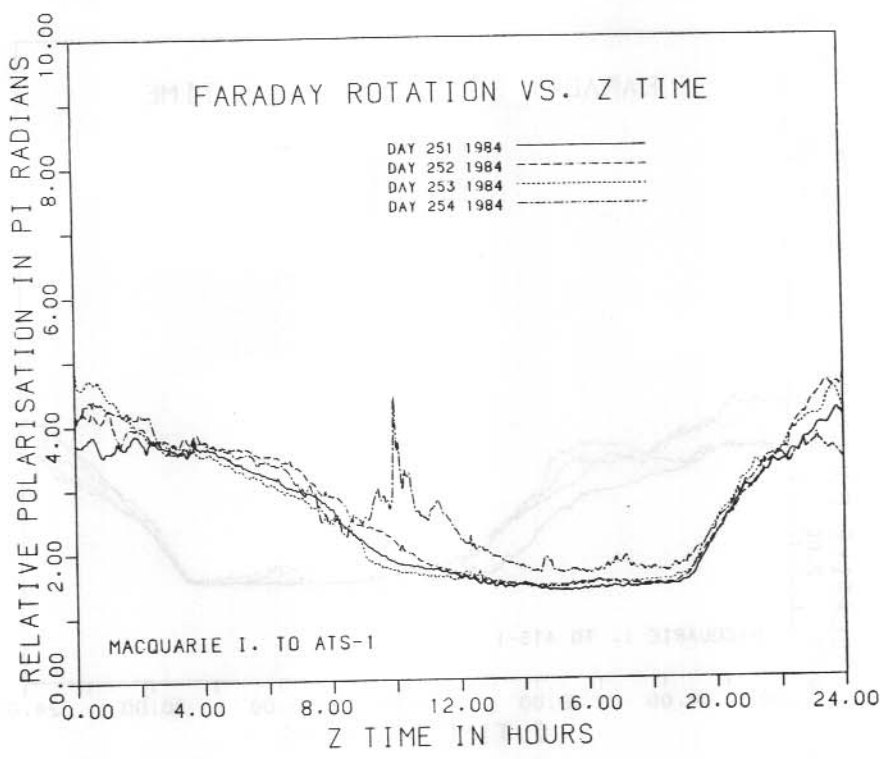


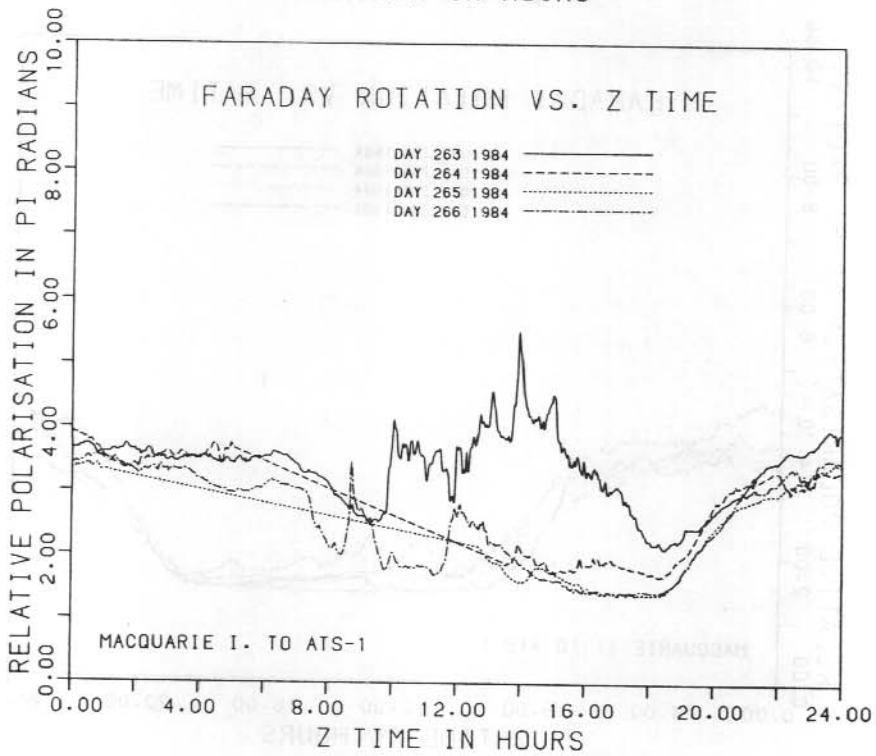
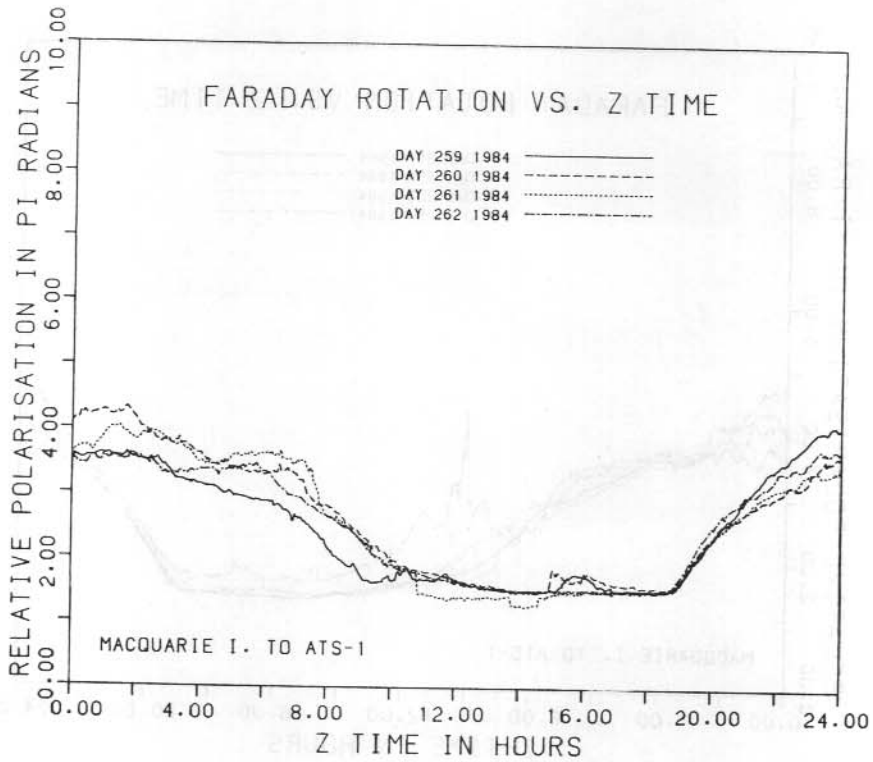


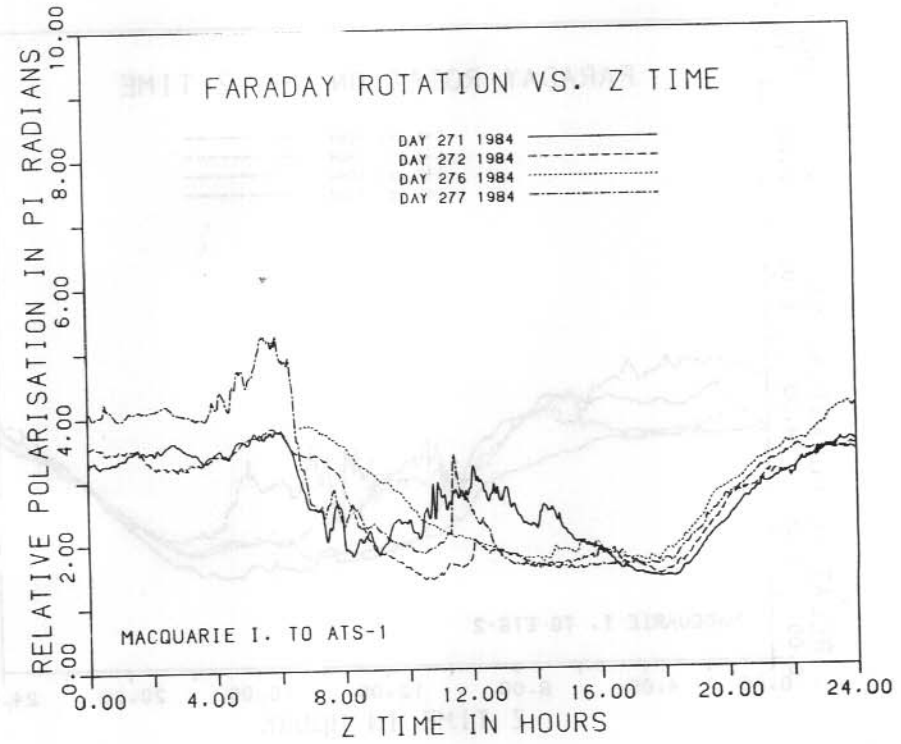
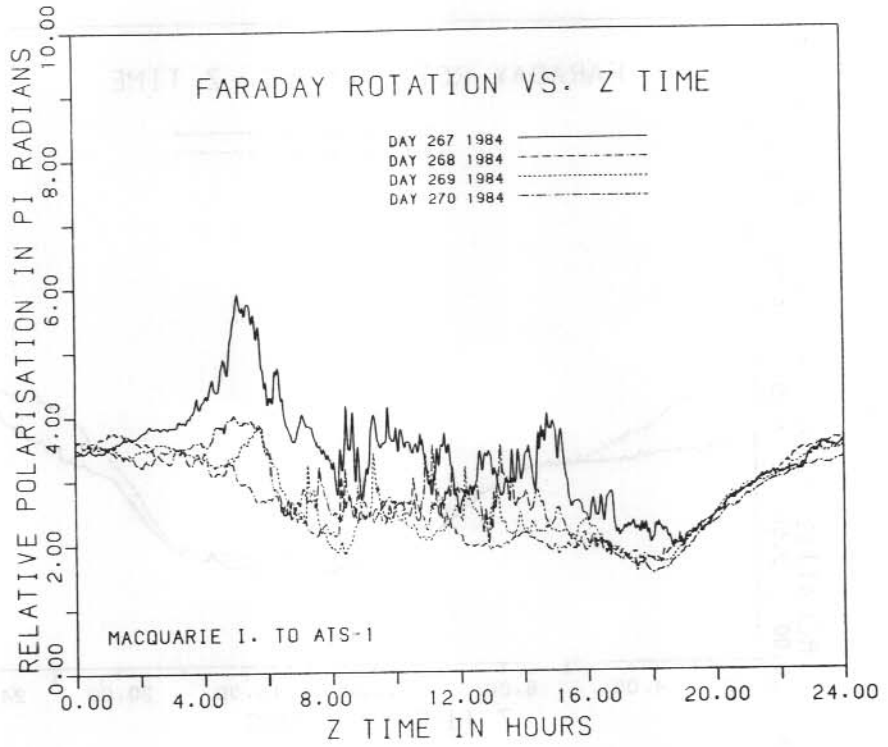


