Ground-based transmitter signals observed from space: ducted or nonducted?

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Importance of propagation "mode"

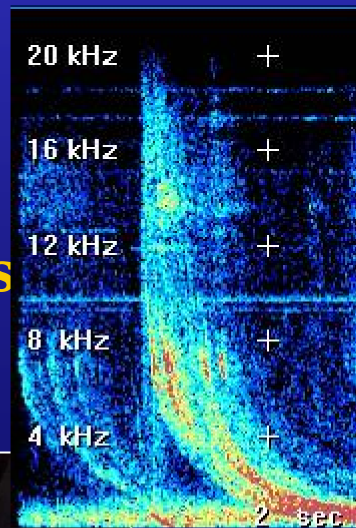
One issue which has raised its head in the last 10-15 years (or so) is the nature of the dominant propagation mode for whistler-mode waves which propagate from the ground into the plasmasphere. This will strongly determine how lightning-generated whistlers and VLF Tx signals interact with energetic radiation belt electrons.

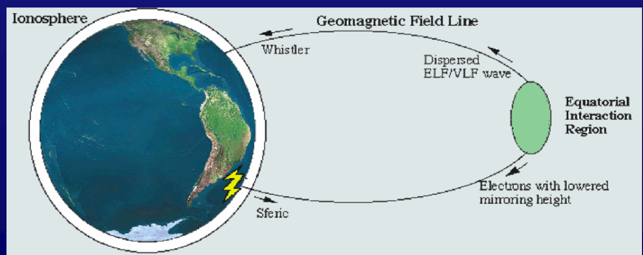
The possibilities are:

ducted propagation dominates

non-ducted propagation dominates

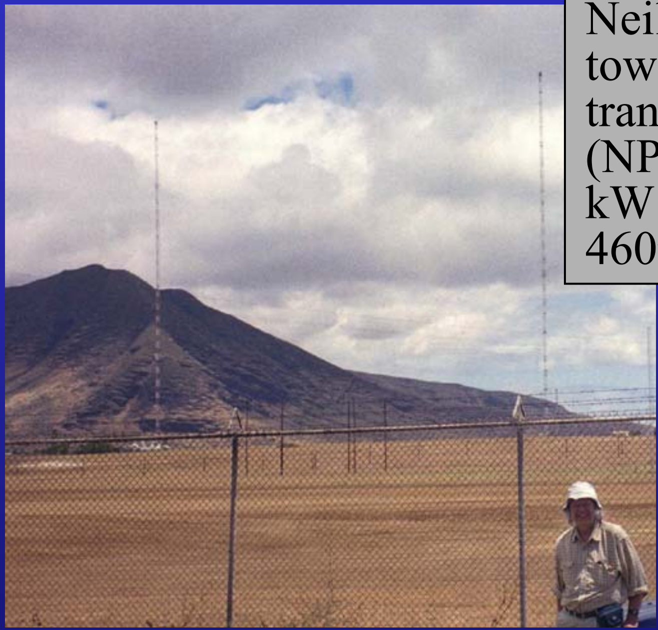
or, some combination of the two



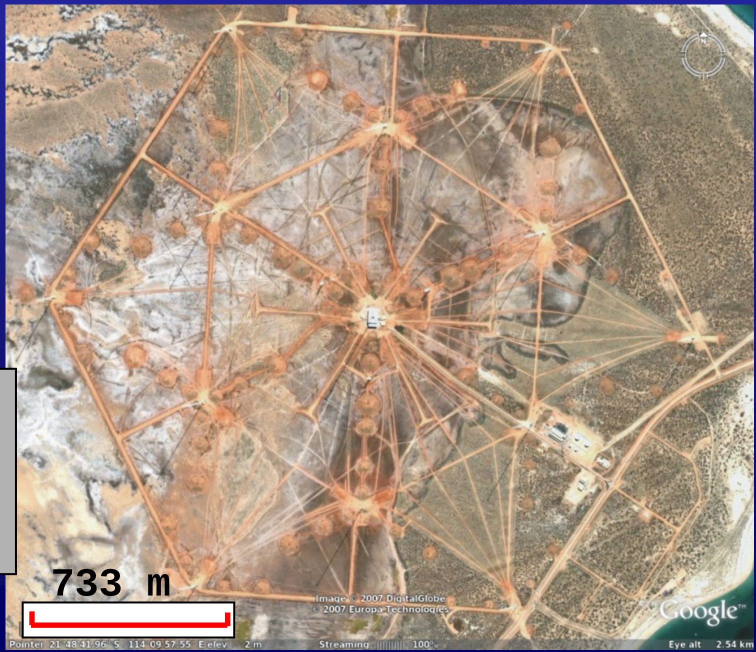


VLF transmitters

One way to test this to use VLF transmitters – these are primarily used for military communications. They have very high output powers and exhibit near continuous operation.



Neil Thomson in front of the towers of the US Navy VLF transmitter at Lualualei, Hawaii (NPM). Radiated power of 500 kW at 21.4 kHz. Each tower is 460m high.

