Ionospheric Faraday Rotation Calibration

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Overview

- Faraday Rotation
  - What is it & why do we care
- Requirements levied by science goals
  - Solar Faraday Rotation
  - Epoch of Reionization
- Previous ways of dealing with it
  - Dual frequency GPS + ionospheric model
- How we can deal with it
  - GPS + differential density calibration + ionospheric model
- Measurements
  - Radio beacons on geosynchronous spacecraft

References

- Reviews
  - Kenneth Davies, Recent progress in satellite radio beacon studies with particular emphasis on the ATS-6 radio beacon experiment (1980)
  - Ionospheric Radio, Kenneth Davies (1990)
  - NASA Technical Report NASA-136 TR-02, Thermal behavior of the ionosphere and observations of the exosphere and the ionosphere by means of distant Earth satellites
  - Erickson et al (2001) VLA observations at 74 MHz
- People
  - Mike Bird (Universitaet Bonn)
    - DSN
  - Anthea Coster (MIT/Haystack)
    - GPS
  - Steve Spangler (University Iowa)
    - VLA

Faraday Rotation

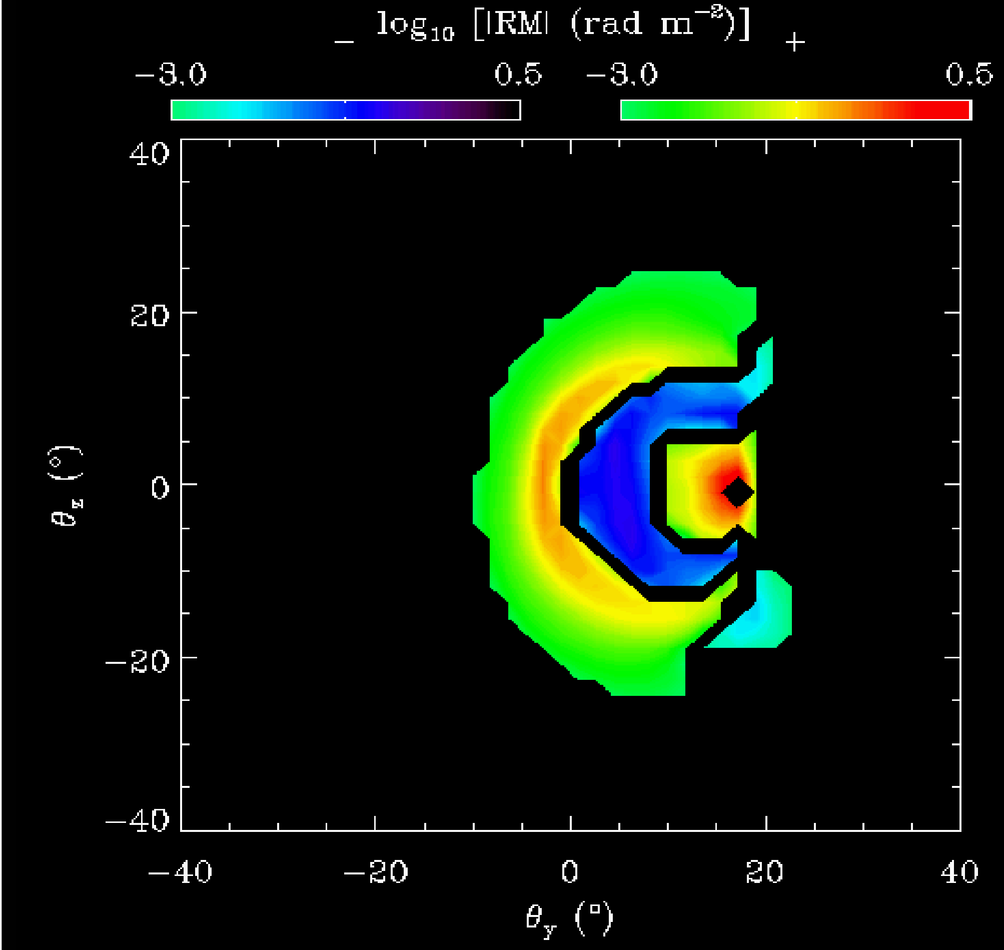
A reminder

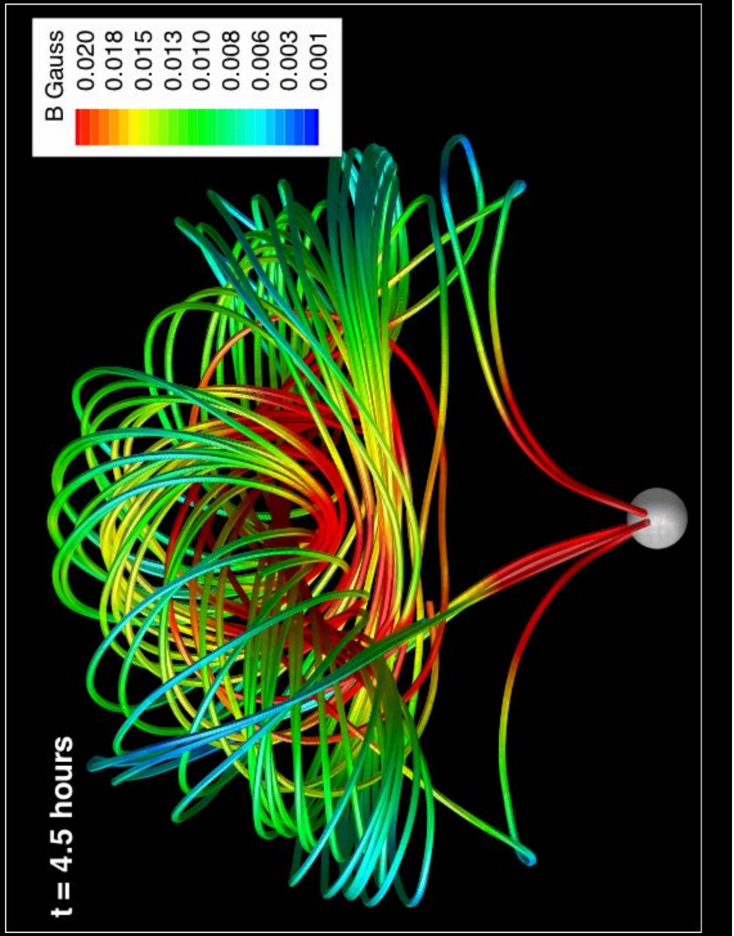
$$FR = \lambda^2 RM$$

$$\overset{[\text{rad/m}^2]}{RM} = 2.63\times 10^{-13}\int \overset{[\text{m}^{-3}]}{n_e(\vec{s})}\,\overset{[\text{T}]}{\vec{B}(\vec{s})}\cdot \overset{[\text{m}]}{d\vec{s}}$$

Requirements levied on MWA-LFD

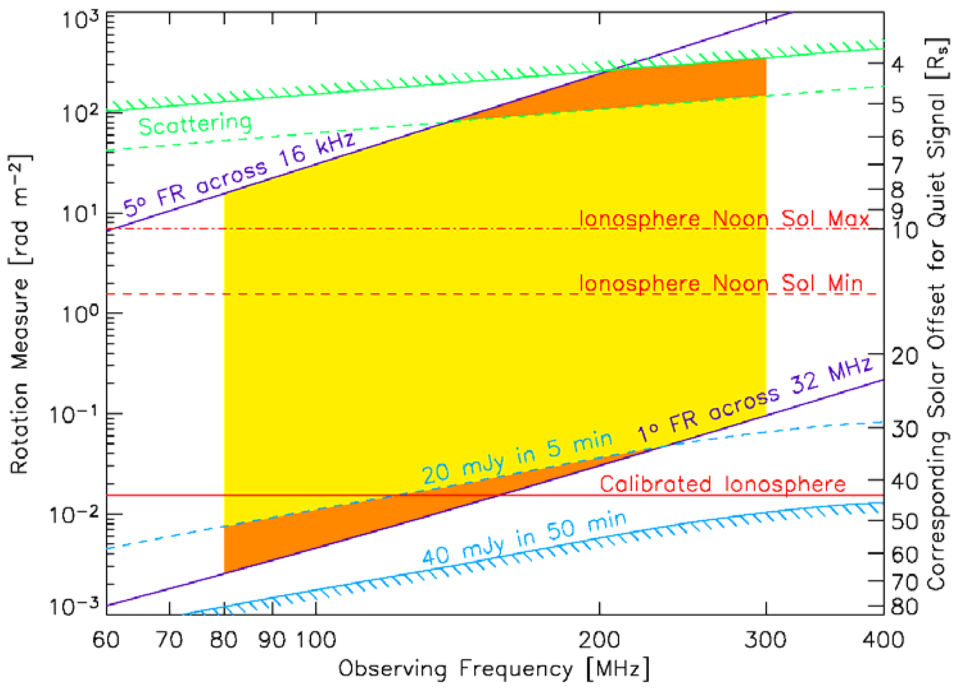
Heliospheric observations





Requirements levied on MWA-LFD

SHI and EOR



- Solar
  - Target: 0.05 rad/m²
  - Desirable: 0.001 rad/m²
- EOR
  - 0.004 rad/m² (~ 1 degree at 150 MHz)