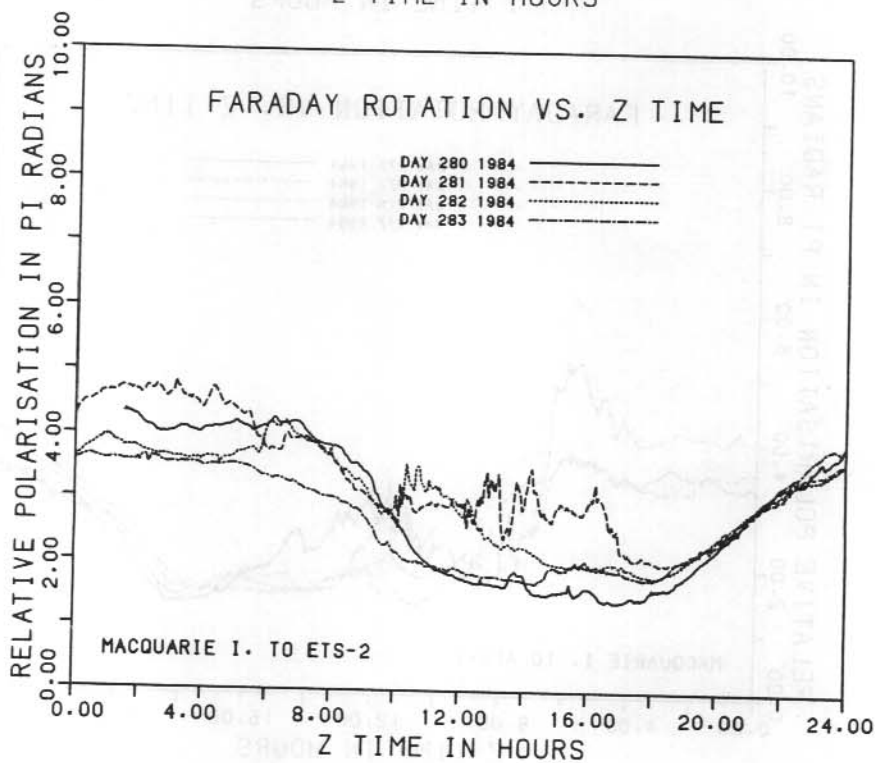
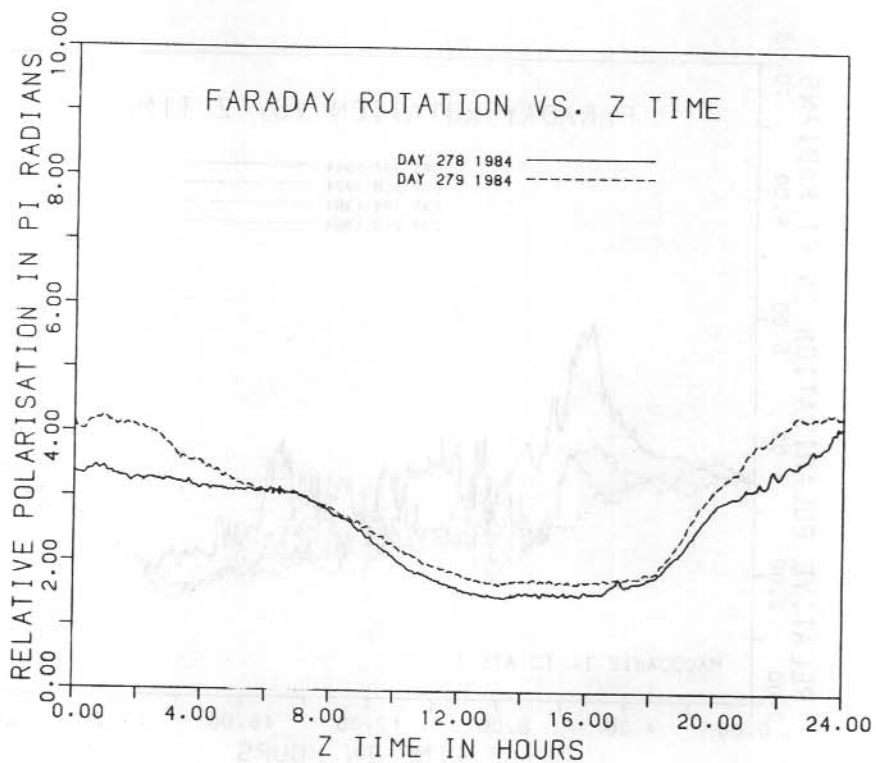


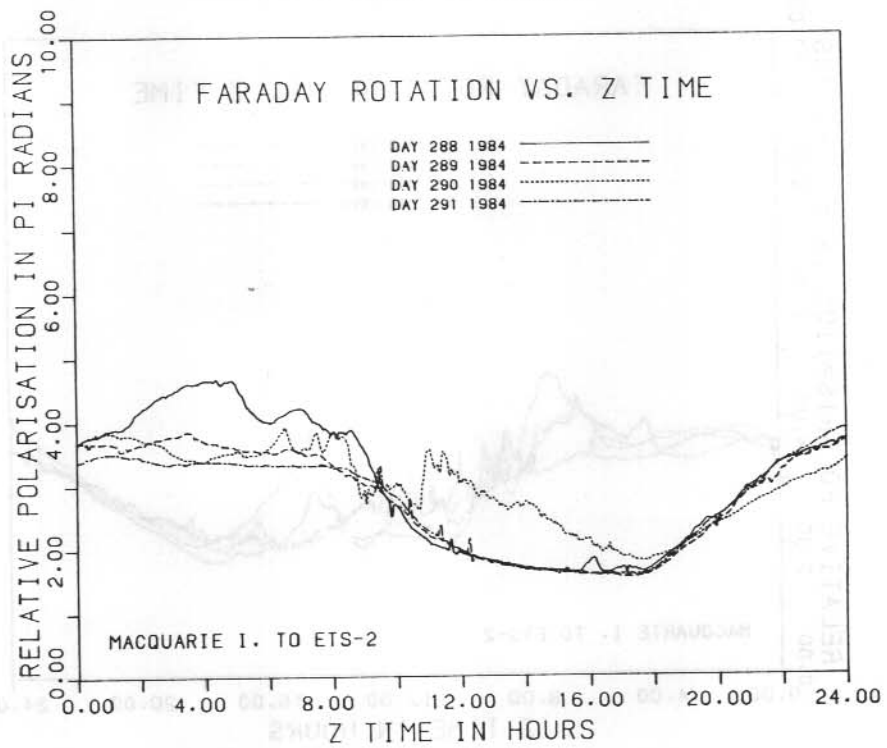
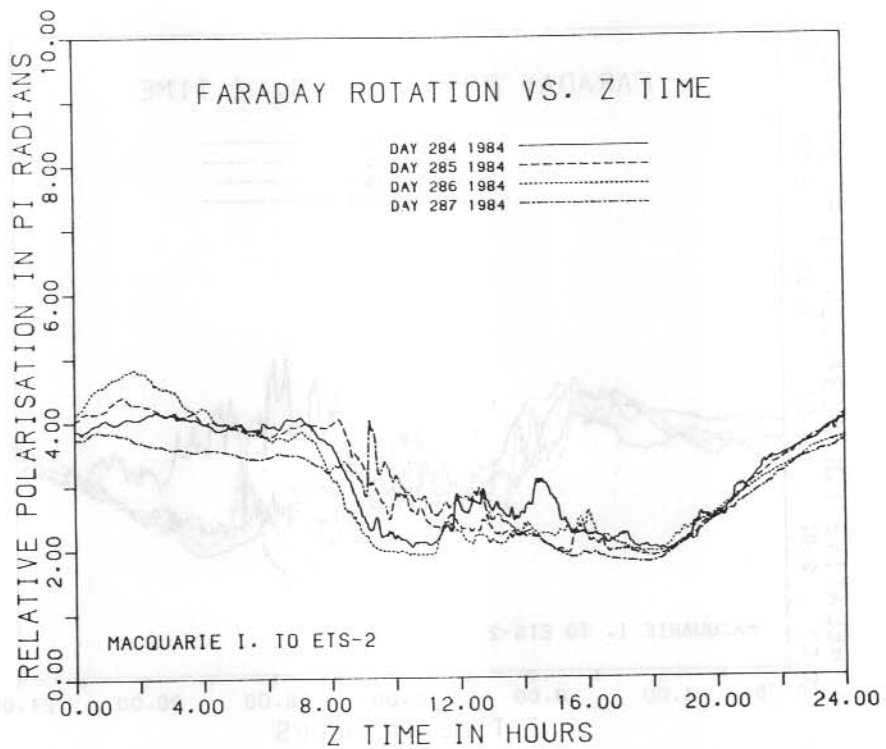


