Active, two-point, plasma wave experiments on OEDIPUS C

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Features of Rocket Missions

Range of disciplines: Aeronomy, Space Environment, Astronomy, Microgravity (in, from, on)

Turn around times smaller than for orbital missions

Focussed, specific research objectives.

Parabolic trajectories, nearly vertical legs, “hover”. (CARE)

Overall time in space is brief (5-20 min) but fruitful if carefully designed. (OEDIPUS C)

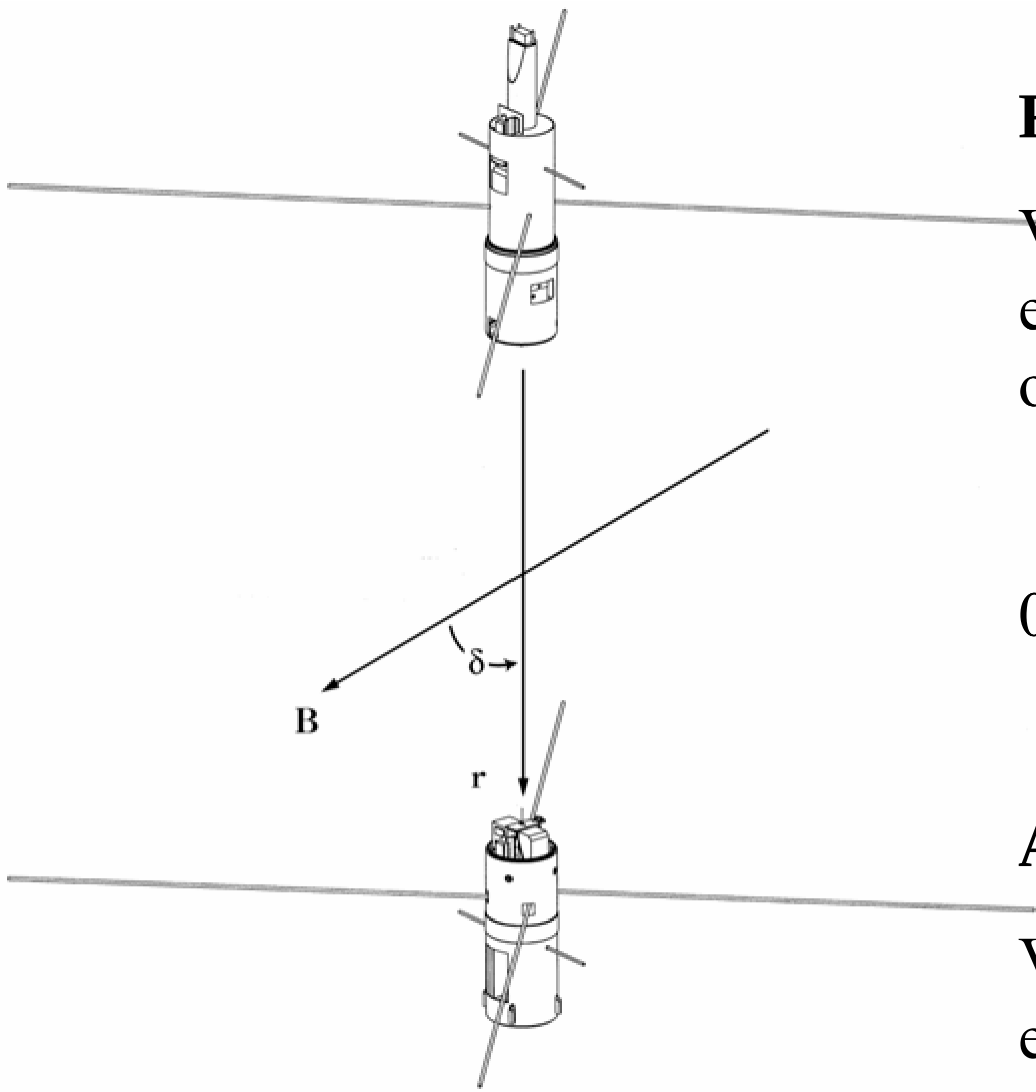
Sole access to important regions of space : Mesosphere to the lower ionosphere. (Joule II)

Microgravity missions: Minutes of free-fall without interference, noise.

Features of Sounding Rockets, cont'd

- Optical obs. of astronom., solar, and planetary sources can be made of radiation at wavelengths absorbed by the lower atmosphere. (GEMINI, ACTIVE)
- Ability to fly relatively large payload (~500 kg) masses on inexpensive vehicles. (GEMINI)
- Ability to use the Earth's limb as an occulting disk to observe astronomical sources close to the Sun.
- Aim at specific geophysical targets such as the aurora, equatorial electrojet, noctilucent clouds, polar wind (Cusp)
- Access to remote geophysical sites and southern hemisphere astronomical objects. (Eclipse studies, 1970; Cape Parry dayside aurora, 1974)
- Slow vehicle speed with respect to the ambient medium, slower than orbiting satellites yields better resolution of structure. (GEODESIC)
- Ability to fly simultaneous rockets along different trajectories, e.g., with different apogees, flight azimuths (Eclipse studies, 1970).
- Free-flying sub-payloads from a single launch permit small separations. (OEDIPUS)
- Exploits possibilities in active experiments (Waterhole, CARE, OEDIPUS) .

OEDIPUS C right after separation



Forward subpayload has

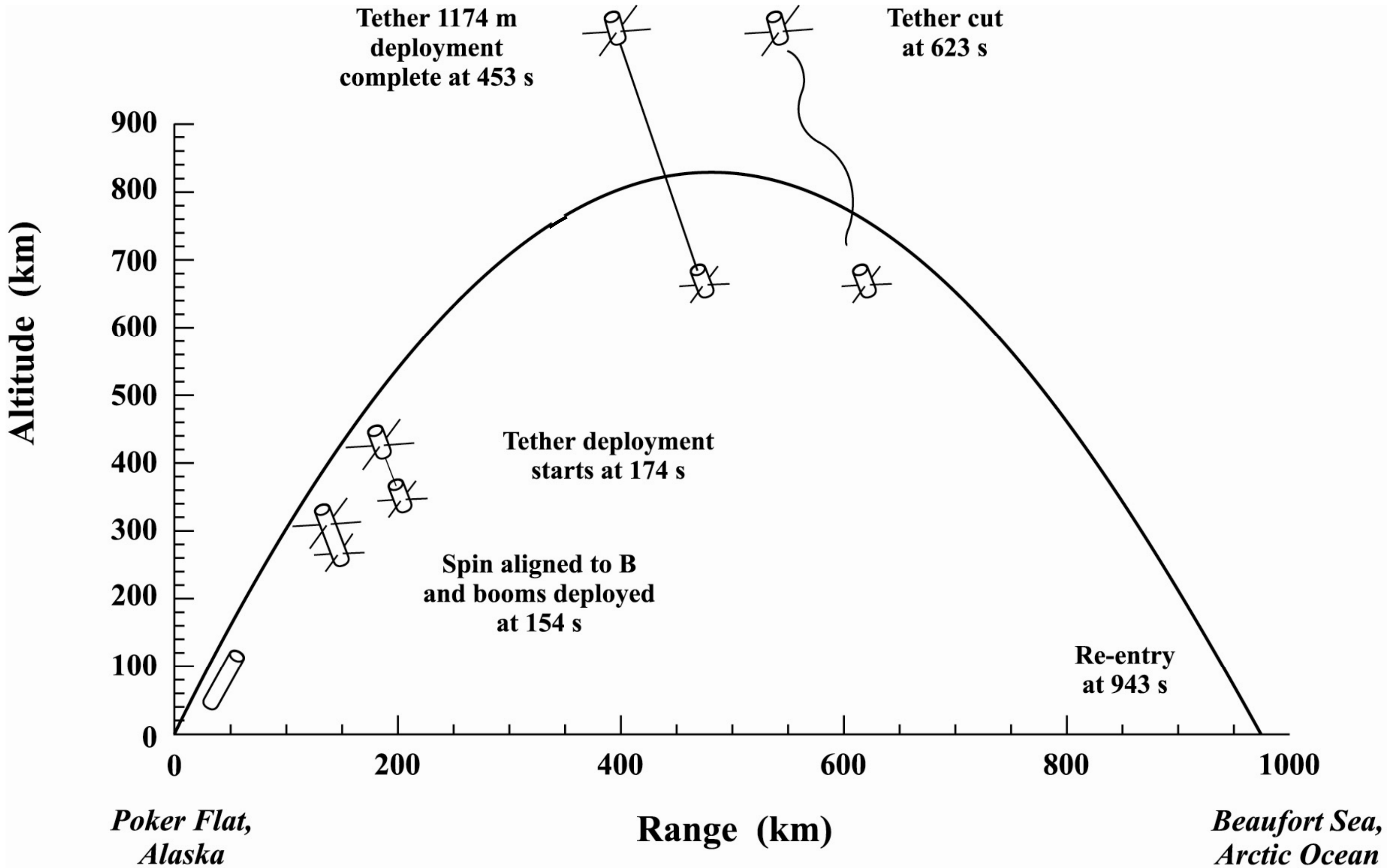
VLF-HF exciter (HEX), energetic-particle and other instruments.

$0.2° < \delta < 5°$.

