1998 CEDAR Workshop

Boulder, Colorado

June 7-12, 1998

Tutorial Lecture

by Michael Mendillo
Boston University

Equatorial Aeronomy

TUTORIAL #2: EQUATORIAL AERONOMY

– Michael Mendillo
Boston University

– CEDAR '98
10 June

OUTLINE

- **GOALS:**
  - Background Ionospheric Physics for Low Latitudes
  - Preparation for a "drop-in" at MISETA Workshop [Multi-Instrument Studies of Equatorial Thermospheric Aeronomy] (Thermospheric: includes ionization)

- **NOT COVER:**
  - Review of Diagnostic Techniques
  - Traditional Review Paper [i.e., talk only about your results]
  - Proper Review Paper [comprehensive survey of all contributions]

References

- Rishbeth + Garriott
- Hargraves
- Kelley
- Int. Symp. Eq. Aer. Proceedings; Last in JASTP/Sept '99

Production of an Ionosphere

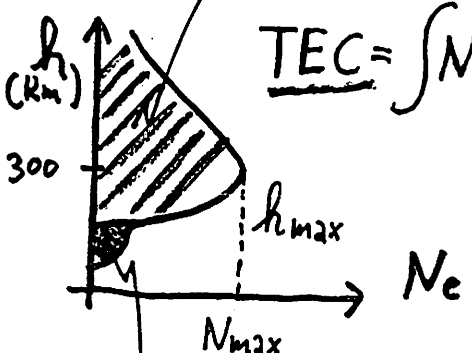
- Solar EUV + $O \longrightarrow O^+ + e^-$

Loss: $O^+ + \begin{Bmatrix} N_2 \\ O_2 \end{Bmatrix} \longrightarrow \begin{Bmatrix} NO^+ \\ O_2^+ \end{Bmatrix} + O$ (1)

$\begin{Bmatrix} NO^+ \\ O_2^+ \end{Bmatrix} + e^- \rightarrow \begin{Bmatrix} N + O \\ O^* + O \end{Bmatrix}$ (2)

$O^* \rightarrow O + h\nu\,(6300 \text{Å})$

"Airglow"

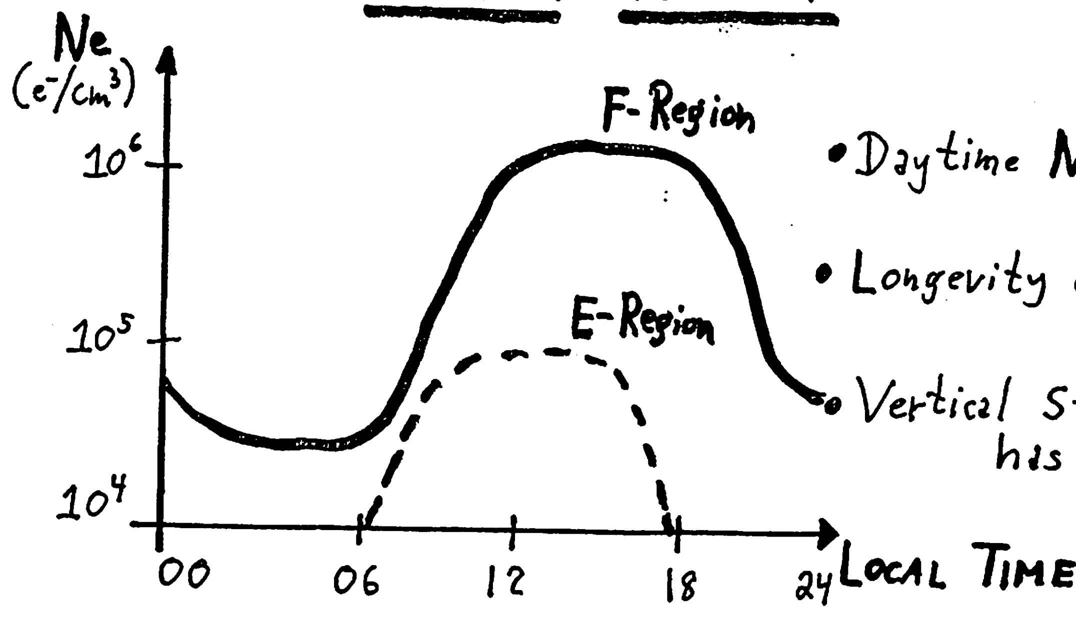


$TEC = \int N_e(h)\, dh$

$f_o F2 (MHz) \approx 9 \sqrt{N_{max} (10^6 e^-/cm^3}$

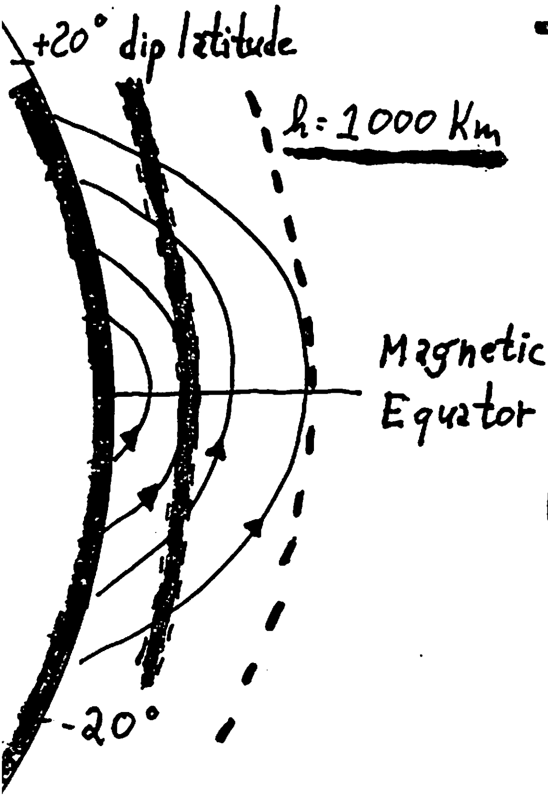
E-Region (solar production of molecular ions)

Diurnal Pattern



- Daytime $N_e \propto O/N_2$
- Longevity due to (1) vs. (2)
  "Slow" "Fast"
- Vertical structure has smallest H.

EXPECTATIONS FOR LOW-LATITUDE IONOSPHERE



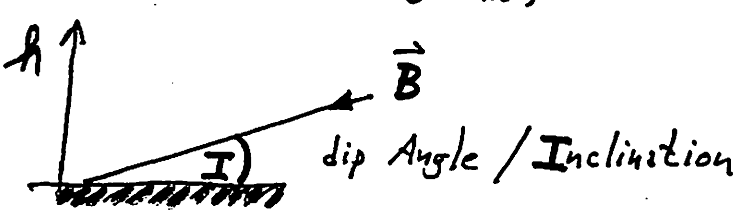
- $\delta_\odot$ varies little ⟹
  - Minor Latitude Effects
  - Minor Seasonal Effects

- $\vec{B}$ "within" Ionosphere ⟹
  - Minor changes during Geomagnetic Storms
  - No auroral precipitation to produce small scale Ne irregularities

- $\vec{B}$ mostly horizontal ⟹
  - Plasma dynamics induced by Neutral Winds (U_m) small.

$$\vec{V}_h = \vec{U}_m \sin I \cdot \cos I$$

($\vec{V}_h$: vertical; $\vec{U}_m$: meridional)



Departures from "Chapman-like" behavior:

ANOMALIES vs. IMPROVED PHYSICS

Theoretical approach

Geophysical Inputs:

Neutral densities
Neutral wind
Neutral temperature
Solar flux
Energetic particle precipitation
Electron temperature
Ion temperature
Electric field
Magnetic field

D. ANDERSON

Equation of Motion

$$N_i m_i \frac{d\bar{V}_i}{dt} = N_i m_i \bar{g} - \nabla(N_i k T_i) + eN_i(\bar{E} + \bar{V}_i \times \bar{B})$$

$$- N_i m_i \nu_{in}(\bar{V}_i - \bar{U}) - N_i m_i \nu_{ik}(\bar{V}_i - \bar{V}_k) - N_i m_i \nu_{ie}(\bar{V}_i - \bar{V}_e)$$

Continuity Equation

$$\frac{\partial N_i}{\partial t} + \nabla \cdot (N_i \bar{V}_i) = P - L$$

$$\frac{\partial N_i}{\partial t} + \bar{V}_{i\perp} \cdot \nabla N_i = P - L - \nabla \cdot (N_i \bar{V}_{i\parallel}) - N_i \nabla \cdot \bar{V}_{i\perp}$$

$$\bar{V}_{i\perp} = \frac{\bar{E} \times \bar{B}}{B^2}$$

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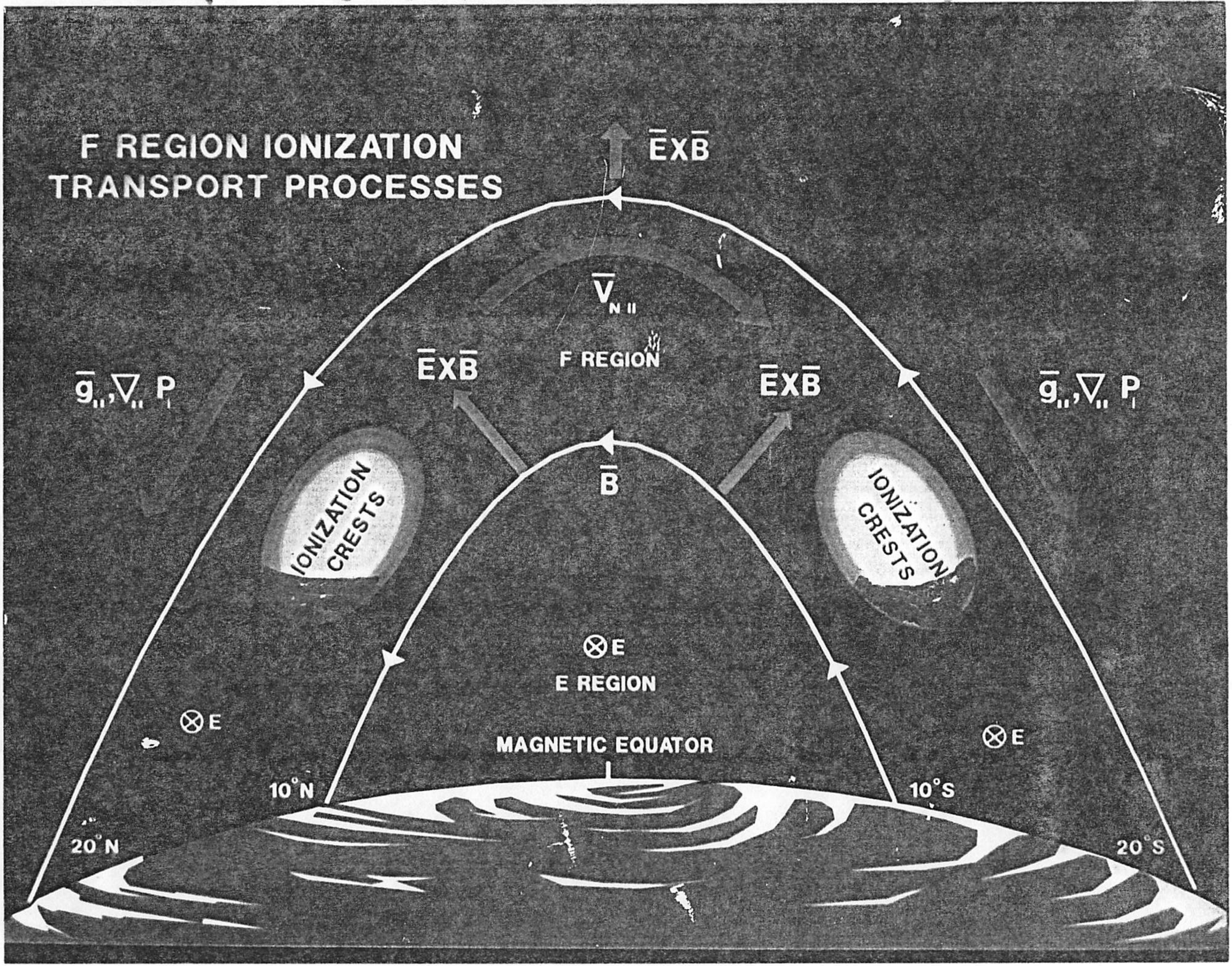
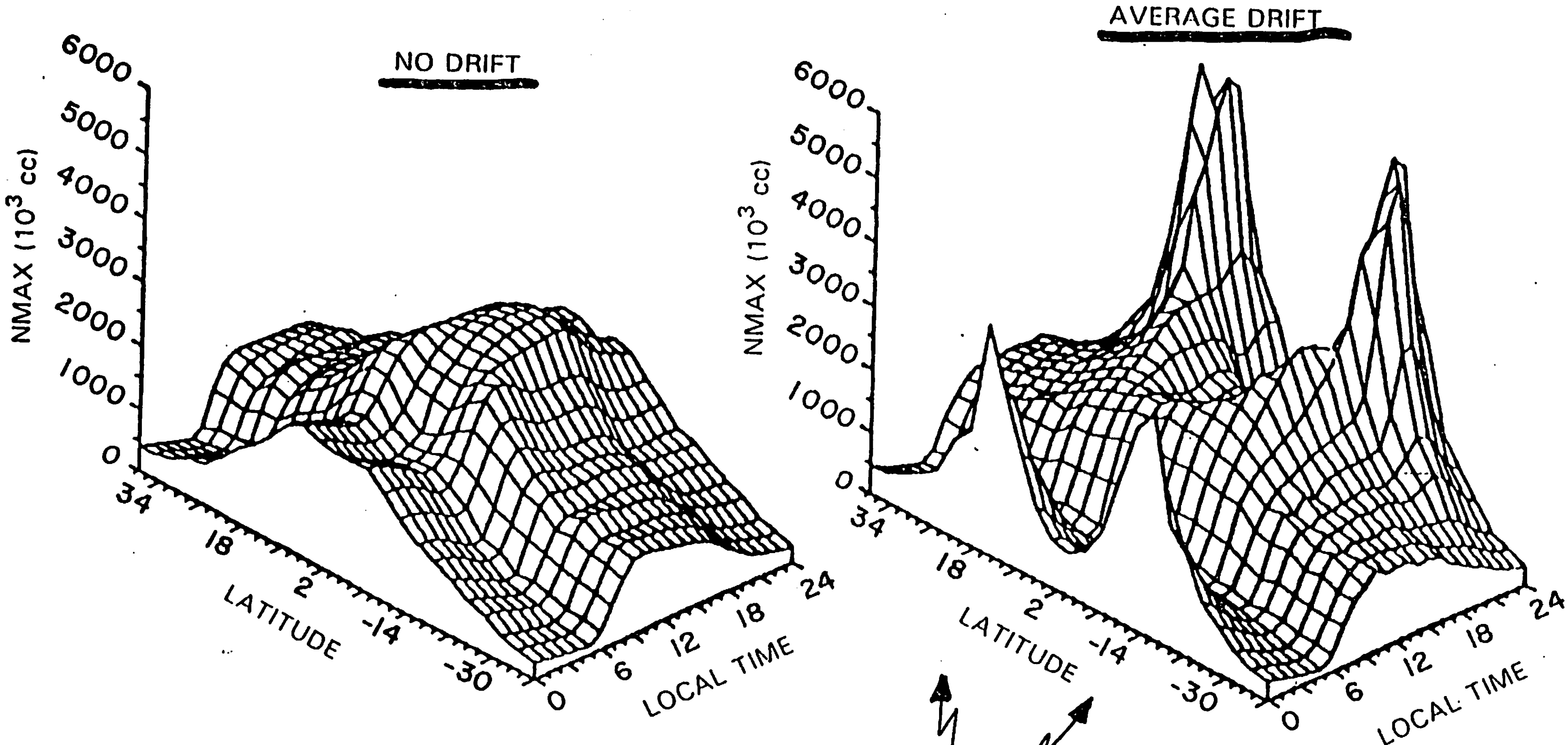
6300Å ↓ TROPICAL ARCS ↓ 6300Å



EFFECT OF ELECTRODYNAMICS - Model Results



Appleton ANOMALY
Equatorial ANOMALY
Equatorial Ionization Anomaly (EIA)
"INTERTROPICAL ARCS" => Airglow signature