Ionospheric RM

Rough estimates

$$FR = \lambda^2 RM$$

[rad/m^2] [m^{-3}] [T] [m]

$$RM = 2.63\times10^{-13}\int n_e(\vec{s})\,\vec{B}(\vec{s})\cdot d\vec{s}$$

$$RM \approx 2.63\times10^{-13}\,\vec{B}_o\cdot\hat{s}\int n_e(\vec{s})\,ds$$

$$RM \approx 2.63\times10^{-13}\,\vec{B}_o\cdot\hat{s}\,\sigma_e(\hat{s})$$

[rad/m^2] [nT] [TECU] (1 TECU = 10^{16} e m^{-2})

$$RM \approx 2.63\times10^{-6}\cdot B\cdot TEC$$

Ionospheric RM

Rough estimates

[rad/m^2] [nT] [TECU] (1 TECU = 10^{16} e m^{-2})

$$RM \; ; \; 2.63 \times 10^{-6} \cdot B \cdot TEC$$

Height (m)	Magnitude (nT)	Inclination (deg)
0	55668.08	-60.6
1000	55639.51	-60.6
10000	55383.24	-60.63
100000	52903.98	-60.58
350000	46742.47(*)	-60.46

[rad/m^2] [TECU] (1 TECU = 10^{16} e m^{-2})

$$RM \; ; \; 0.12 \cdot TEC$$

[deg]

$$\Delta\phi \; ; \; 28 \cdot TEC$$

(@ 150 MHz)

[deg]

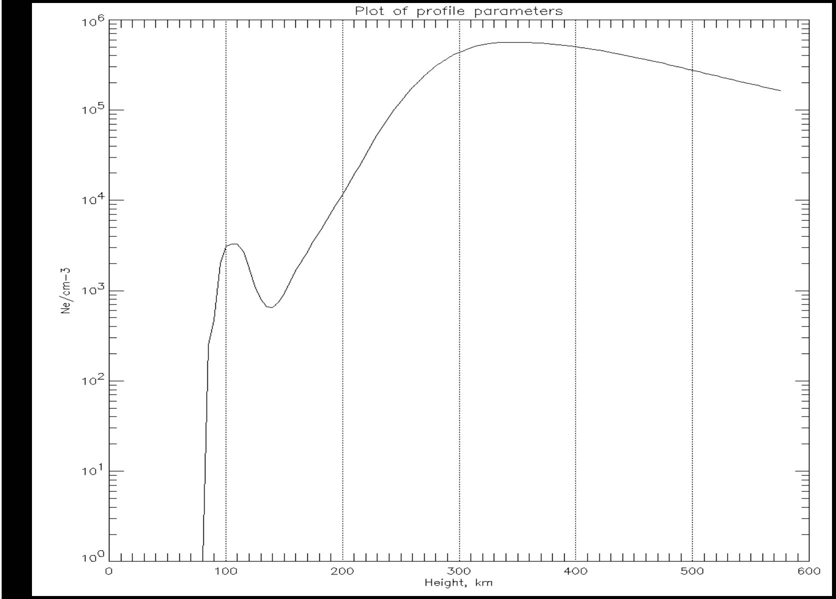
$$\Delta\phi \; ; \; 7 \cdot TEC$$

(@ 300 MHz)