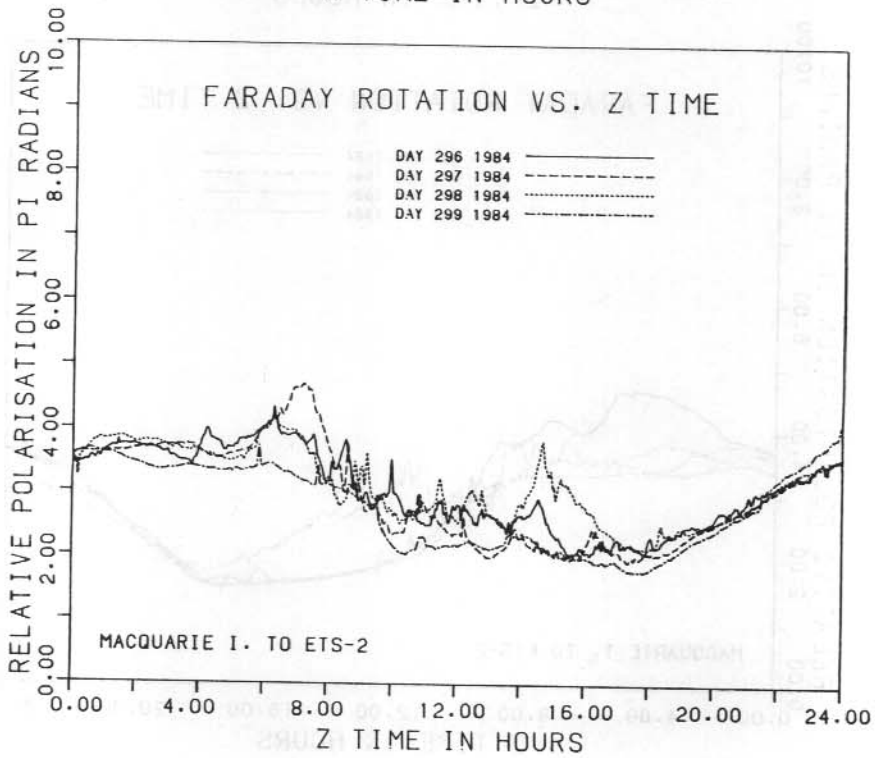
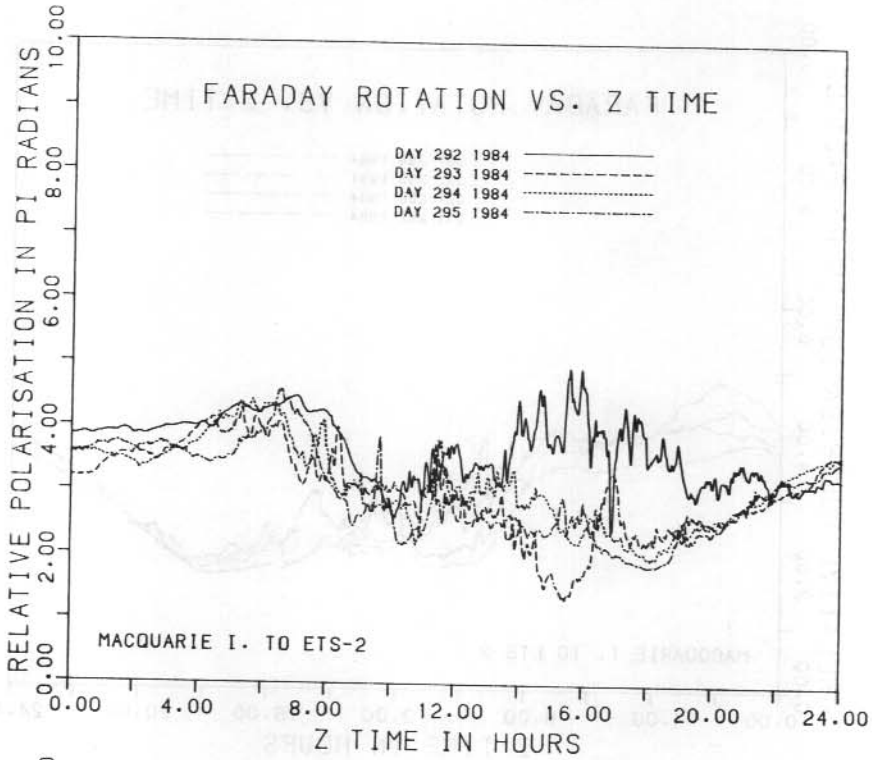


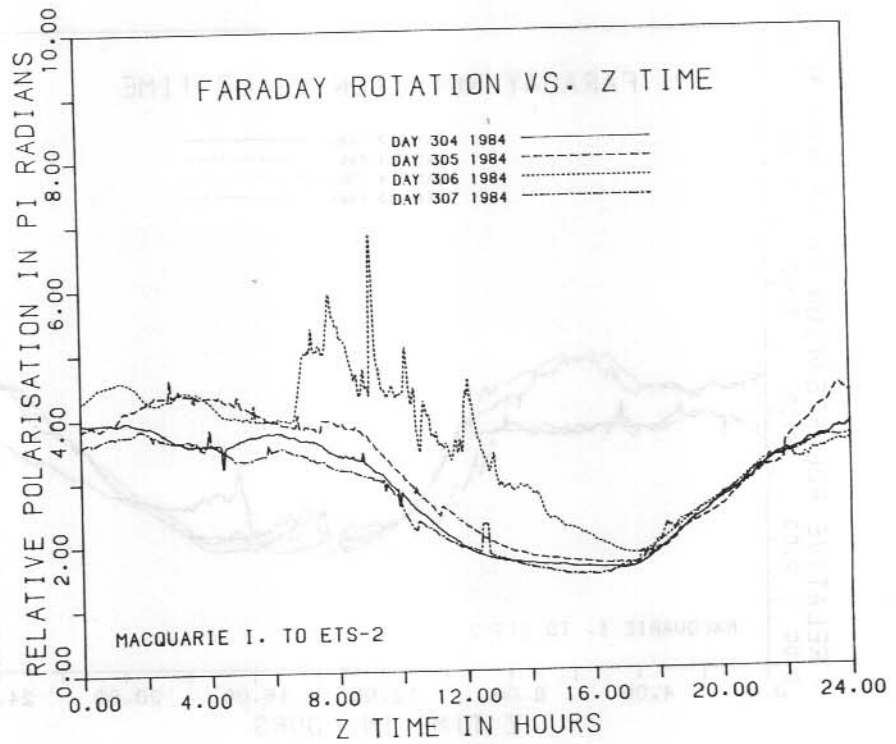
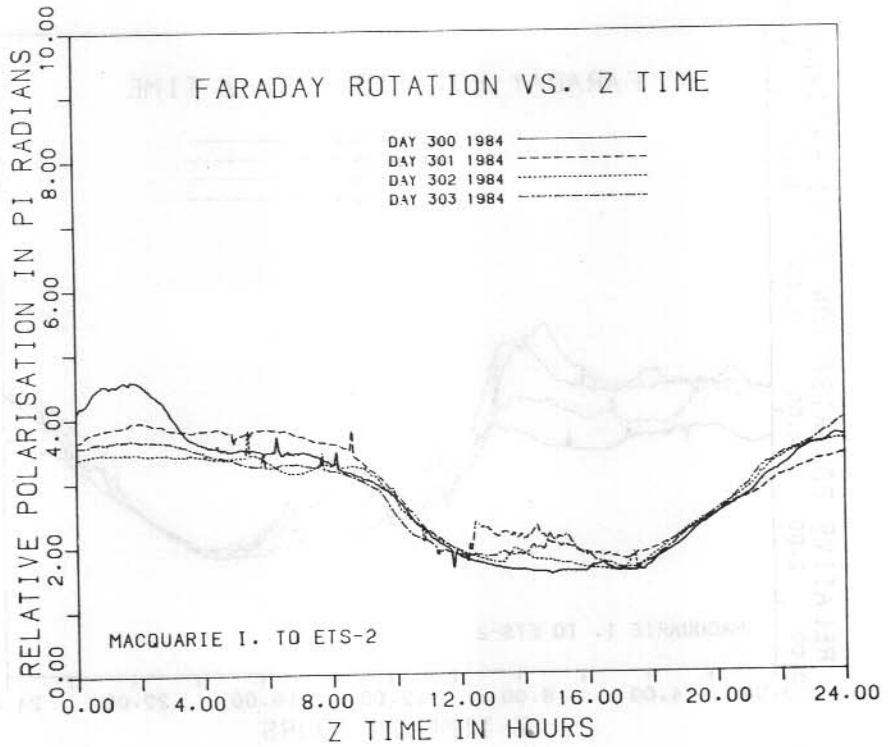