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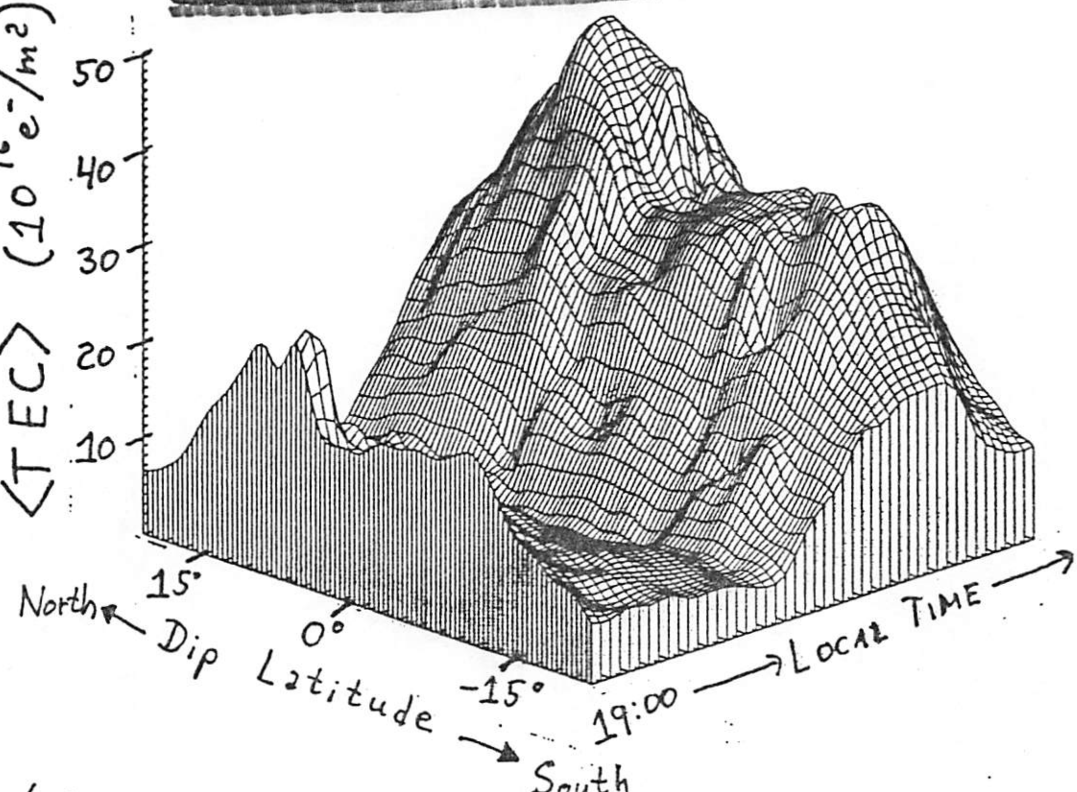
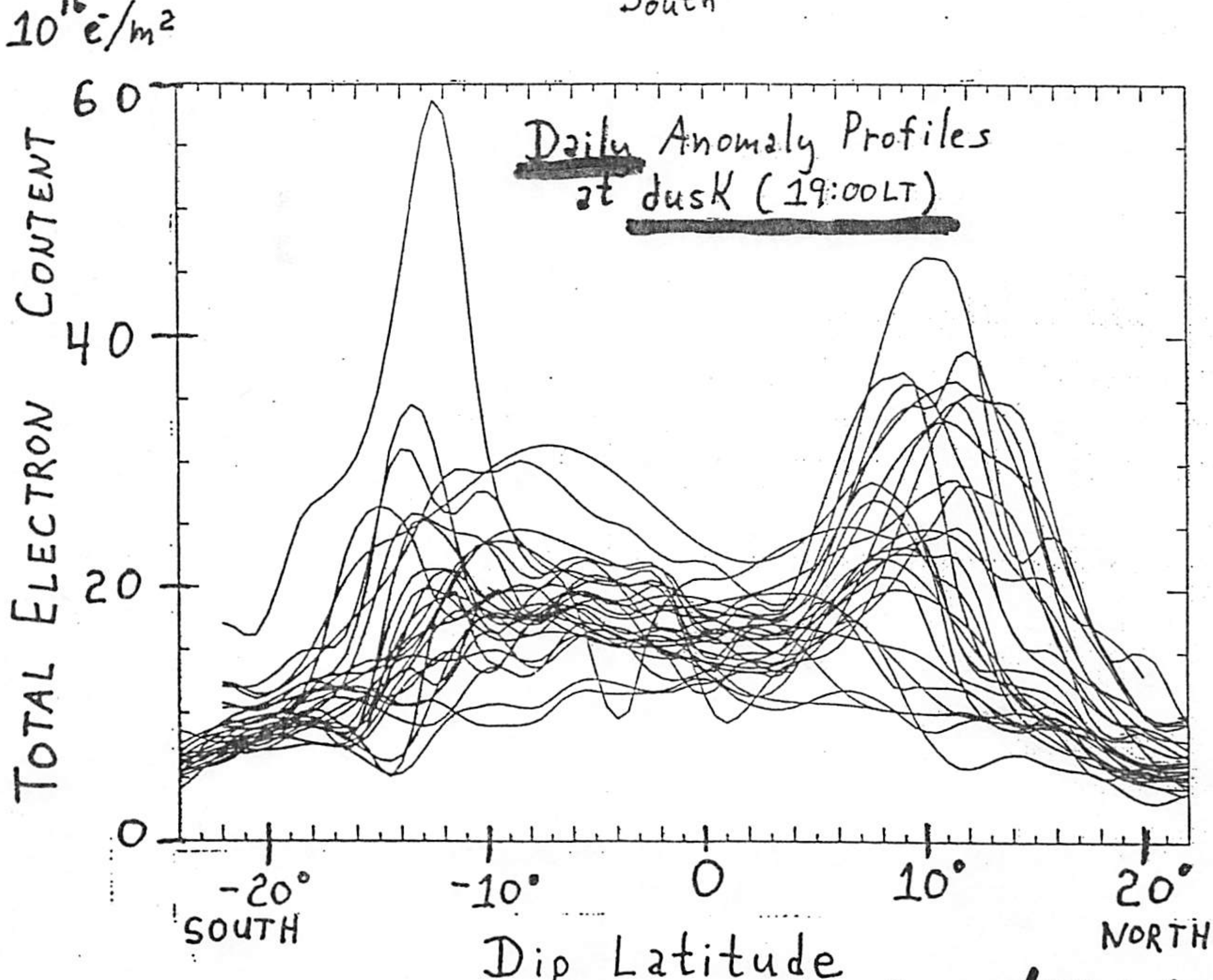
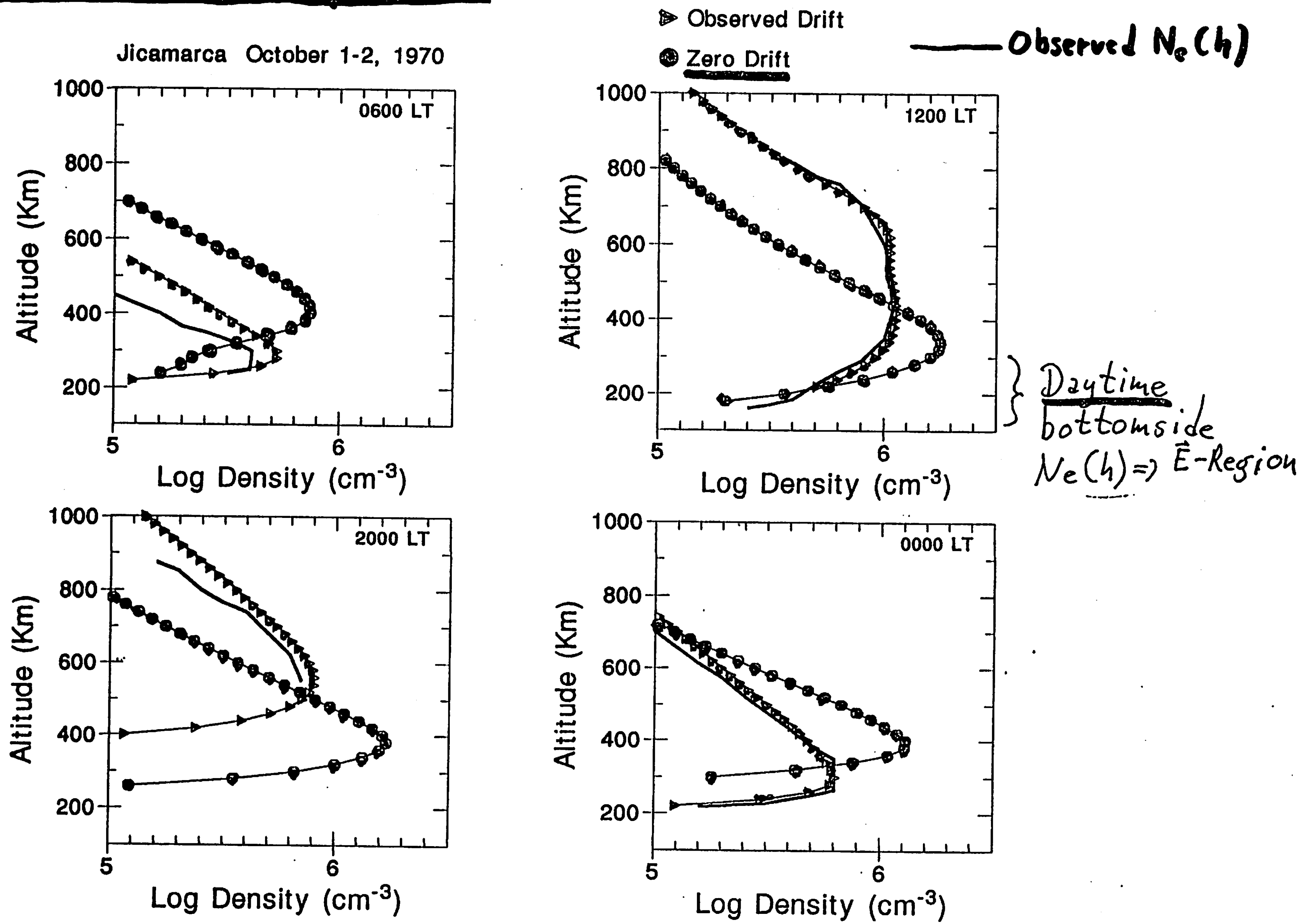
— GPS TOTAL ELECTRON CONTENT —





B. LIN / J. AARONS

Model-Data Comparisons:



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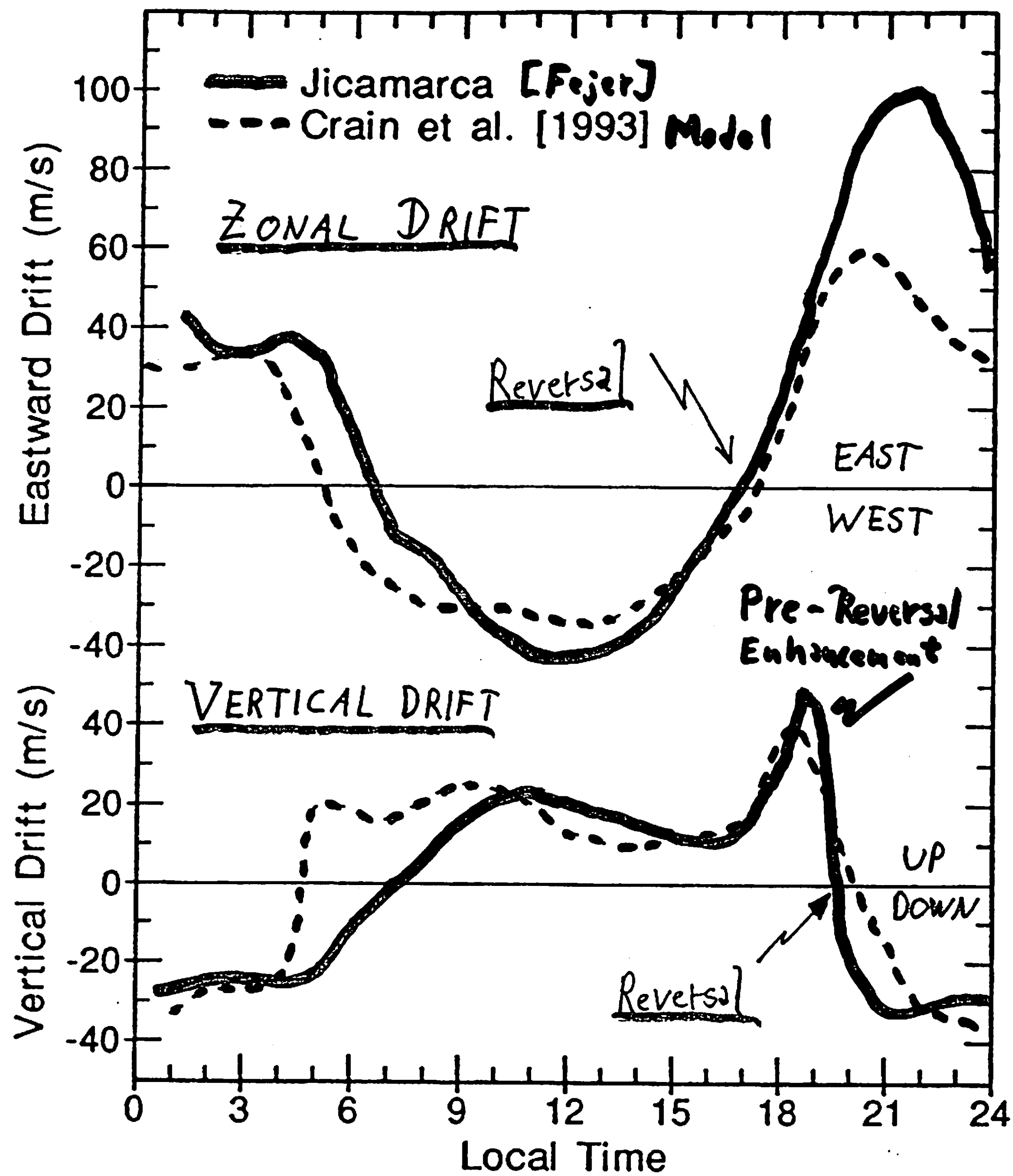
DYNAMO MODELS FOR IONOSPHERIC DRIFTS



Neutral Winds ($\mathcal{U}$) $\Rightarrow$ ions, e^- $\perp \vec{B} \Rightarrow \vec{E}$

Electric Fields Cause Plasma Drifts ($\vec{V}_p$)

Plasma Drift move ionization through

H Neutral Atmosphere: $H_z << H_{horizontal}$

(Scale Height)

EXAMPLES OF WINDS AND TEMPERATURES

HEIGHT = 300 Km

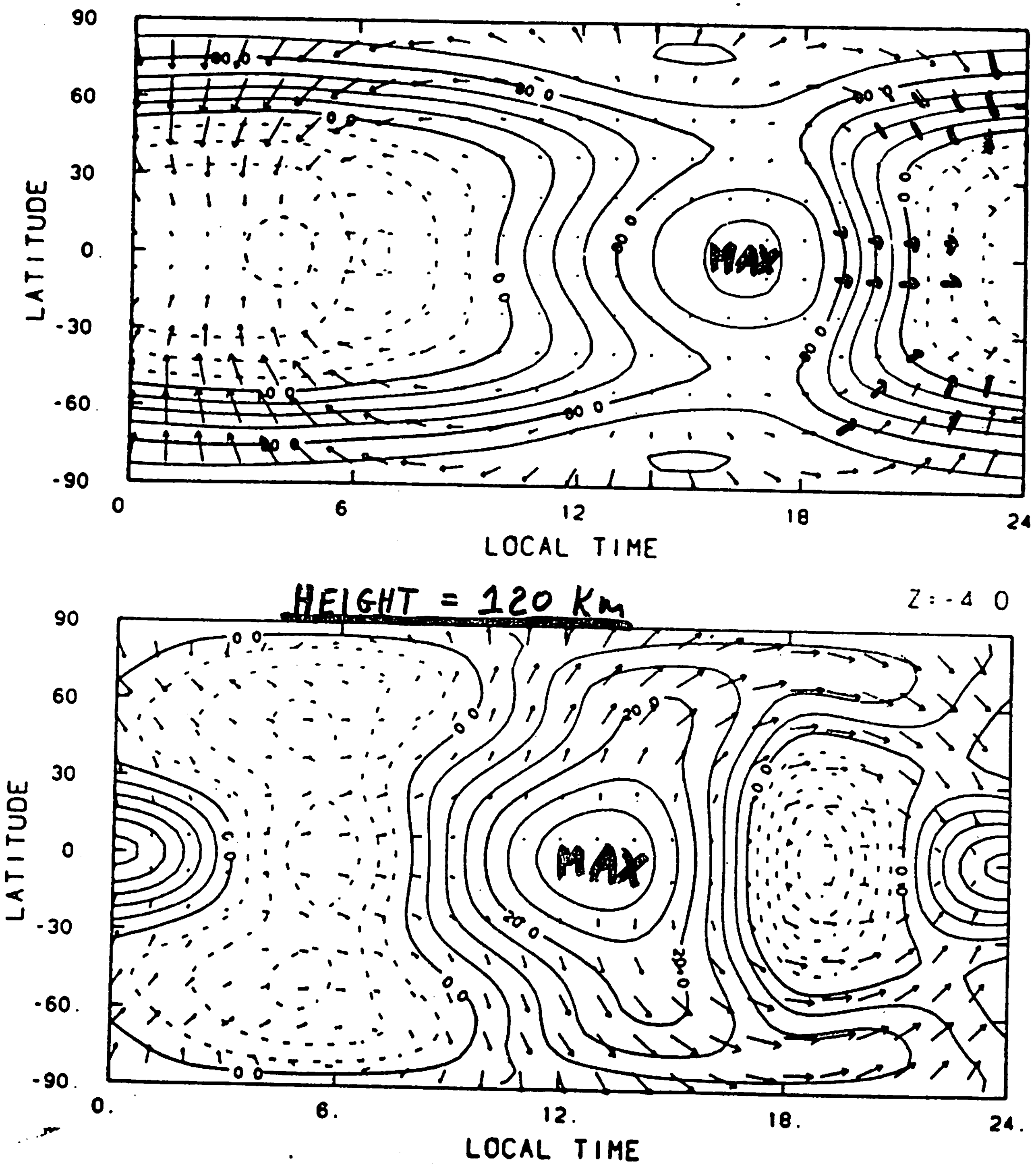


Figure 17-26. Calculated global distribution of winds and perturbation temperature (K) along two constant pressure surfaces.

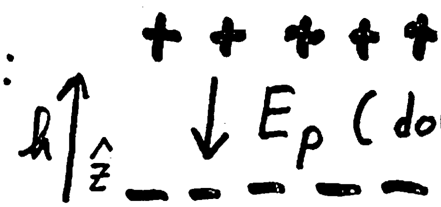
(AFGL) HANDBOOK

EXAMPLE: F-REGION DYNAMO --- Zonal Drifts

Post-sunset conditions: $\vec{u}_n \rightarrow$ (east) $\quad \Uparrow \vec{B}$ (north)

$$O + \begin{Bmatrix} O^+ \\ e^- \end{Bmatrix} \text{ via } \begin{Bmatrix} \nu_{ni} \\ \nu_{ei} \end{Bmatrix}, \quad \vec{F} = q(\vec{u}_n \times \vec{B})$$

O^+ displaced upward:



$\downarrow E_p$ (down), $\vec{E}_p = -\vec{u}_n \times \vec{B}$

$\vec{B}$ (north) $\Uparrow \otimes E_p$ (down) : $\vec{V}_p (O^+ + e^-) = \dfrac{\vec{E}_p \times \vec{B}}{B^2}$

$$\vec{V}_p = \frac{-(\vec{u} \times \vec{B})_z \times \vec{B}}{B^2} = \vec{u}_n$$

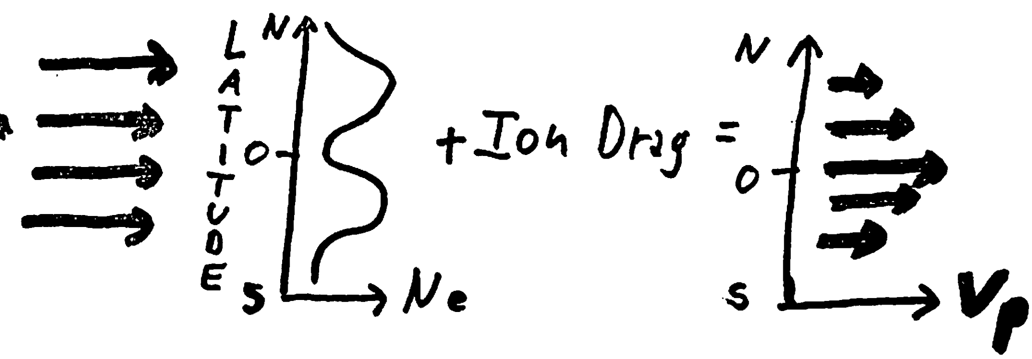
∴ An Eastward wind produces an Eastward Plasma Drift.