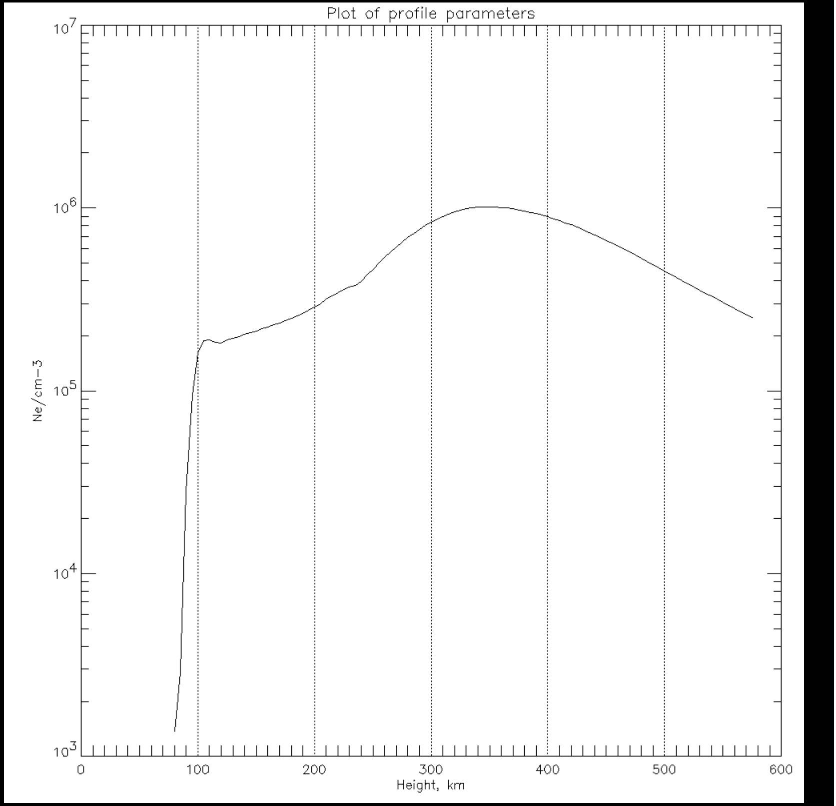
Simulated density above Mileura

NASA CCMC

Peak ~ 350 km



Night



Day

Ionospheric RM

Rough estimates

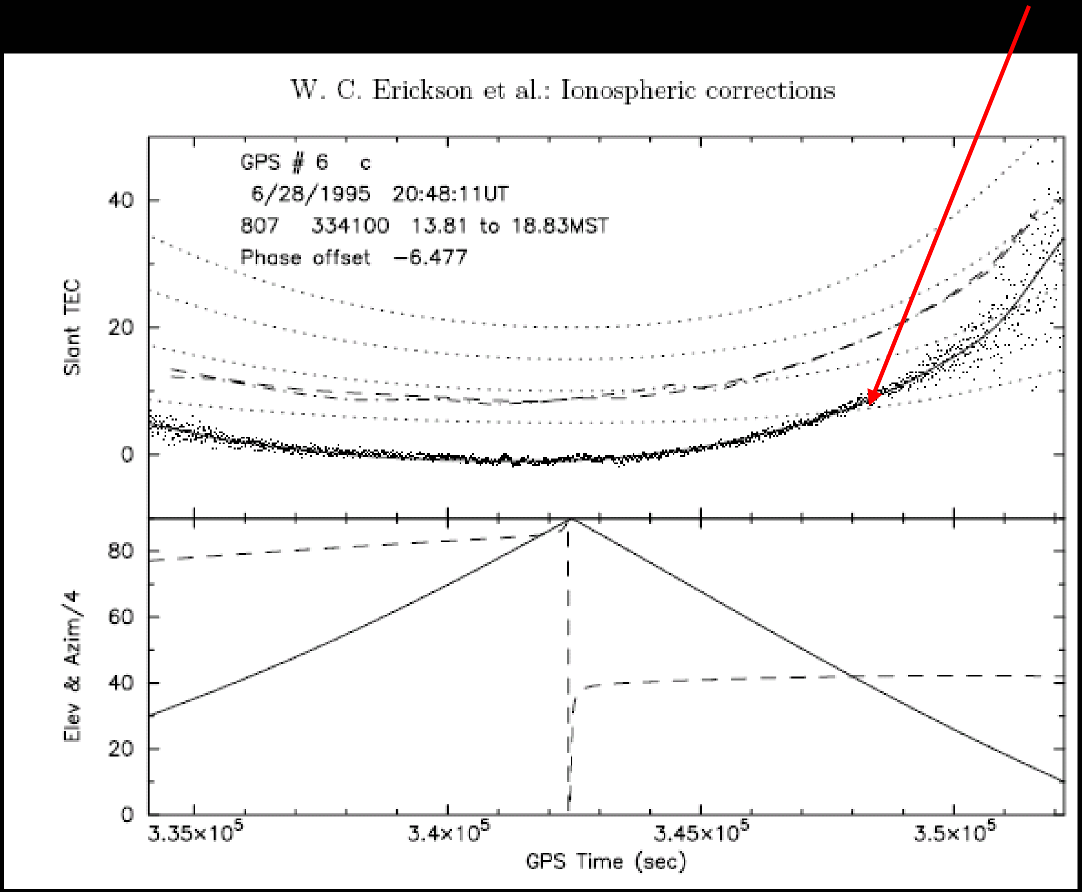
TEC	RM	@150 MHz	@300 MHz
[TECU]	[rad/m^2]	[degrees]	[degrees]
1	0.1	28	6.9
5	0.6	140	34
10	1.2	280	69
20	2.4	560	139

Ionospheric calibration at VLA

Observations at 327 MHz

Simple spherical slab model

Corrected observations & model



Erickson, 2001

Phase corrections with separation

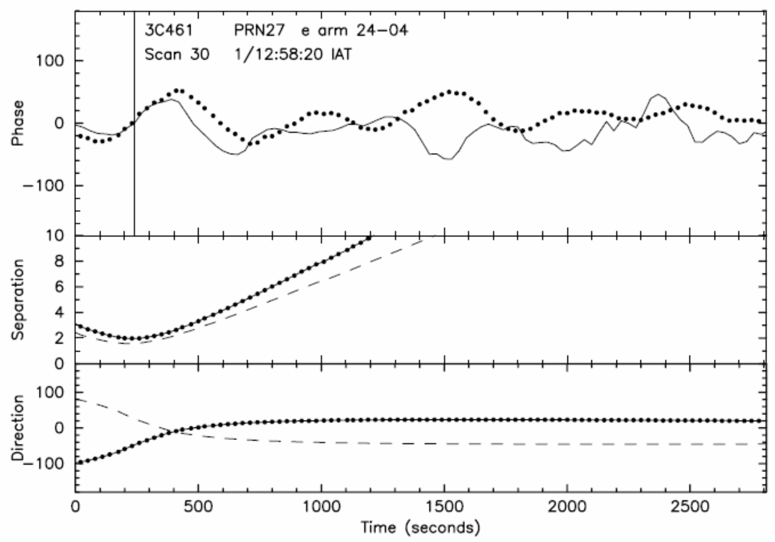


Fig. 7. The measured and predicted phases for a long SE-arm baseline are shown in the top panel. The dots are the measured phases; the solid line is the prediction. The vertical line represents the point of closest approach between 3C 461 and PRN 27. The middle panel shows the angular separations in degrees (dots) and the linear separations between the satellite and radio source ionospheric puncture points in units of 10 km (dashed line). The bottom panel gives the position angles of the satellite-to-source lines

Erickson, 2001

- Correct phase delays on baselines using observations from single GPS receiver on ground
- Correction works very well within about three degrees
- Multiple distributed receivers and additional terms in fit do not help

Feed into RM corrector in AIPS++

Six km baselines, sunrise

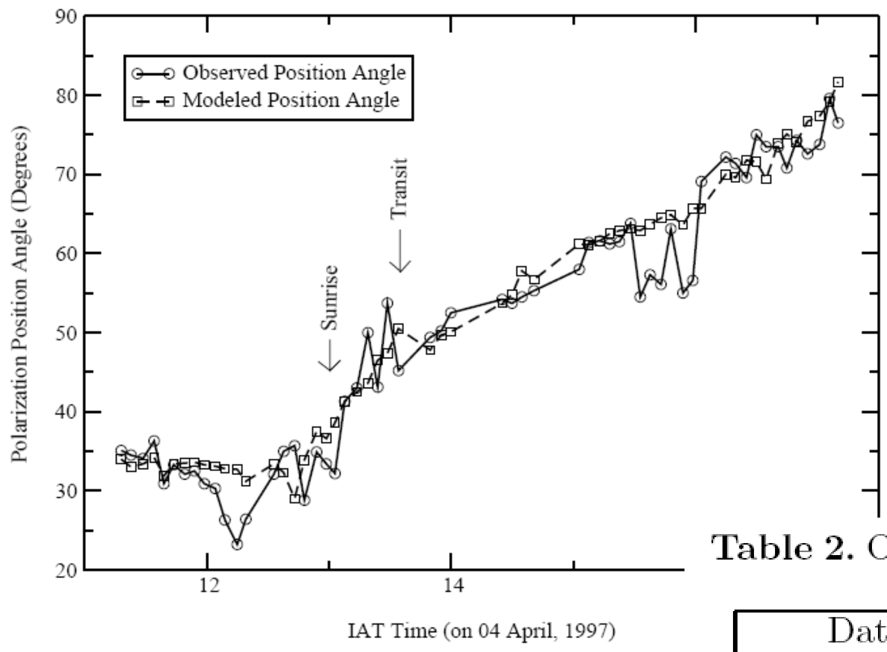
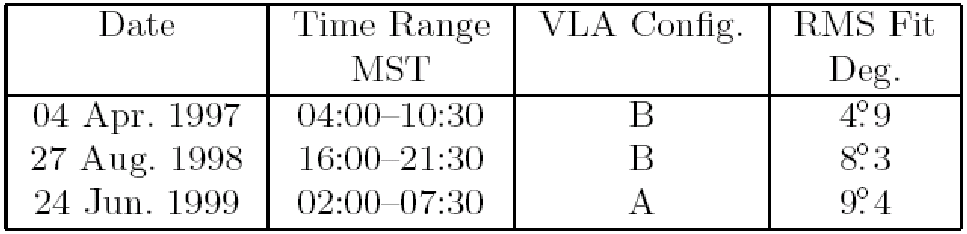


Fig. 9. The change of observed and predicted p
ization of the pulsar PSR 1932+109 through da
1997. The standard deviation between the observ
model for a single 5-min integration is 4°.7. The
viation of the mean of the 59 integrations, i.e. 4°

- 3 of 8 observations had large changes in pulsar polarization angle and were studied
- Feed GPS to infer gradient across sky and combine with ionospheric density model
- 5 minute integrations limited by time and smaller scale structures