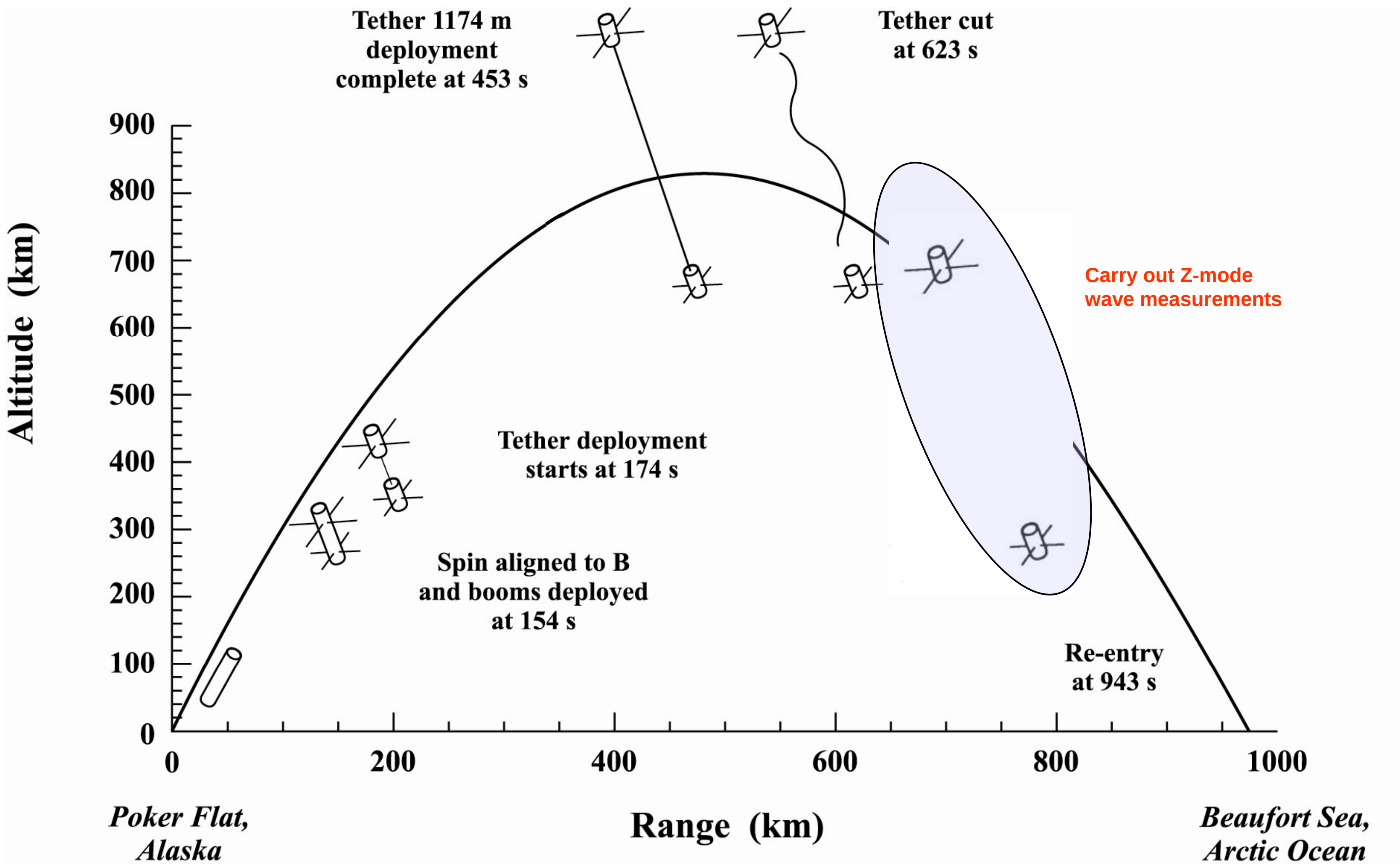
Aft subpayload has

VLF-HF receiver (REX), energetic-particle and other instruments.

Principal events along trajectory



Run 2-point propagation experiment



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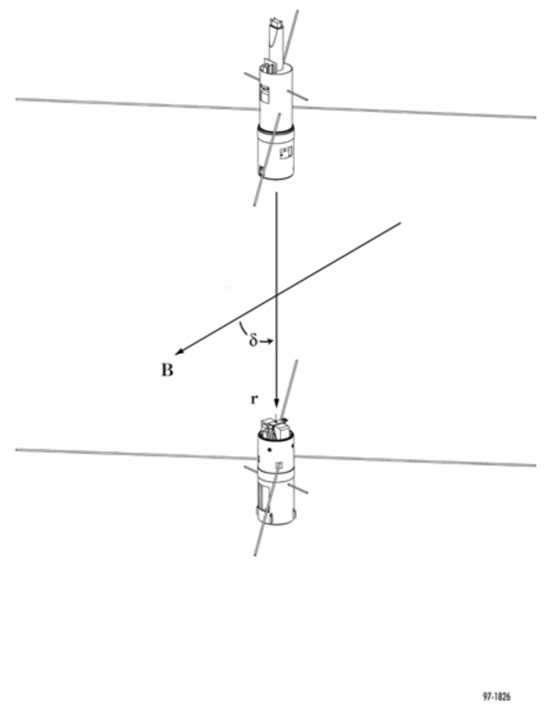
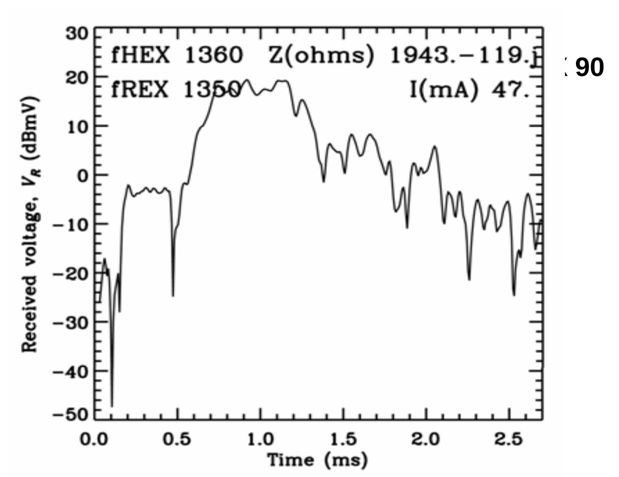
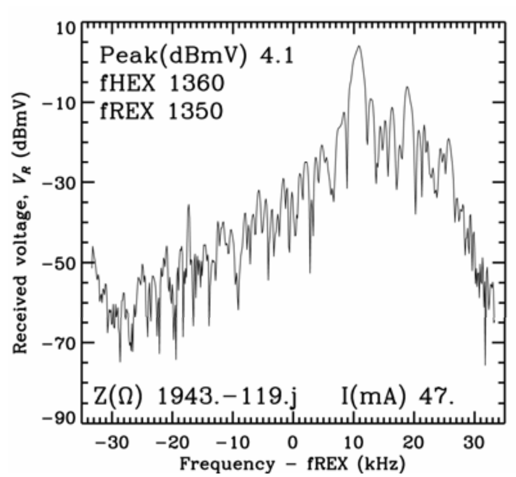
Experiment Conditions

- A double-V dipole was excited with RF pulses and resulting pulses received at a distance of about 1200 m on a similar dipole.
- The separation vector between the transmitter and receiver lay along a direction at about 5° from the axis of the Earth's magnetic field **B**.
- The received frequencies *f* lay in the range $max\{fc, fp\} < f < fuh$, where *fc* is the electron gyrofrequency, *fp* the plasma frequency and *fuh* the upper-hybrid-resonance frequency (slow Z mode).