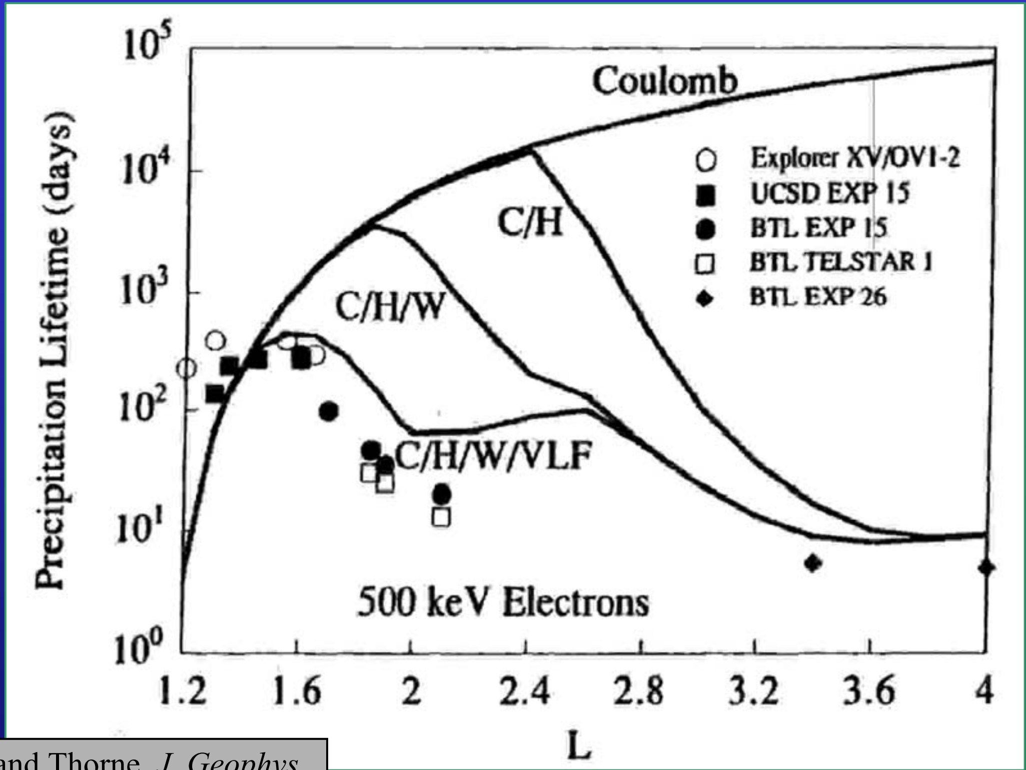


GoogleEarth view of the US Navy VLF transmitter NWC (Australia). Radiated power of ~1 MW at 19.8 kHz. The towers are 300-390m high.

What is the issue?

Calculations based on non-ducted propagation indicate manmade VLF transmitters drive the dominant losses of energetic electrons (>100keV) in the inner radiation belts.

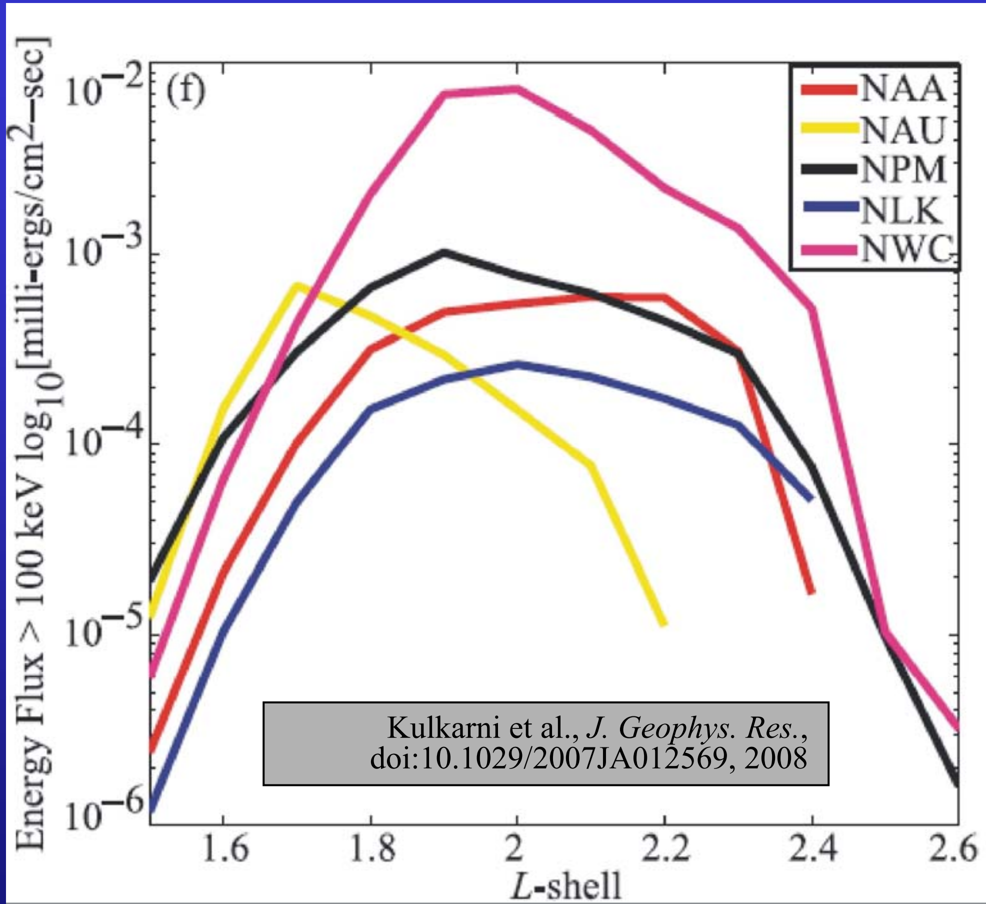
WM SOURCES:
plasmaspheric hiss = **H**
VLF Chorus = **C**
whistlers = **W**
VLF transmitters = **VLF**



Abel and Thorne, *J. Geophys. Res.*, vol. 103, 1998.

Thus determining if non-ducted propagation is the primary propagation path for man-made transmissions (and lightning) will strongly influence our understanding of the radiation belts.

Why does this matter? - II



A nice example of this comes from a recent paper showing the potential impact of manmade VLF Tx through their precipitation fluxes, assuming non-ducted propagation.

Because of non-ducting, >100keV resonances are possible to much higher L-shells, which would not be the case for classical ducted propagation.

NOTE: NWC only 25% greater NPM at *L*=1.7, NWC peak at *L*=2.
c.f. Gamble talk this afternoon.

Why does this matter? - II

While the earlier *Abel and Thorne* [1998] study concluded that non-ducted waves from VLF transmitters along non-ducted lightning generated whistlers were very important loss drivers in the inner radiation belt and slot region, a recent study came to a very different conclusion.

Meredith et al. [2009] compared data and calculations and found that non-ducted lightning generated whistlers had a negligible contribution to the decay rate. They conclude that plasmaspheric hiss PLUS ducted whistlers are the dominant loss drivers.

Meredith et al., *J. Geophys. Res.*, vol. 114, doi:10.1029/2008JA013889, 2009.