@150 MHz: 23, 39, 44
@300 MHz: 5, 9, 11

Table 2. Observing Log of VLA Faraday rotation observations

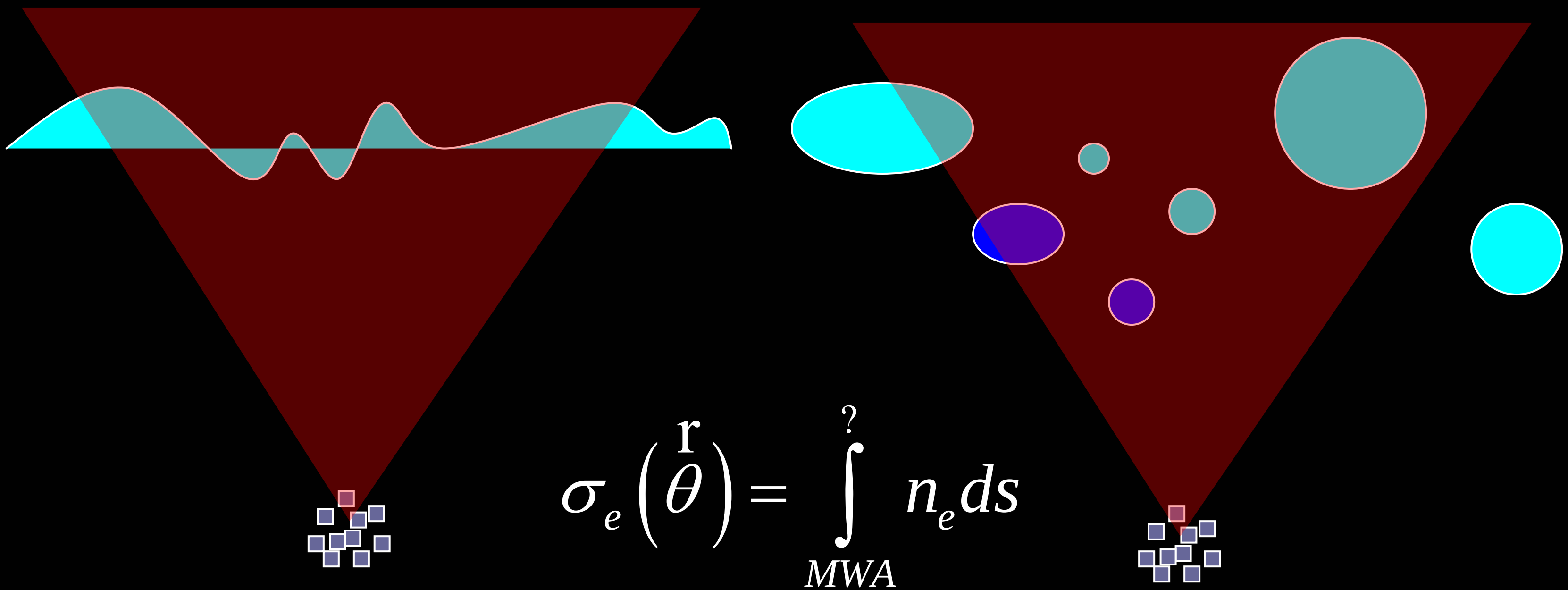


Date	Time Range MST	VLA Config.	RMS Fit Deg.
04 Apr. 1997	04:00–10:30	B	4°.9
27 Aug. 1998	16:00–21:30	B	8°.3
24 Jun. 1999	02:00–07:30	A	9°.4

Erickson, 2001

Density and RM variation

Connect ionospheric calibrations



$$\sigma_e\left(\vec{\theta}\right) = \int_{MWA}^{?} n_e ds$$

$$\sigma'_{cal}\left(\vec{\theta}\right) = \nabla_{\vec{\theta}}\sigma_e\left(\vec{\theta}\right)$$

Density and RM variation

Connect ionospheric calibrations

$$\sigma_e\left(\vec{\theta}\right) = \int_{MWA}^{\infty} n_e ds \qquad \sigma'_{cal}\left(\vec{\theta}\right) = \nabla_{\vec{\theta}}\sigma_e\left(\vec{\theta}\right)$$

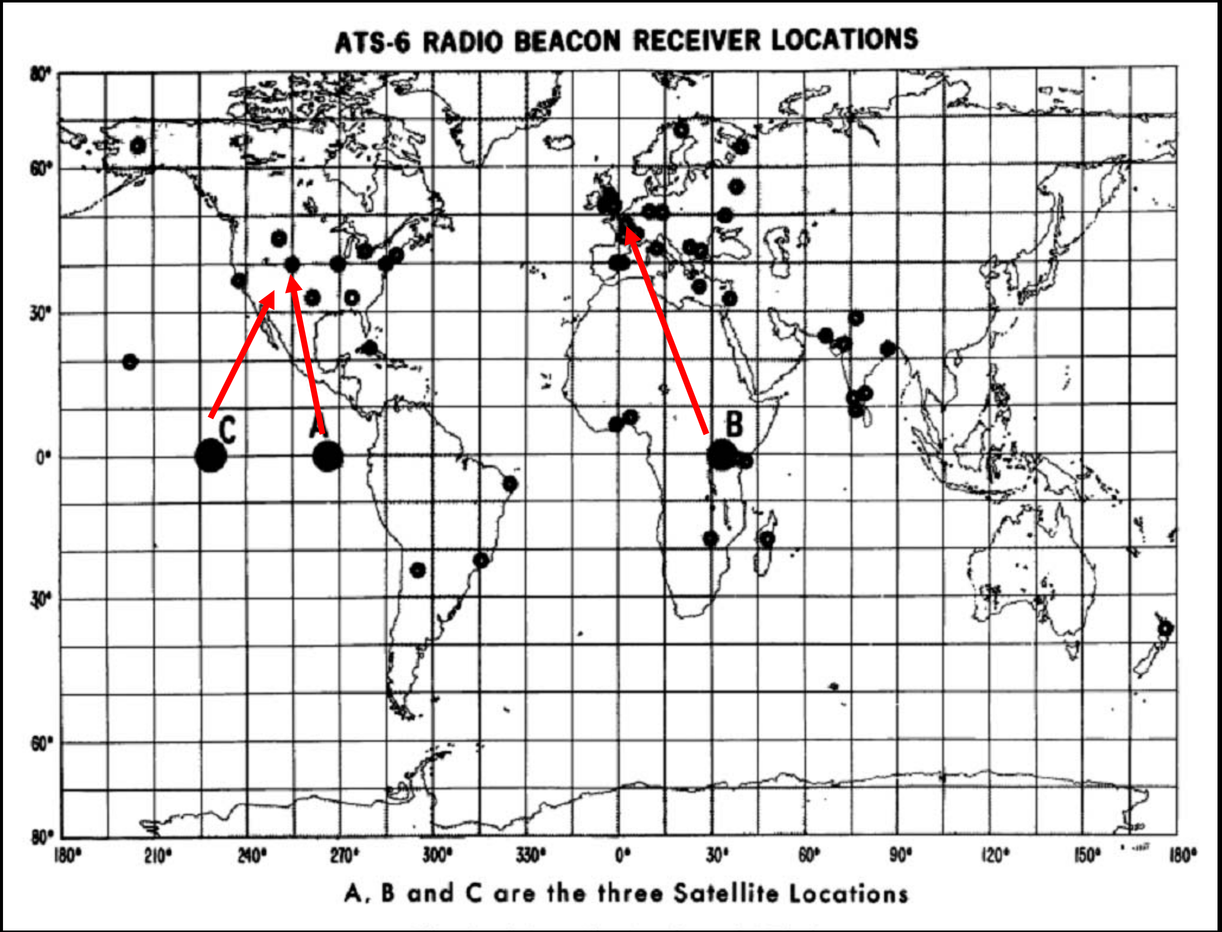
$$\sigma_e\left(\vec{\theta}\right) = \int_{\vec{\theta}_{ref}}^{\vec{\theta}} \sigma'_{cal} + \sigma\left(\vec{\theta}_{ref}\right) = \sigma_{gps}\left(\vec{\theta}\right) + \sigma_{ps}\left(\vec{\theta}\right)$$

$$\sigma_{ps}\left(\vec{\theta}\right) / \sigma_{gps}\left(\vec{\theta}\right) \sim 10^{-4}$$

How closely does TEC track FR?