Observations of Z-mode waves by HEX and REX

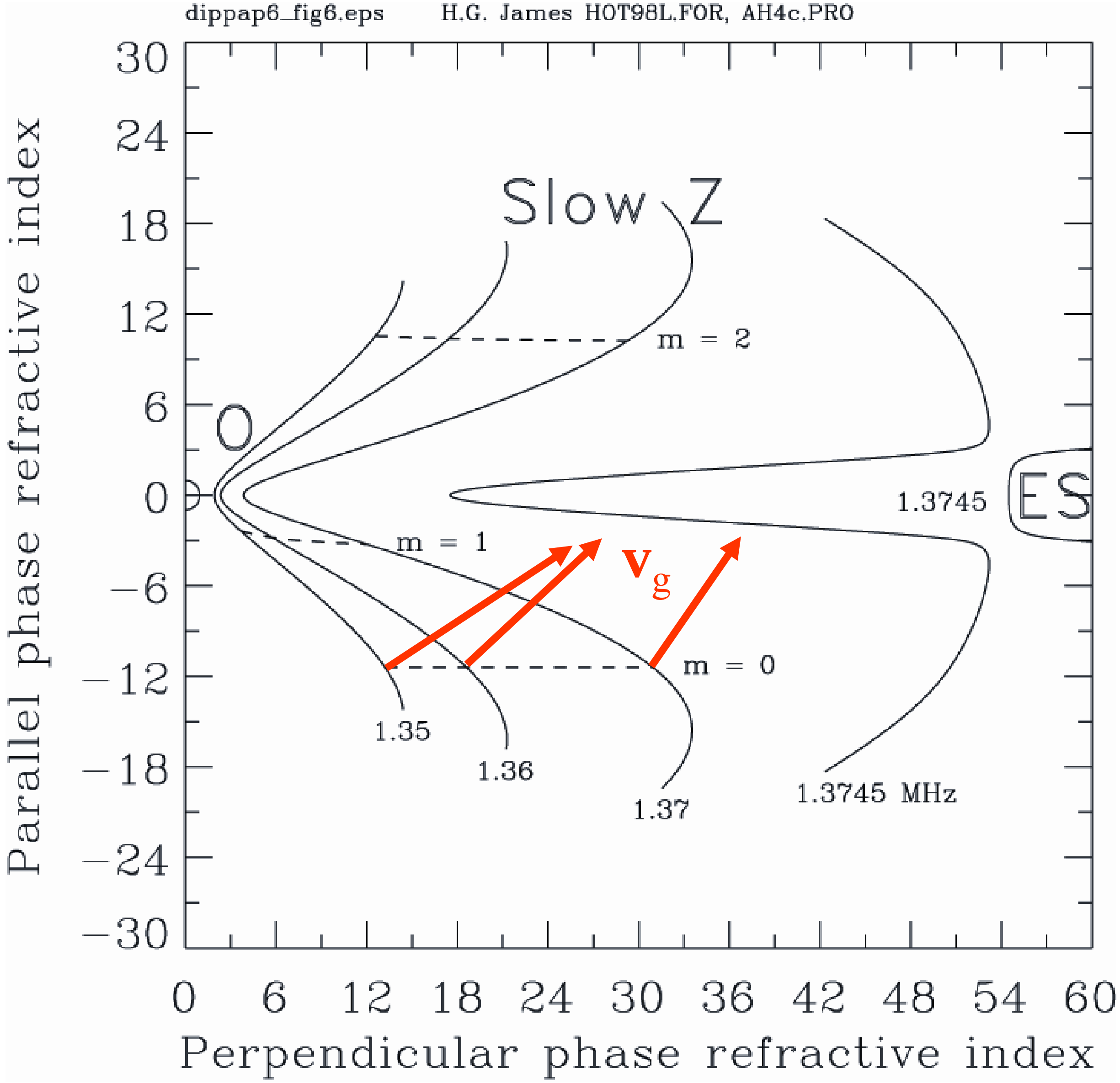






Hot-plasma dispersion surfaces

- $f_c = 1.299$ MHz
- $f_p = 0.45$
- $f_{uhr} = 1.3748$
- $T = 5000$ K



Source of Z-mode waves

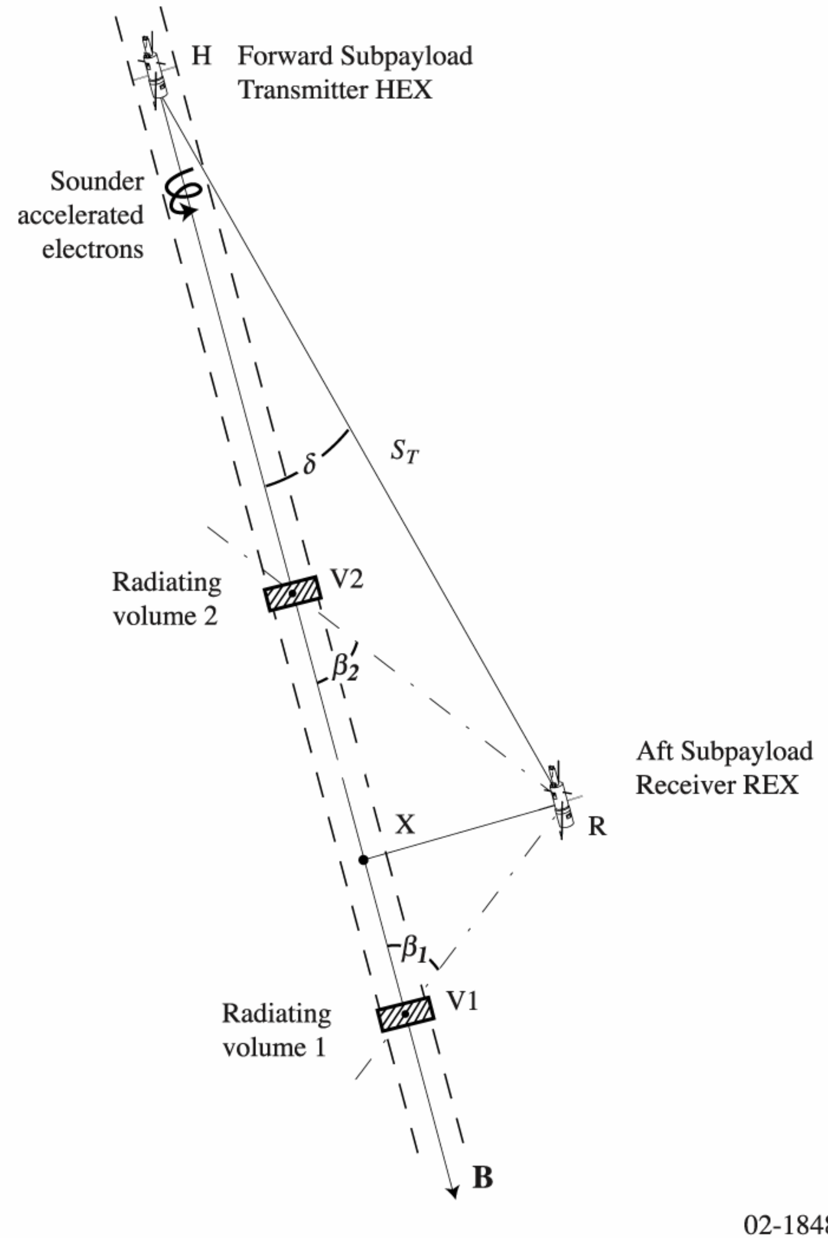
Propagation near the upper oblique resonance cone investigated using complete electromagnetic hot-plasma dispersion relation.

There are no Z-mode solutions for rectilinear propagation from transmitter to receiver with the observed group delays and directions.

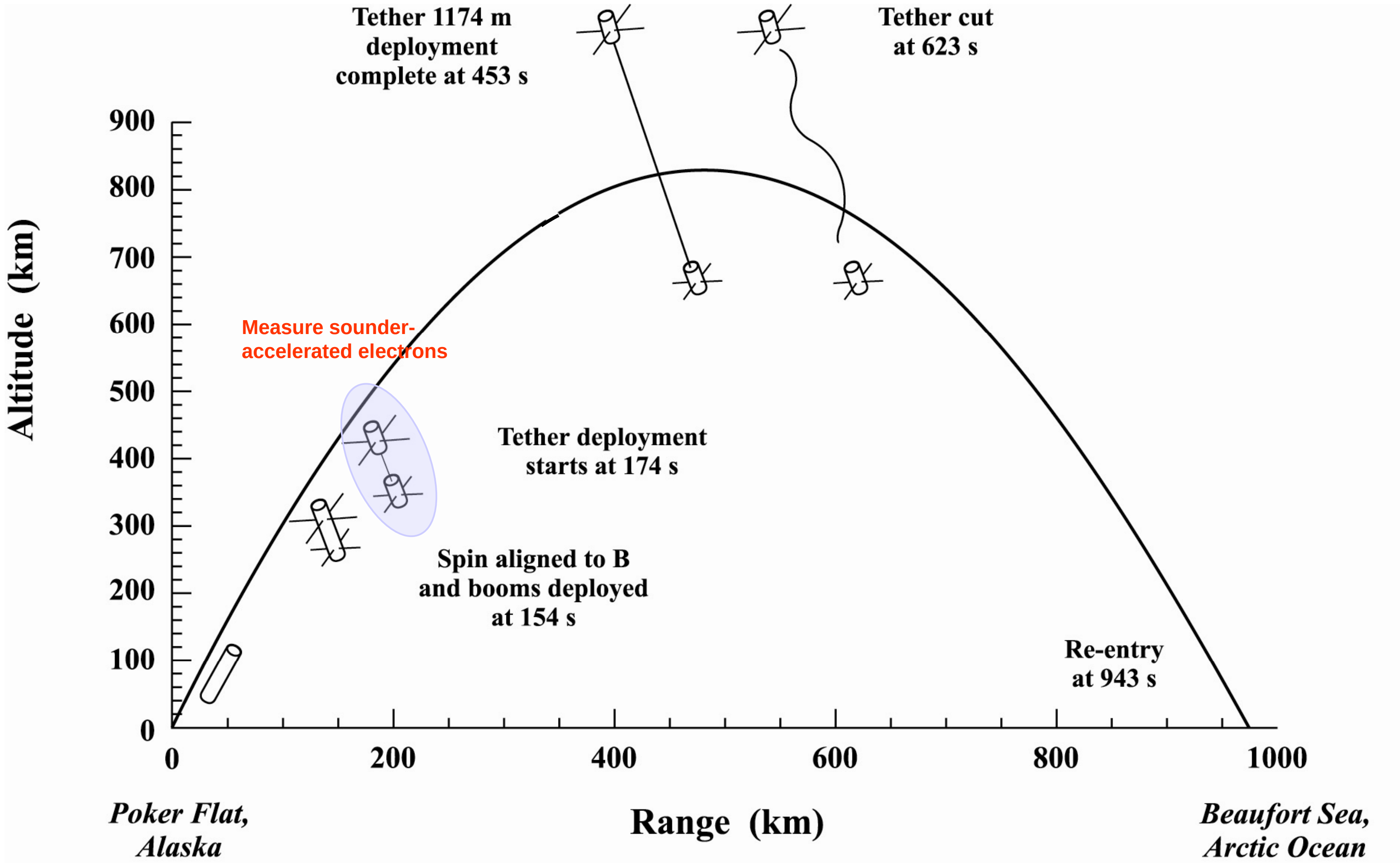
Therefore consider incoherent Z-mode radiation from sounder-accelerated electrons (SAE).

- Geometry of transmitter, receiver and sources of SAE radiation

Total signal delay comprised of time required by electron to travel to radiating site plus wave signal delay from site to REX



Sounder-accelerated electrons measured while subpayloads are close and field-aligned



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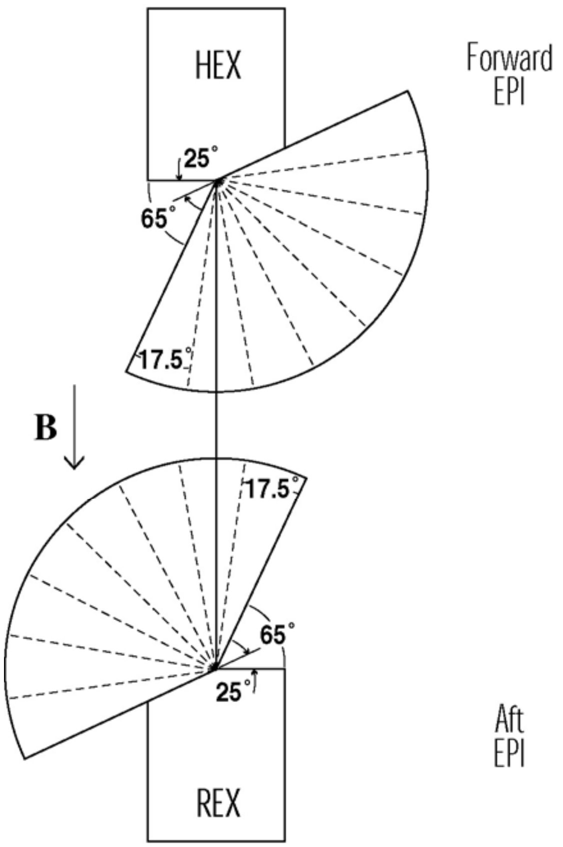
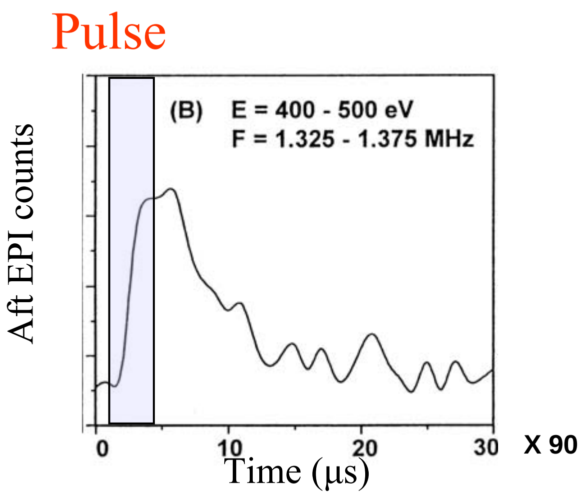
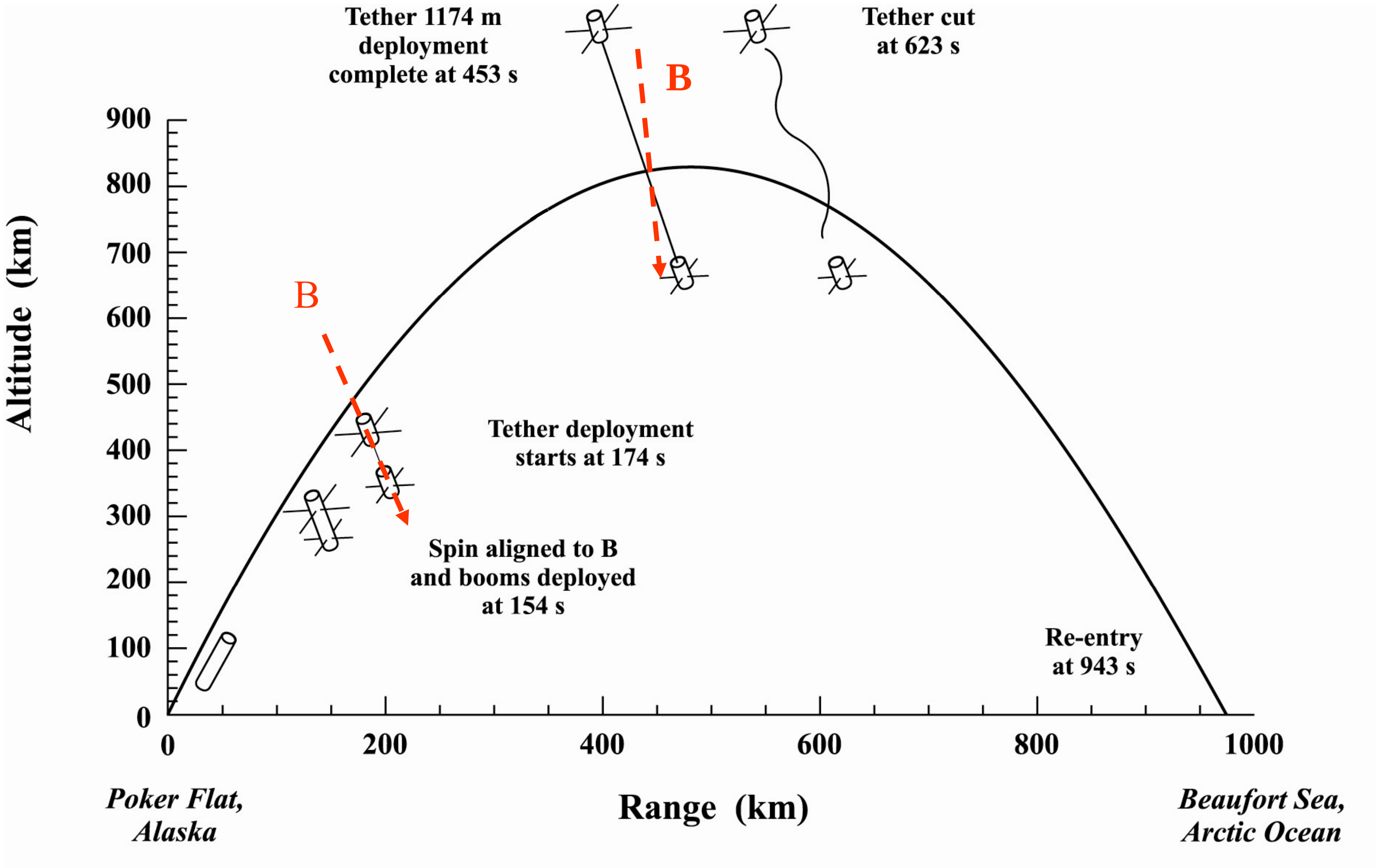
Observations of sounder-accelerated electrons with Energetic Particle Instruments