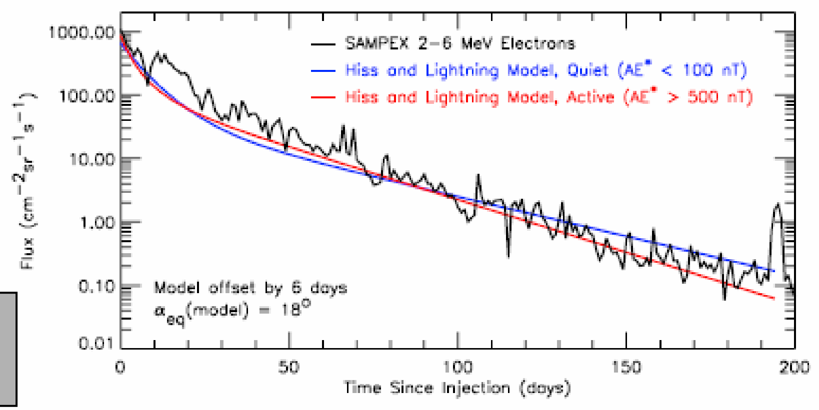
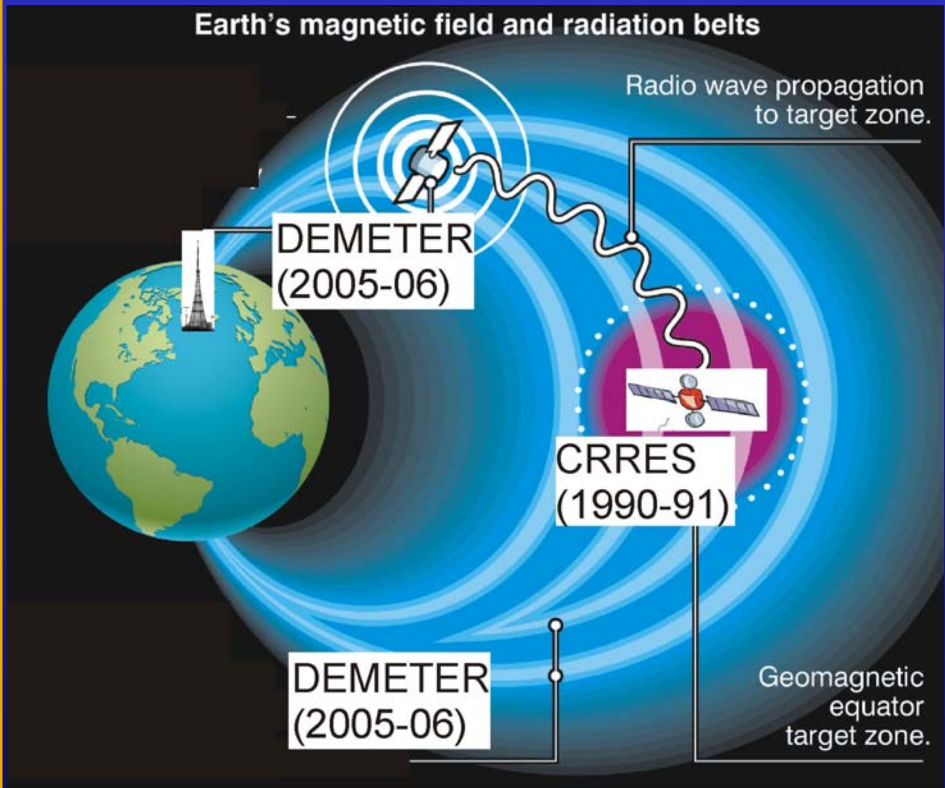


Figure 7. (top) Time evolution of 2–6 MeV electron flux (black) measured by SAMPEX at $\alpha_{eq} = 18°$, starting on DOY 328, and the decay of the model distribution function due to the combined spectrum of plasmaspheric hiss and guided whistlers for (blue) quiet and (red) active conditions. (bottom) Time evolution of the models shifted in time by 6 days into the simulation.

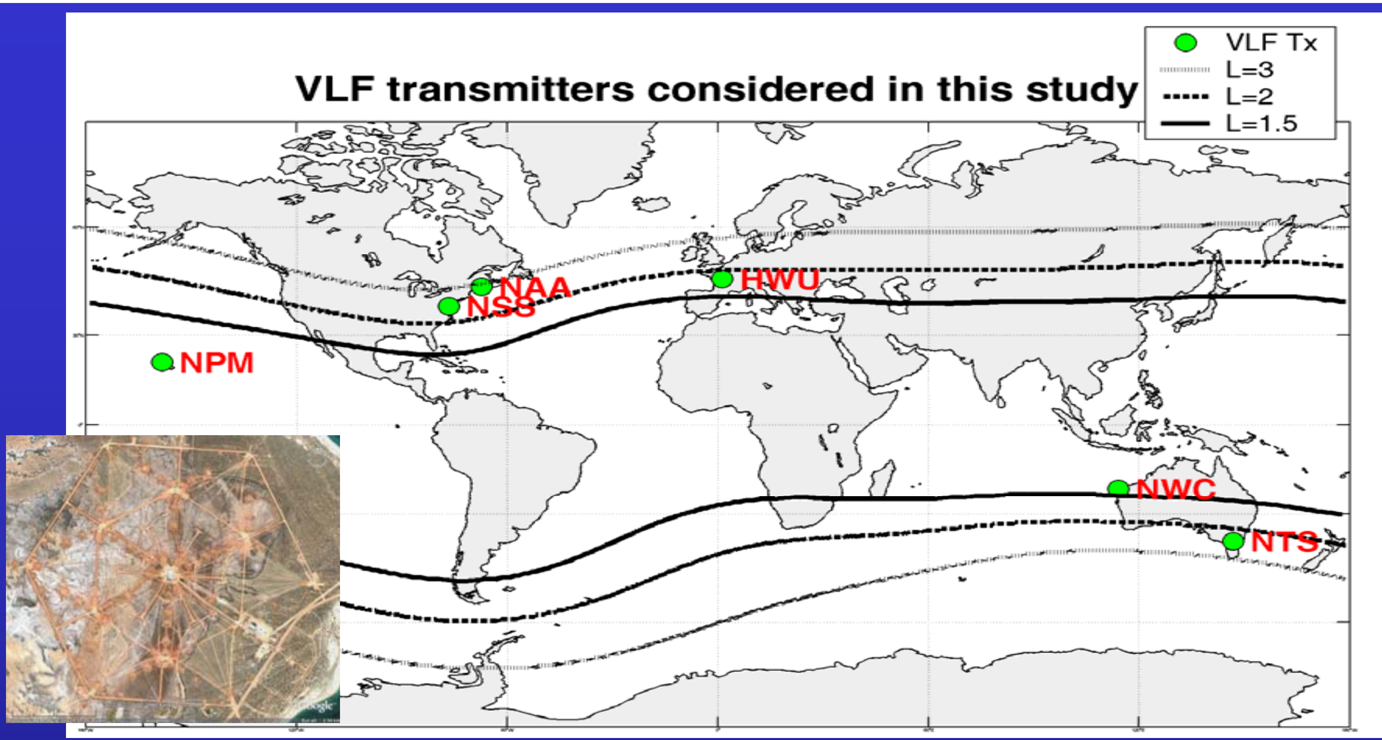
So there is some uncertainty as to the relative dominance of non-ducted VLF waves as a driver of radiation belt losses.