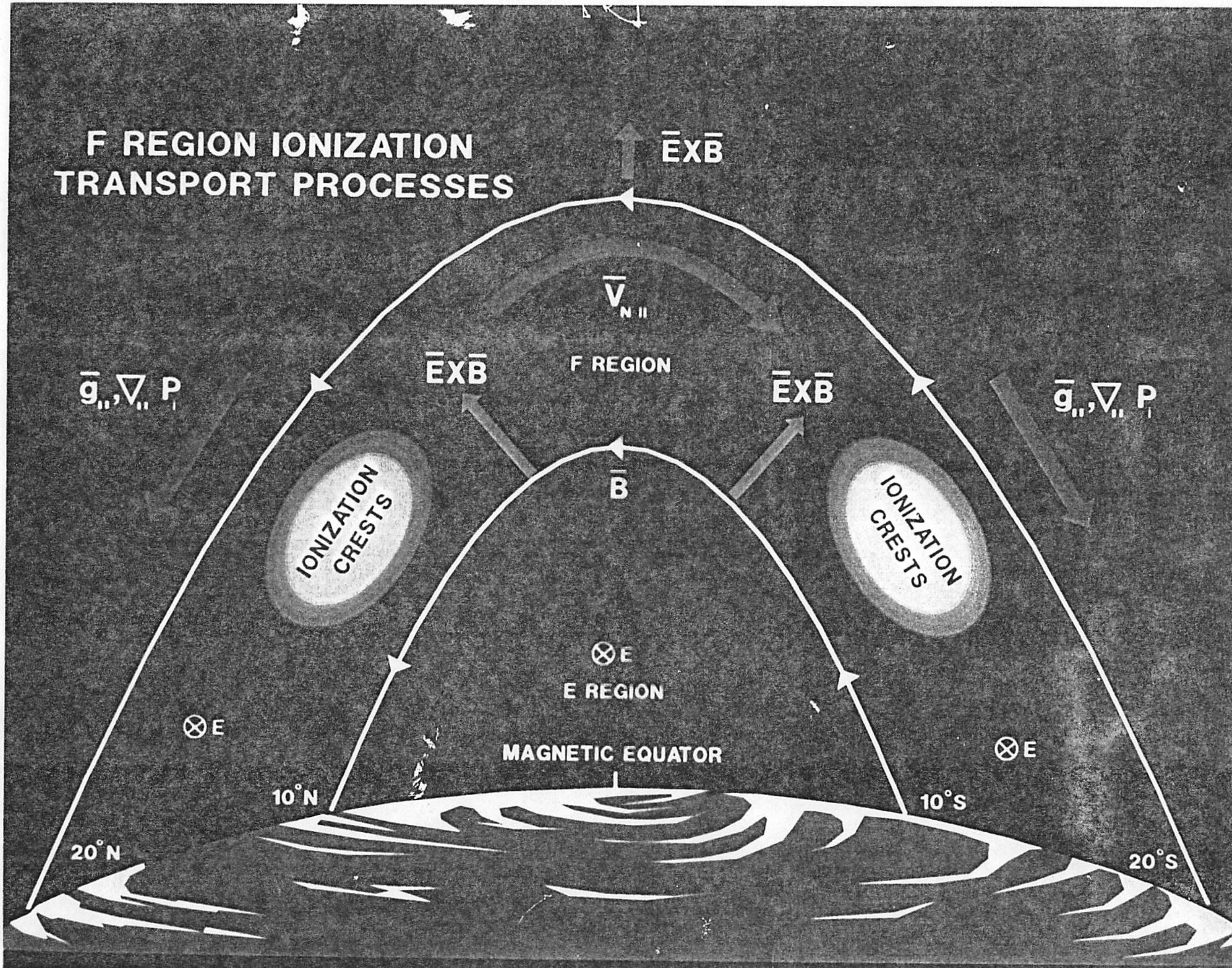
-- Complications:

- Role of E-Region: $\vec{V}_p = \dfrac{\Sigma_p^F}{\Sigma_p^F + \Sigma_p^{E,N} + \Sigma_p^{E,S}} \vec{u}_n$

- Vertical + Horizontal Gradients in u + N_e:

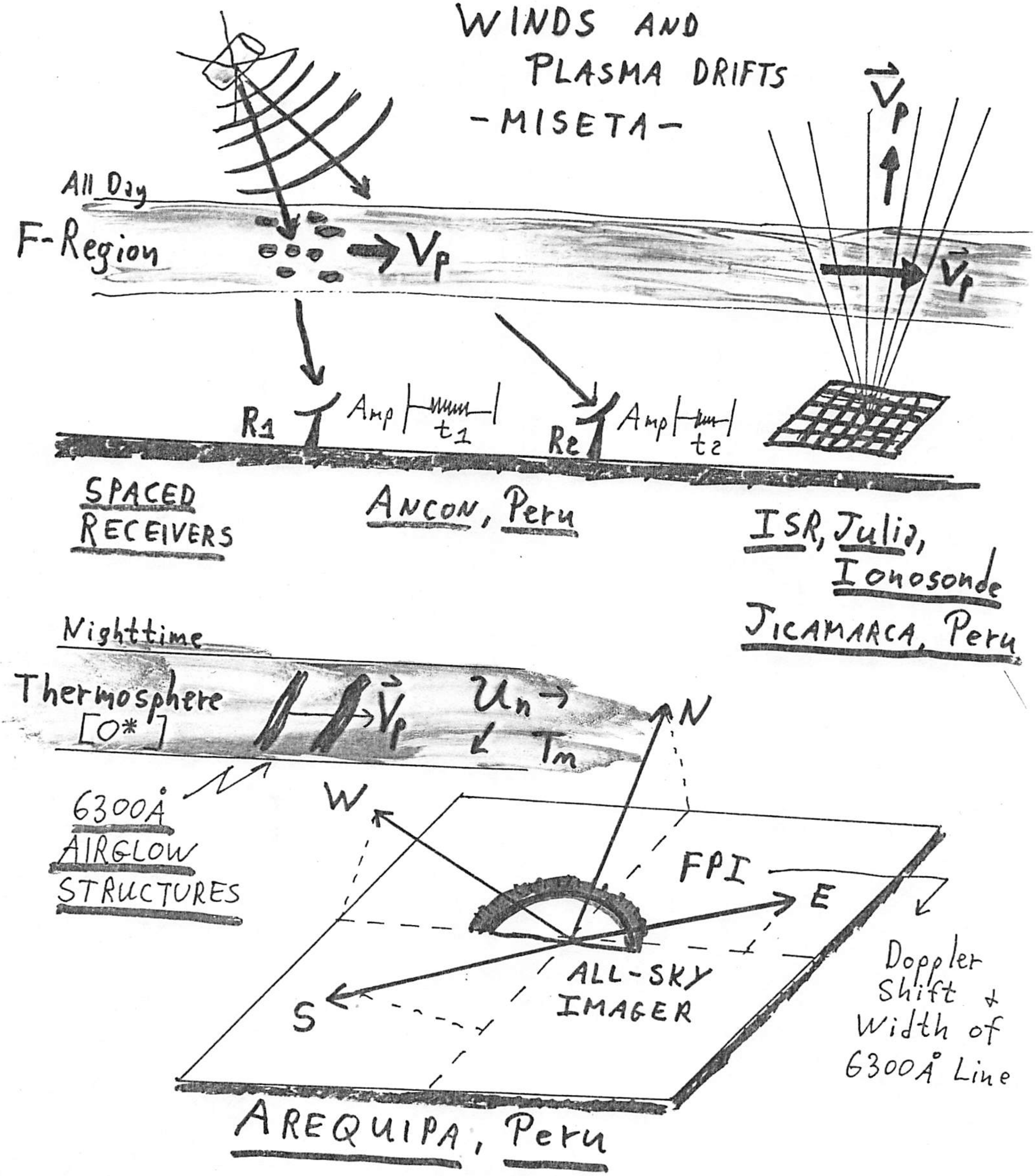
e.g., u_n





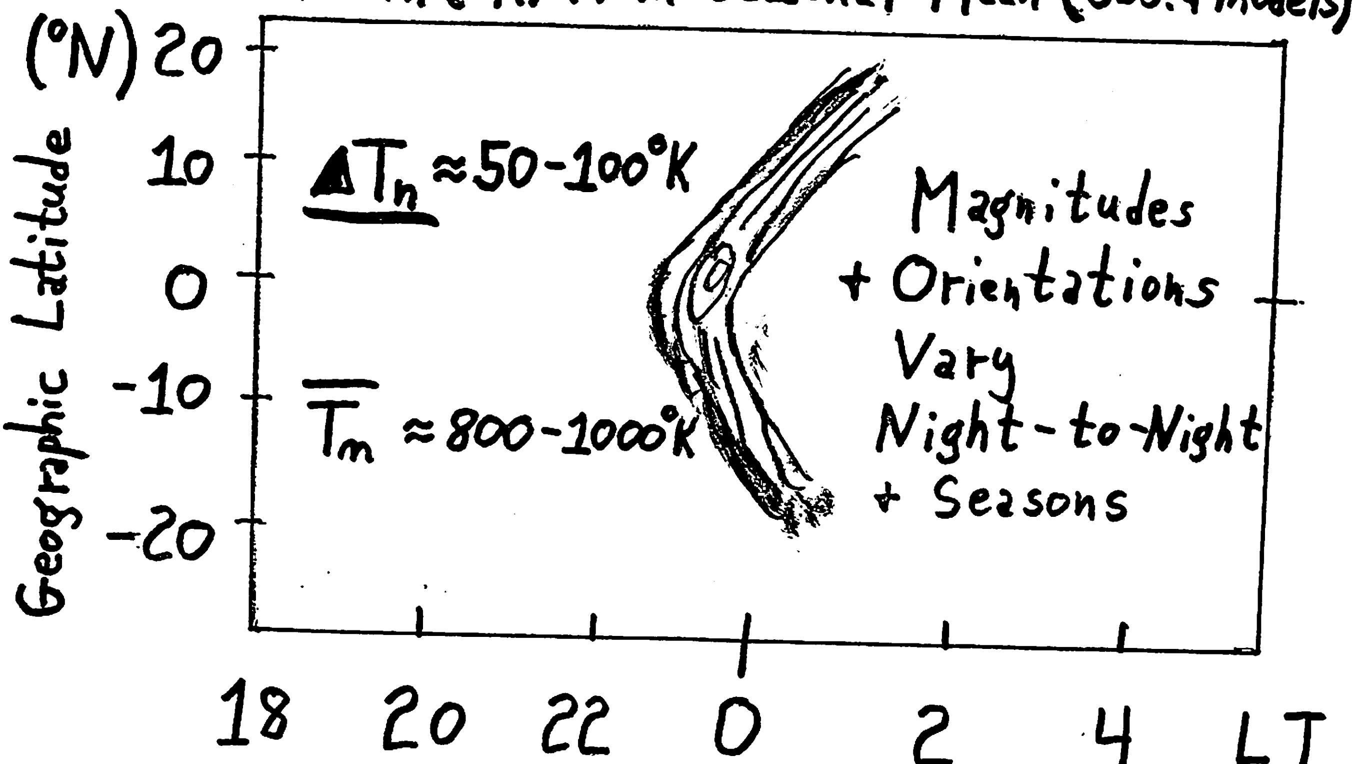
F REGION IONIZATION
TRANSPORT PROCESSES
$\bar{E}X\bar{B}$
$\bar{V}_{N\parallel}$
$\bar{E}X\bar{B}$
F REGION
$\bar{E}X\bar{B}$
$\bar{g}_{\parallel}, \nabla_{\parallel} P_i$
$\bar{g}_{\parallel}, \nabla_{\parallel} P_i$
IONIZATION CRESTS
$\bar{B}$
IONIZATION CRESTS
⊗E
E REGION
⊗E
⊗E
MAGNETIC EQUATOR
10°N
10°S
20°N
20°S

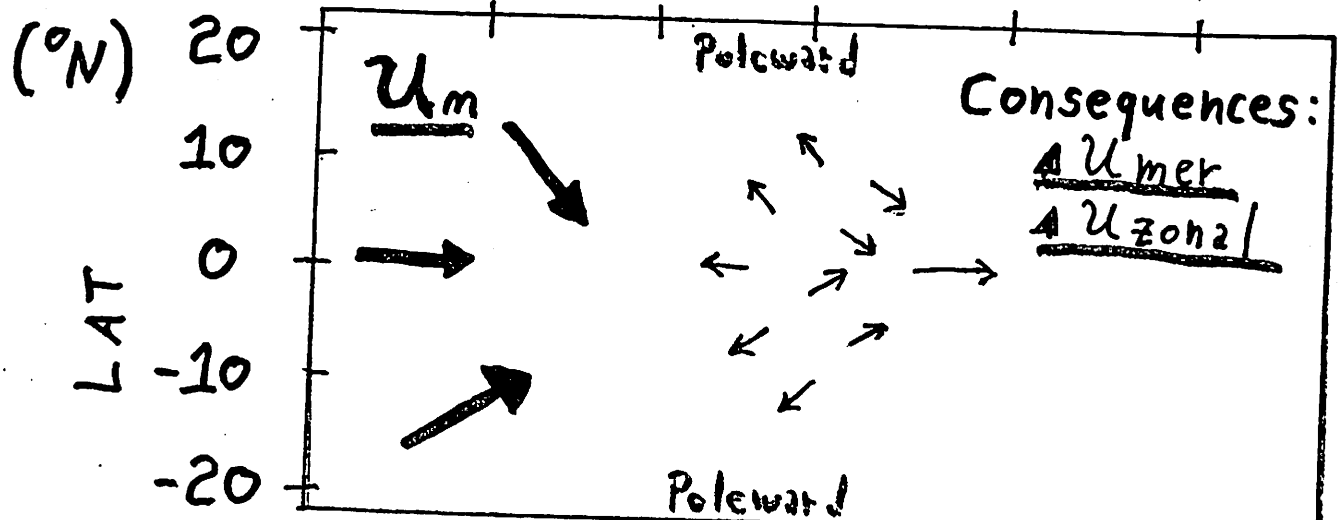
WINDS AND PLASMA DRIFTS
-MISETA-



Effects of Variable Winds:

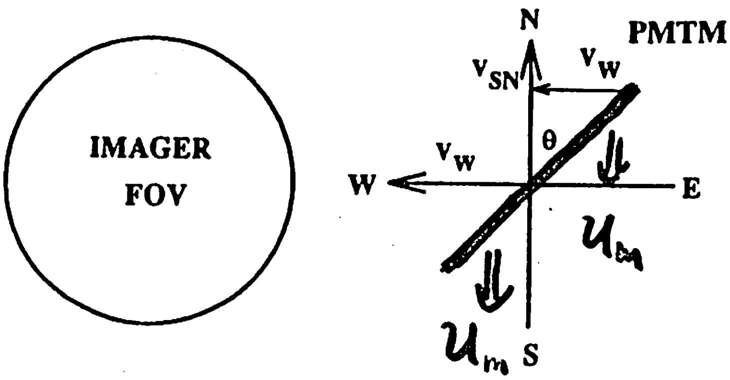
- Shifts in LT of Zonal + Vertical Reversals.
- Disturbed Dynamo (Auroral Input).
  -- Travelling Atmospheric Disturbances (TAD).
- Midnight Pressure Bulge (Tidal Interactions).





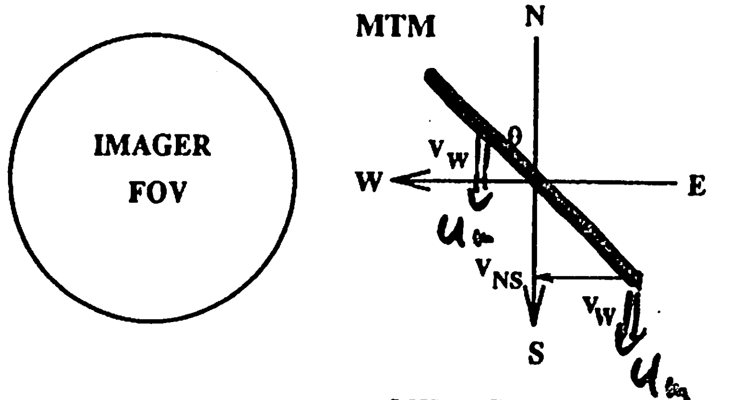
x

Geometry of “Brightness Waves”



PRE-MIDNIGHT BW
ORIENTATION ANGLE
CALCULATION

AVG. PRE-MIDNIGHT $\theta = 45$



MIDNIGHT BW
ORIENTATION ANGLE
CALCULATION

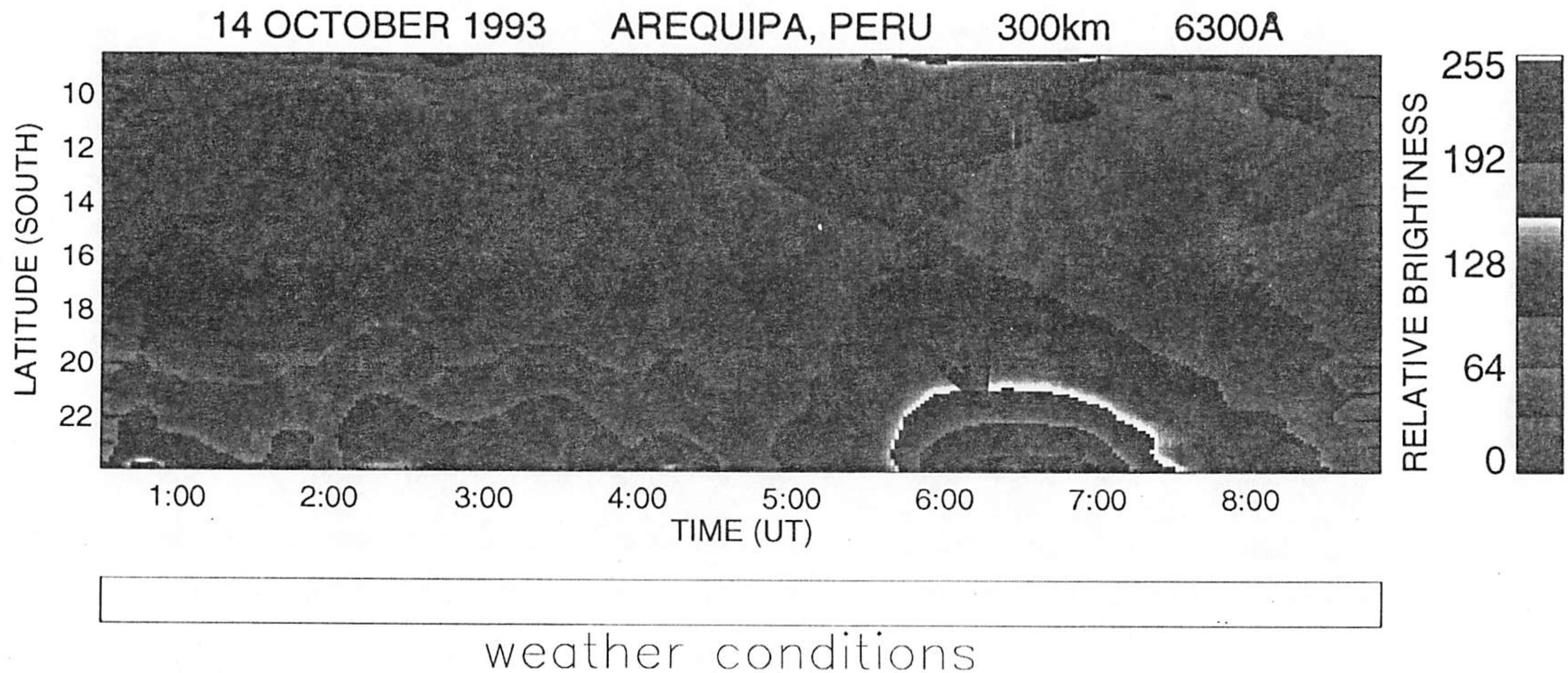
1993 AVG. MIDNIGHT $\theta = -52$
1994 AVG. MIDNIGHT $\theta = -45$

$$\theta = \tan^{-1}(V_w / V_{ns})$$

V_W = Earth’s corotation speed

V_{NS} = Apparent meridional velocity

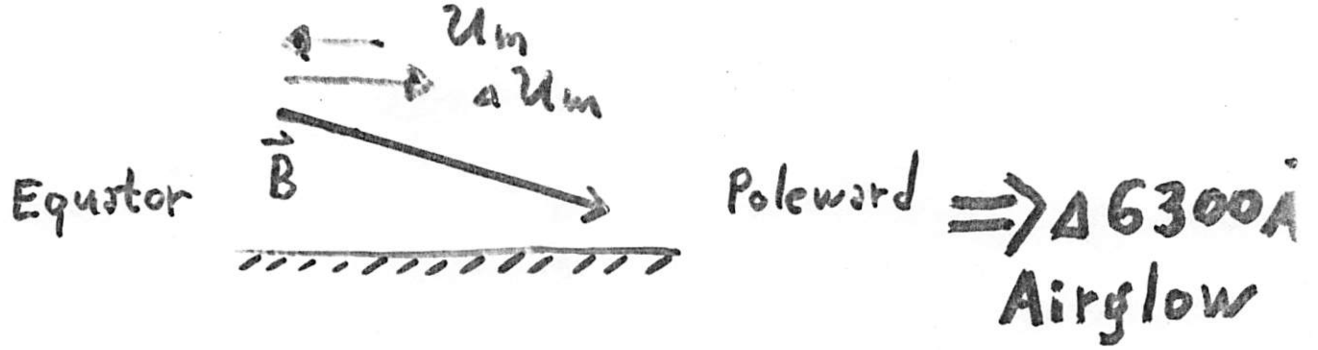
Observable : V_{NS}
Derived : θ - Orientation of nightly MTM pattern