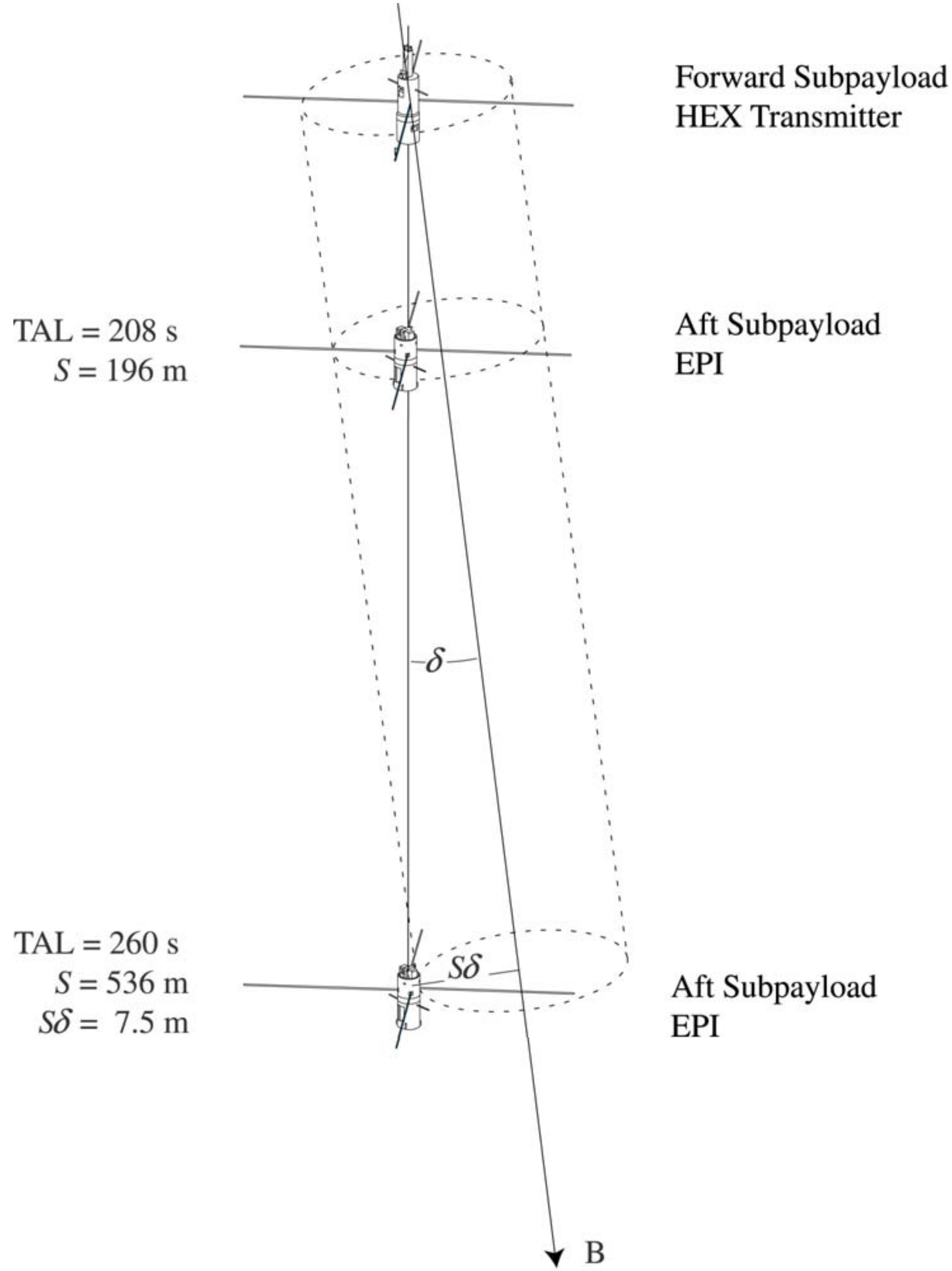




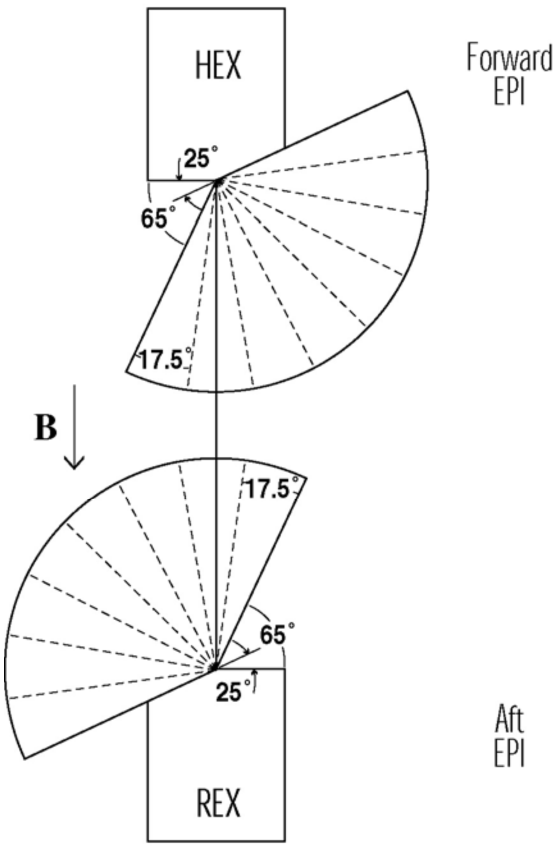
Angle between separation vector and terrestrial magnetic field B increases along trajectory



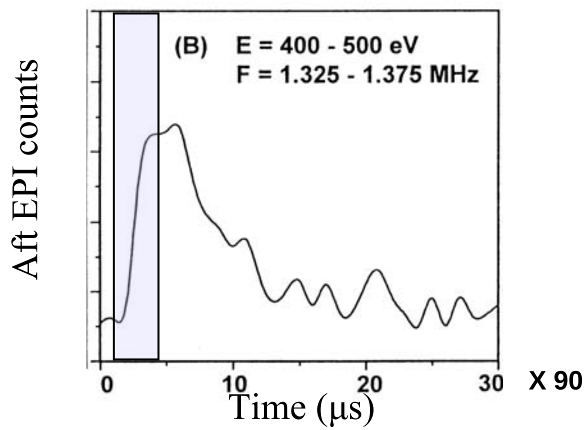
Increasing cross-field separation of HEX and REX eventually cuts off HEX-excited electrons at REX

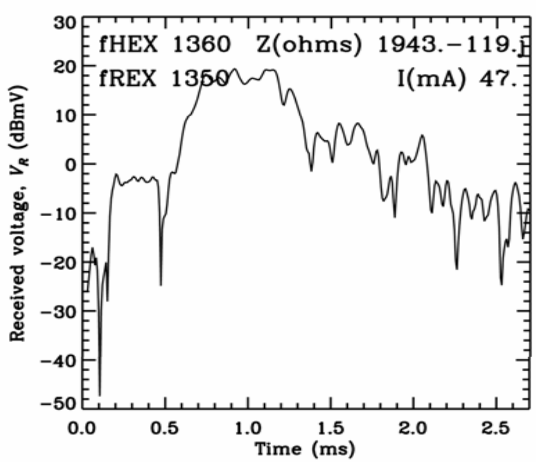


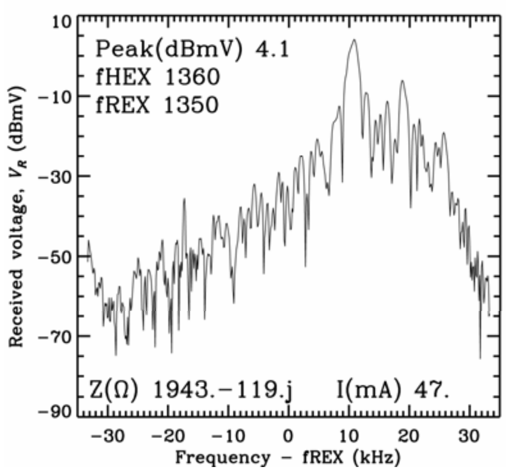
Observations of Z-mode waves by HEX and REX



Pulse







Radiation from SAE

OC transmitter produces strong SAE from 10 eV to 10 keV at Z-mode frequencies

SAE travels helically downward toward the receiver.

