Life Cycle of Gravity Waves on Venus studied from Occultation Signals using Time-Frequency Transforms

USSR, Double Mission: VENERA-15, VENERA-16 (1983-84)

"Canonical" signal representation (at processing level 2):

(a) differential Doppler frequency time derivative (dF/dt) and (b) normalized signal power

VENERA-15,16:
S-band – 32cm
X-band - 8cm
Orbit period ~24hrs
3 occultation seasons
(1983-1984)

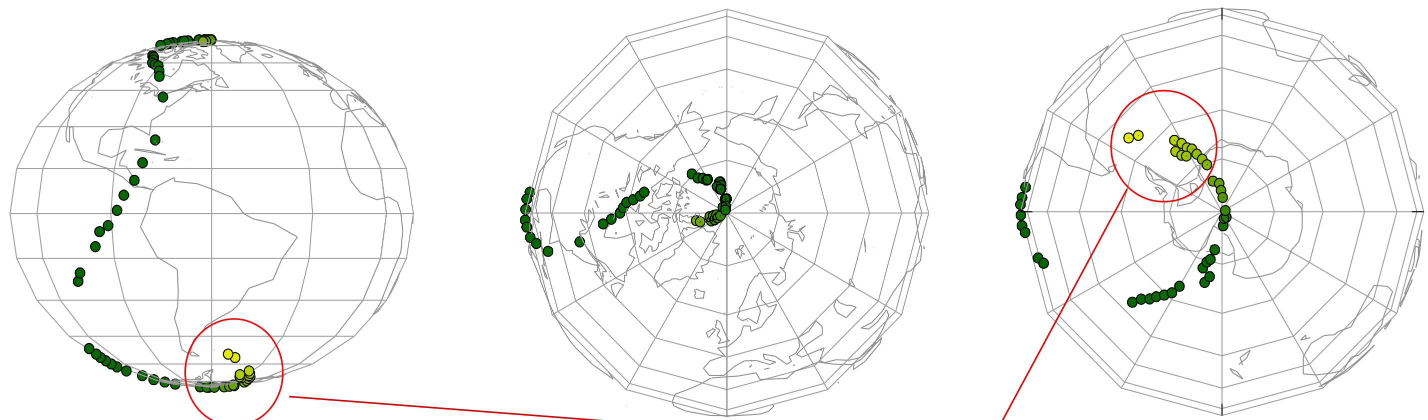
Two signal channels normalized for comparison according to "adiabatic invariant" relation.

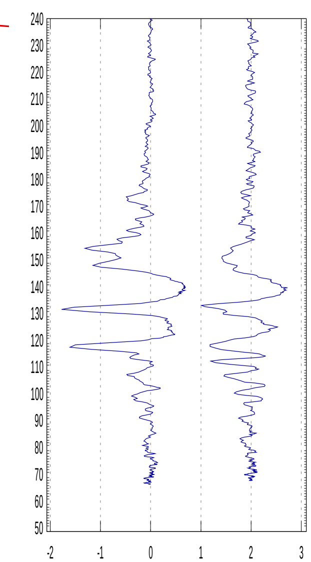
VEX VeRa occultations
S-band – 13 cm
X-band – 3.8 cm
Many occultation seasons
(2006 - present)