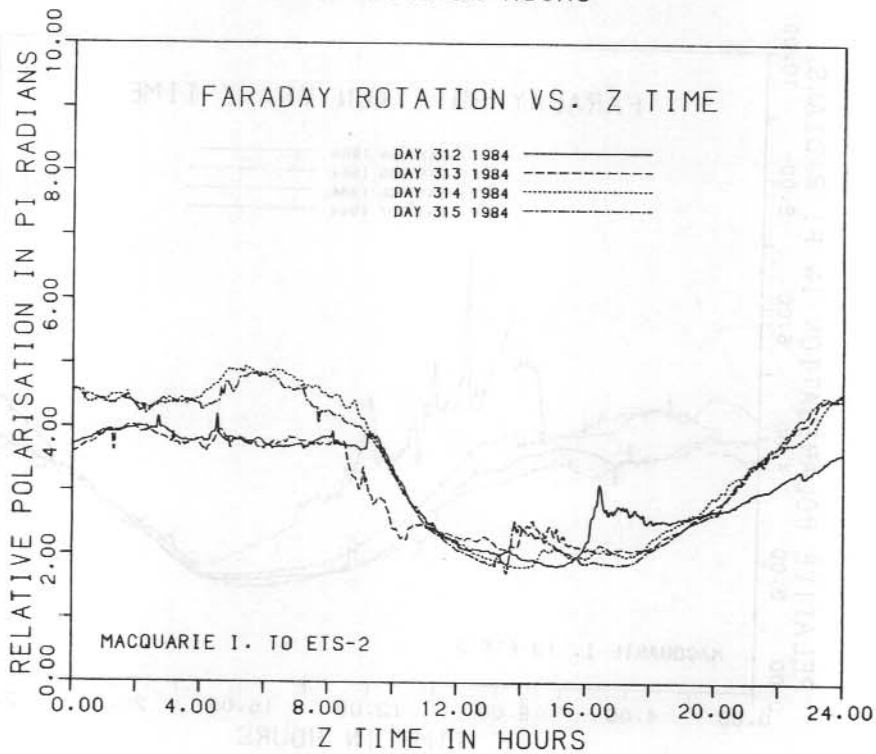
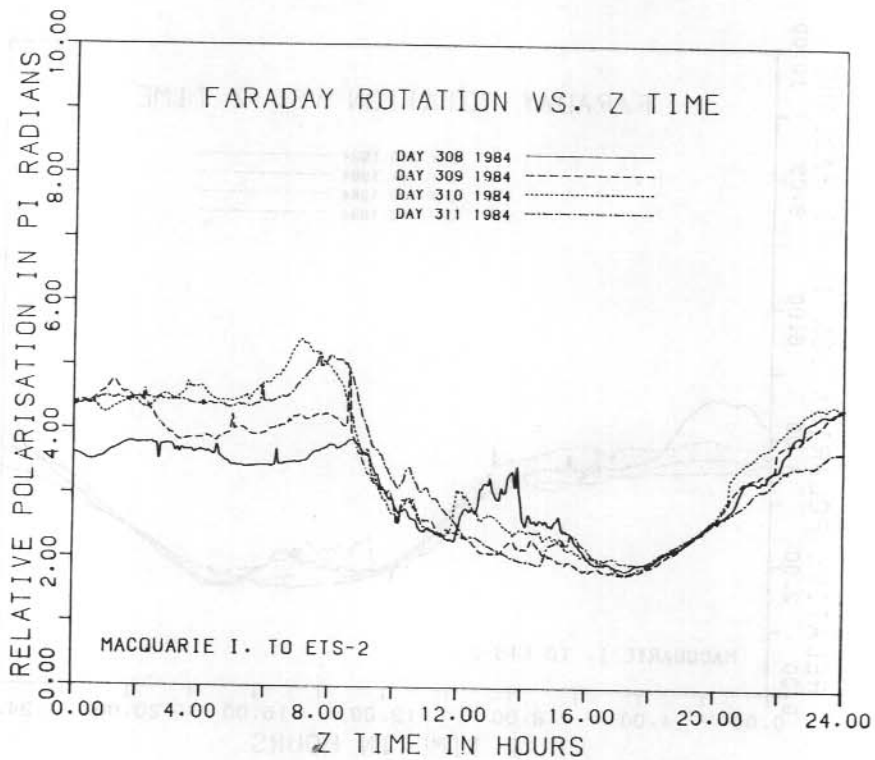


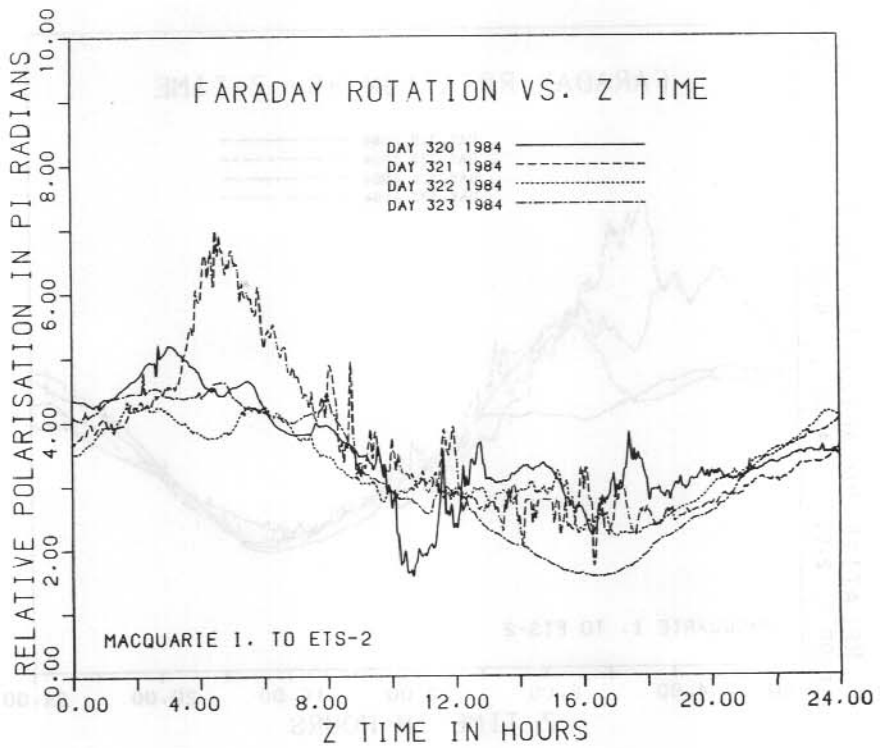
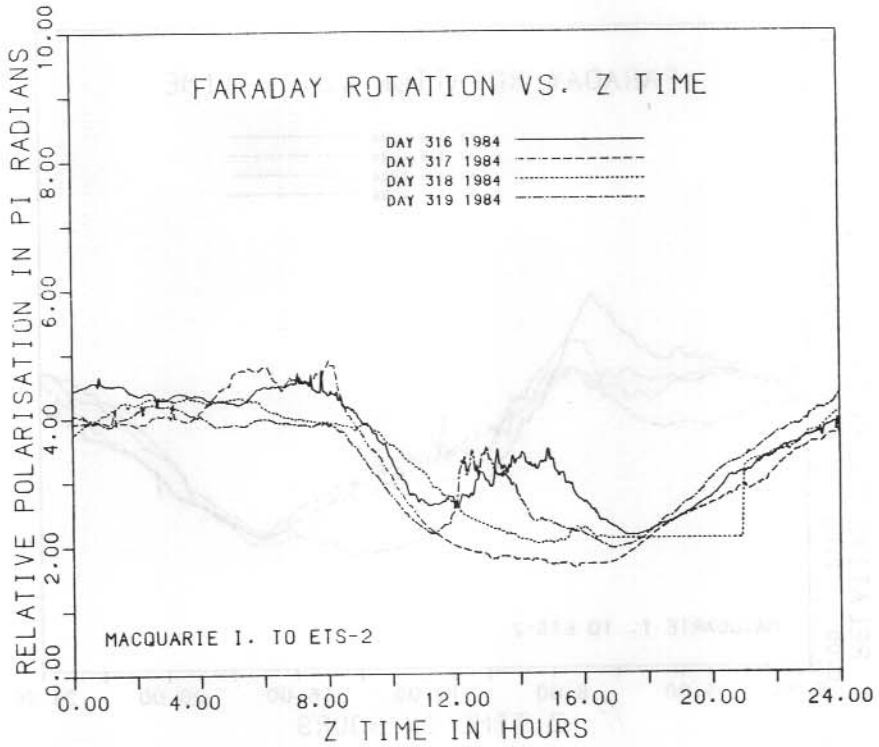


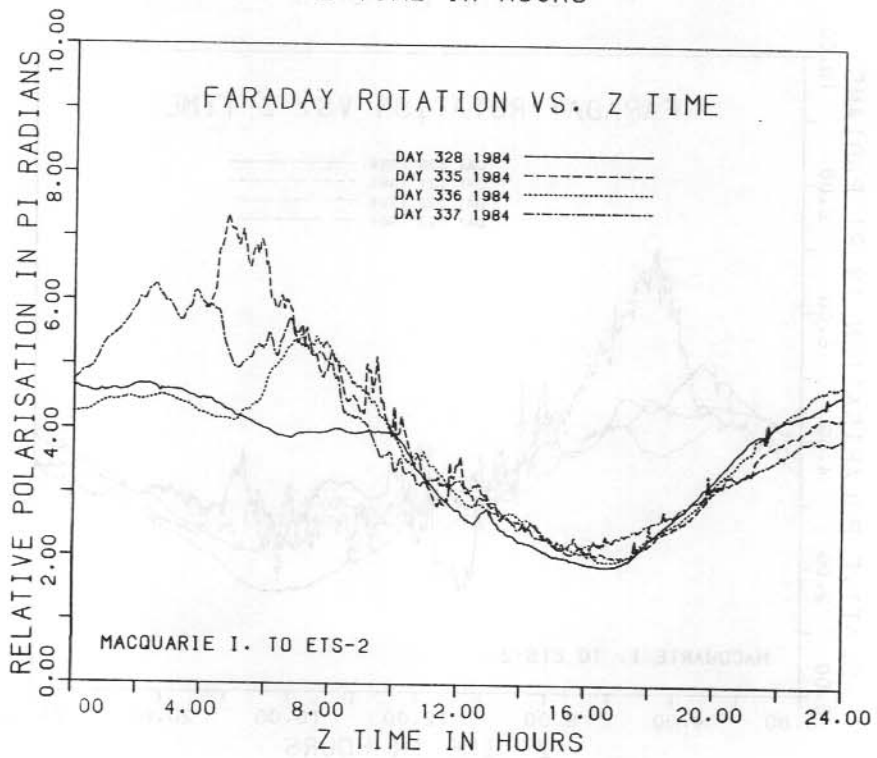
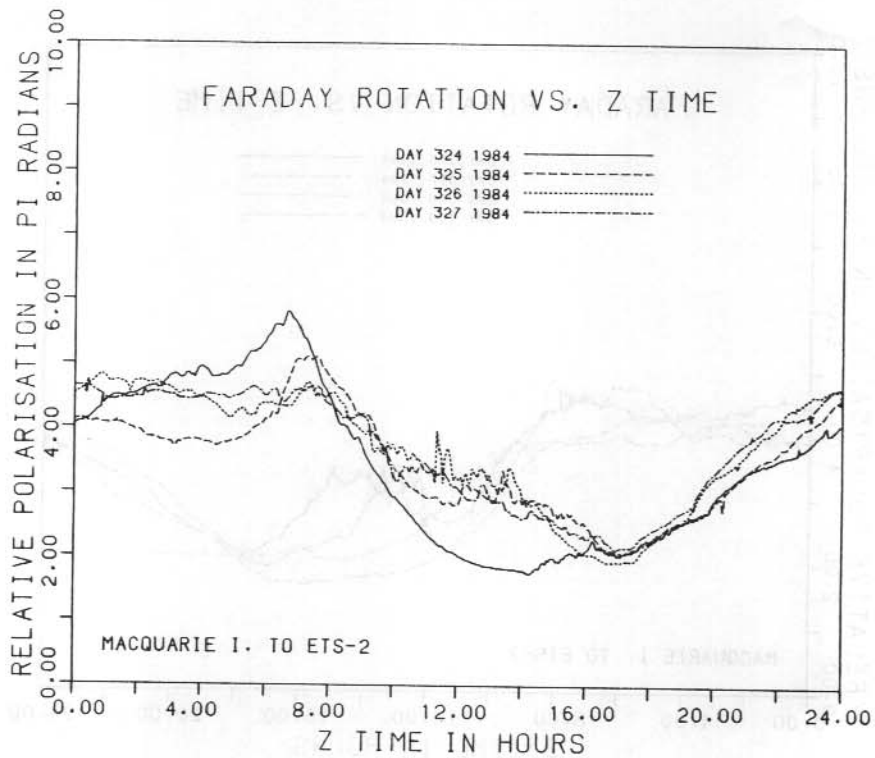