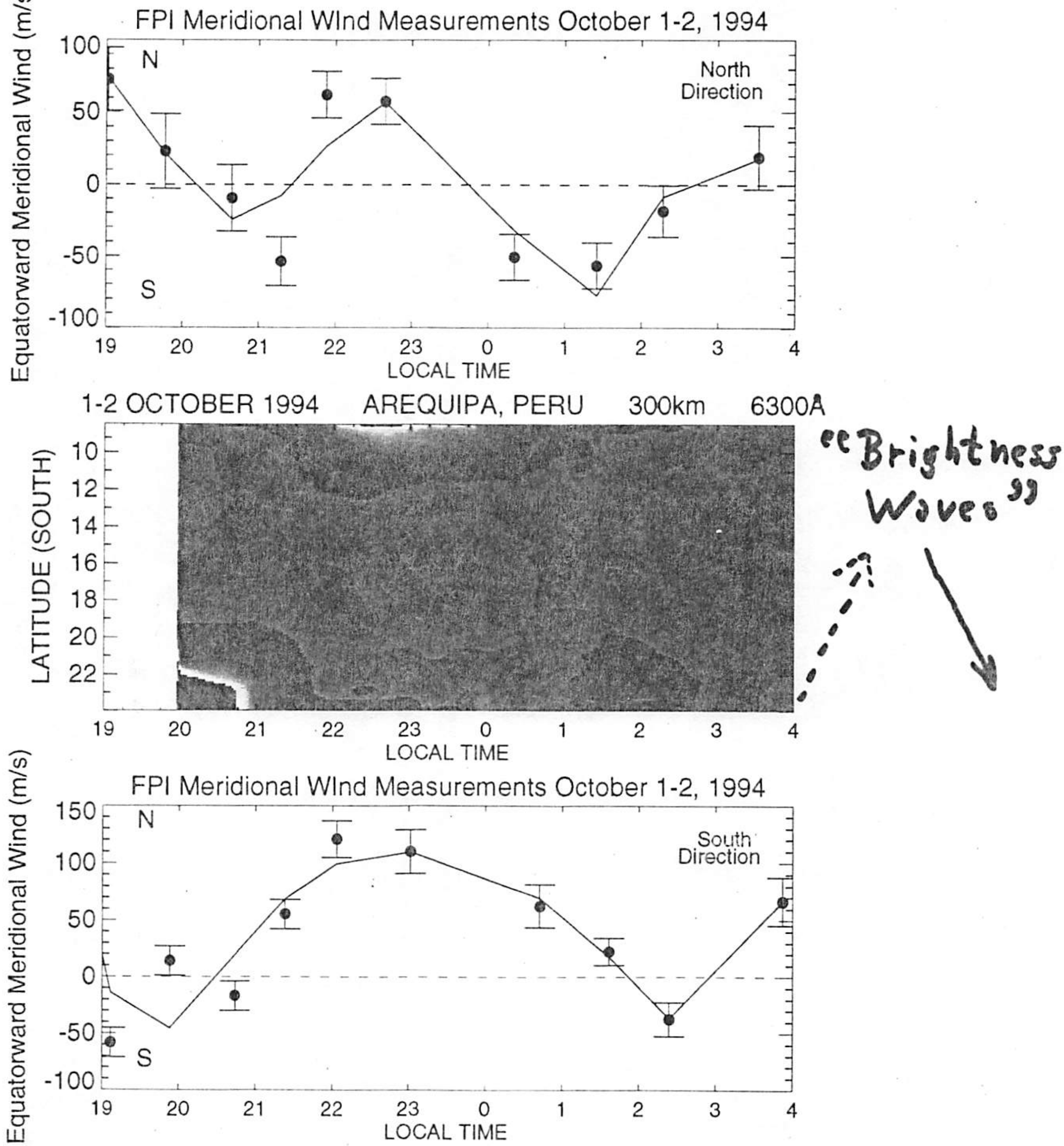


↑

MIDNIGHT

"V_{N-S}" ≈ 250 m/sec





COMPARISON OF FPI (WINDS IN MERIDIAN)
WITH 6300Å Meridional Brightness Patterns.

Arequipa, Peru

J. Meriwether + M. Colerico

FPI OBSERVATIONS AND

COMPARISON OF TIEGCM AND MSIS86 NEUTRAL TEMPERATURE MODELS

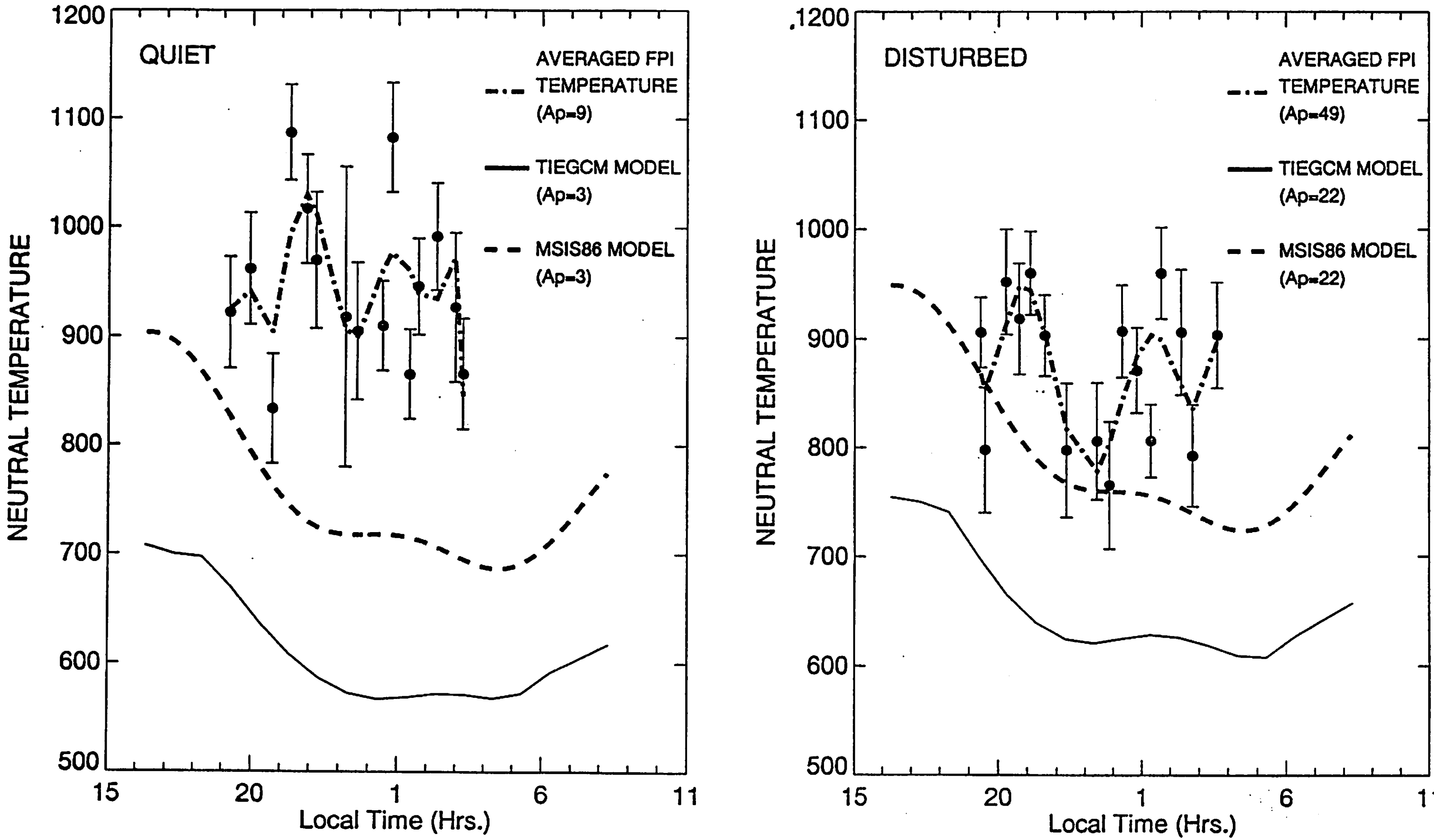


Figure 13.

M. Colerico, J. Meriwether & C. Fesen

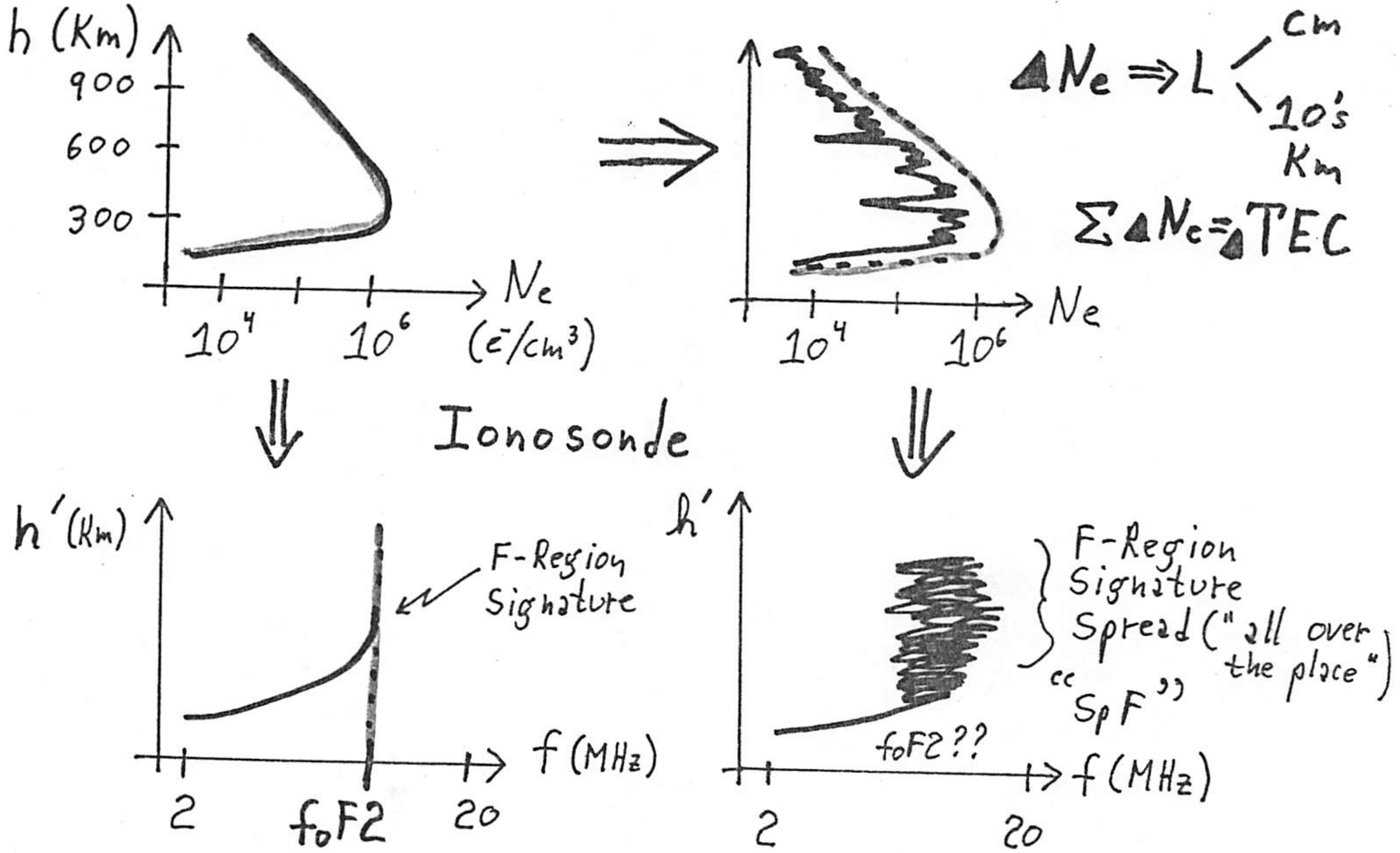
MISETA Issues in the CEDAR Phase III Era:

- Neutral ⇄ Ion Coupling
  - Time Constants < Quiet? / Disturbed?
  - Importance of $\vec{E}$-region after Sunset?
- TADs --- ever seen one?
- Variability in MTM --- magnitude and orientation
  --- Does it matter?
- Modelling MTM --- magnitudes and orientations.
- Electrodynamics --- penetration, shielding, over-shielding of substorm electric fields.
- Ionospheric Storms at low latitudes.

- Small Scale Irregularities.

EQUATORIAL SPREAD-F (ESF)

"A sudden, localized transformation of ionospheric plasma at low latitudes from homogeneous electron densities into highly irregular structures"



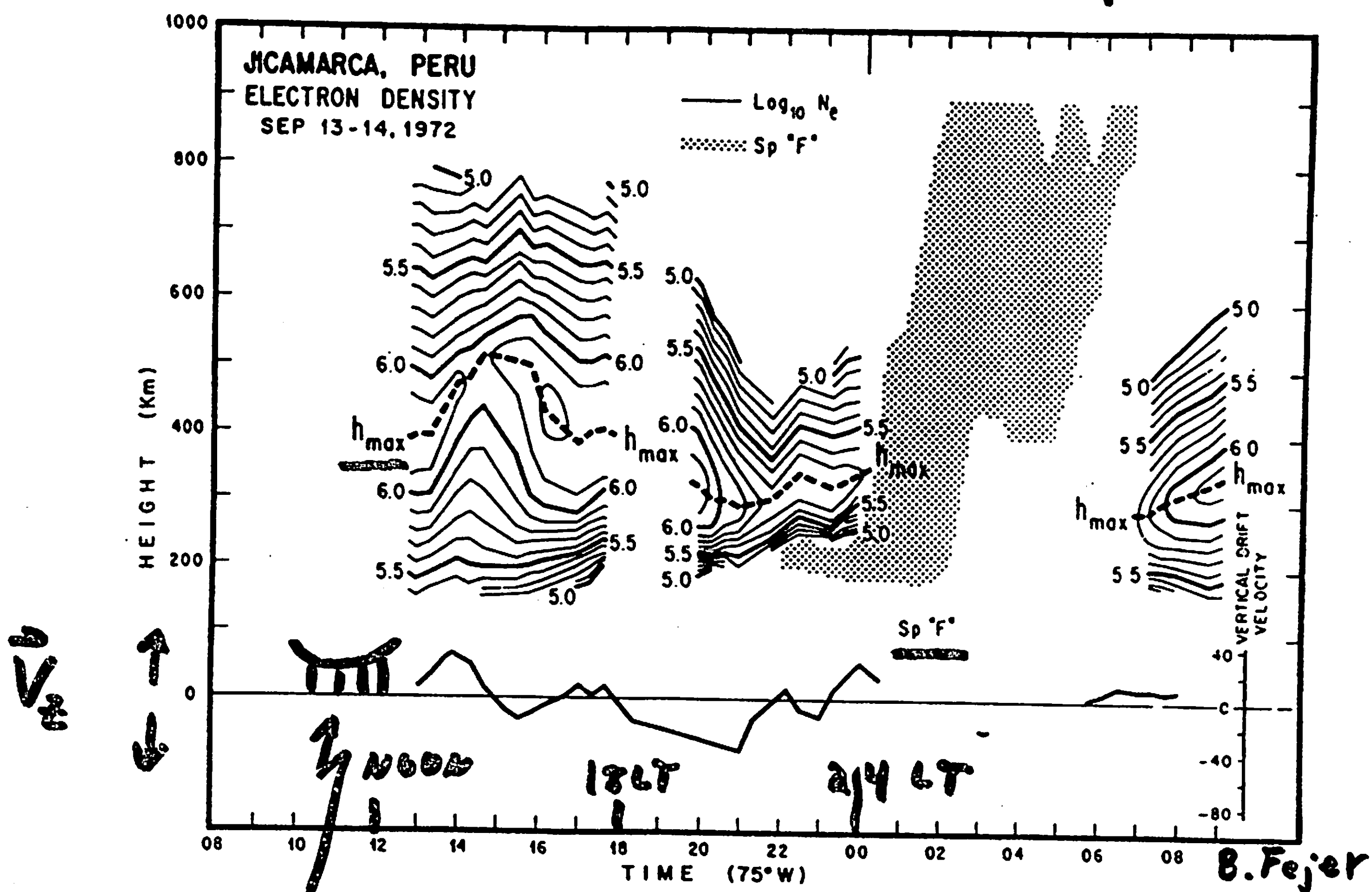
---And, so, the most explosive/dramatic space plasma physics instability in the near-Space-environment is named after the failure of a diagnostic capability.

---A more physics-based name would have been nice.