Wave-SAE resonance: $f - mf_c = (nf/c)\cos\theta_s\, v\cos\alpha$

The resonance condition and dispersion relation together require θs values near the upper-oblique resonance cone.

Time delays like those observed can be explained with Z-mode n and θ_s values, for m = 0, 1 or 2.

Hot-plasma dispersion surfaces

- $f_c = 1.299$ MHz
- $f_p = 0.45$
- $f_{uhr} = 1.3748$
- $T = 5000$ K

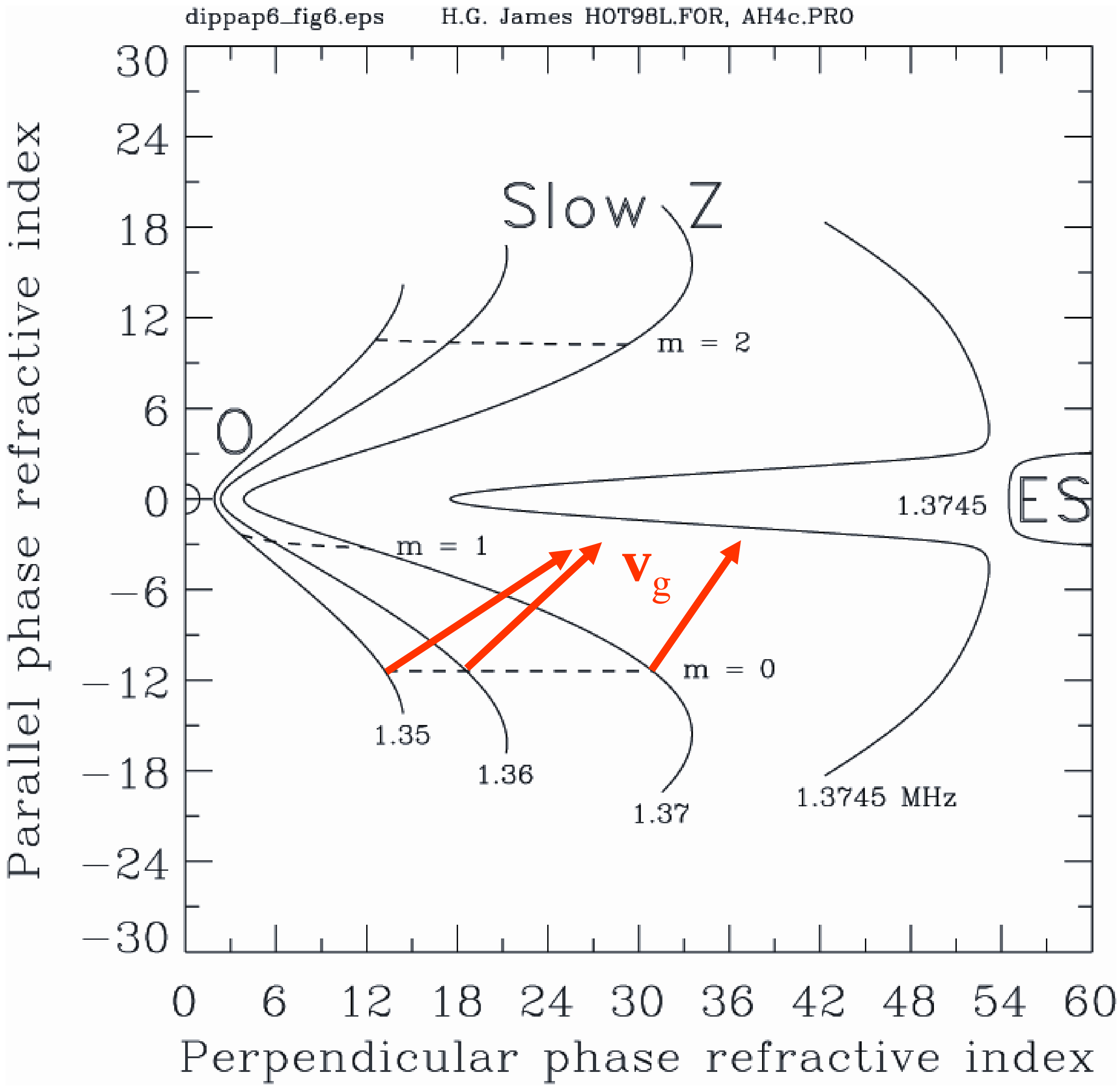
Wave-particle resonance condition:

$\omega - m\omega_c = k_{par}v_{par}$

or

$f - mf_c = (nf/c)\cos\theta_s\, v\cos\alpha$

Example plotted:
Energy = 3 keV
$v = 32.5$ km/ms
Pitch angle, $\alpha = 36^o$



Incoherent radiation theory

$$E^2 = \frac{2S}{\varepsilon_0 v_g} = \frac{2\pi q^2}{v_g r^2 \sin\beta \varepsilon_0^2} \frac{d\omega}{d\beta} \left\{ \mathbf{v}^* \cdot \mathbf{T}_{adj}\left(\theta_s\right) \cdot \mathbf{v} \right\} c / \left[\lambda_0^3 \left| v_{par} \right| \omega^2 (n_Z^2 - n_O^2) \right],$$

where

T is the wave tensor whose determinant $|\mathbf{T}| = 0$ is the hot-plasma dispersion relation, having roots n_Z and n_O;

$\mathbf{v} = [\frac{m v_\perp}{u} J_m(u), -i v_\perp J'_m(u), v_{par} J_m(u)]$; $v_\perp, v_{par}$ are the velocity components;

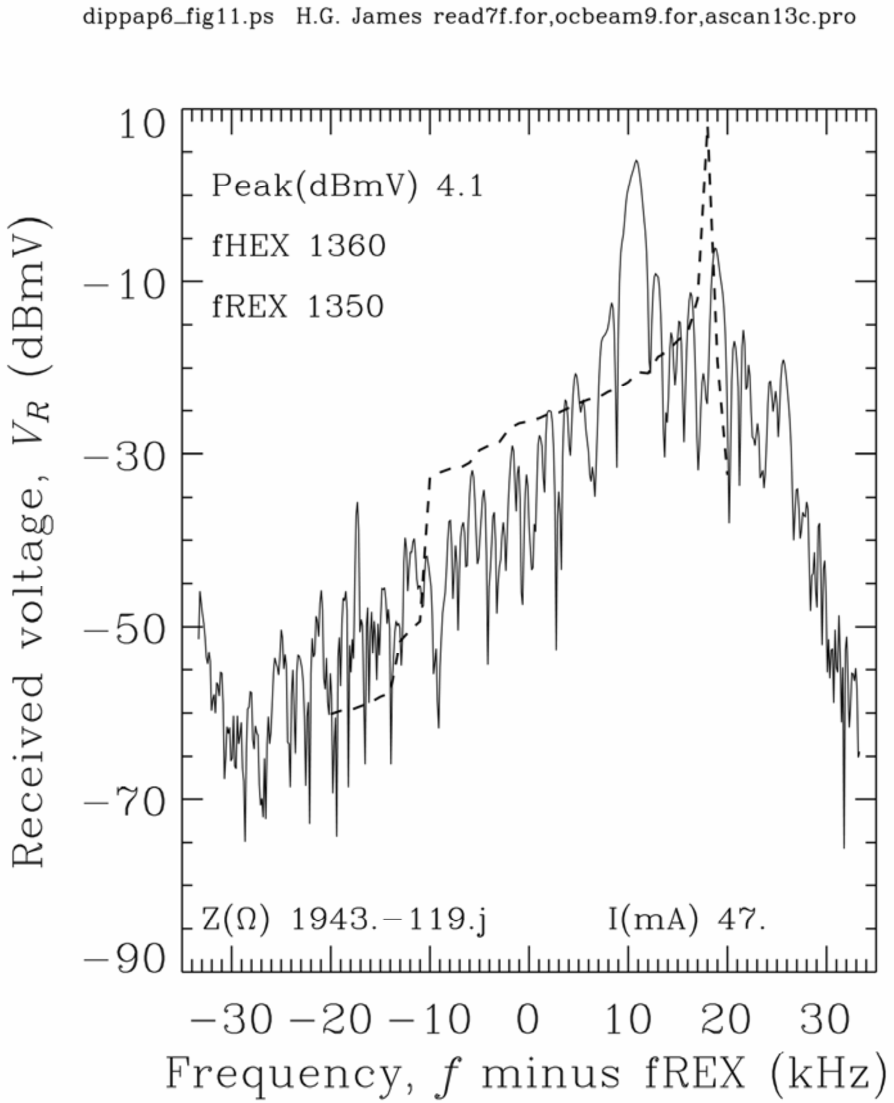
m is the cyclotron order; $u = v_\perp n f \sin\theta / c f_c$; $\beta = \angle(\mathbf{B}, \mathbf{v}_g)$.

$d^2 P_m / d\phi df \rightarrow dP_m / d\Omega \rightarrow \mathbf{S}$; $\langle \mathrm{W} \rangle = |\mathbf{S}| / v_g$; $\langle \mathrm{W} \rangle = \frac{\varepsilon_0}{4} |\mathbf{E}|^2$; $V = \mathbf{E} \cdot \mathbf{L} / 2$.

Observations compared with theory

SAE Parameters

α (°)	36	36	54	54
m	0, 2	1	0, 2	1
En.(keV)	1-10	.01- 0.1	2-10	.01- 0.1
j_d $[\text{cm s sr eV}]^{-1}$	10^6	10^8	10^6	10^8
N (10^{12} el.)	3.6	4.0	4.4	5.5



James, H.G., Slow Z-mode radiation from sounder-accelerated electrons, *JASTP 66*, 1755-1765, 2004.

James, H.G., Radiation from sounder-accelerated electrons, *Adv. Sp. Res 38*, 2533-2540, 2006.

Results

- Transmission of strong, dispersed Z-mode pulses arising from sounder-accelerated electrons was observed and investigated.
- The observed Z-mode receiving dipole voltages are within an order of magnitude of the values predicted by the theory of incoherent emission by spiraling electrons.
- The double-payload experiment exploited advantages offered by a sounding rocket for small-separation, active, focussed experiments.
- These advantages provided insight into how an active antenna works in a plasma – best, or only, done with a sounding rocket.