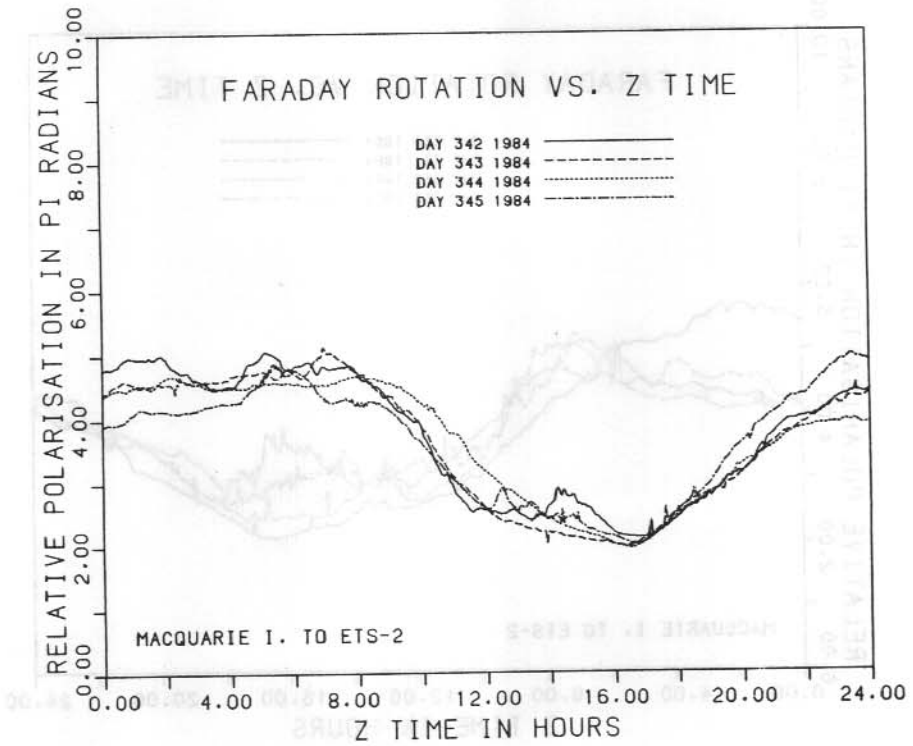
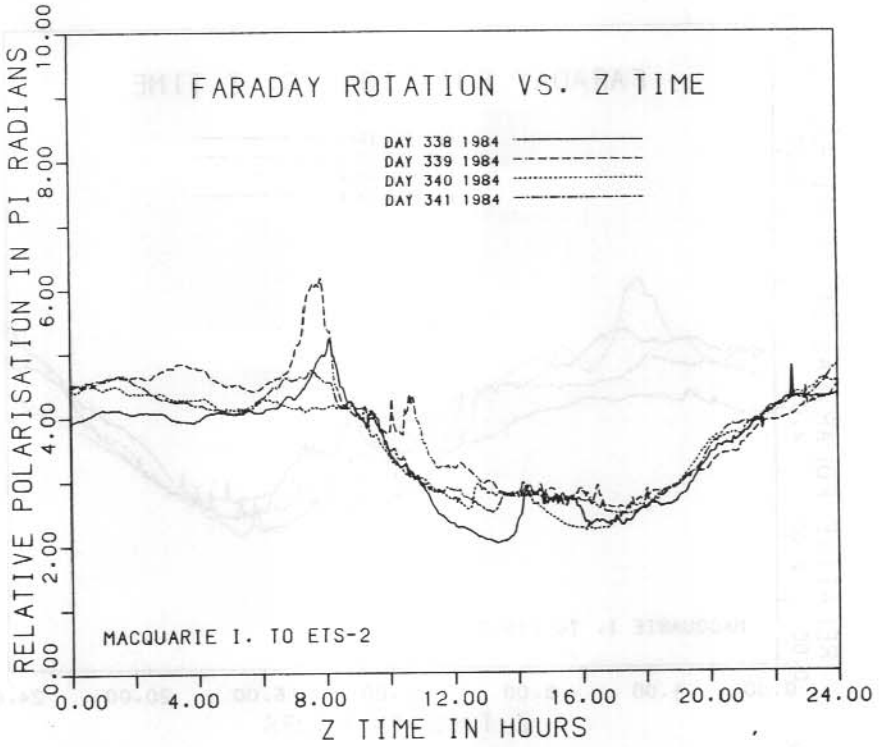


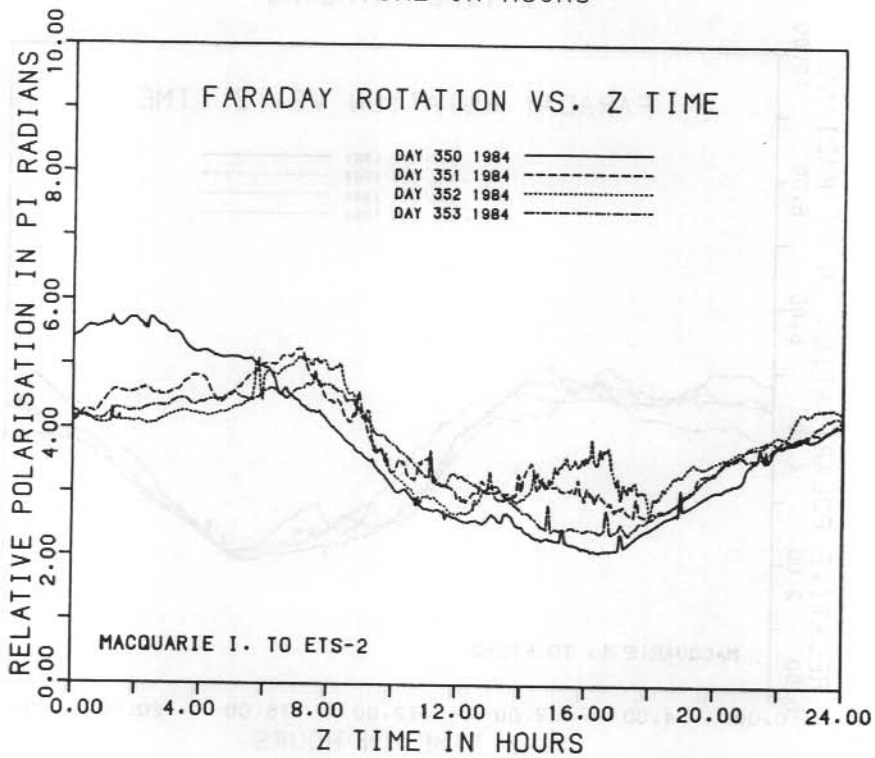
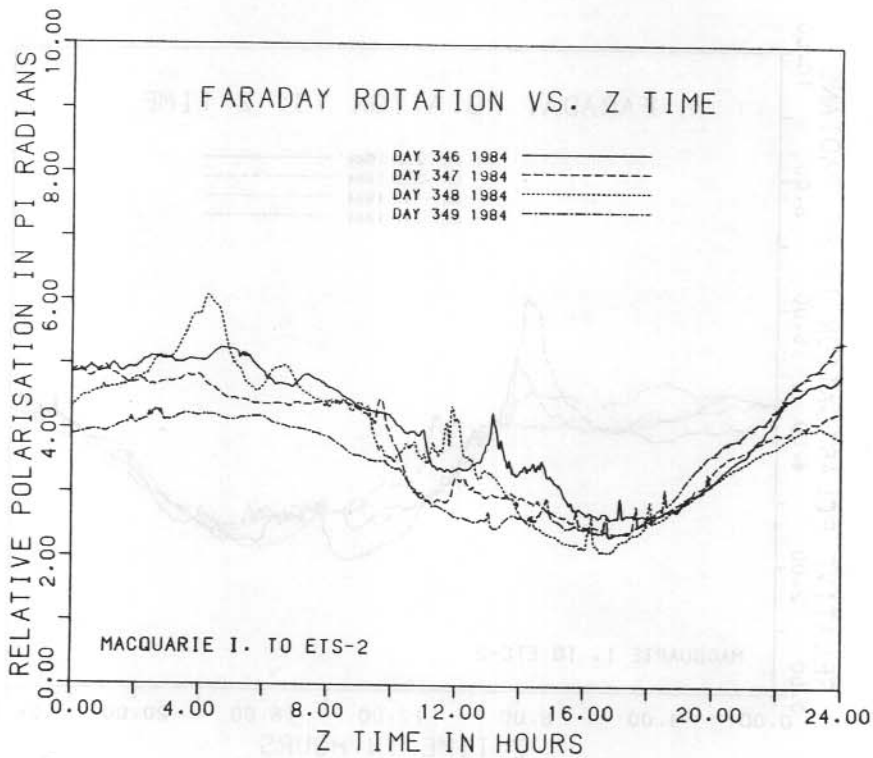