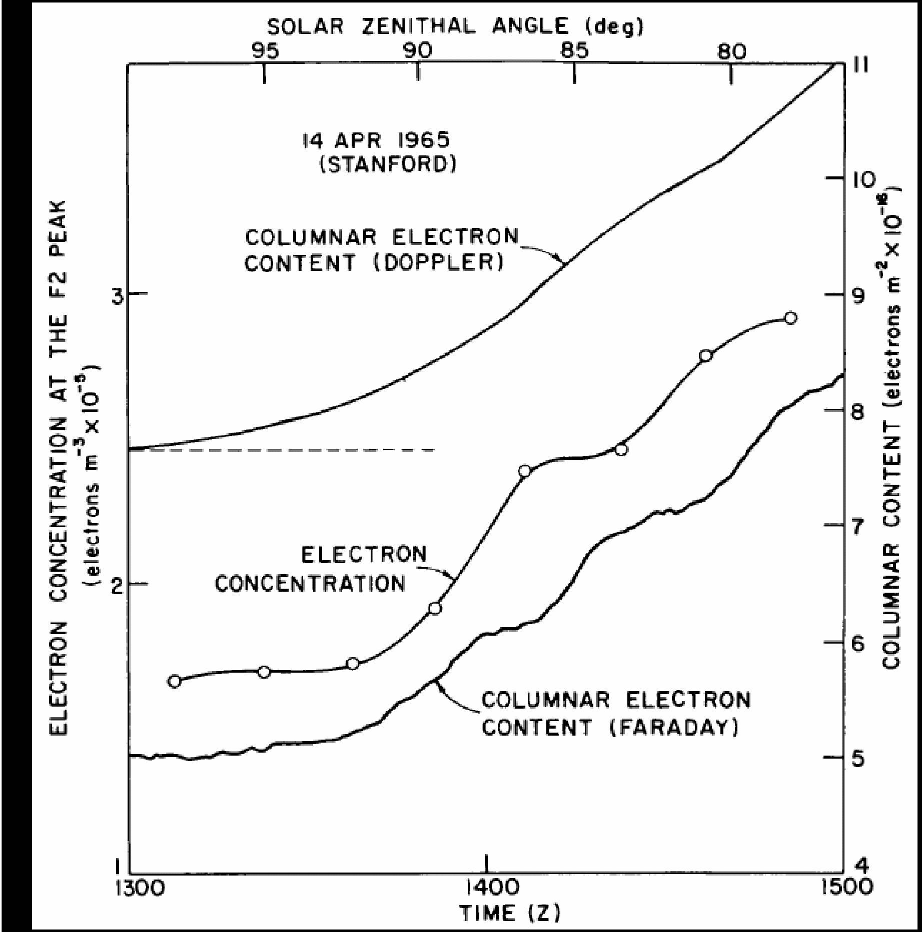
$$RM \sim 2.63\times10^{-13}\,\vec{B}_o \cdot \hat{s}\sigma_e\left(\hat{s}\right)$$

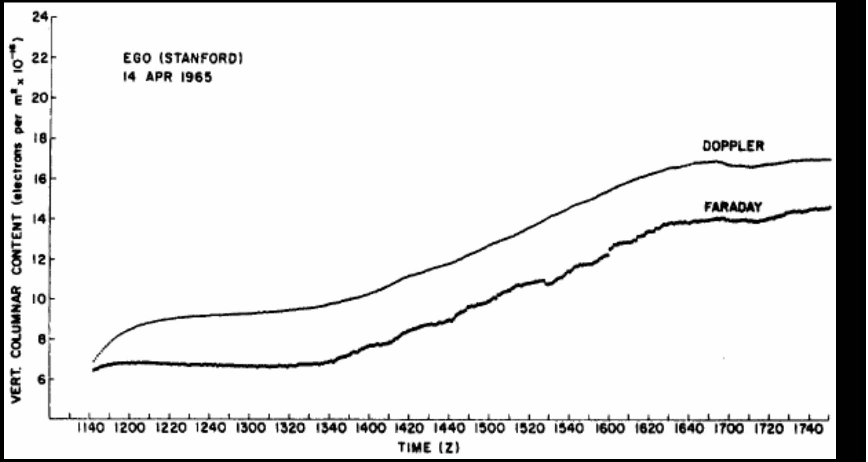
ATS-6 Radio Beacon Experiment



A, B and C are the three Satellite Locations

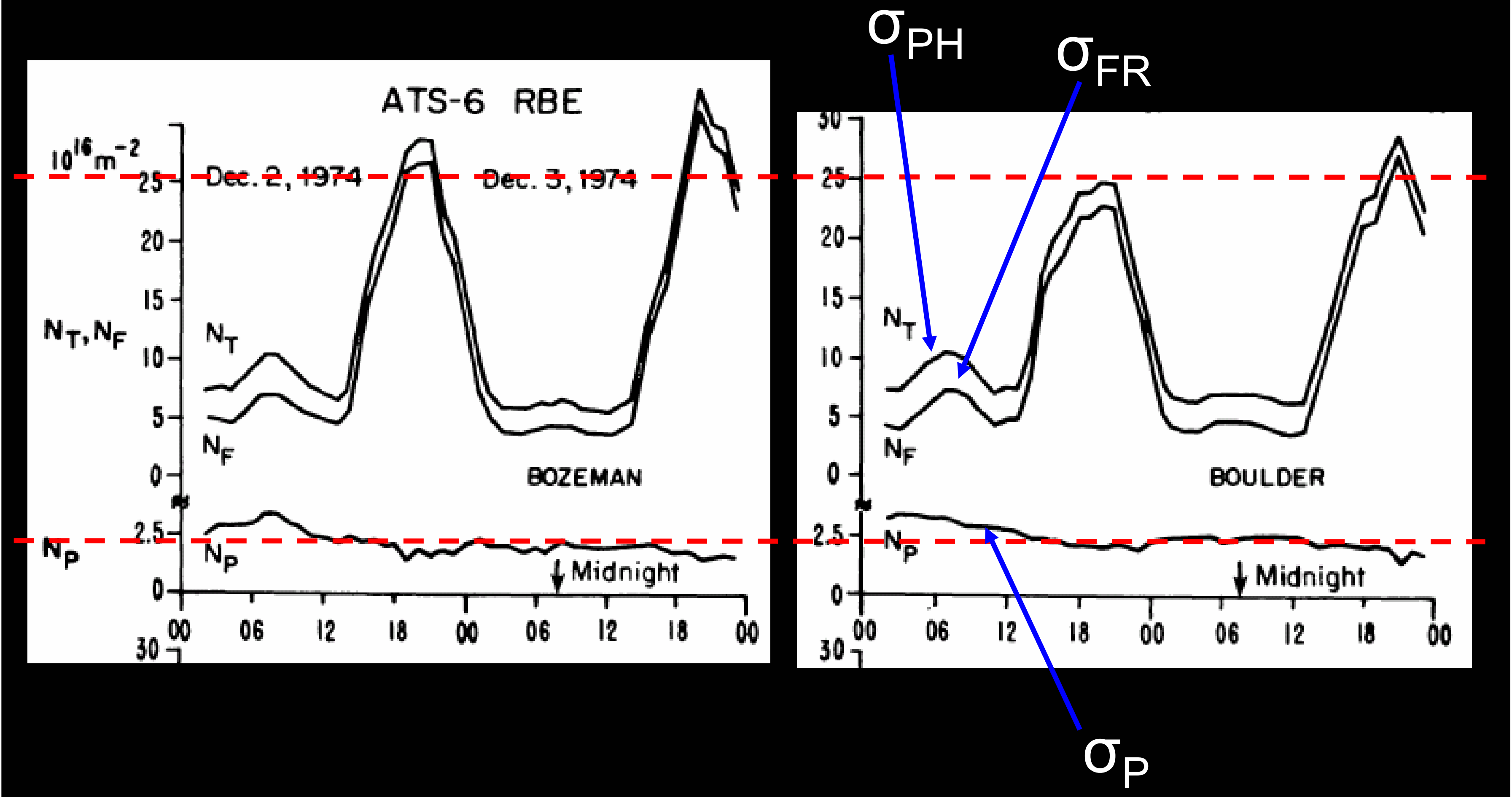
Measurements of σ_{PH} and σ_{FR} *(and density)*