How to test which is dominant?

It is challenging to use lightning and ground-based measurements of precipitation to determine whether ducted or non-ducted is dominant, due to the unknowns (where is the duct?). Thus we will move into space, and use large fixed location VLF transmitters.



We investigate the regions where strong transmitter signals are observed in the ionosphere directly above the transmitter, in the magnetosphere near where the signals cross the geomagnetic equator, and in the ionospheric region geomagnetically conjugate to the transmitter.



Call sign	freq (kHz)	L	Half gyro L
NPM	21.4 (23.4 in 1990)	1.17	2.73
NWC	19.8	1.44	2.8
HWU	18.3	1.83	2.88
NTS	18.6	2.33	2.86
NSS	21.4	2.43	2.73
NAA	24.0	2.93	2.63

These VLF Tx span the range of inner RB L-shells, and also represent a range of output powers, from ~100kW to 1 MW.

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DEMETER

- Sun-synchronous polar orbit, altitude of 710 km
- Data available for inv. lat. <65°
- Observations at 10.5 and 22.5 LT
- Launched late June 2004,
  still operational

Wave Data

Take VLF wave data from the *Instrument Champ Electrique* (ICE), which provides continuous measurements of the power spectrum of one electric field component. Spectra up to 20kHz, with a frequency channel resolution of 19.25 Hz. Look only at nighttime (22.5 LT) observations.

Taken data from Jan 2005 and August/September 2005.

CRRES

Combined Release and Radiation Effects Satellite
(CRRES)

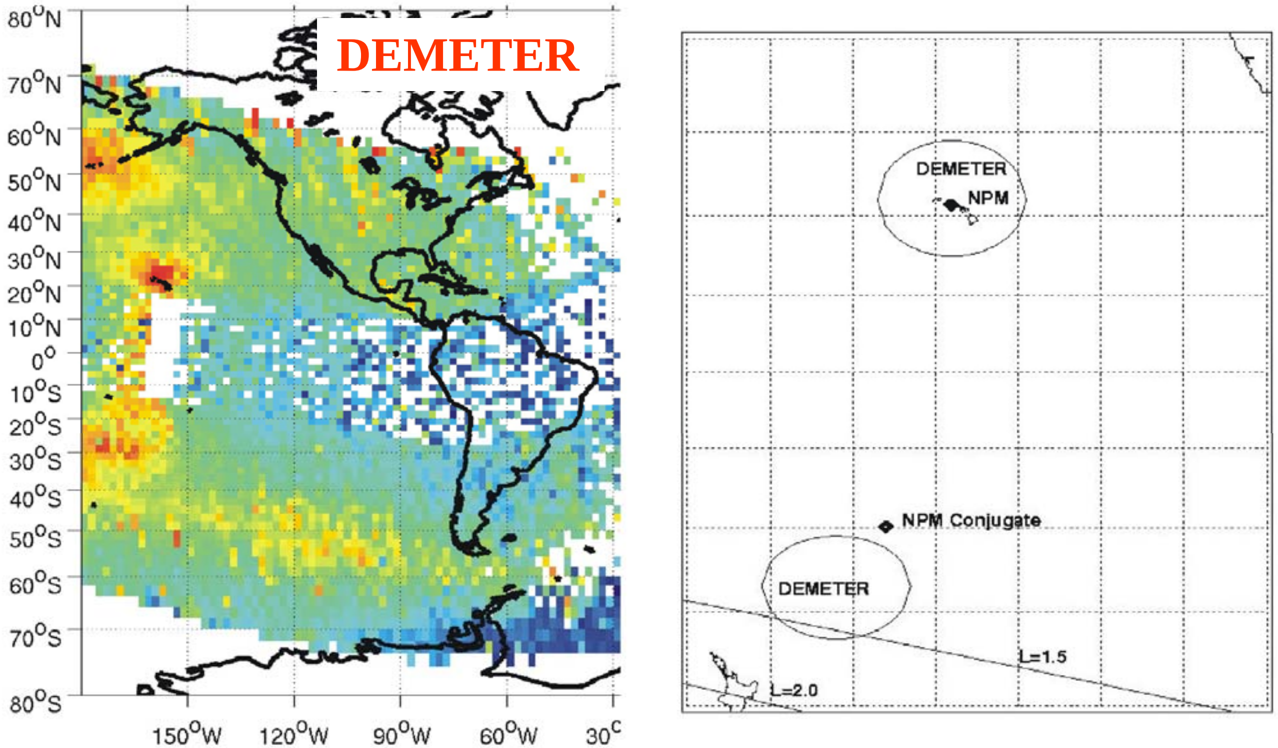
- Low inclination
- GTO orbit (perigee 305 km, apogee 35,768 km)
- Period of 10 hours
- $1.05 < L < 8$
- $-30^{o} < \lambda_m < +30^{o}$ (i.e. around the geomagnetic equator)
- Launched 25 July 1990,
  failed 12 October 1991

Wave Data

Take VLF wave data from the CRRES sweep frequency receiver Band 3 (6.4 to 51.7 kHz examined by 32 steps inside each band). Typical bandwidth of 900 Hz (c.f., VLF transmissions ~200 Hz).

Look only at nighttime observations.