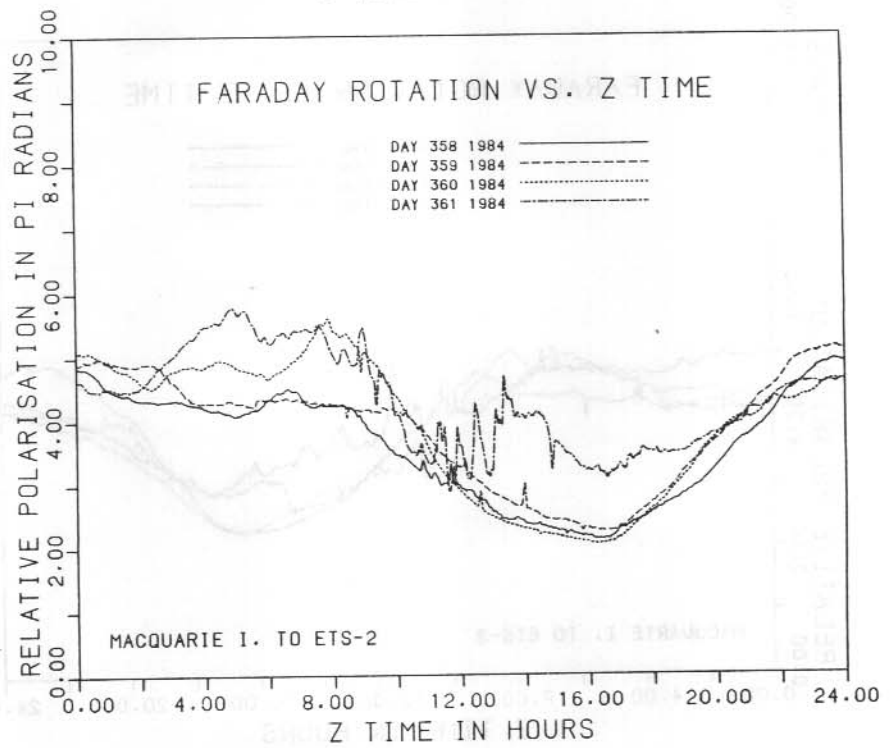
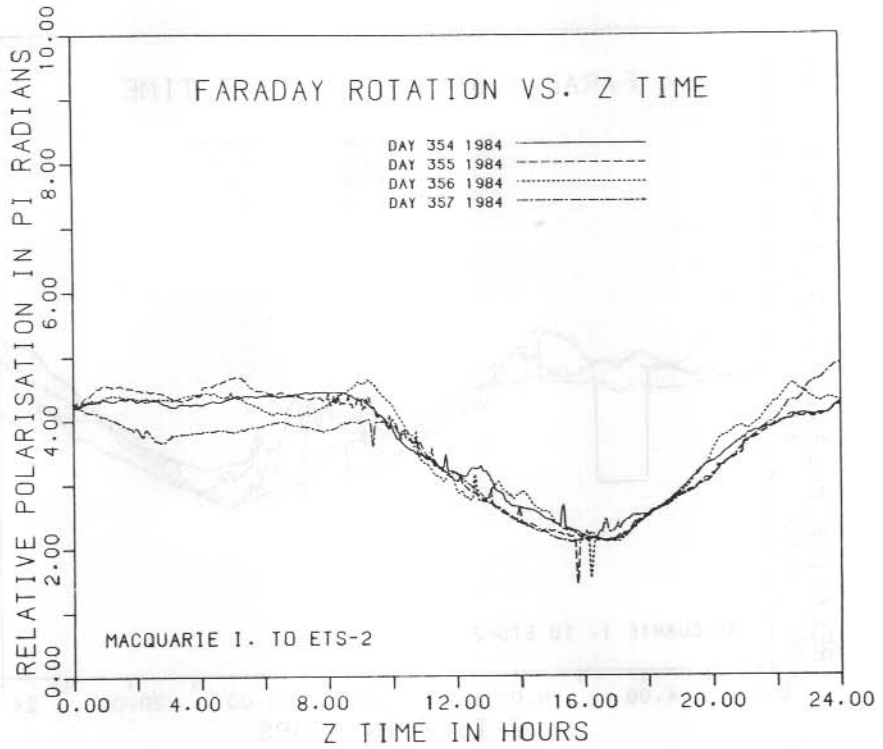


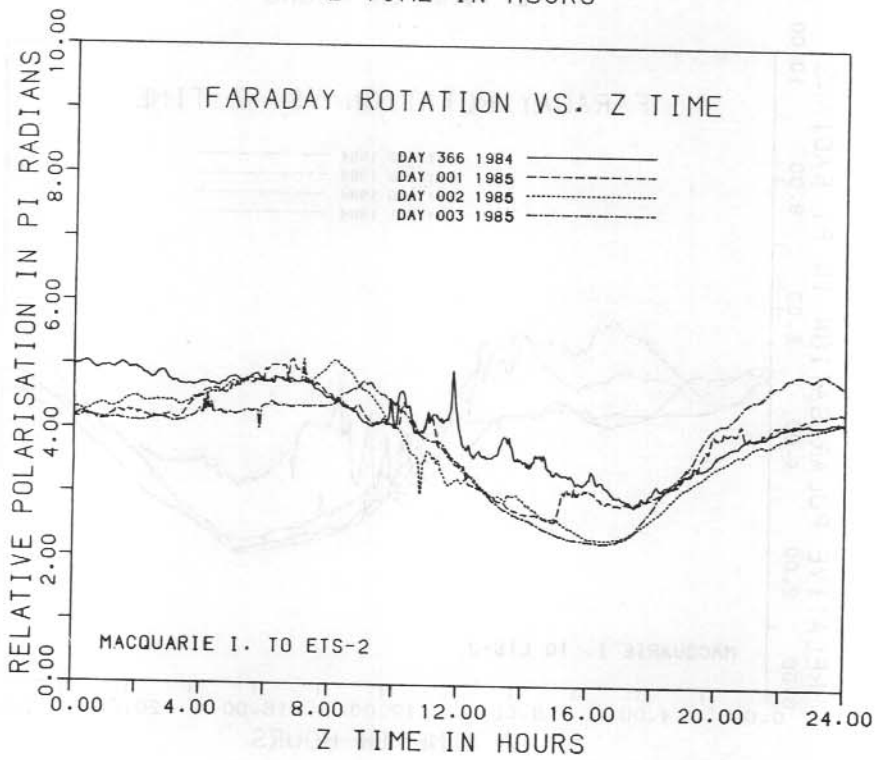
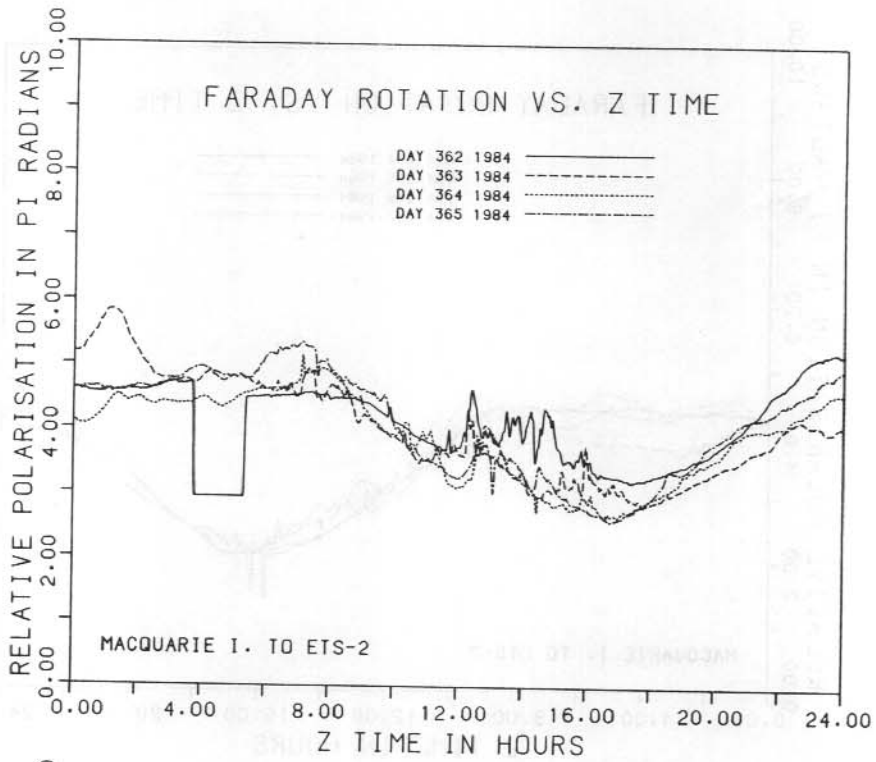