Comparisons of σ_{PH} and σ_{FR}

Locations of density variations

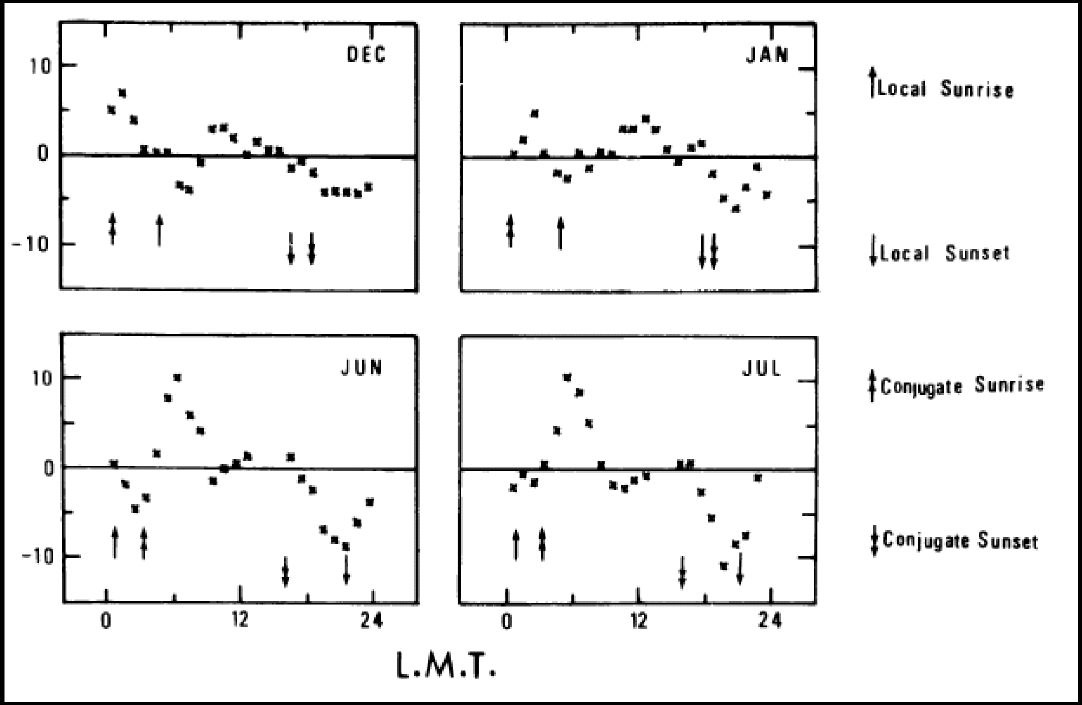


σ_{PH}

σ_{FR}

σ_P

Time derivative of difference

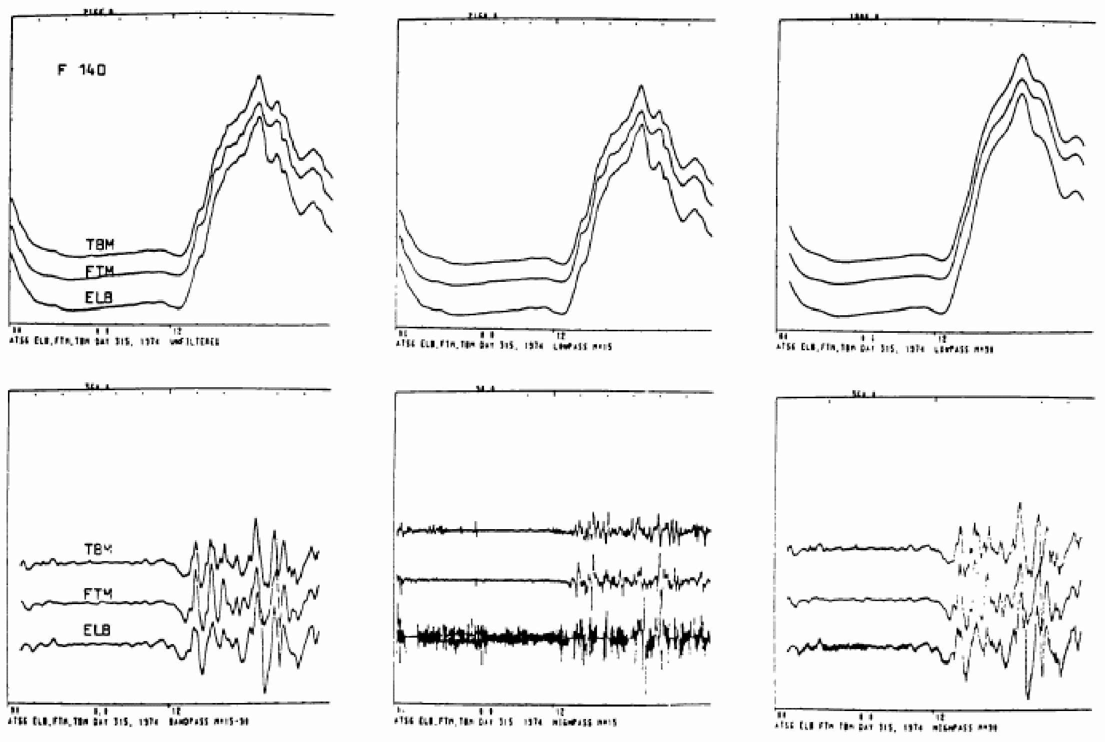


On average a difference of 0.001 rad/m^2 will develop in 850 seconds

$$\frac{d}{dt}\left(\sigma_{ph}-\sigma_{fr}\right);\ 10^{-5}[\mathrm{TECU/s}]=1.2\times10^{-6}[\mathrm{rad/m^2/s}]$$