(a) Power signal useless in ionosphere

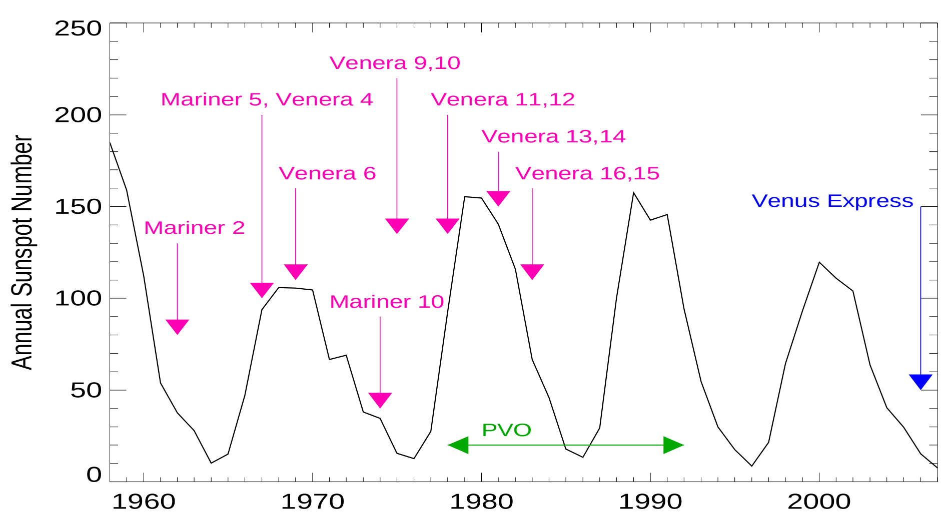
(b) S-band signal lost power after season 1

(c) "Canonical" signal form: X, S, Diff Doppler freq. as a function of time.





Season 1: best geometricaly (closest dist. Btw Earth, Venus)
Time: he dataset obtained in October 1983
Location: the studied subset covers 58-85 deg south daytime data



Signals from Season 01 (October 1983)