Results

- Transmission of strong, dispersed Z-mode pulses arising from sounder-accelerated electrons was observed and investigated.
- Solution of the resonance condition with a hot-plasma dispersion relation provides signal delays like those measured.
- However, transmission cannot be explained as direct propagation from HEX to REX.
- The observed Z-mode receiving dipole voltages are within an order of magnitude of the values predicted by the theory of incoherent emission by spiraling electrons.
- The double-payload experiment exploited advantages offered by a sounding rocket for small-separation, active, focussed experiments.
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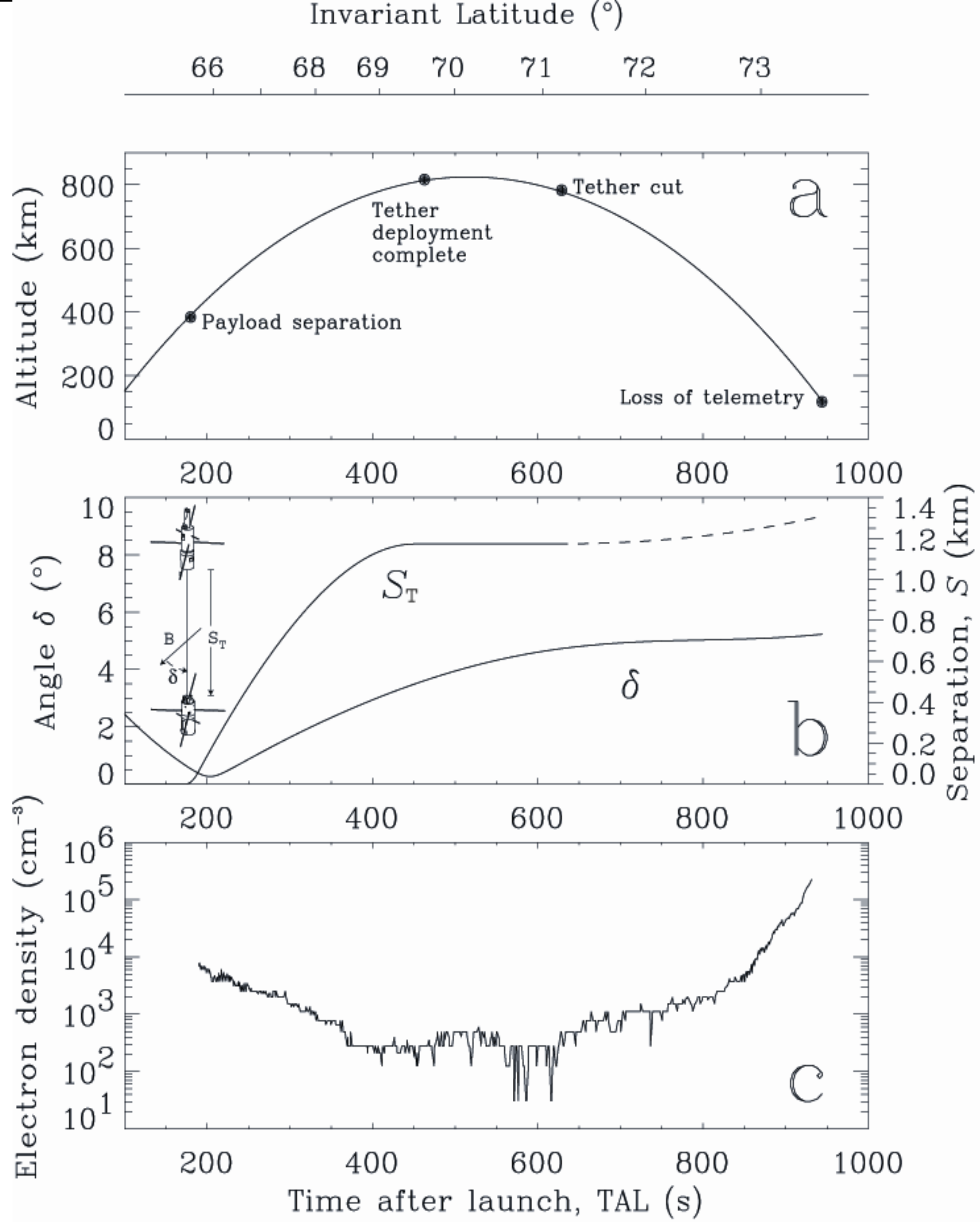
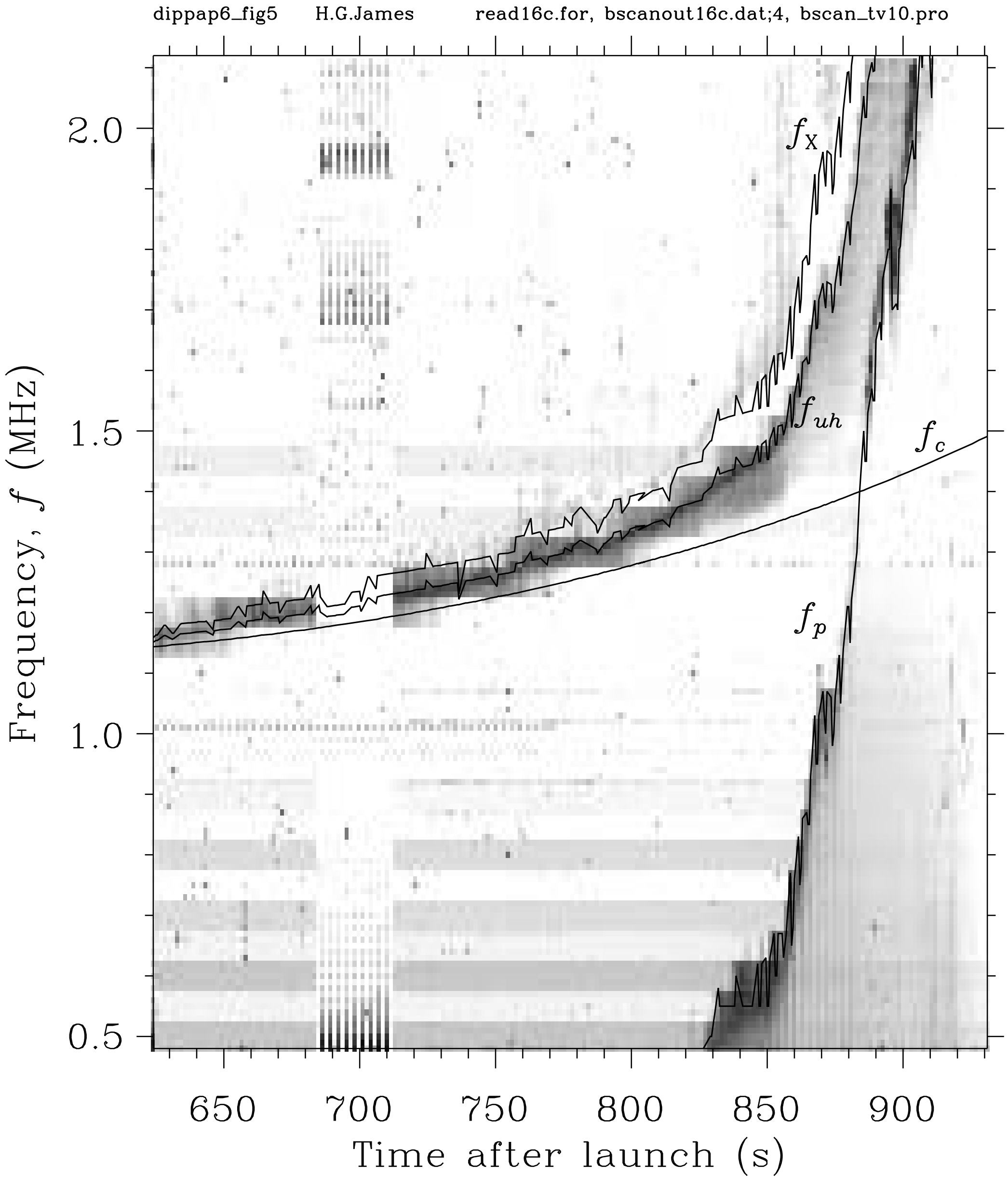
OEDIPUS-C
Flight events