Tracking TID with 3 Stations

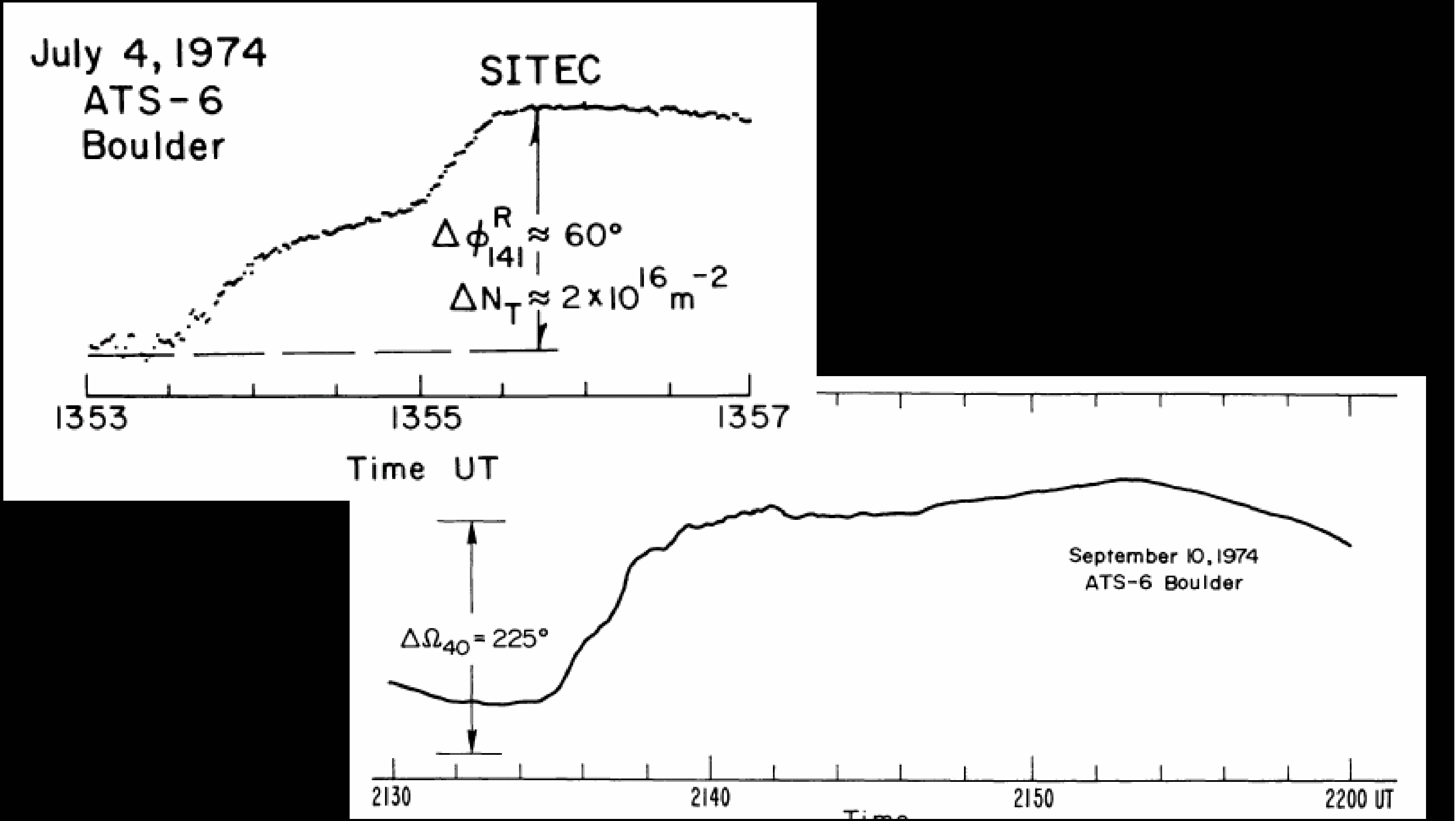
Large scale features highly correlated



Shorter scale features poorly correlated – true in general

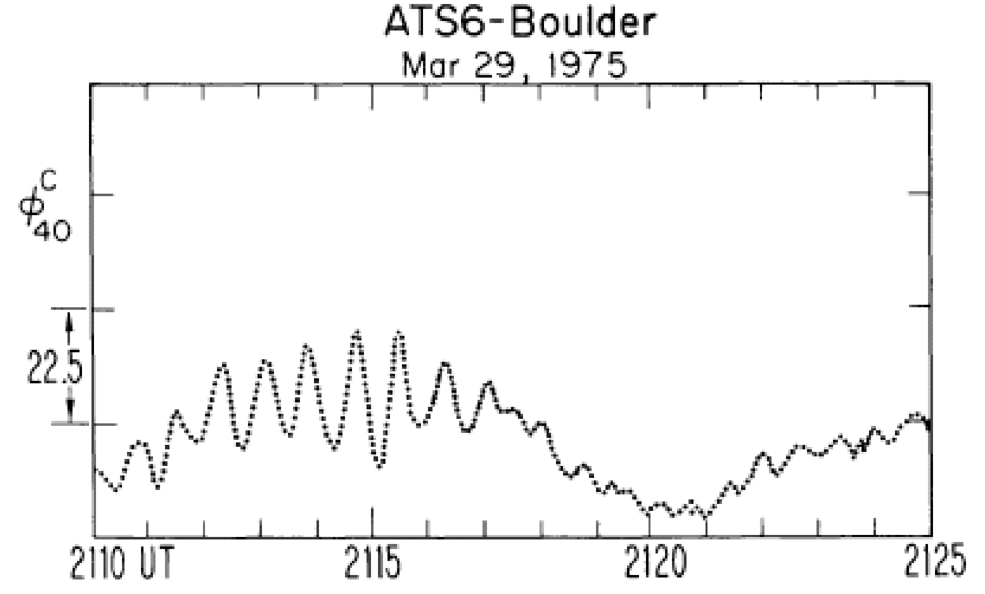
- Periods
  - 15-90 minutes
- Wavelengths
  - Several 100 km
- Speeds
  - 100-200 m/s
  - 140 m/s day
  - 110 m/s night
- Shape
  - 25% Elongations

Sudden TEC enhancements



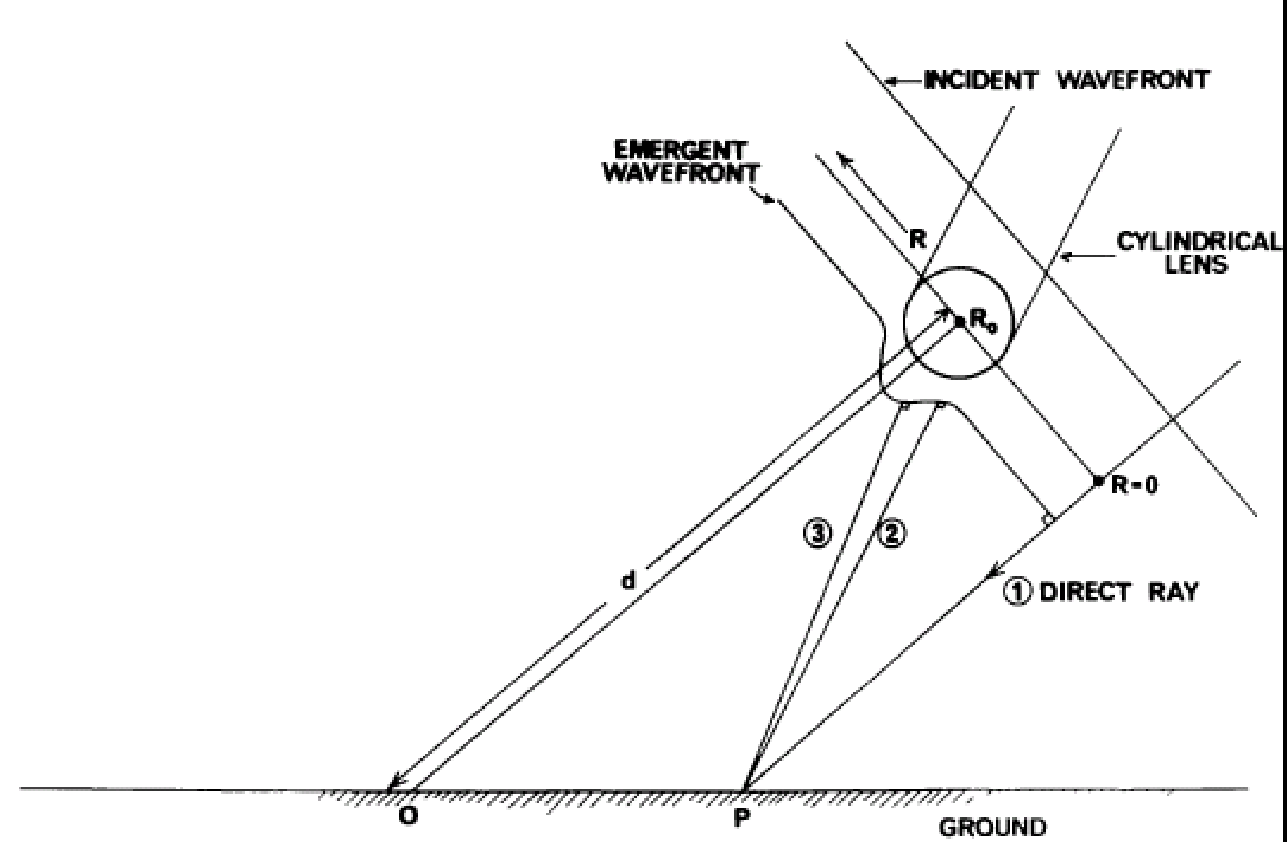
Micropulsations

- Periodic and non-periodic
- Last from seconds to minutes
- Last for several hours near non on quiet days
- 0.01%-0.1% total electron content