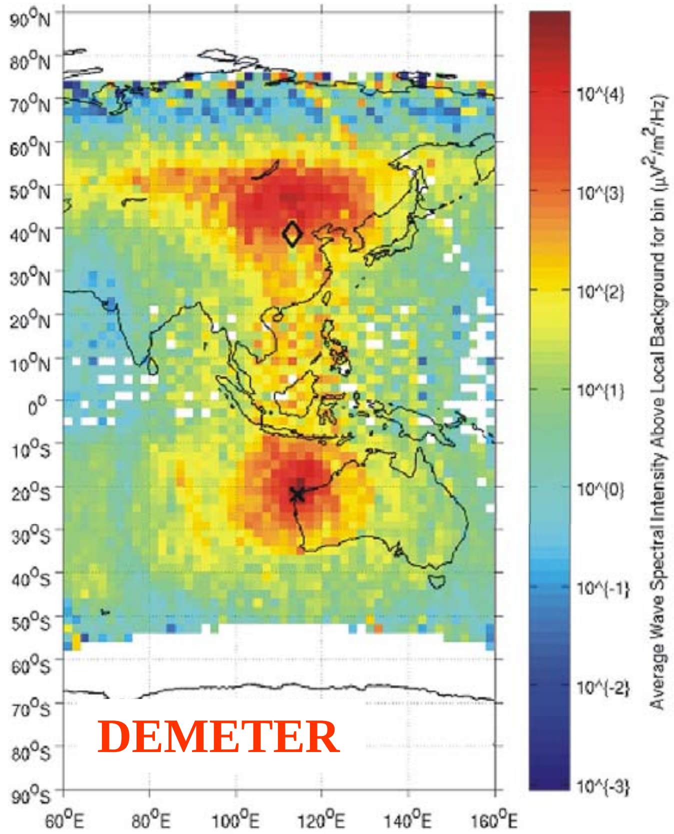
NPM L=1.17

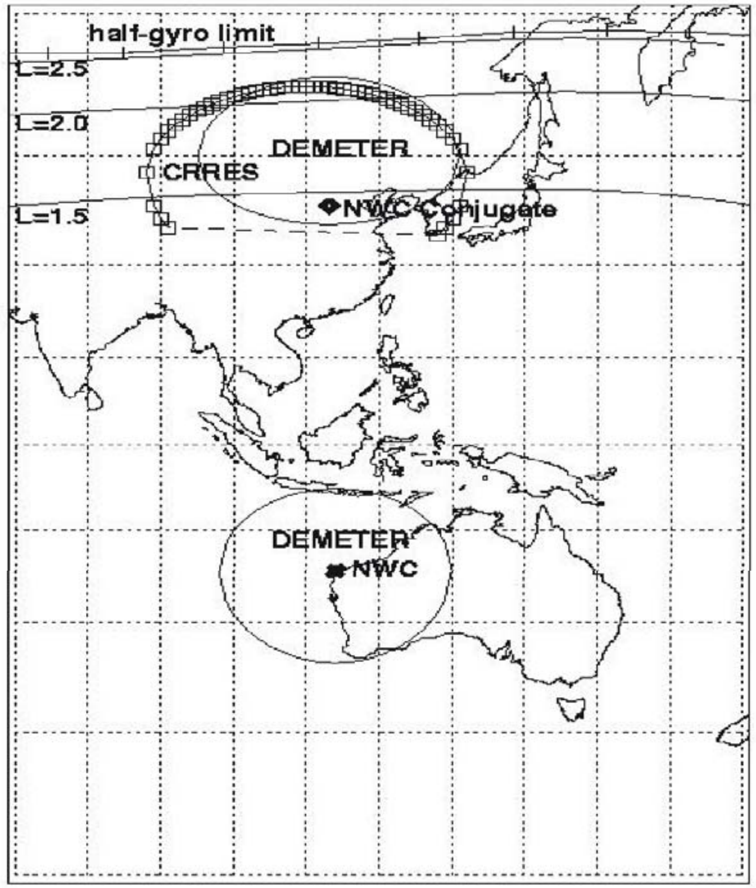


No CRRES observations for NPM, as it lies outside the receiver frequency range. Very strong poleward shift (7º from conjugate), as expected for predominantly non-ducted propagation due to the low L of the transmitter location. Neil Thomson has studied ducted waves from NPM for ~20 years. They occur for only a few hours every 3 days, and range over $1.6<L<2.5$.

Non-ducted propagation clearly dominates here.