Tx-Rx
Geometry

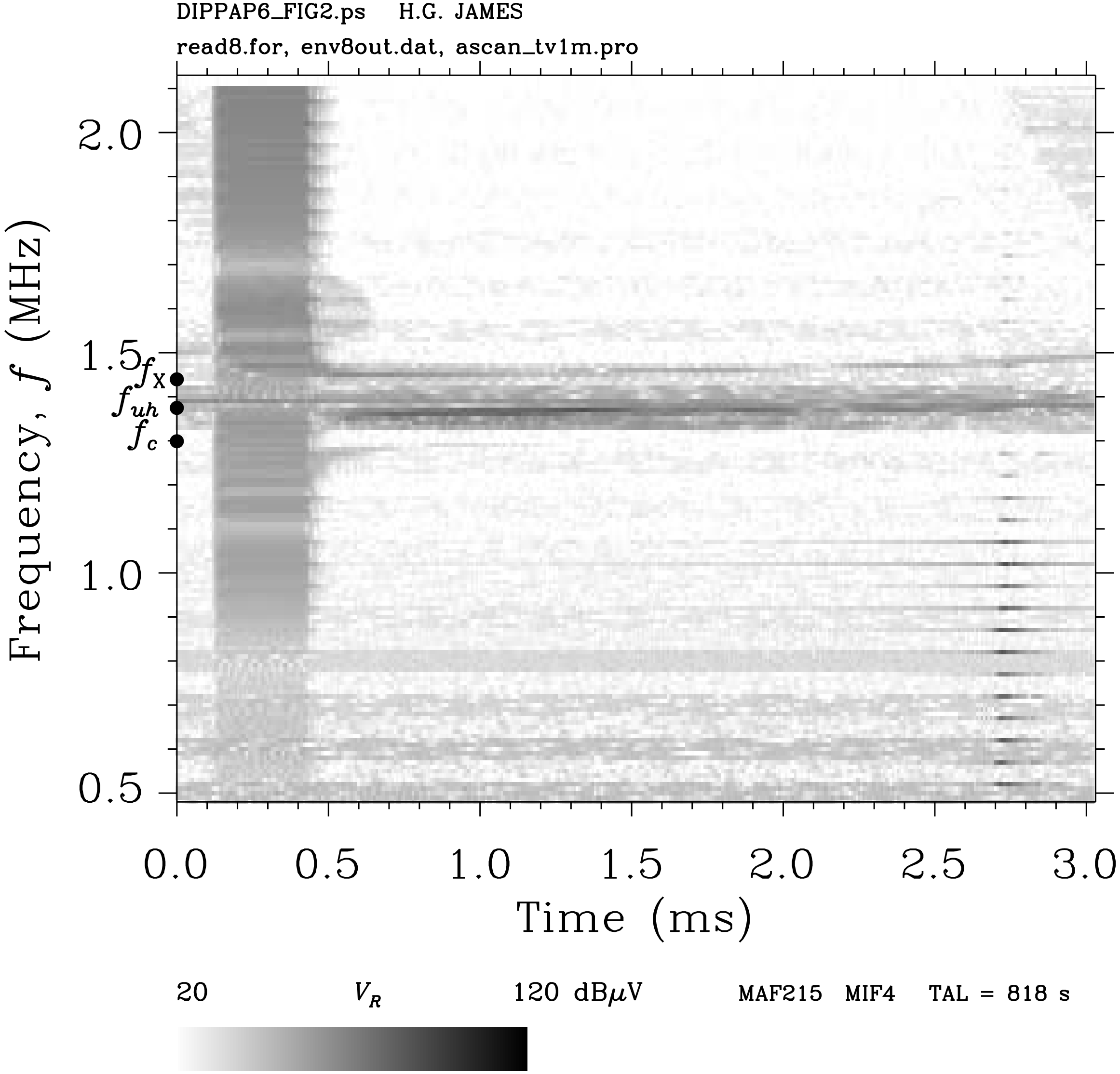
Density at
payload



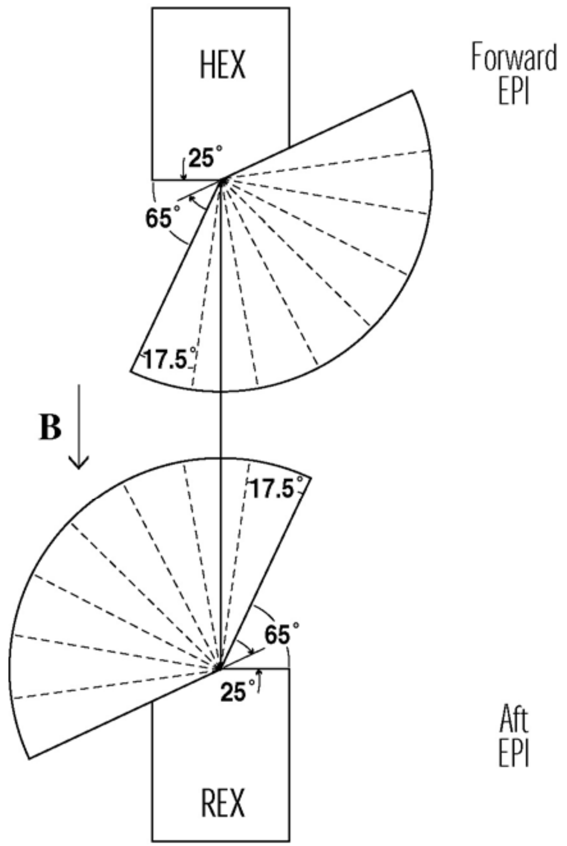
Summary of down-leg ionograms

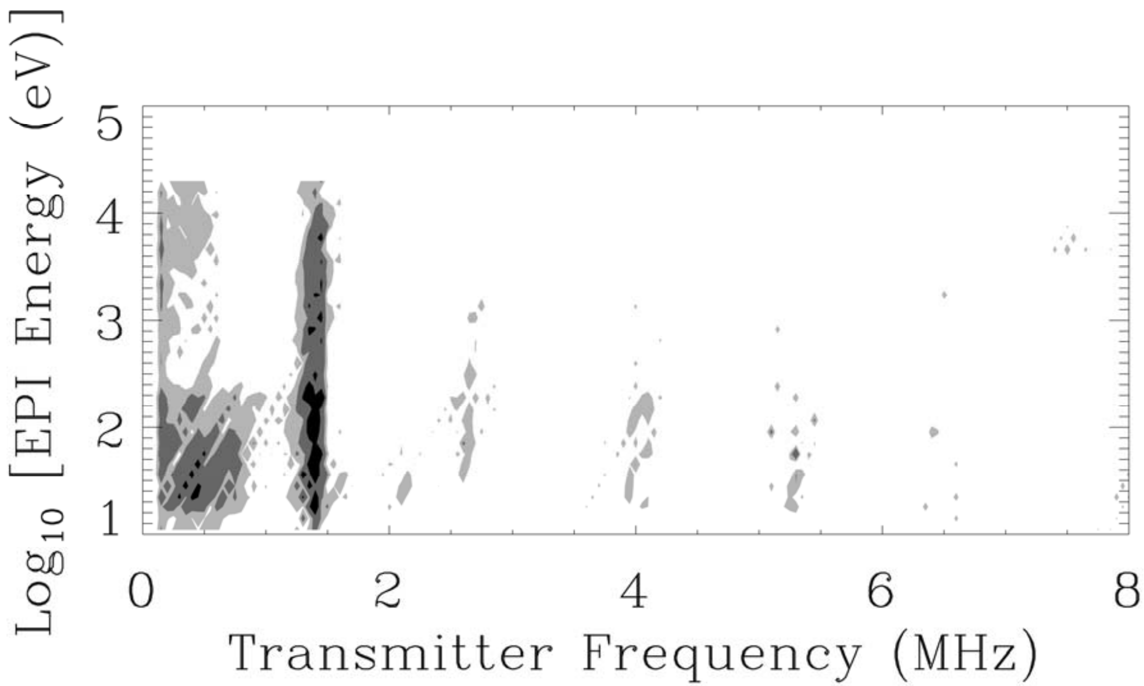


Ionogram with strong, dispersed Z-mode pulses

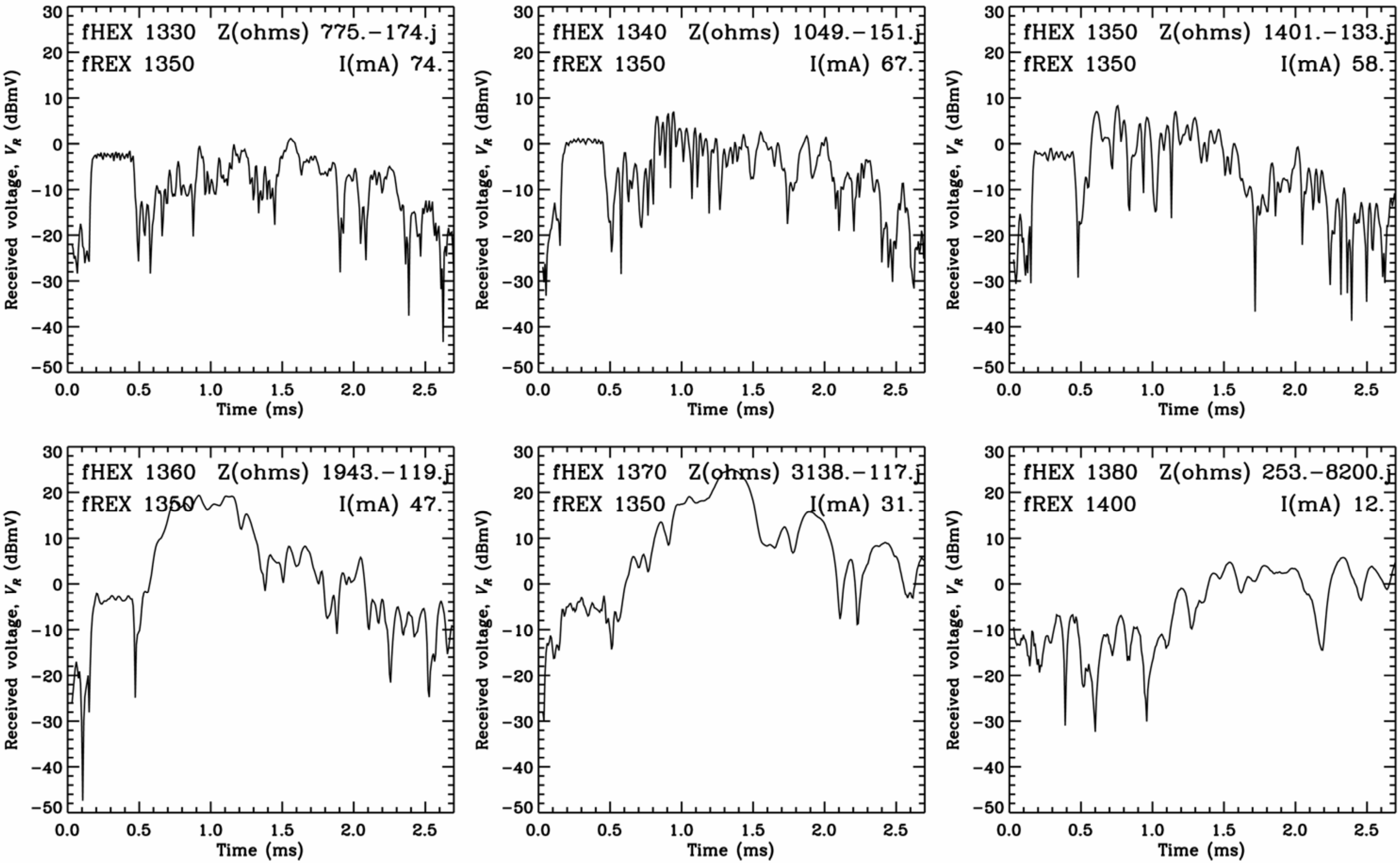


Observations of sounder-accelerated electrons with Energetic Particle Instruments