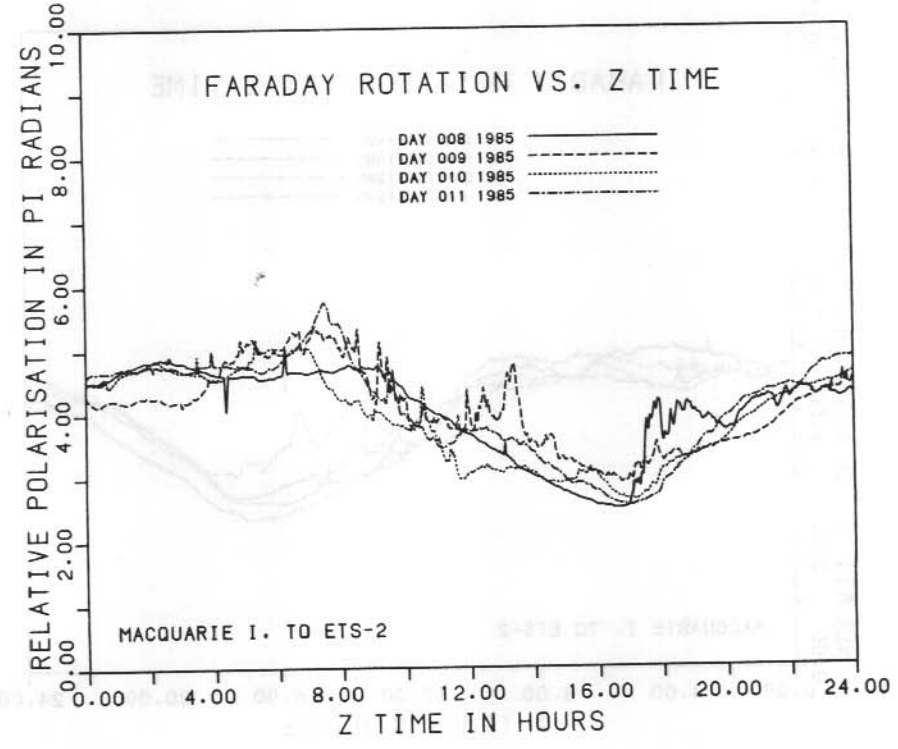
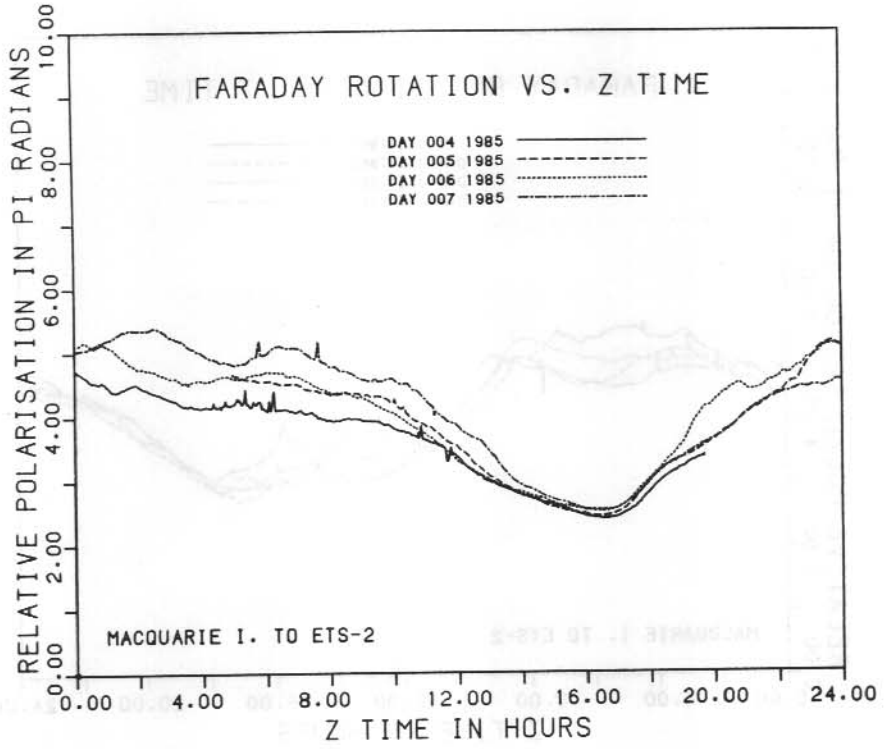


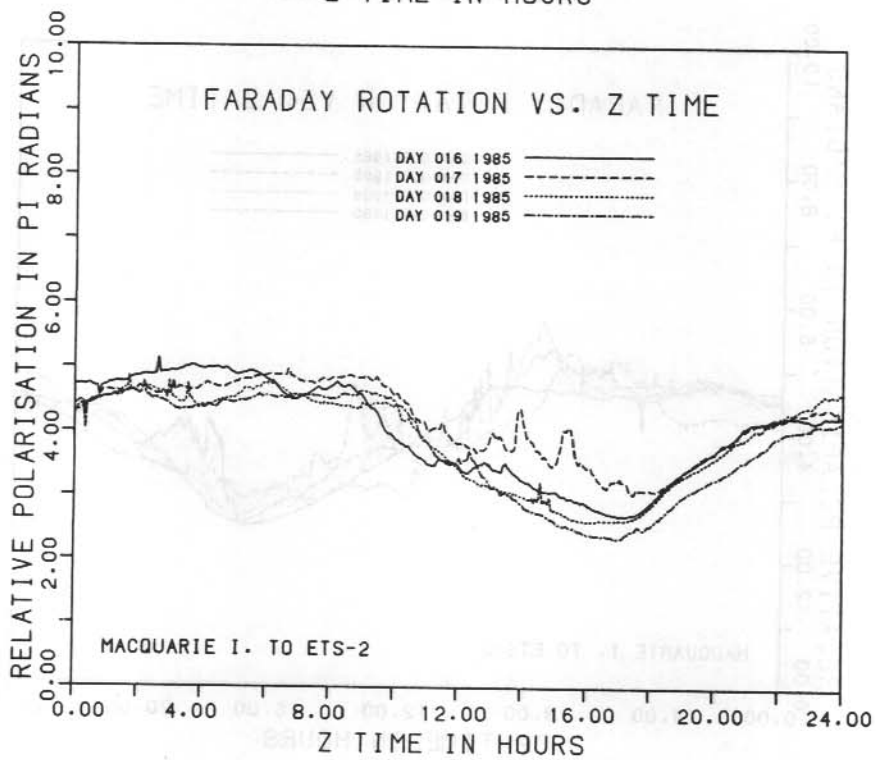
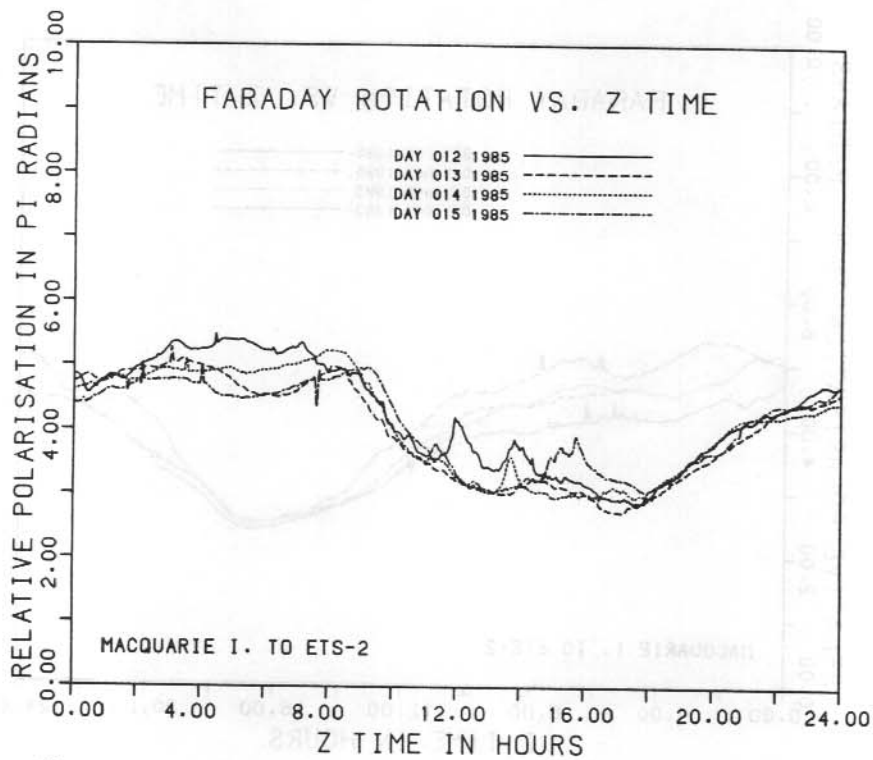


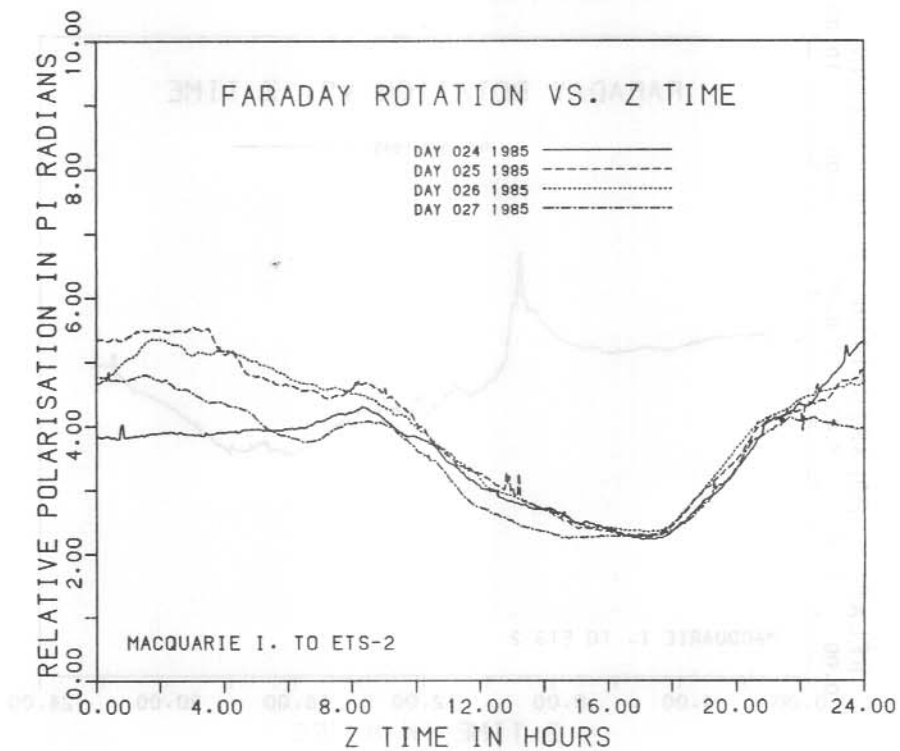
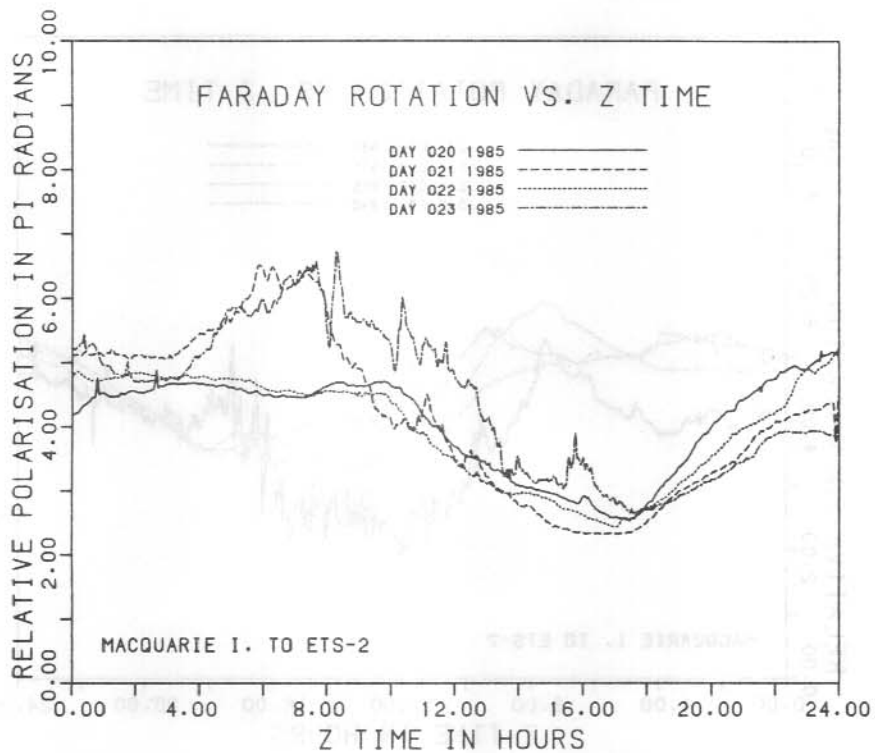