NWC *L*=1.44

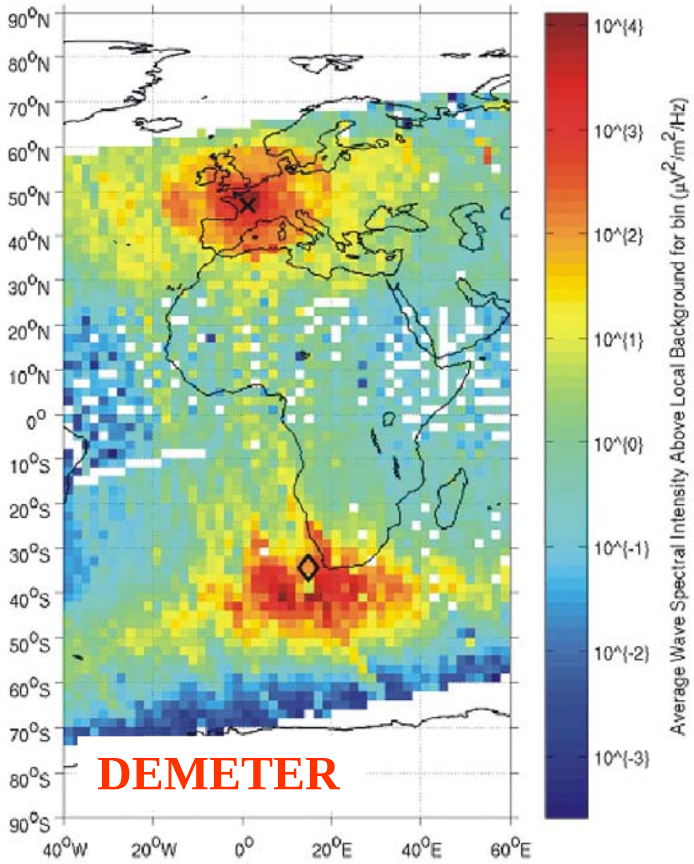


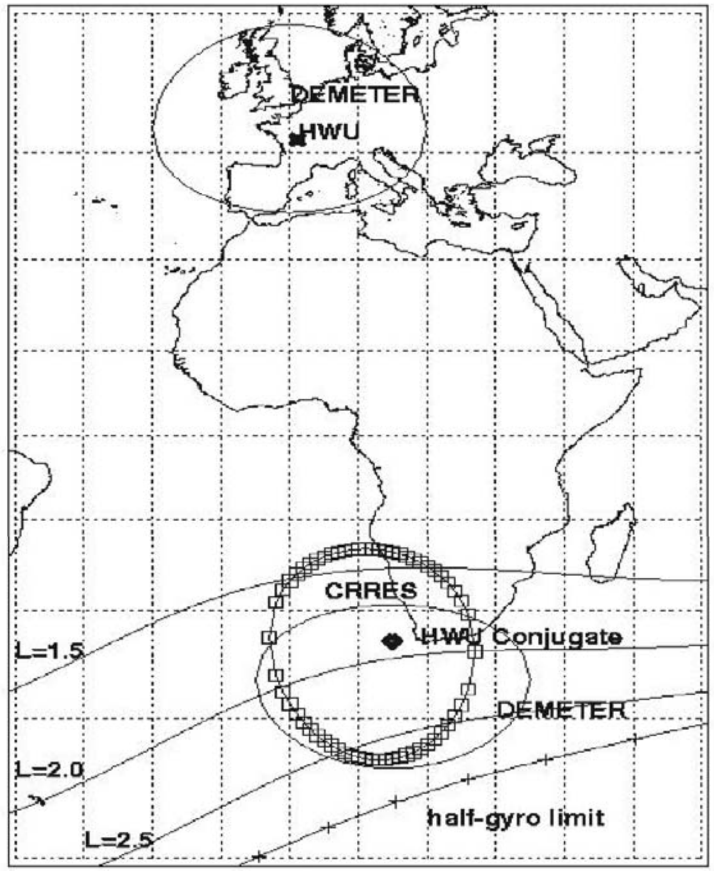


Same pattern in CRRES & DEMETER observations. Peak power shifted 10° polewards. Wave power propagating primarily within the *L*-range expected for ducted waves (*L*=1.6-2.6).

NOTE: Consistent with observed interaction between ducted NWC transmissions & 100-300keV electrons [Sauvaud et al., 2008, this afternoon].

HWU L=1.83

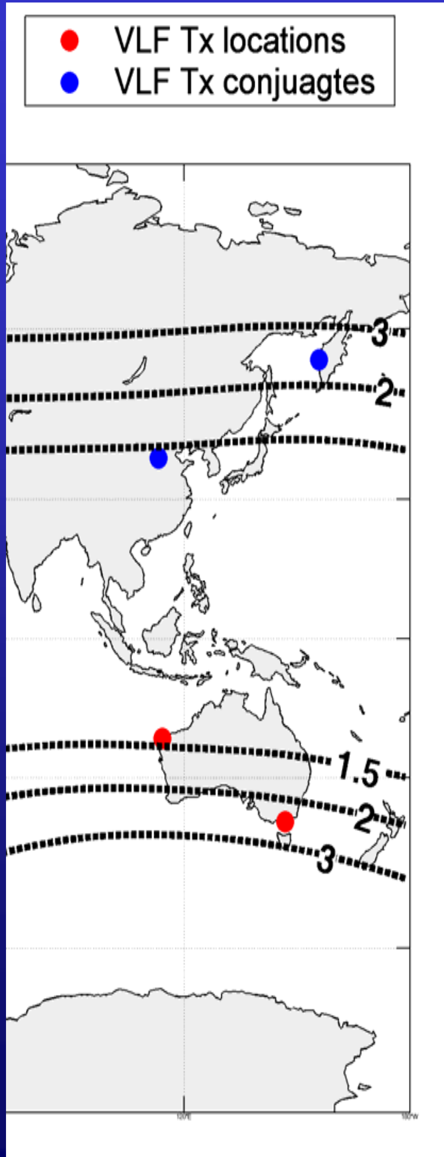


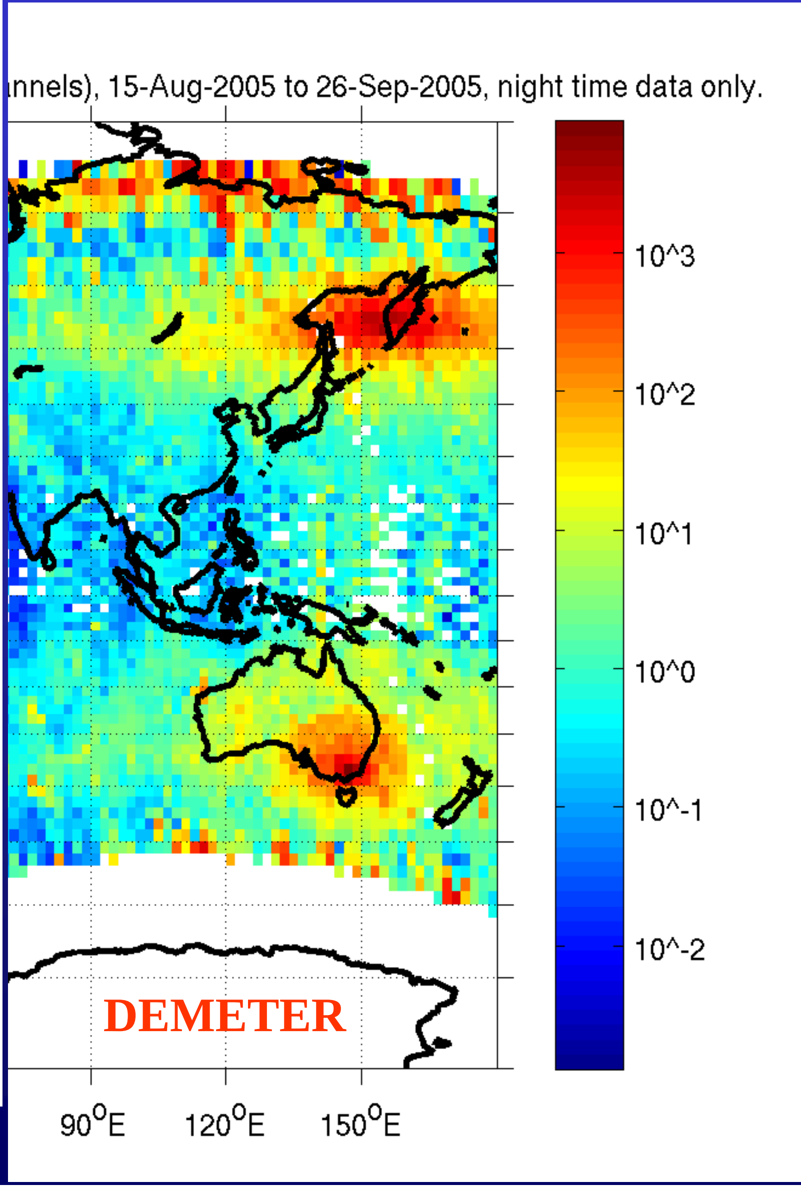


Same pattern in CRRES & DEMETER observations. Power in conjugate region starts around L where ducting expected to start. Wave power limited to the conjugate region, no signs of significant poleward propagation.