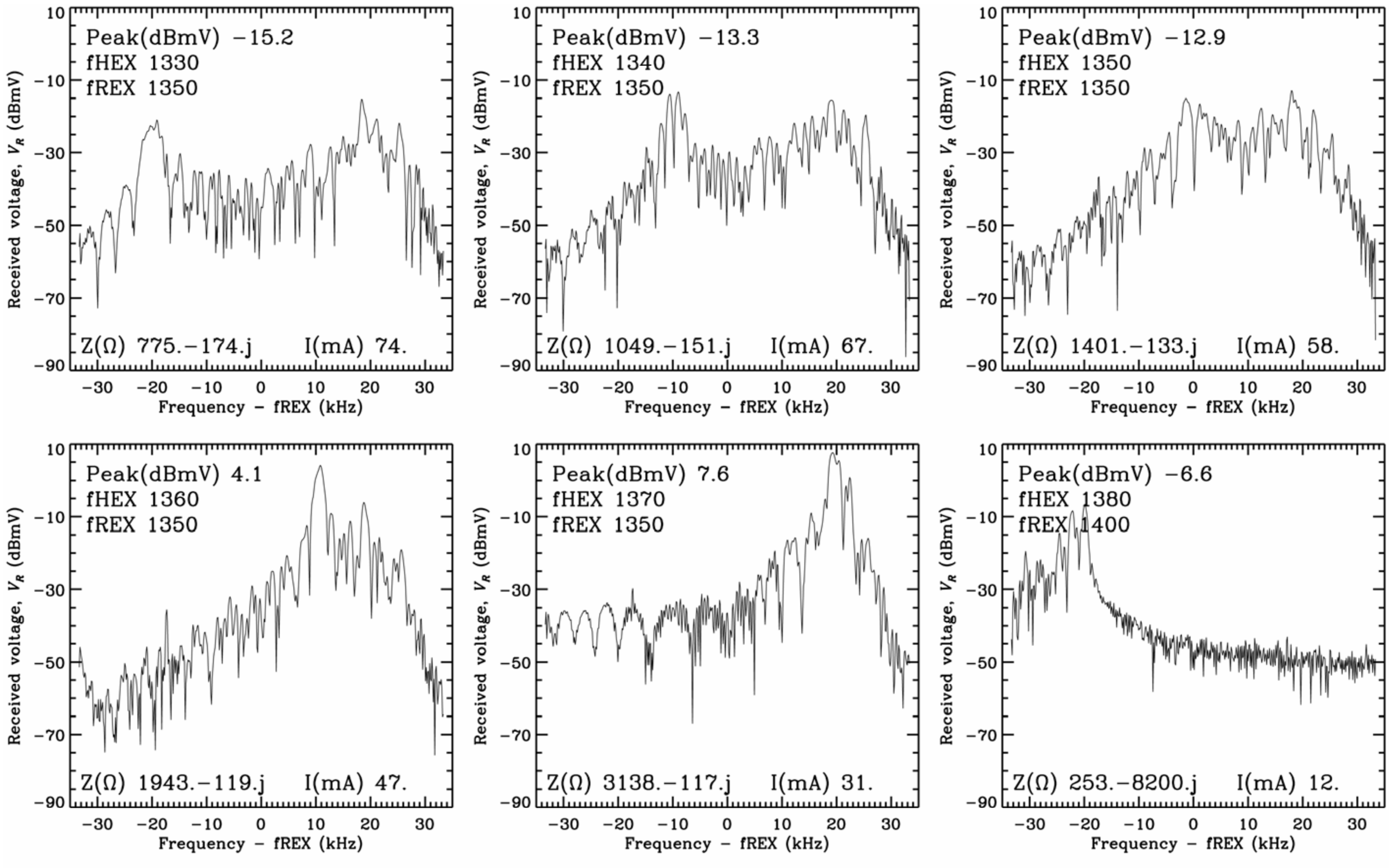




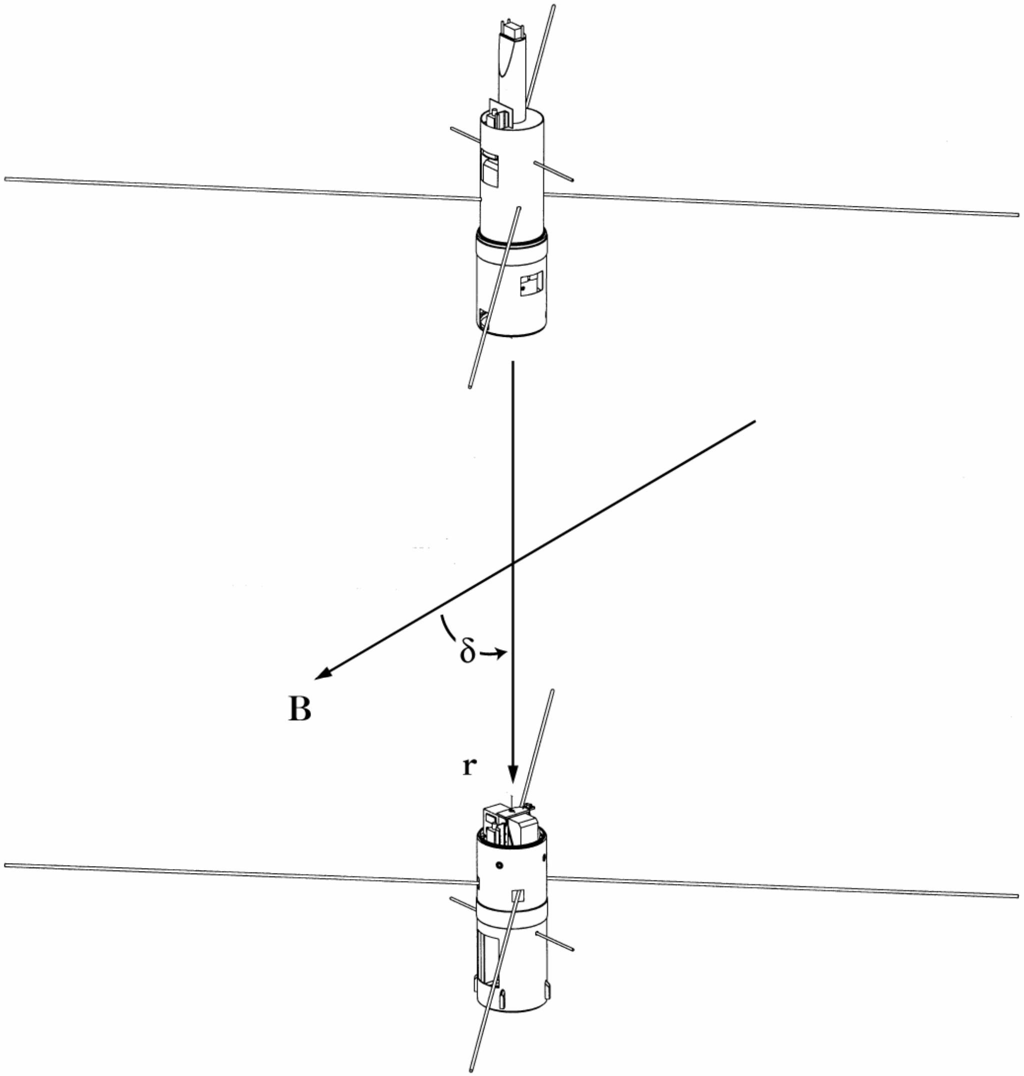
Detailed amplitude scans



Detailed spectra



OEDIPUS-C Double Payload



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Two or more subpayloads at micro scale separation

1. Limiting scale sizes to resolve: r_{ci}, λ_{ES}, . . .
2. Credibility of two separated measurements of one observable?
3. Compare simultaneous measurements of same parameter before separation.
4. Observe how parameters change with separation.

Hot-plasma dispersion surfaces

- $f_c = 1.299$ MHz
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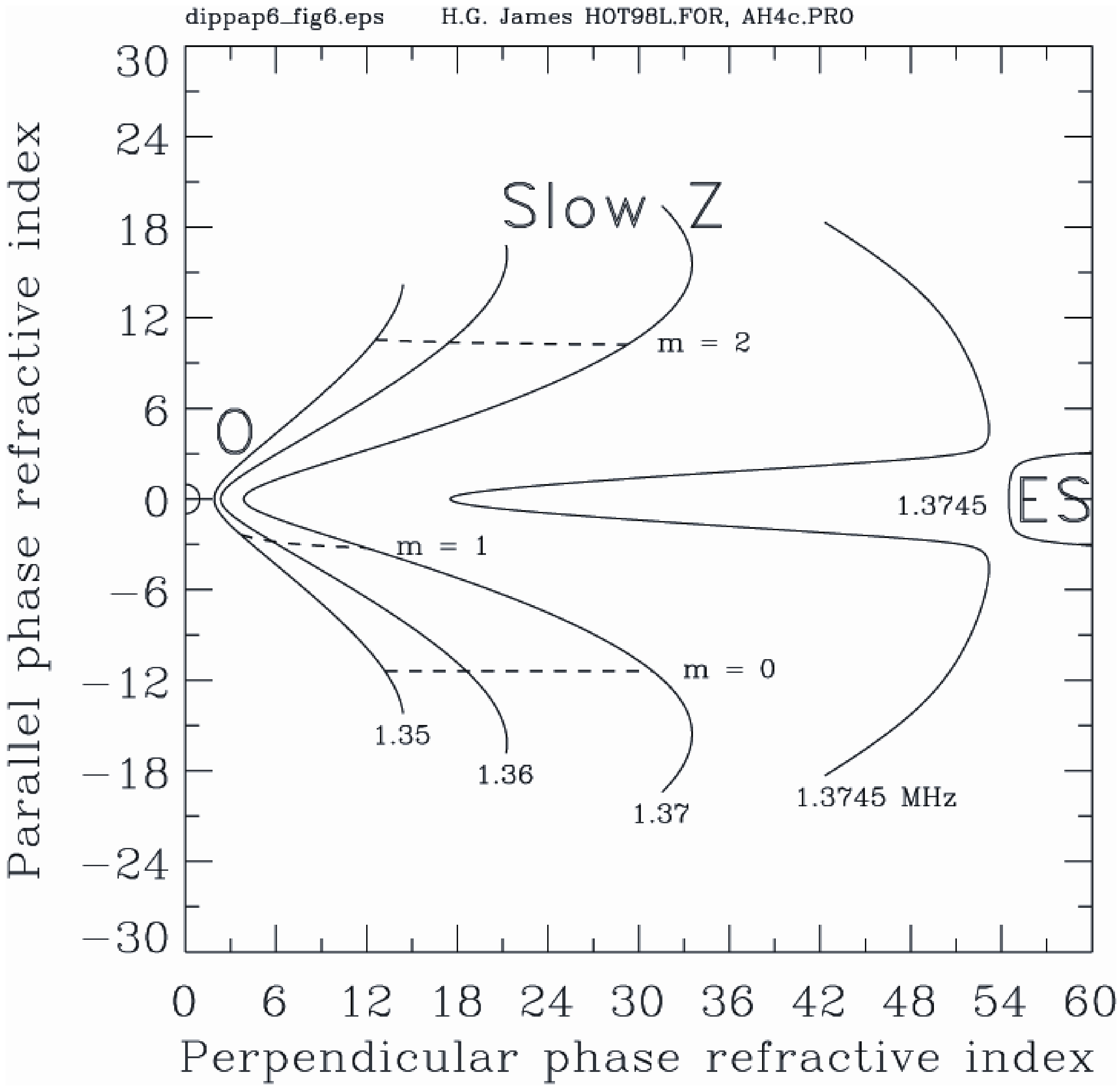
- $T = 5000$ K
- Energy = 3 keV
- $\alpha = 36^o$



Solutions of resonance condition, parametrical in total signal delay

Total signal delay comprised of time required by electron to travel to radiating site plus wave signal delay from site to REX

Cases of strongest observed SAE used for α