[<u>E</u>quatorial <u>S</u>cintillation <u>F</u>ields
<u>E</u>quatorial <u>S</u>tructures + <u>F</u>luctuations]

RADAR DIAGNOSTICS

$\vec{k} \perp \vec{B}_0$ (i.e., Geomagnetic Equator)



Fixed Vertical

Incoherent scatter Radar (ISR)

- For unstructured Ionosphere

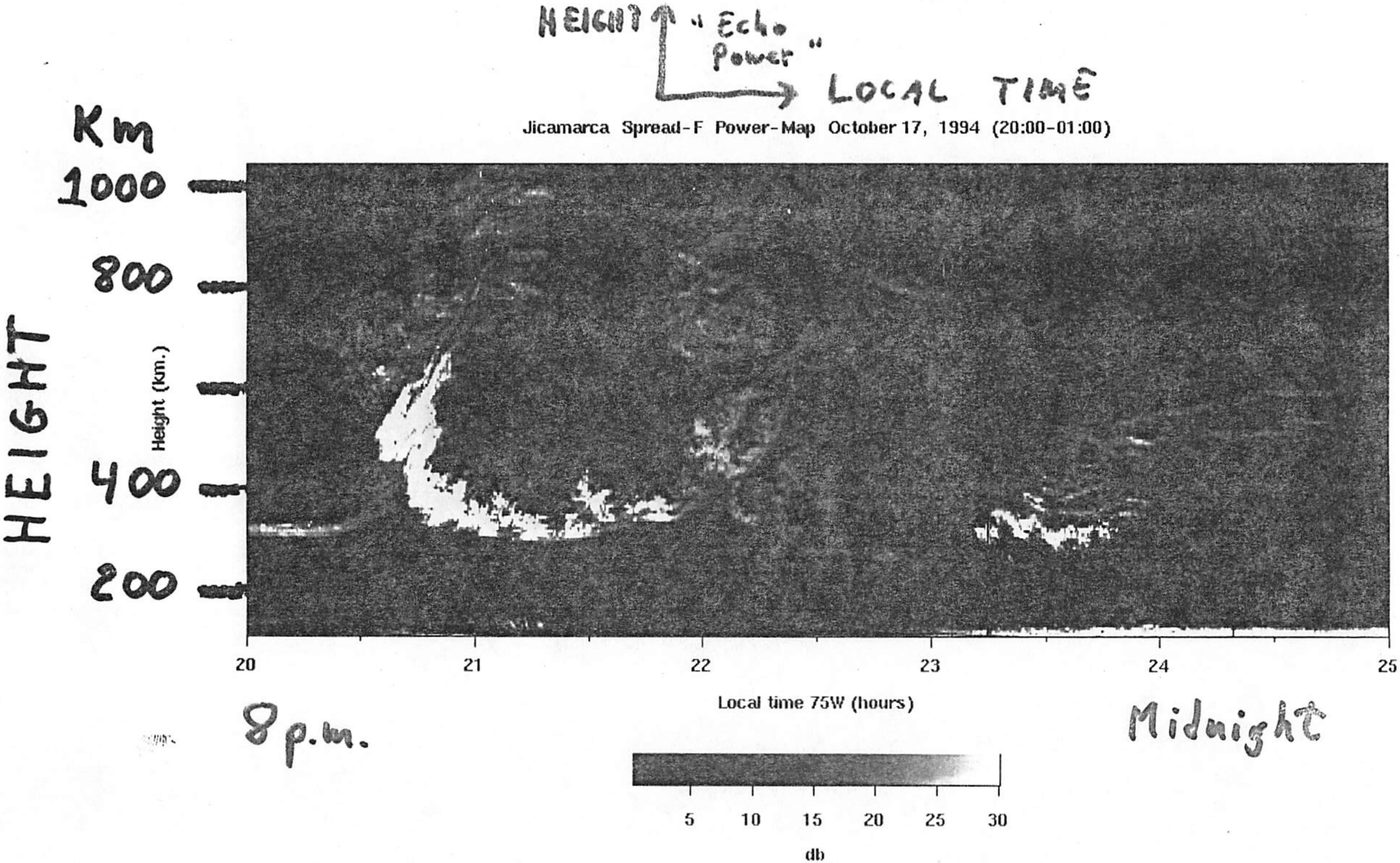
  Signal $\Rightarrow N_e, T_e, T_i, \vec{V}_p$ all f(height)

- For $N_e + \Delta N_e$ & $\vec{k} \perp \vec{B}_0$, Echo >> ISR

  Coherent Backscatter only (no parameters)

  Echoes $\Rightarrow$ "Plumes" of irregularities (ESF)

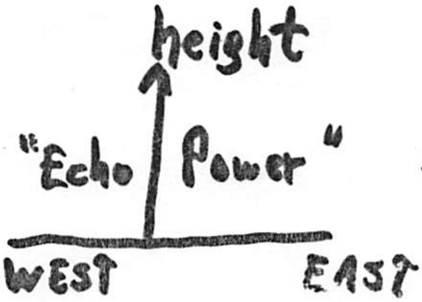
JICAMARCA ESF PLUMES



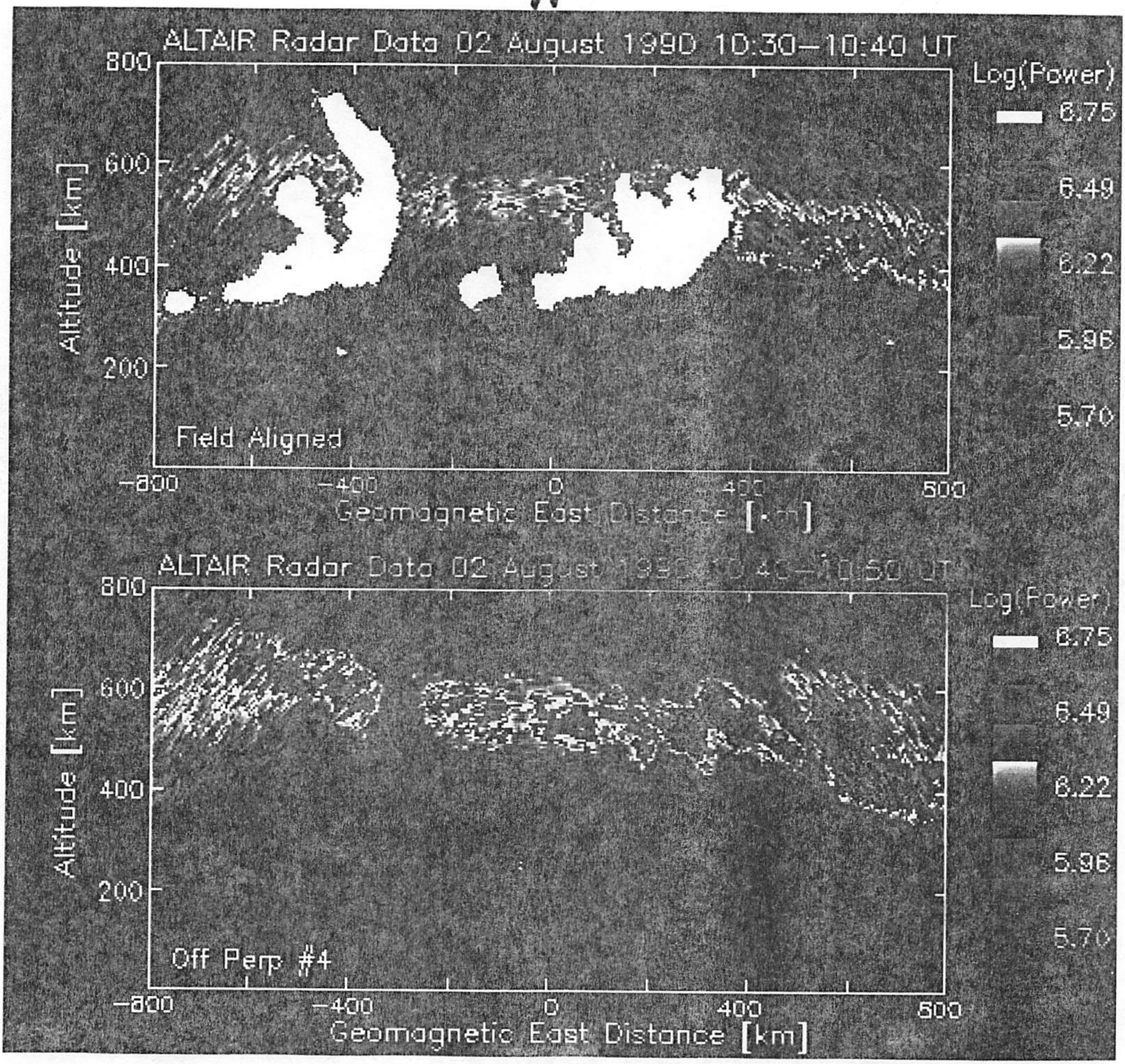
---A rising "bubble" with small scale irregularities

↓?

R. Woodman



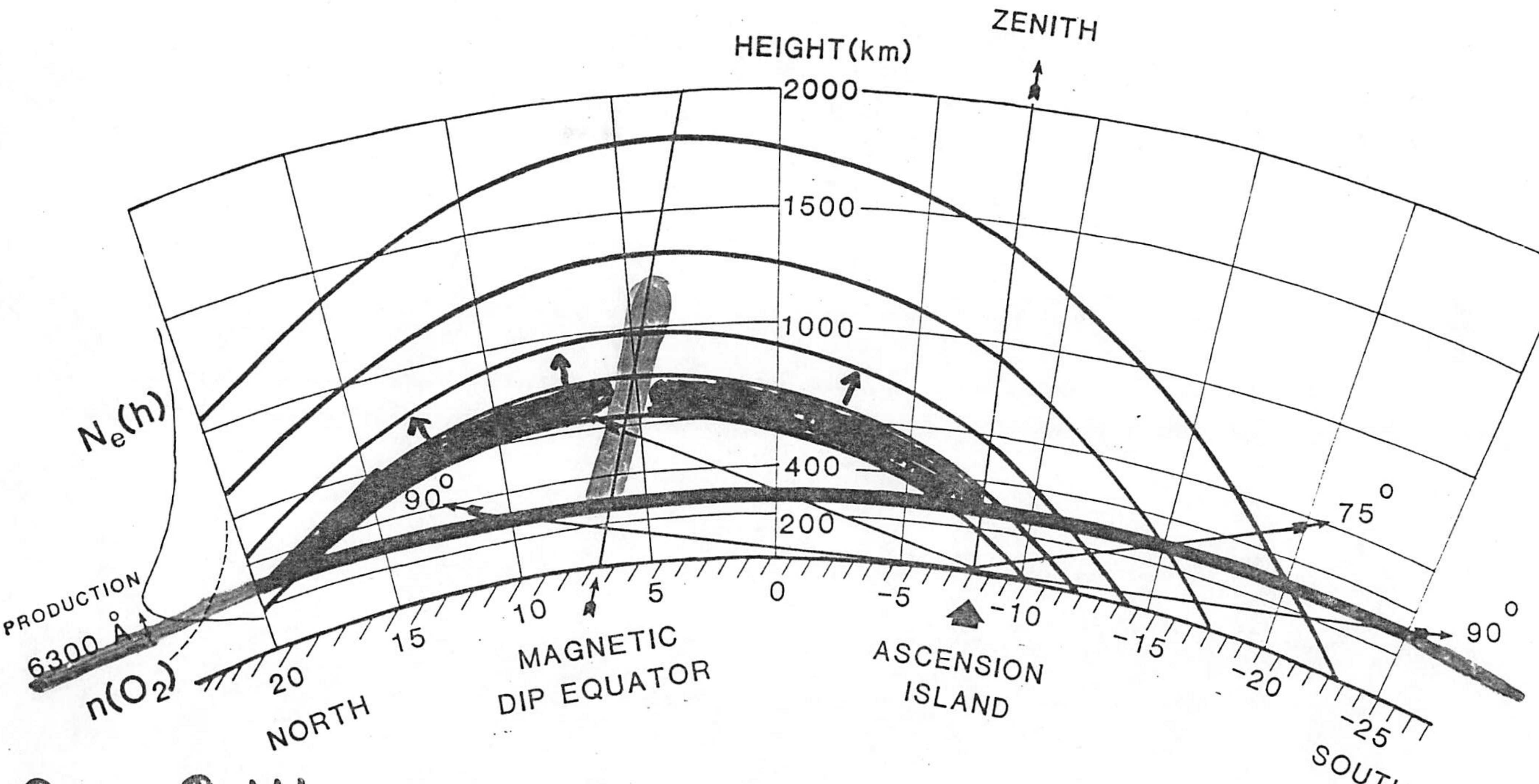
ALTAIR = SCANNING ISR — $\vec{\lambda} \perp B$ / $\vec{\lambda}$ not $\perp \vec{B}$



"Rising Bubble" ⟹ Plasma Depleted Flux Tube Interchange

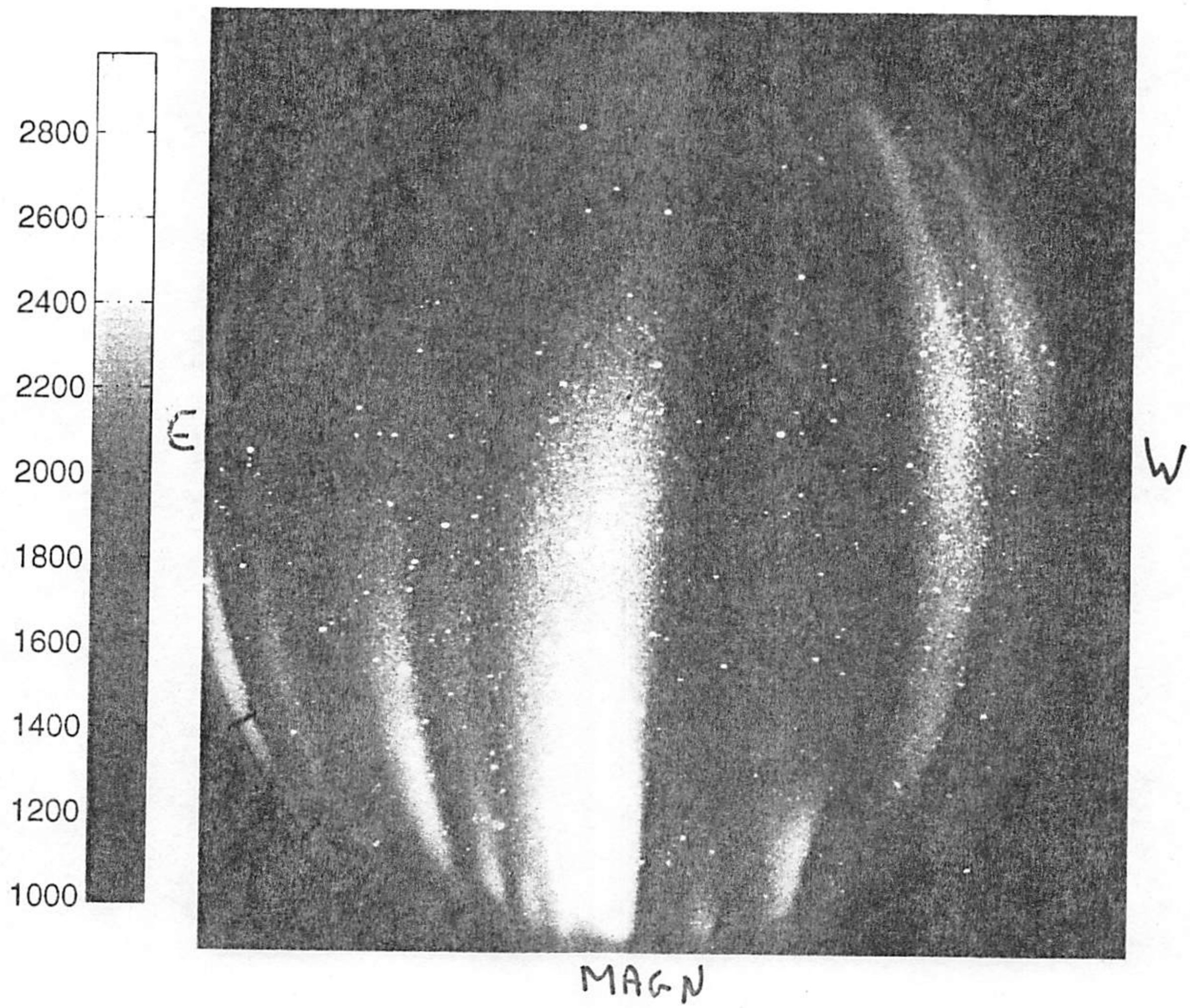
R. TSUNODA

ASCENSION ISLAND MAGNETIC MERIDIAN
AIRGLOW VIEWING GEOMETRY



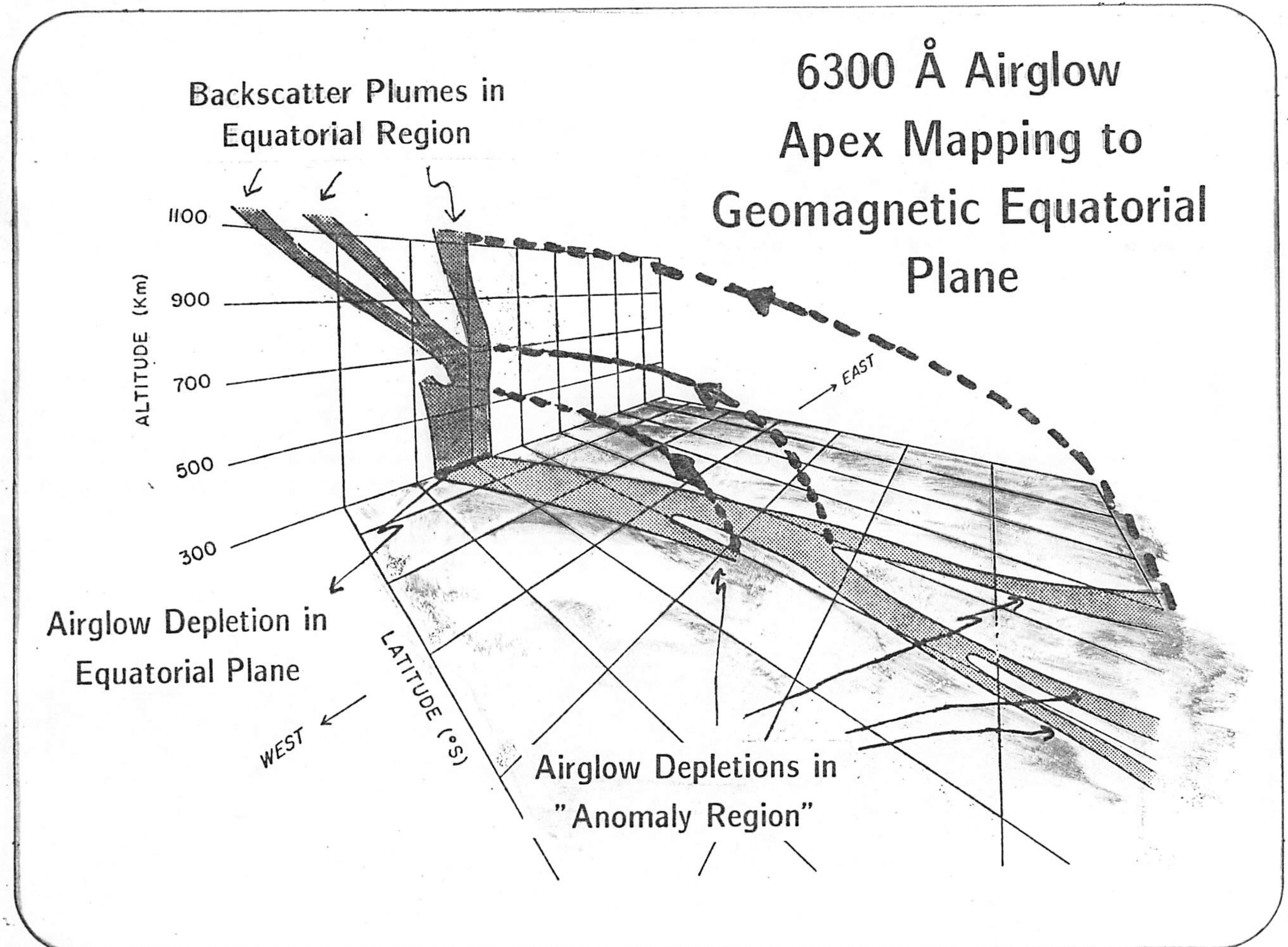
Rising Bubble at Equator = cross-section of Depleted Fluxtube Rising ⇒ Leaving below Airglow Depletions as meridian "foot prints"