NTS - *L*=2.33

Peak power in the conjugate hemisphere is at the Tx conjugate. No poleward shift atall! Ducted?





No CRRES data as this Tx started quite recently!

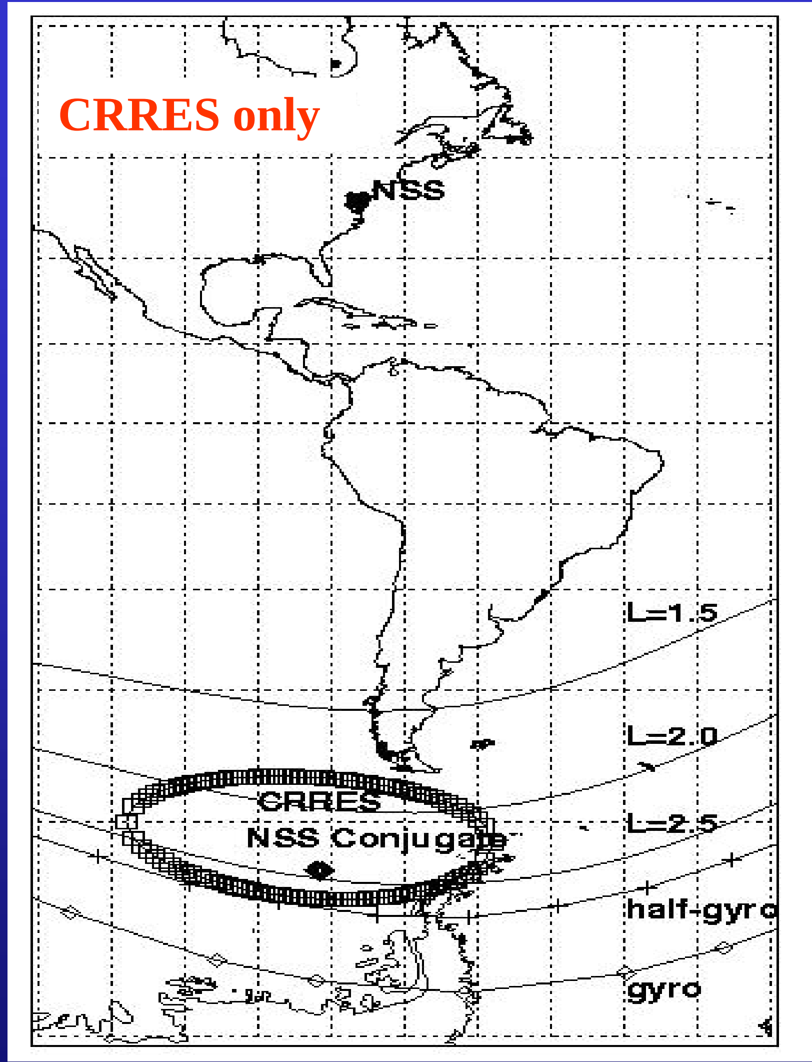
But was then shut down in late 2008.

NSS - L=2.43

NSS was shut down on 18 January 1996, and was permanently decommissioned shortly afterwards. Thus no DEMETER observations are possible!

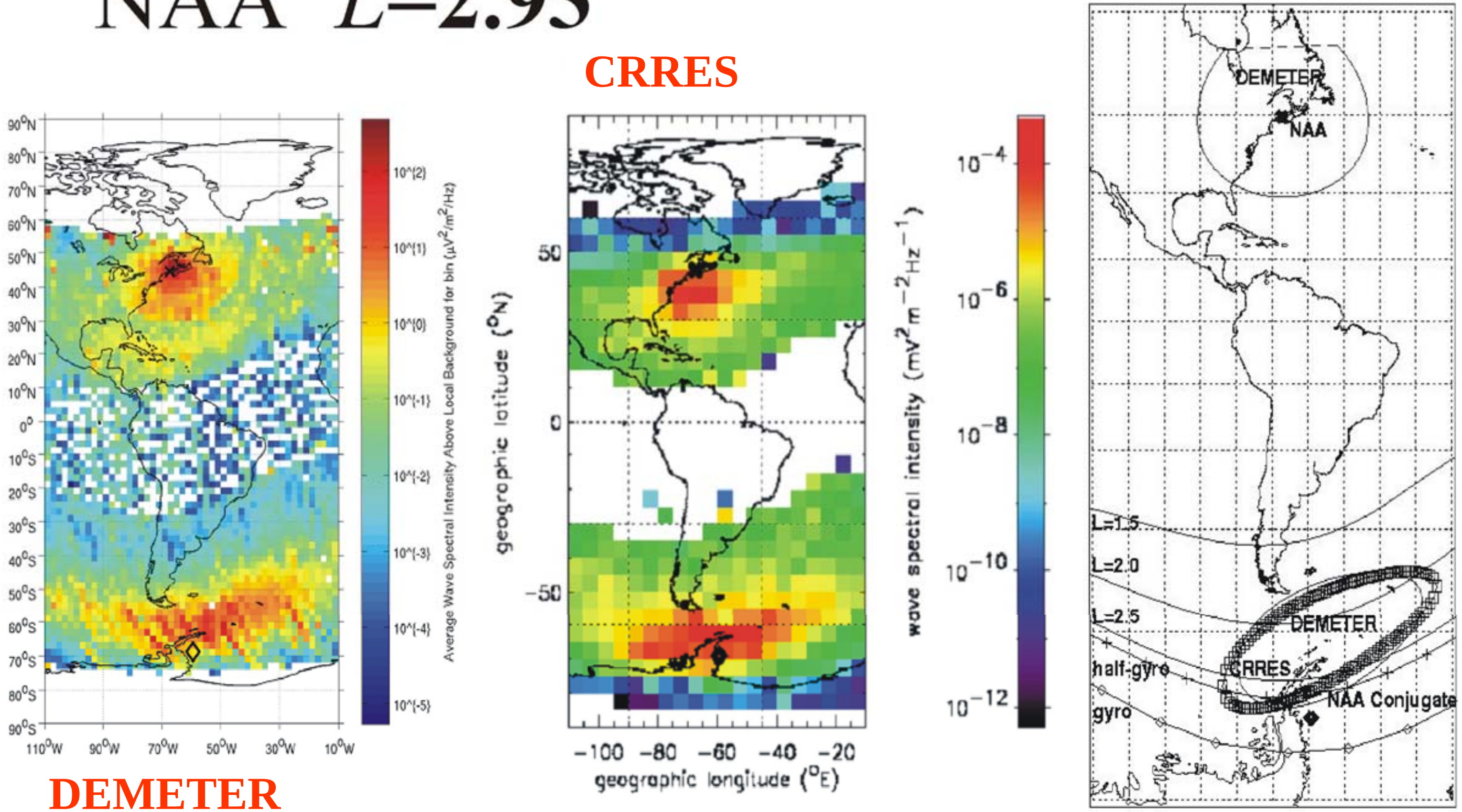
Looking only at the CRRES data, we find that the peak power region is shifted 4º equatorwards of the conjugate region. No power seen above the half-gyro frequency.