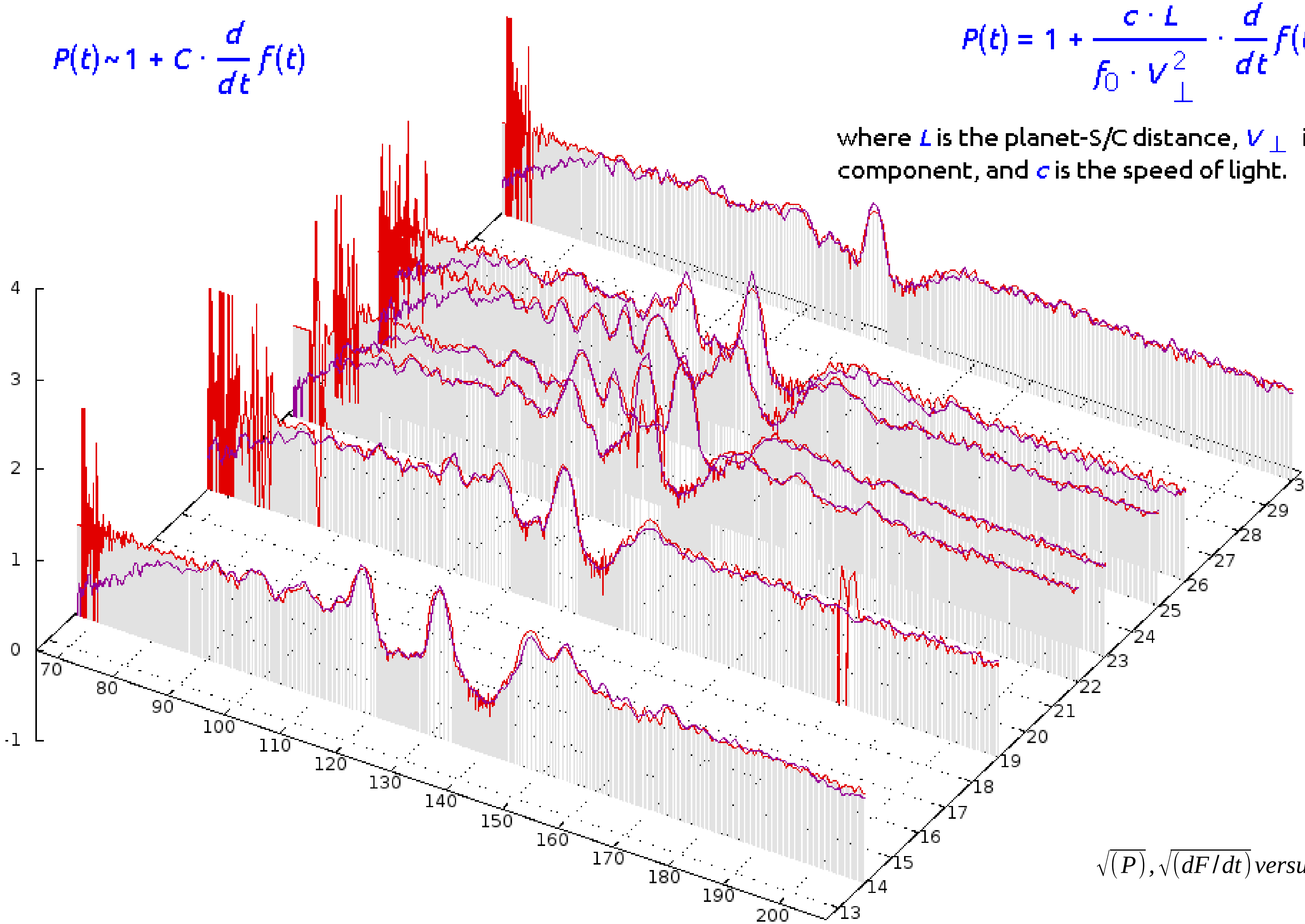
Signals plotted against “true” altitude

Data from two channels when normalized accordingly match:

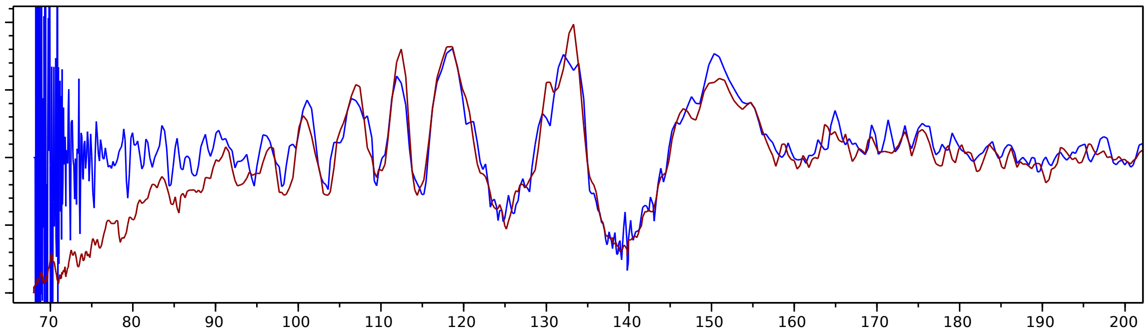
$$P(t) \sim 1 + C \cdot \frac{d}{dt} f(t)$$

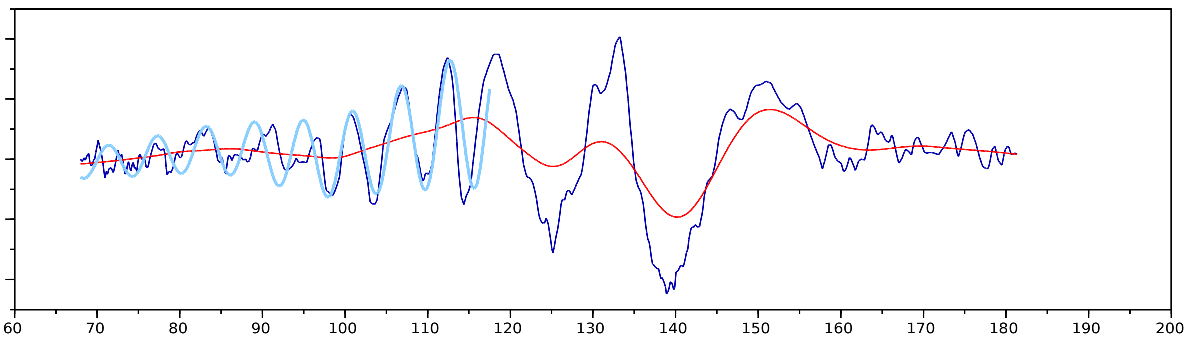
$$P(t) = 1 + \frac{c \cdot L}{f_0 \cdot V_\perp^2} \cdot \frac{d}{dt} f(t)$$

where L is the planet-S/C distance, $V_\perp$ is a S/C speed component, and c is the speed of light.