CHRISTMAS ISLAND (630 nm)

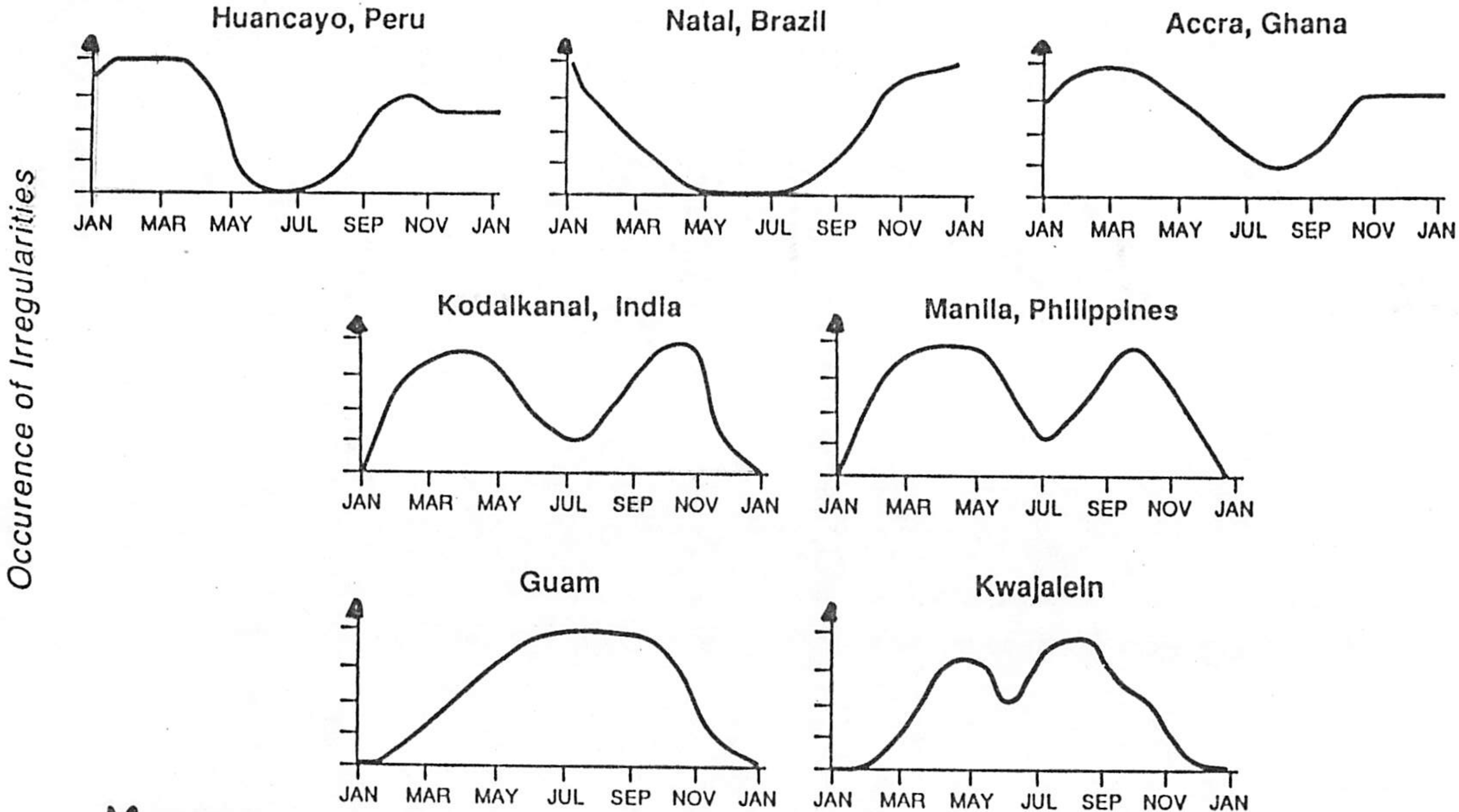


F-REGION DEPLETIONS

M. TAYLOR


6300 Å Airglow
Apex Mapping to
Geomagnetic Equatorial
Plane
Backscatter Plumes in
Equatorial Region
1100
900
700
500
300
ALTITUDE (Km)
EAST
WEST
LATITUDE (°S)
Airglow Depletion in
Equatorial Plane
Airglow Depletions in
"Anomaly Region"

WHERE AND WHEN DOES ESF OCCUR?

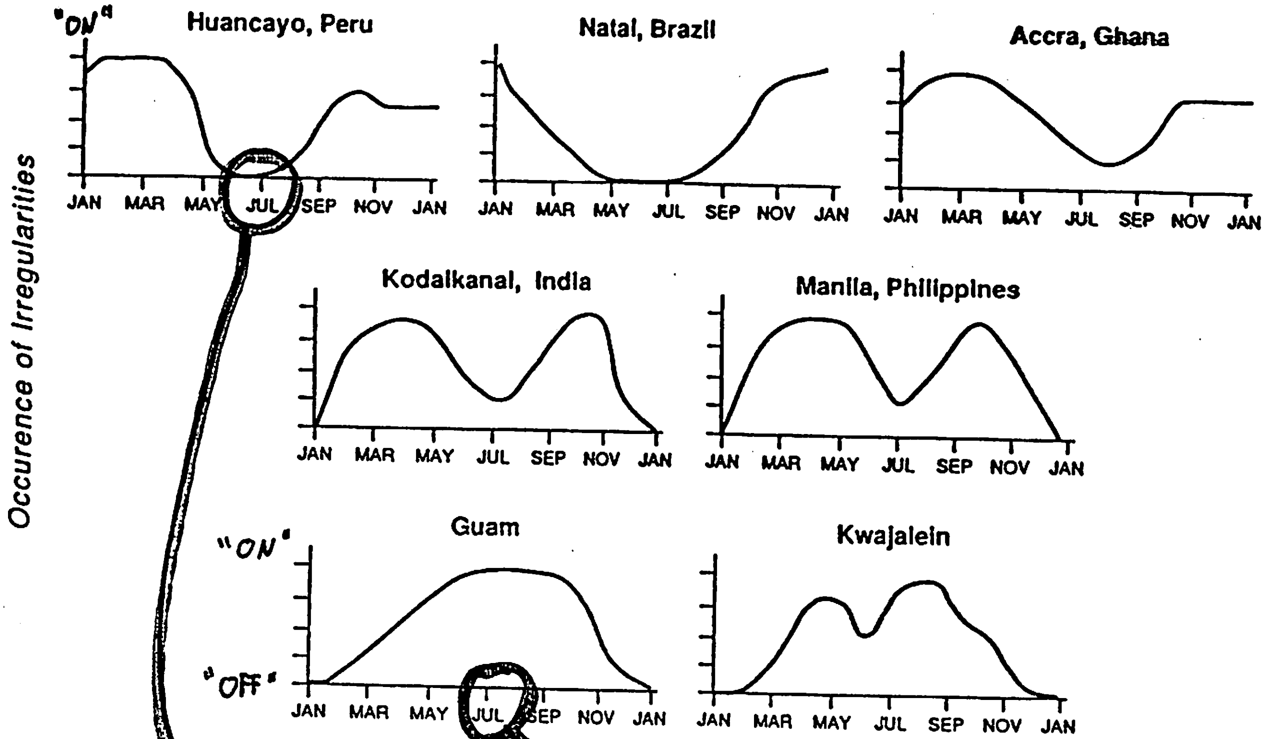


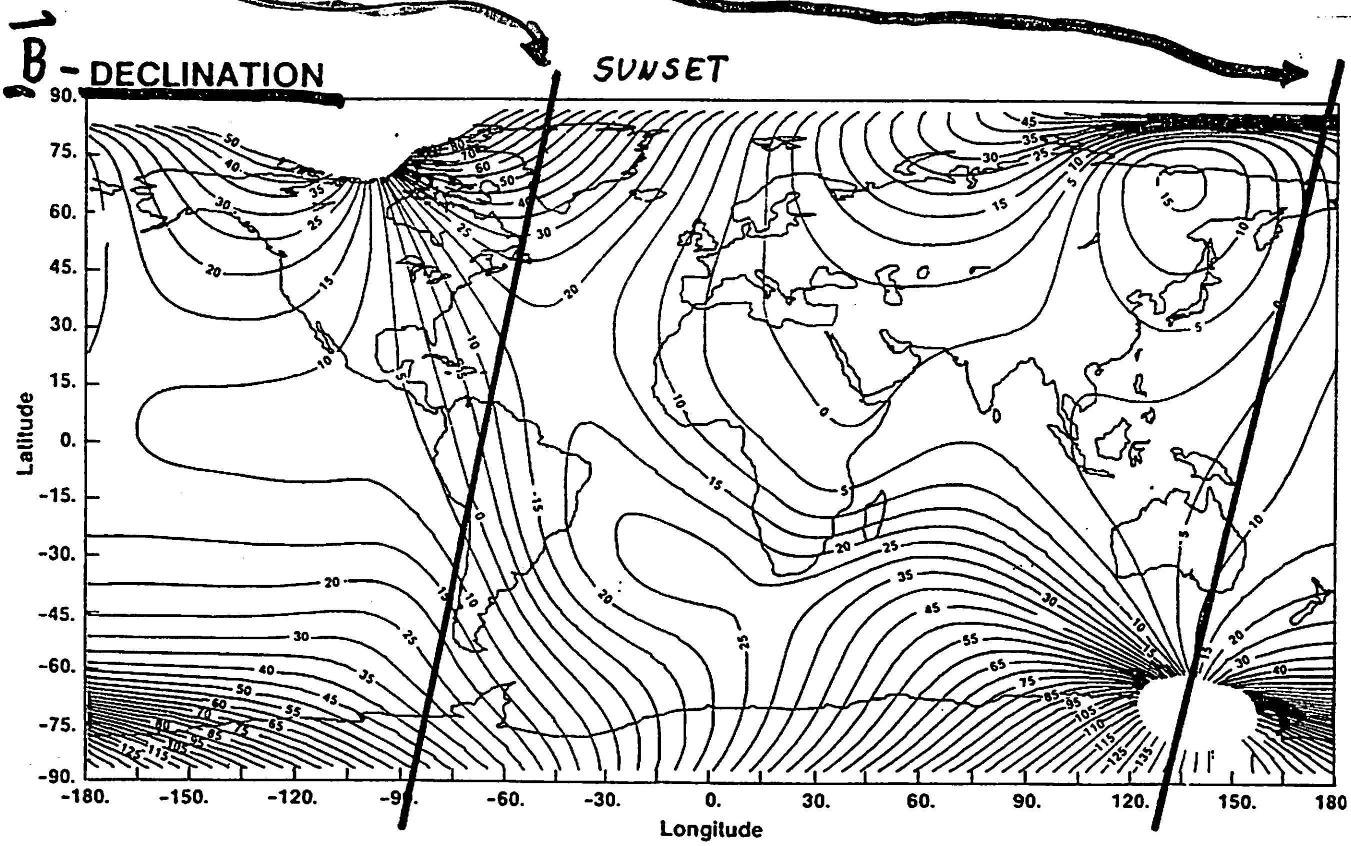
- A MONTHLY [redacted]-Longitude Pattern ⇒ fluxtubes are interhemispheric
- Post-Sunset to Pre-Dawn ⇒ A "pure" F-Region Effect

"Spread-F Season" occurs when/where solar terminator (sunset line) is parallel (± several degrees) to magnetic meridian. This allows E-regions at N/S ends of $\vec{B}$ to decay away simultaneously.

J. Aarons

EXAMPLE: JUNE-JULY PERIOD





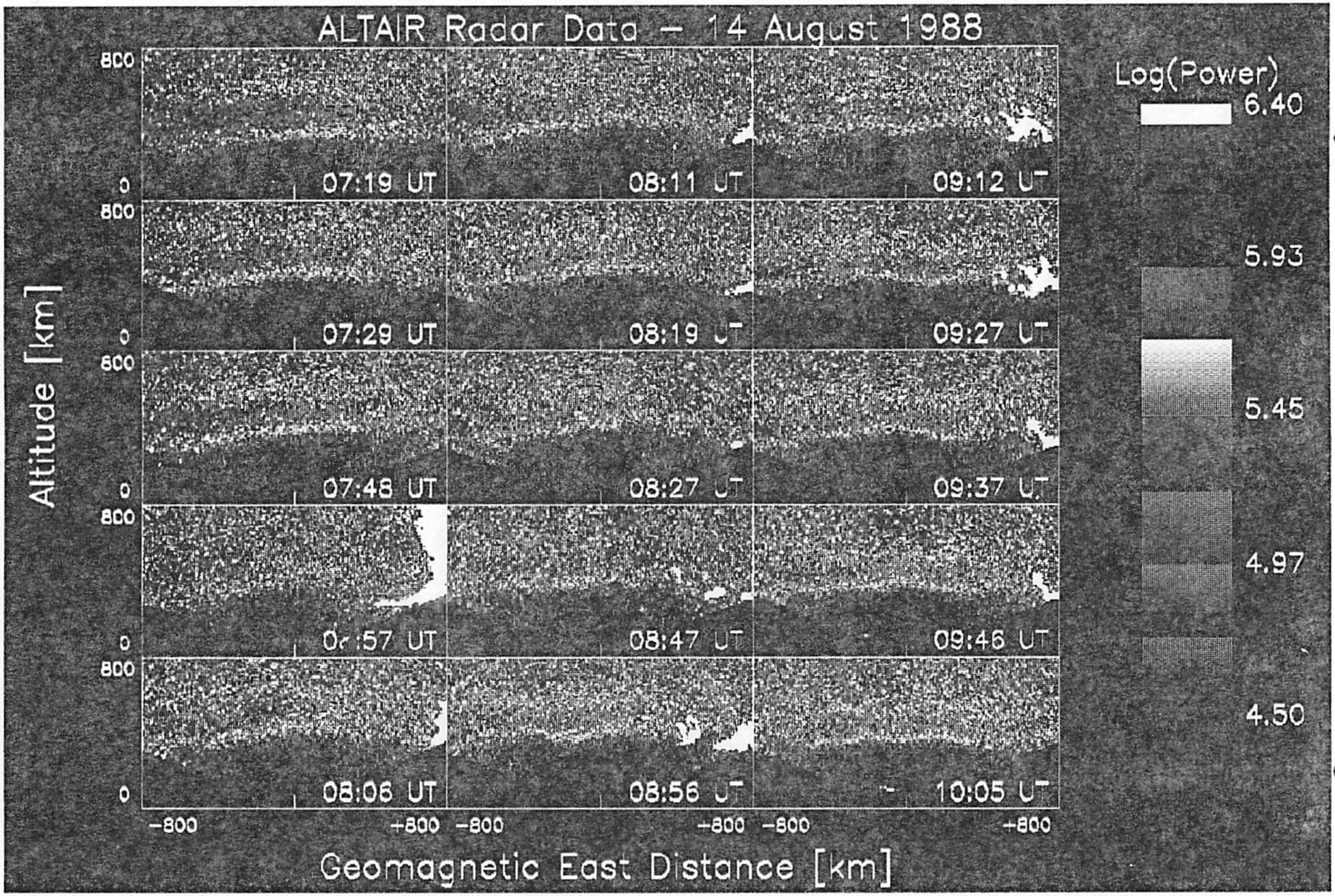
Note: When Sunset // $\vec{B}$, Thermospheric winds // $\vec{B}$ are minimal (small inter-hemispheric assymmetries)

∴ Two Ways ≡ Spread-F Season

DAY-TO-DAY VARIABILITY WITHIN A SPREAD-F SEASON
e.g. KWAJALEIN in August

SUNSET → LT

9 p.m

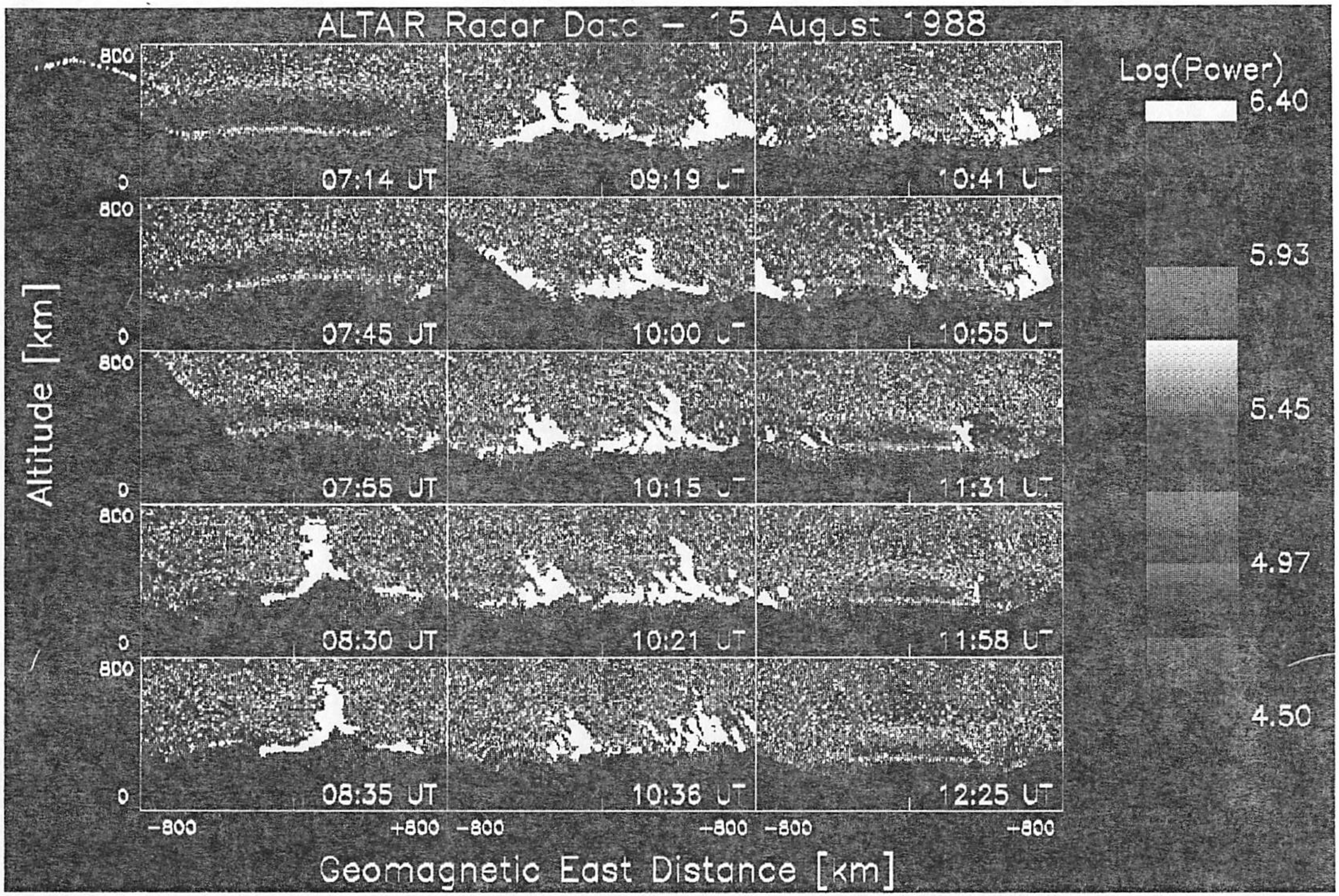


LT

8pm

10pm

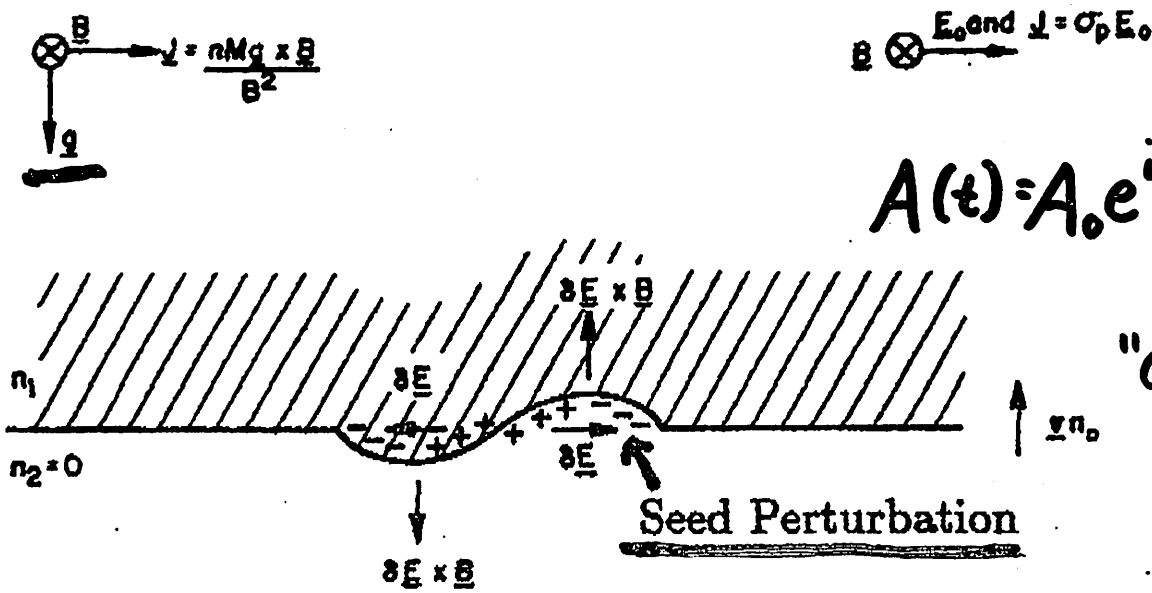
The Next Night



When ESF is "ON" — it is not subtle or elusive —
Any radio/optical system that is sensitive to $\Delta Ne/Ne$ will see it.