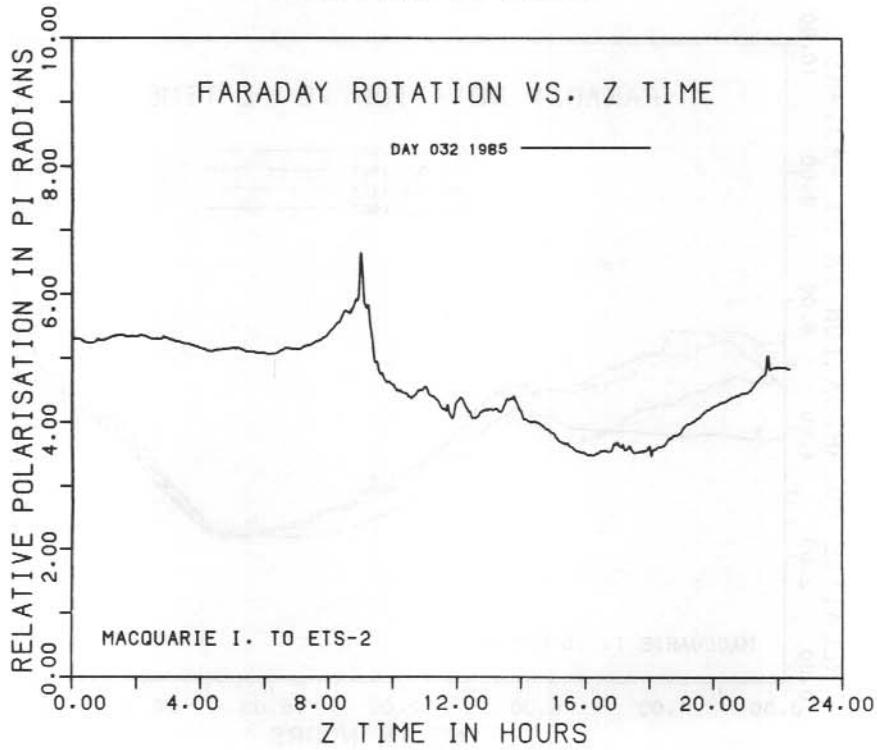
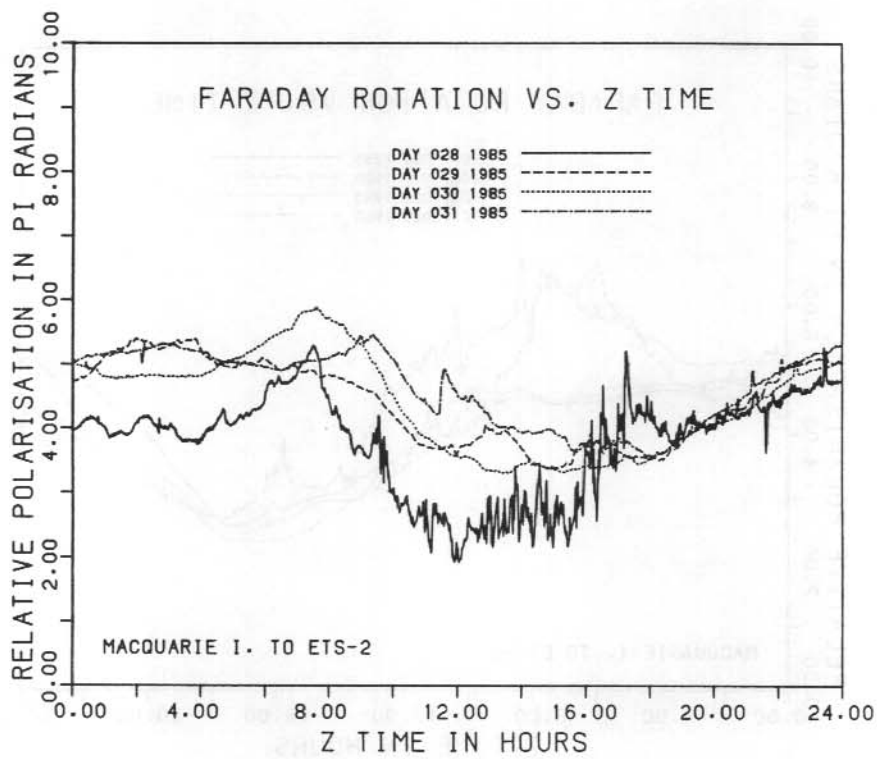


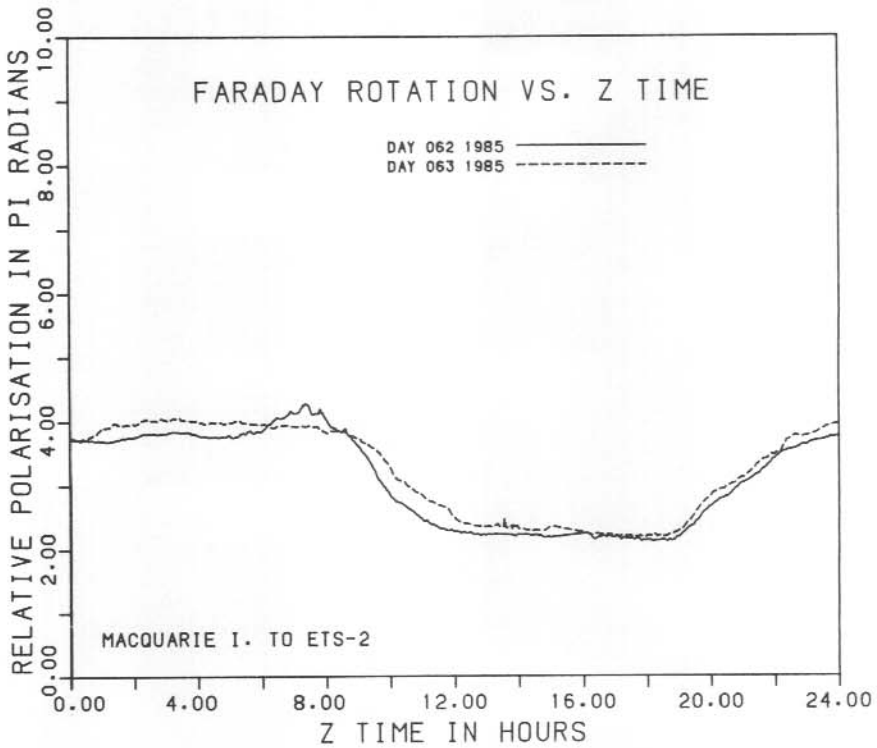
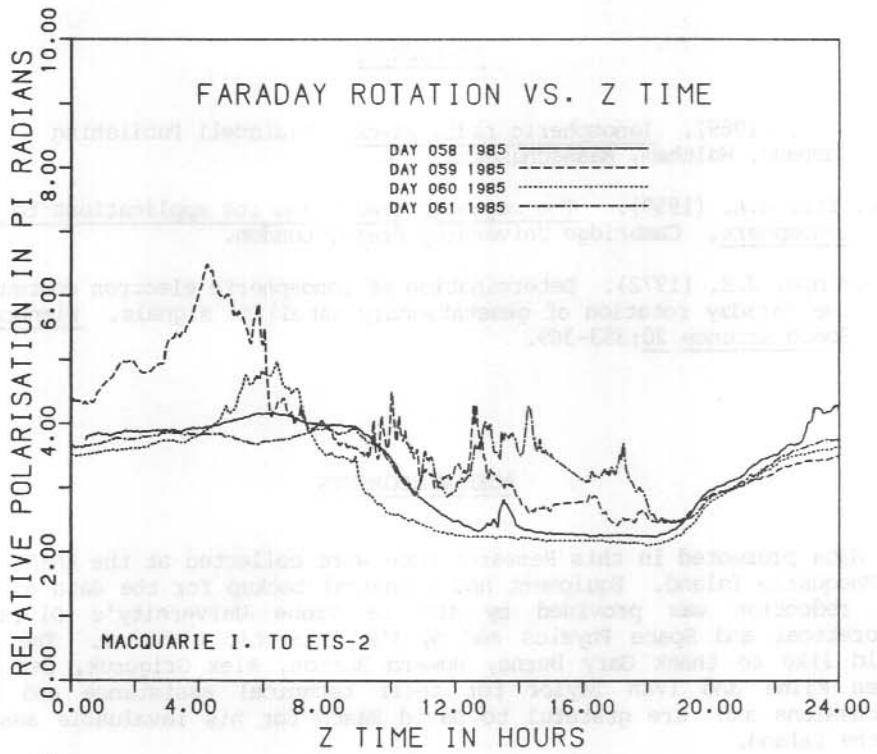












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