Strongly suggests ducting is the dominant mechanism.



NAA L=2.93

CRRES



DEMETER

NAA is located above the half gyrofrequency cutoff for its frequency. In this case, the DEMETER and CRRES patterns are different in the northern hemisphere, consistent with the cutoff. In the southern hemisphere, very little power beyond the half gyrofrequency cutoff line. Fully consistent with ducted propagation. Very strongly suggests ducting is dominant.

Acknowledgements

I want to acknowledge the DEMETER Guest Investigator programme, through which we have had access to DEMETER data. My students and I are <u>very</u> grateful to our French colleagues for this access, and for their assistance in working with the data.

Thankyou to CNES and all the scientists involved in making DEMETER such a wonderful, insightful mission!

Conclusions

By combining observations made just above the ionosphere by DEMETER and those at the geomagnetic equator by CRRES, we have provided the first experimental examination of the relative importance of ducted and non-ducted precipitation.

- At low L (i.e., $L<1.6$) a significant proportion of wave-power is non-ducted, as expected.
- Beyond $L>1.6$ waves become increasingly ducted.
  By $L\approx2$-3, there is very little evidence of non-ducted waves.
- This will have implications for studies which assume the dominance of non-ducted propagation.
- NWC is particularly well placed to produce scattering of inner RB energetic electrons, as it has both requirements of high power and low L. This has, of course, been discussed by others at this workshop!

Thankyou!

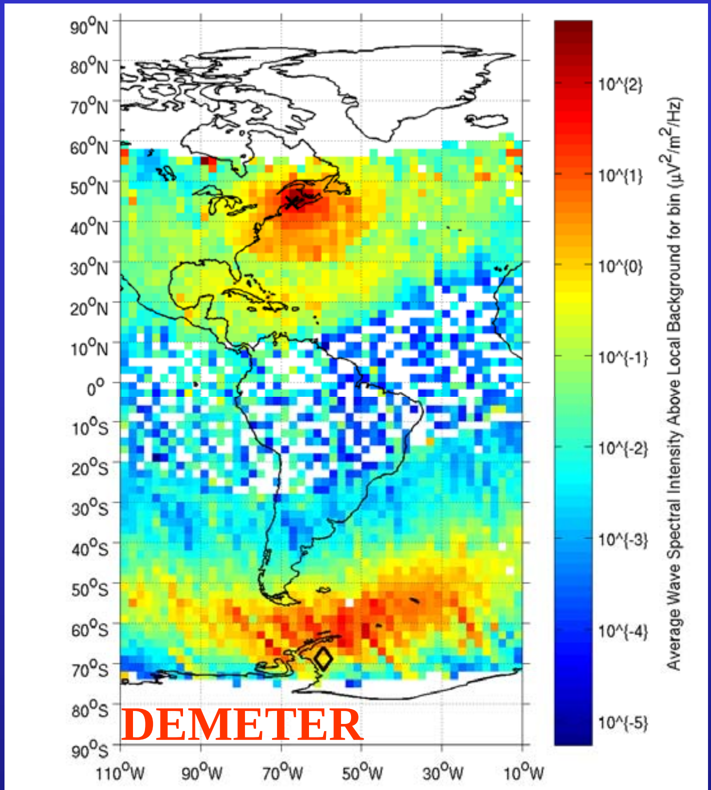
Craig J. Rodger in the cistern of the Hagia Sophia Basilica during the URSI conference [21 August 2011].

Are there any questions?

How small is the non-ducted component for NAA?

We have used techniques to suppress lightning noise, which is very strong in the North American sector.

The difference between the point above the Tx (×) and its conjugate location (◊) is 170 times. The conjugate peak wave power is ~20 times larger than seen at the conjugate point (which is above the half-gyro cutoff).



The fact that the half gyrofrequency cutoff plays such a strong role is indicative of ducted propagation. At best, one might argue that the non-ducted fraction was ~5% of the ducted, although the pattern is suggestive of much less non-ducted propagation.

Implications for VLF Tx gyroresonance

For the transmitters whose propagation paths are dominated by ducted propagation, we can determine the likely electron precipitation energies (in keV) expected from each transmitter assuming parallel (0º wave normal angle) cyclotron resonance interactions at the field line geomagnetic equator.

Call sign	L-shell Tx	*L shell peak conjugate power*	Resonance energy (keV)
NPM	1.17	1.2-1.5	nonducted
NWC	1.44	1.4-2.2	757 - 29
HWU	1.83	1.5-2.7	520 - 5
NSS	2.43	1.7-2.7	189 - 3
NAA	2.93	1.8-2.6	105 - 3