The Standard Model

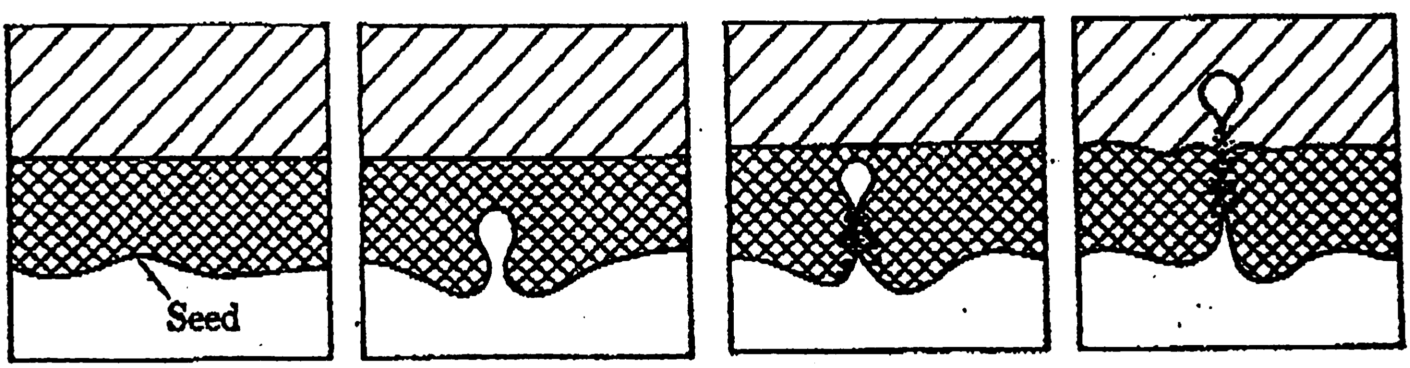
Geometry at Magnetic Equator Allows Development of the Rayleigh-Taylor Instability



$$A(t) = A_0 e^{i\omega t} e^{\gamma t}$$

γ → "Growth Rate"

Plasma (MHD) Analog to Classical Hydrodynamic Instability: Heavy Fluid over a Light Fluid



Principal Characteristics:

1. Rising "Bubble" of Depleted Plasma.
2. Smaller-Scale Turbulence/Instabilities at Edges of Bubble.

Entire Process called Equatorial Spread F Because of Effects Observed by Ionosondes.

The Gravitationally-Driven Rayleigh-Taylor Instability

GROWTH RATE

$$\gamma_{R-T} = \left[\frac{\vec{E}\times\vec{B}}{B^2} - \vec{U}_n - \frac{\vec{g}}{\nu_{in}}\right]\cdot\frac{\vec{\nabla} Ne}{Ne}\left(\frac{\Sigma_p^F}{\Sigma_p^{E,No} + \Sigma_p^F + \Sigma_p^{E,So}}\right)$$

All fluxtube-integrated Quantities

FAVORABLE CONDITIONS

1) E-Region Vanish after Sunset
   (Fluxtube-aligned sunset ⟹ Seasonal-longitude pattern

2) Steep bottomside gradient of Ne(h)

$$\frac{\nabla_{\perp B} Ne(s)}{Ne(s)} = \frac{1}{L} \rightarrow \text{small is good}$$

3) Upward Motion of F-region

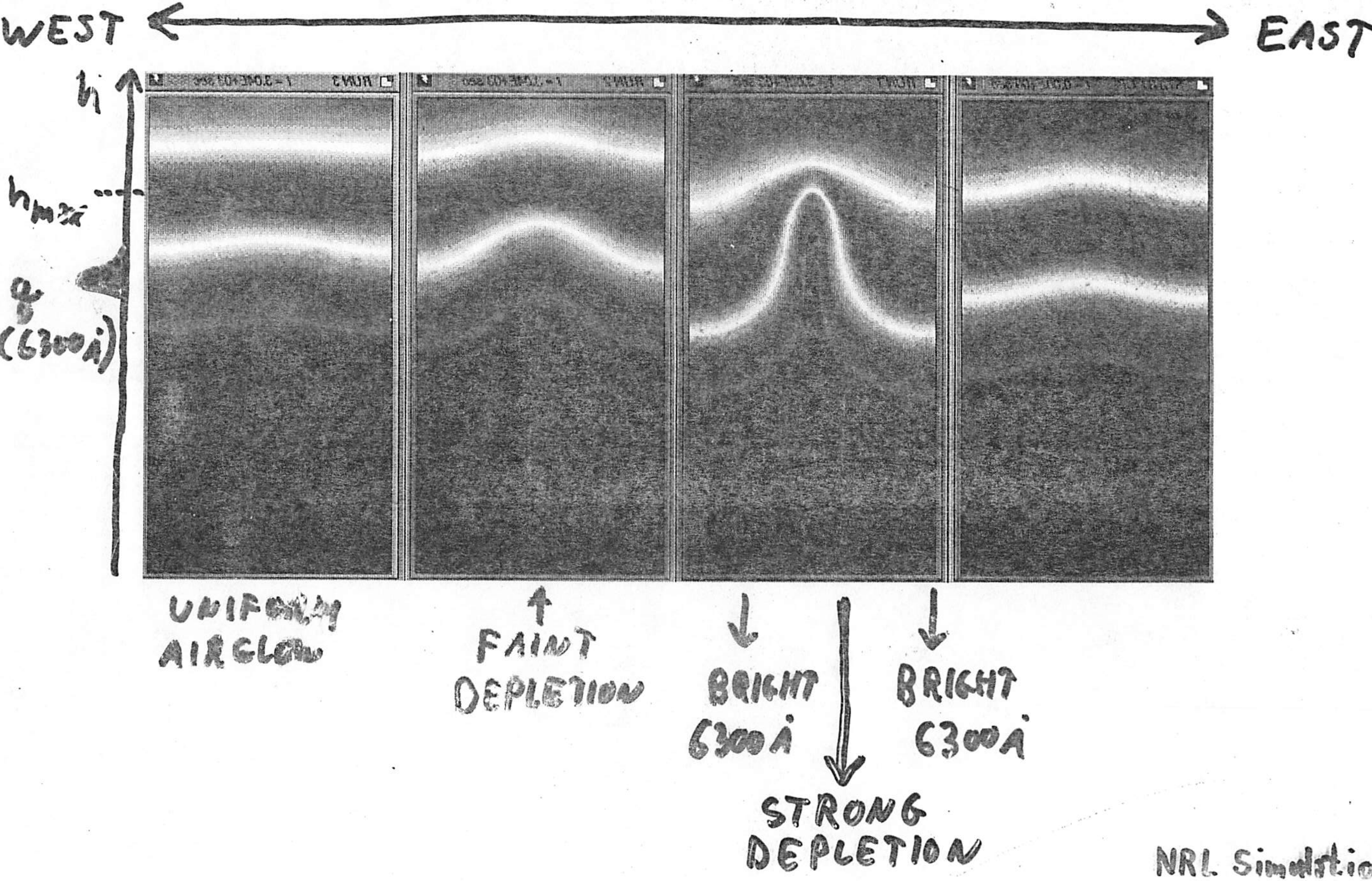
$$\gamma \propto V_{\perp\vec{B}} \quad \text{and} \quad \nu_{in} \rightarrow 0$$

4) Seed Perturbation (e.g., GRAVITY WAVE)

UNFAVORABLE CONDITIONS

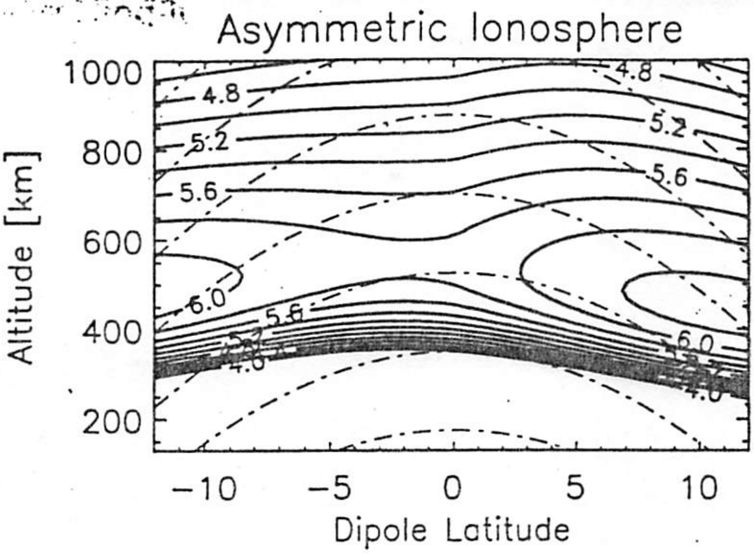
Absence of Above; Meridional Winds
V_p Downward

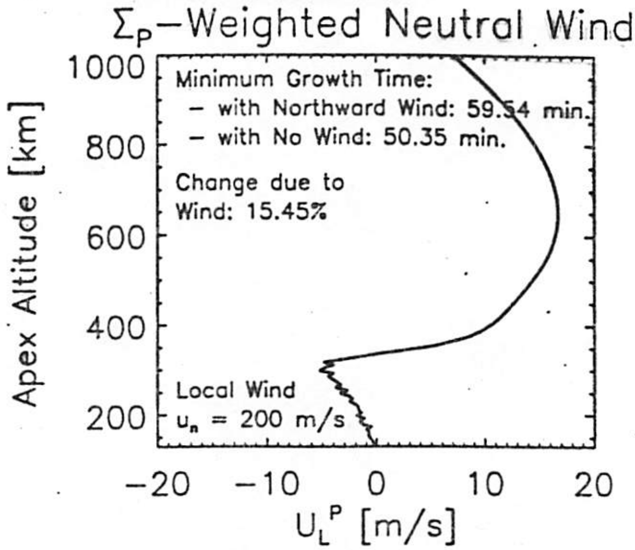
SPATIAL CHARACTERISTICS OF 6300Å SIGNATURES OF ESF PLUMES



NRL Simulation

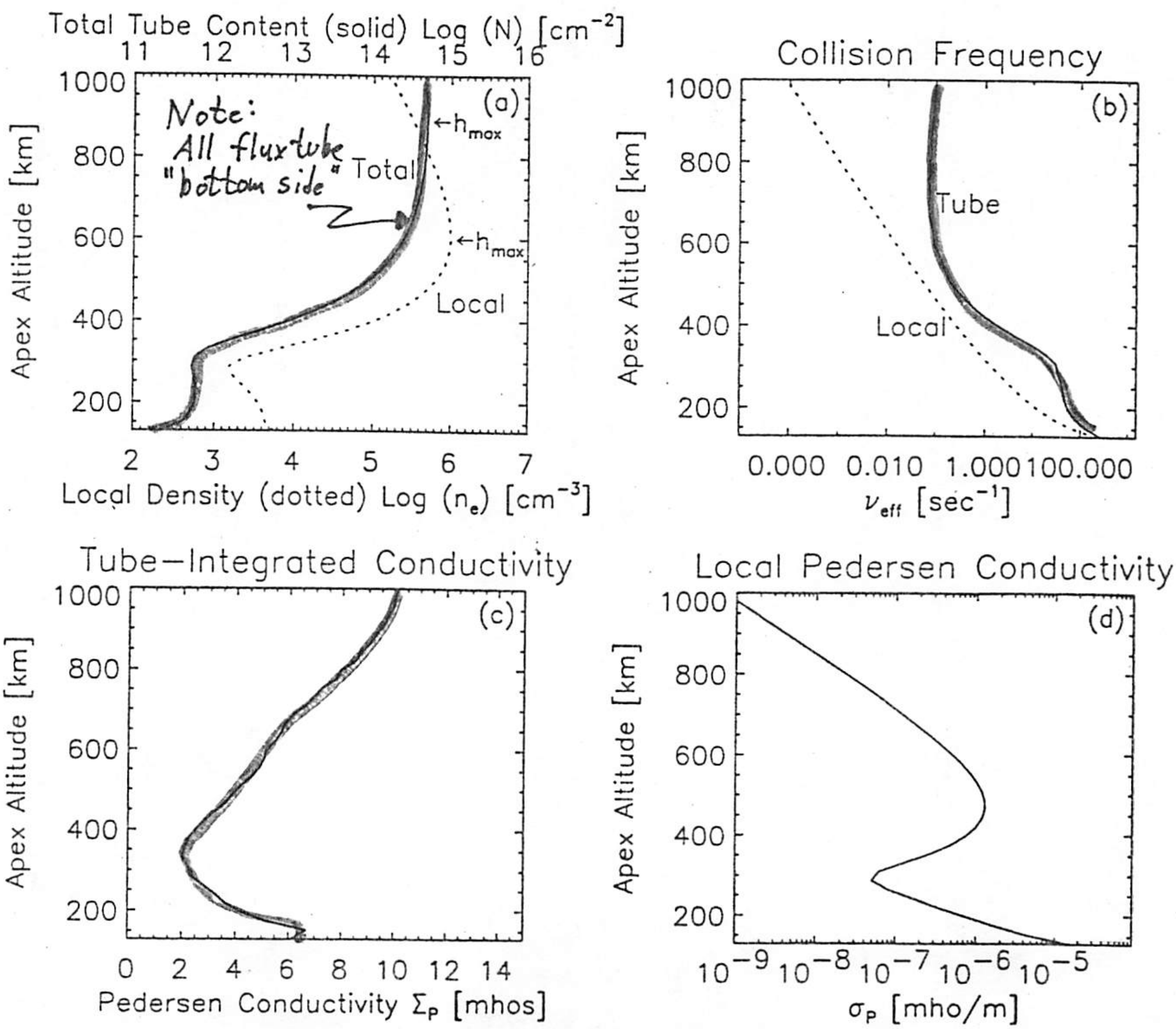
FLUXTUBE-INTEGRATED QUANTITIES





$$N_T = \int N_e(s)\, A(s)\, ds \qquad \sigma_p(\text{local}) = N e\, m_i\, \nu_{in} / B^2$$

$$U_m = \frac{\int u_m\, \sigma_p\, A(s)\, ds}{\int \sigma_p\, A(s)\, ds} \qquad T_{Tube} = \frac{\int \gamma_{local}\, \sigma\, A(s)\, ds}{\int \sigma\, A(s)\, ds}$$



sutton

EXAMPLE: Fluxtube vs Local conditions

What determines the maximum Apex height for an ESF Plume?
--- Buoyancy? "flux tube bubble rises until it finds its equal density height."