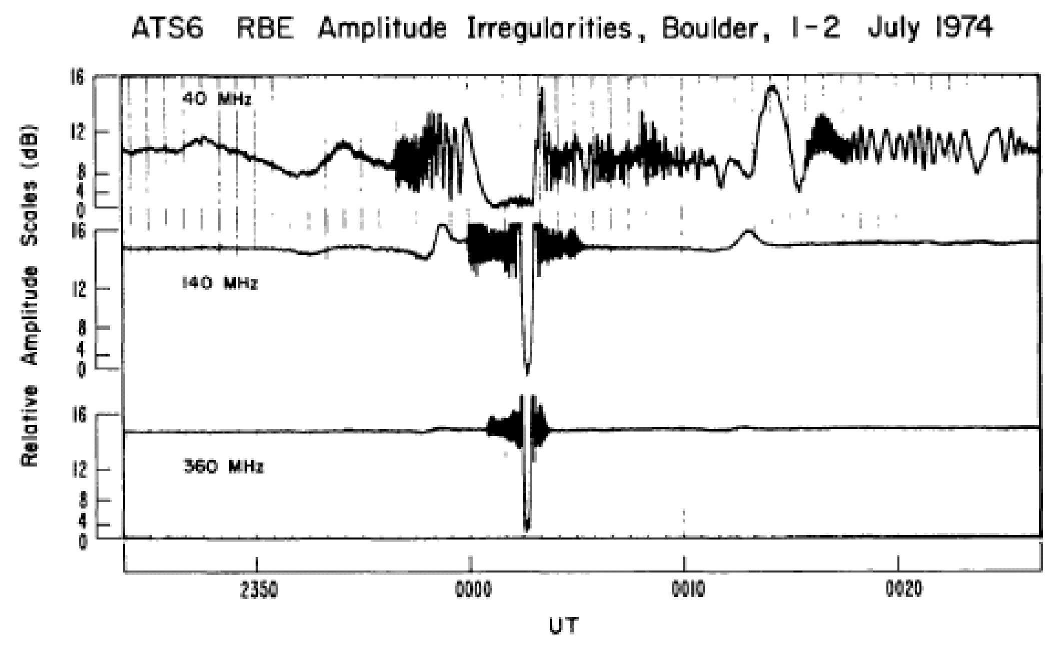


MHz	Degrees	RM	TEC
150	1.6	0.0068	0.057
300	0.4	0.0068	0.057

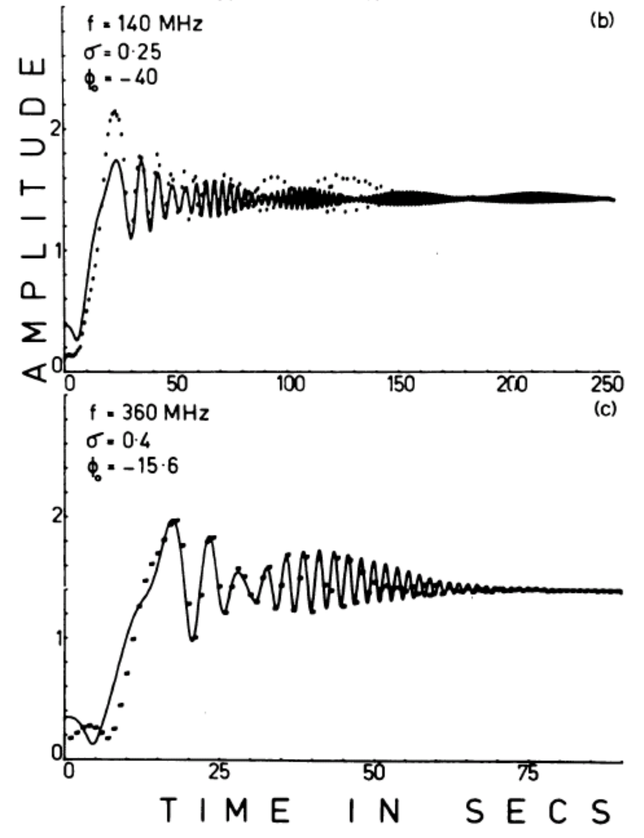
Scintillations



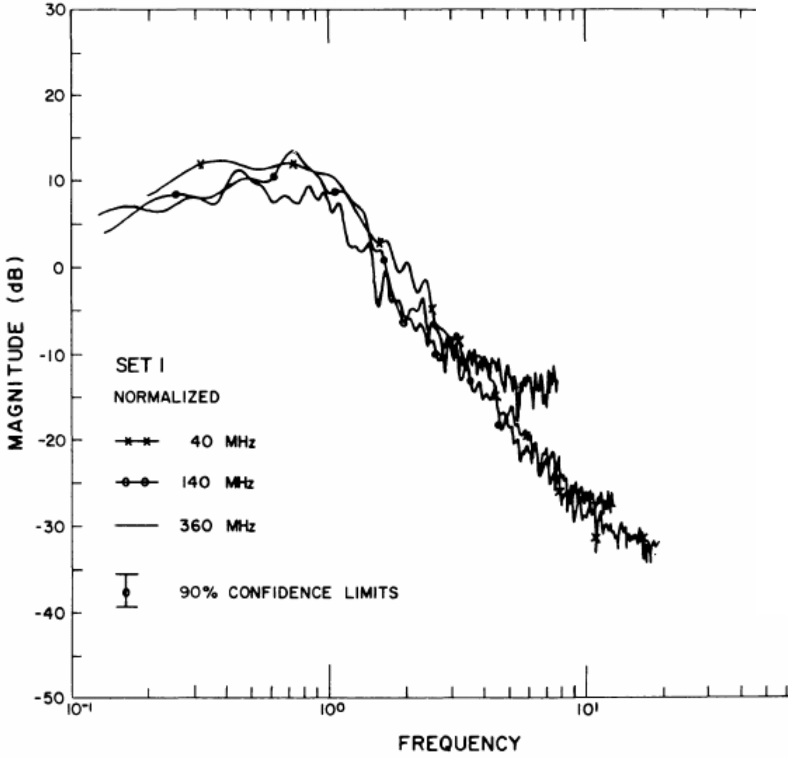
Observations and model

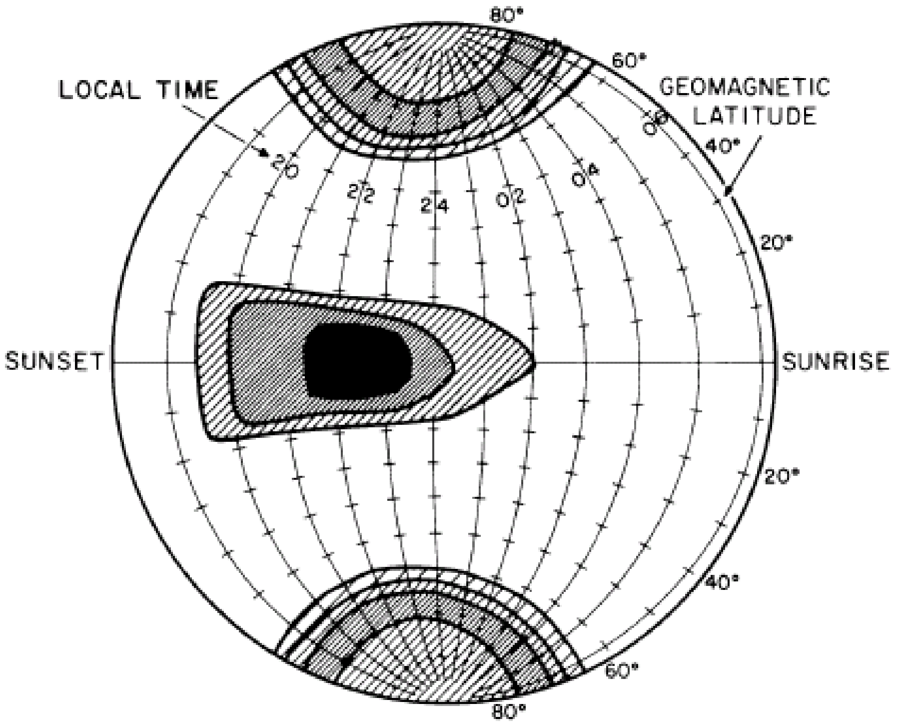


ATS6 RBE Amplitude Irregularities, Boulder, 1-2 July 1974



Power/location scintillations





DEPTH OF SCINTILLATION FADING (PROPORTIONAL TO DENSITY OF CROSSHATCHING)

What next?

- Numerical simulation of ionosphere with Shep
- Analysis of initial dual frequency GPS receiver measurements
- Simulations of FR determination with realistic observations
  - Robust algorithms
- Implementing strawman ionospheric FR calibration
- Effect on observing strategies
  - Solar: May need to observe away from Sun where solar RM small