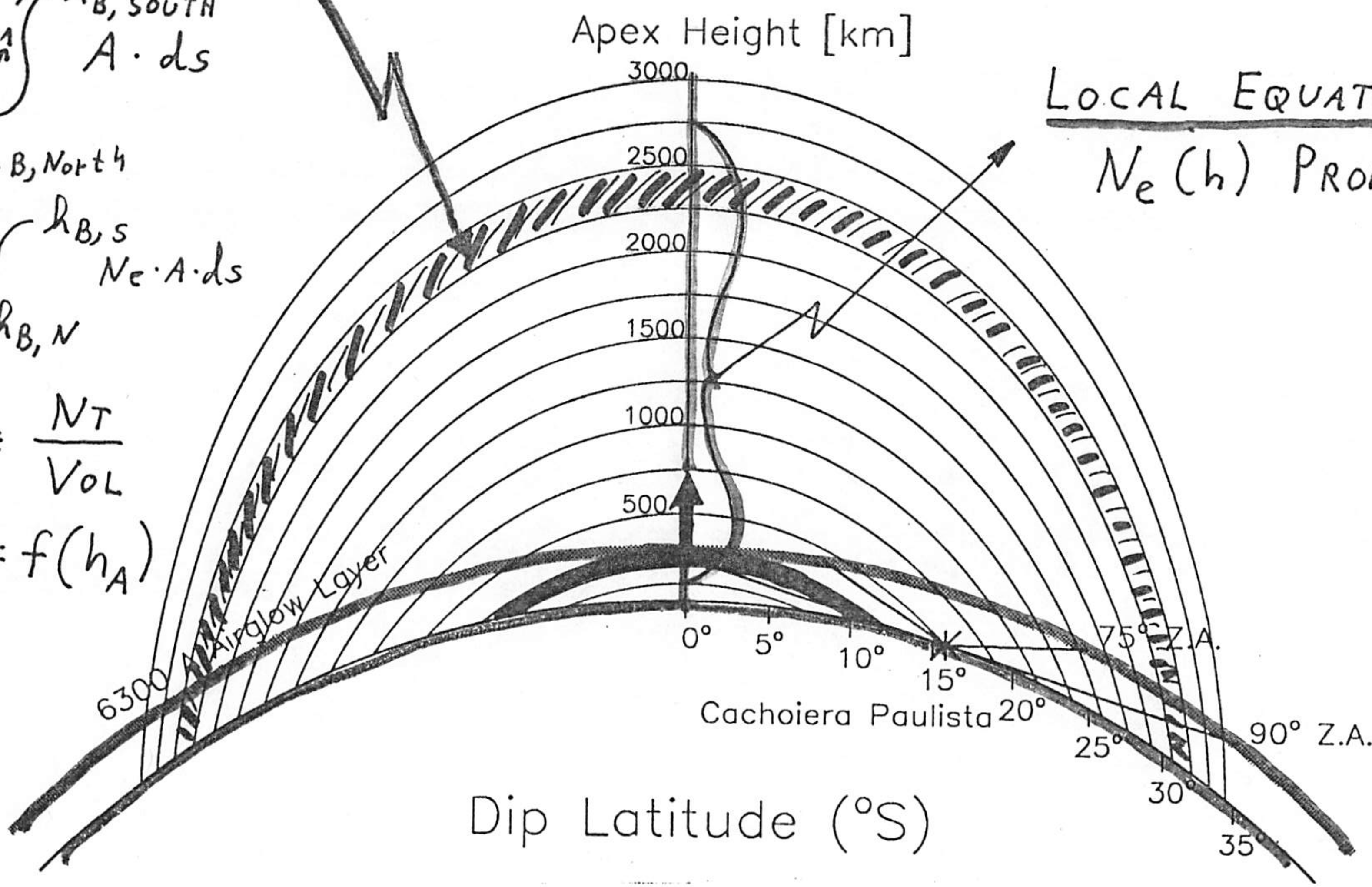
FLUXTUBE QUANTITIES

$$Vol = \int_{h_{B,North}}^{h_{B,SOUTH}} A \cdot ds \quad (h_A)$$

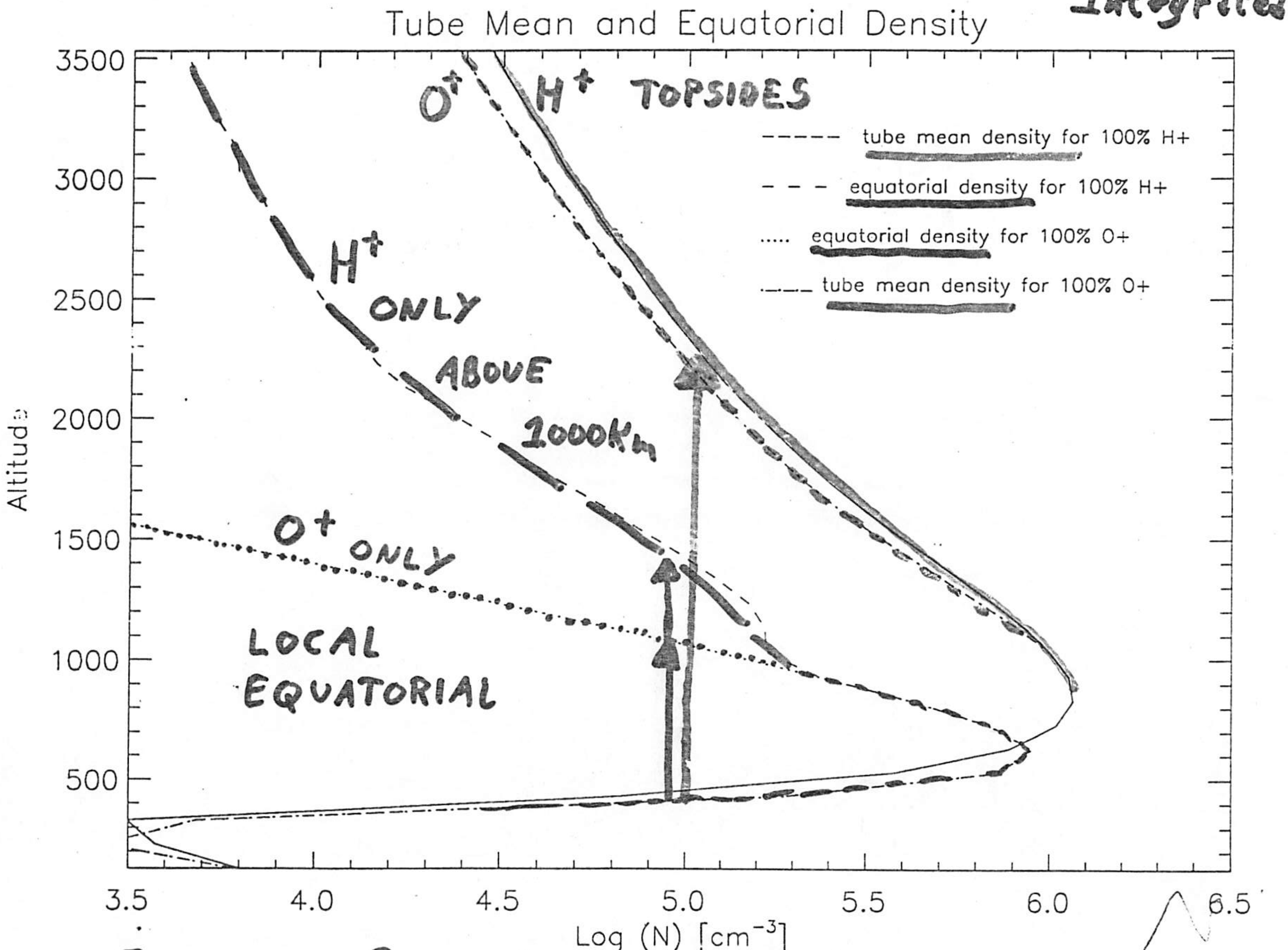
$$N_T = \int_{h_{B,N}}^{h_{B,S}} N_e \cdot A \cdot ds$$

$$\langle N_e \rangle_T \equiv \frac{N_T}{Vol} = f(h_A)$$

LOCAL EQUATORIAL $N_e(h)$ PROFILE



COMPARISONS OF "EQUAL DENSITY POINTS" Local vs. Fluxtube Integrated



BUOYANCY POINT CALCULATIONS by E. ZESTA + S. SHODAN-SHAH
FAIM for O+ (Anderson et al, 1989), 21 MAR '90 AT ~19:30 LT

EXAMPLE: FLUXTUBE-INTEGRATED EFFECT ON GROWTH RATE.

The Stability of Ionospheric Plasma

Consider plasma distributed along magnetic field lines. The growth rate associated with a flux tube is given by:

$$\gamma_{tube} = \frac{\int \gamma_{local} \cdot \sigma \, dz}{\int \sigma \, dz}$$

σ = local Pedersen conductivity

$$\gamma_{local} = \left(\frac{c \vec{E}_{\perp} \times \hat{z}}{B} - \vec{U}_{n\perp} - \frac{\vec{g}_{\perp}}{\nu_{in}} \right) \cdot \frac{\nabla_{\perp} n}{n}$$

Question: What could cause the equatorial ionosphere to be truly stable??

What could give us negative growth rates?

EXAMPLE: Fluxtube-Integrated Effect on Growth Rate

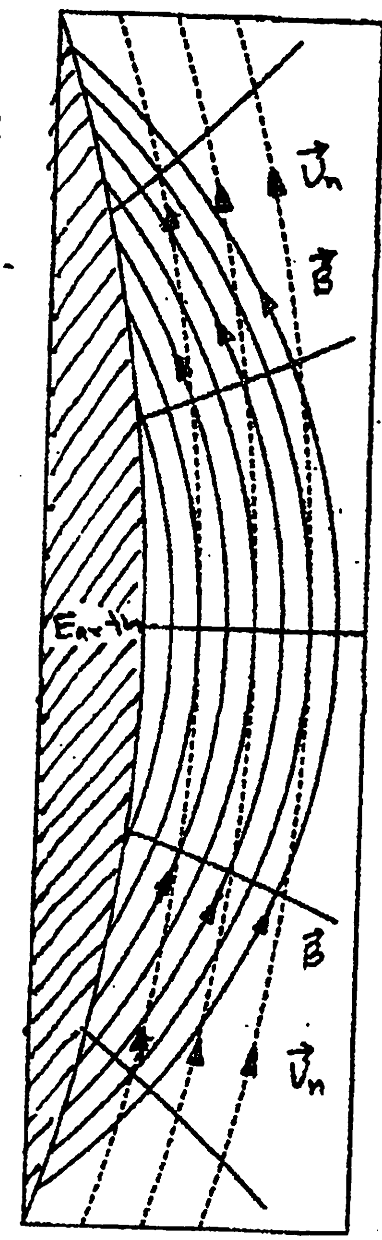
Northward (Trans-equatorial) Neutral Winds in the Equatorial Ionosphere

Effect #1

Meridional $U_n \parallel \vec{B}$

Component moves plasma downward to loss --- molecular ions --- "E-Region-Like" effect

⇒ Stabilize on downwind end.



Effect #2

$\vec{U}_n$ "upward" (stabilizing)

$\vec{U}_n \perp \vec{B}$ up

gravity $\vec{g}$ always "downward" (destabilizing)

Meridional $U_n \parallel \vec{B}$ moves plasma upward --- less loss

⇒ Destabilize on upwind end.

$\vec{U}_n$ "downward" (destabilizing)

$\vec{U}_n \perp \vec{B}$ down

Hemispheric Symmetry ⇒ $\vec{U}_n$ has no effect

BUT: Wind itself causes asymmetry!!

Zalesak + Huba

- Meridional winds deliver a 1-2 punch to the nighttime equatorial ionosphere:

  1) The shift of plasma across the magnetic equator reduces the gravity-driven growth rate (Maruyama effect)

  2) The direct effect of the winds on the shifted plasma drives the net growth rate <u>negative</u>, precluding the development of spread F plumes as long as the winds persist. (New effect)

- For a realistic ionosphere and atmosphere and a meridional wind of 100 m/s:

  We need less than a 400 km displacement of plasma along magnetic field lines to stabilize the entire equatorial ionosphere!!

- The above is from linear stability analysis.

  Nonlinear numerical simulations make the point more dramatically:

Fluxtube-Integrated Issues:

- Nature of "Seed Perturbation"
  - Gravity waves with phase fronts // $\vec{B}$
  - Can Sunset Terminator // $\vec{B}$ ("Spread-F Season") launch Gravity Waves required?
  - Can $\vec{E}_{penetration}$ seed at specific meridians?
- For tube-integrated plasma content, entire equatorial Ionosphere is "Bottomside"
  - What determines "bifurcation height"?
  - What determines maximum Apex heights?
- Where is the observational evidence for the Neutral Wind effect on ESF?
- Do MTM winds affect ESF?
- Does Sporadic-E at dusk affect ESF?
- Role of geomagnetic activity in day-to-day variability of the low latitude F-region?

ESF and Geomagnetic Activity

1. Within "ESF Season" at a given longitude sector,
   (a) ESF onset from 18-24 LT → 0 as $K_p \gg 0$
   (Usually stated other way: ESF occurs during quiet times.)
   "Storms inhibit ESF?"
   (b) ESF onset from 24-06 LT → ∞ as $K_p \gg 0$
   "Storms cause post-midnight ESF?"

2. Within "Non ESF Seasons" at a given longitude,
   ESF onset from 18-06 LT → ∞ as $K_p \gg 0$
   "Storms cause ESF?"

ESF Connection to Space Weather

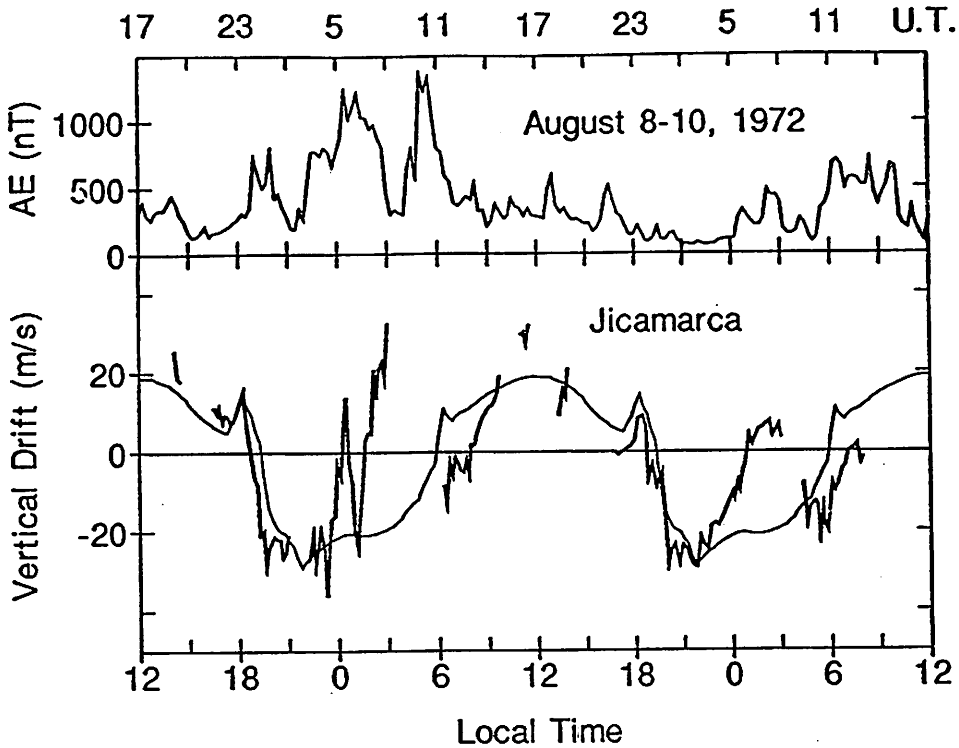
— Penetration / Shielding / Over-Shielding of Magnetospheric $\vec{E}$-fields to low latitudes

IMPORTANT

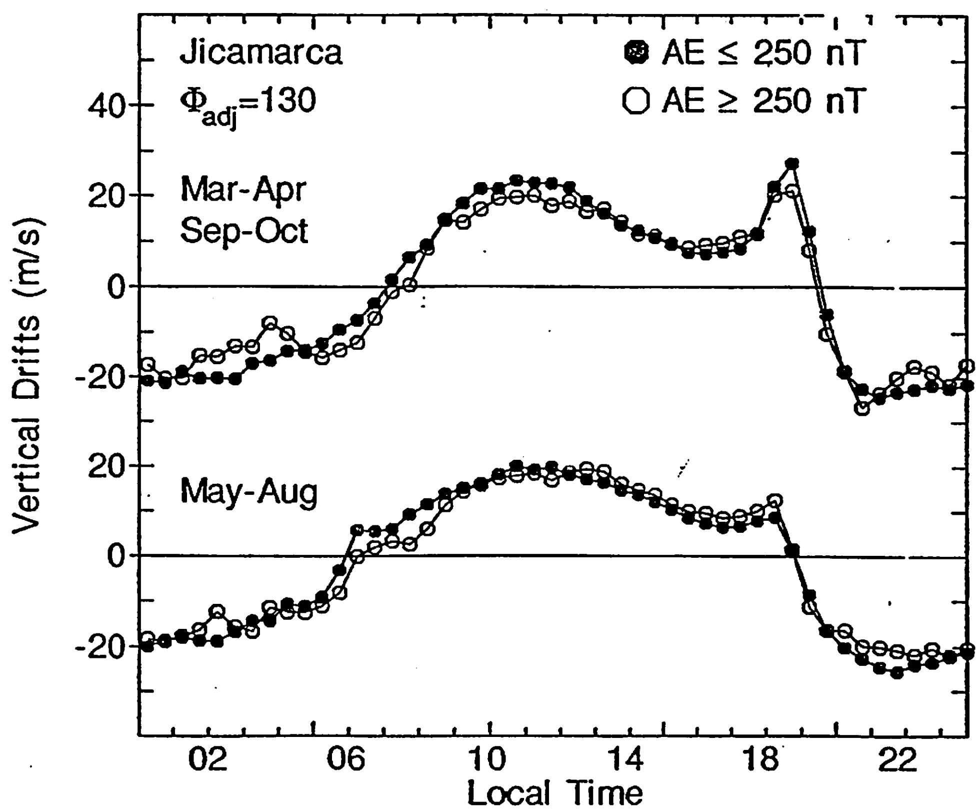
↙ V_p up or down affects γ_{R-T}

↘ Possible "seed"

Large electric field (plasma drift) perturbations are often observed at the equator during disturbed conditions



BUT
The average equatorial drifts during geomagnetically quiet and disturbed conditions are essentially identical !

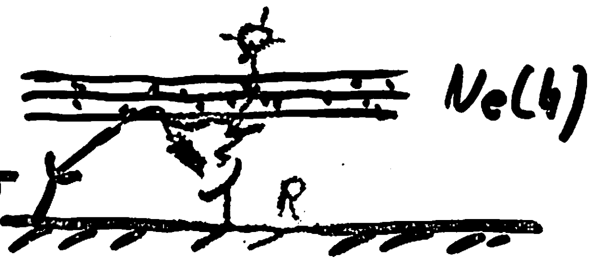


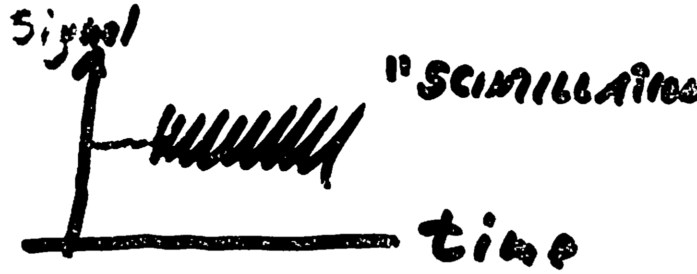
B. Fejer

ESF AND SPACE WEATHER

Ionospheric Disturbances impact:

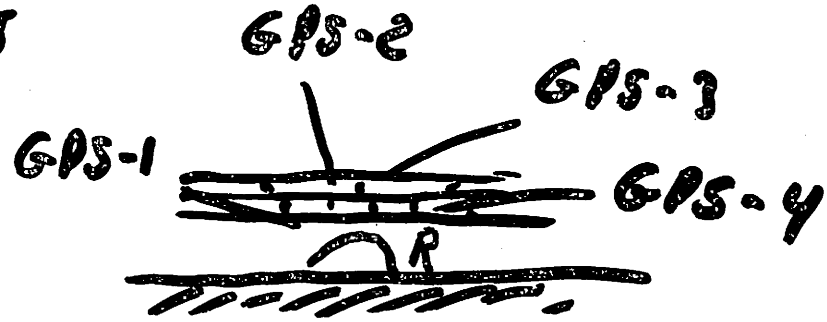
1. Radio Communications





<u>SCINT</u> <u>Effect</u>: Loss of Voice Comm.

2. Navigation/Positioning + "Geolocation"



<u>SCINT</u> <u>Effect</u>: Loss of Receiver Lock

<u>TEC</u> <u>Effect</u>: Range Errors

$$TEC = \int_R^{GPS} N_e(h)\, dh$$

Group Path Delay ⇒ Slant Range Errors

TEC through "ESF Bubble" << TEC of ambient ionosphere + plasmasphere (GPS @ 22,000 km)

FINAL THOUGHTS

- "Level-of-Activity should not be confused with "Productivity."
- The Scientific Method says Theory is verified by observations --- so conduct focused + well defined ones.
- If that does not work--- make more observations.
- Create a New Program:
  Atmospheric Coupling of Regions Observed but Not Yet Modeled

"ACRONYM"