25 Oct 1983 – strong oscillations below Chapman layers



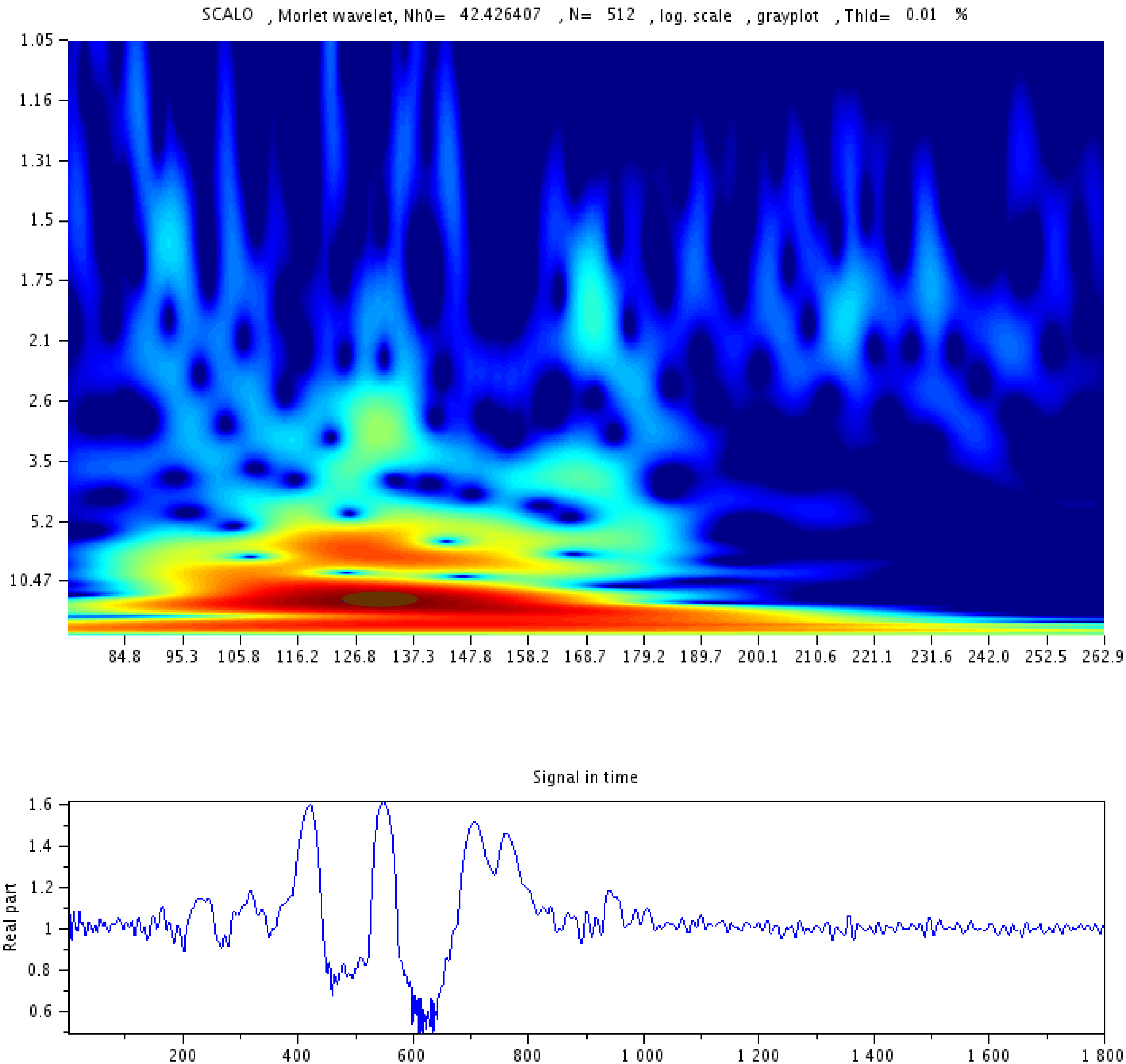


$$s(h) \approx 0.005 \cdot e^{-\frac{z}{30}} \cdot \sin\left(2 \cdot \frac{\pi}{5.9} + 1.0\right)$$

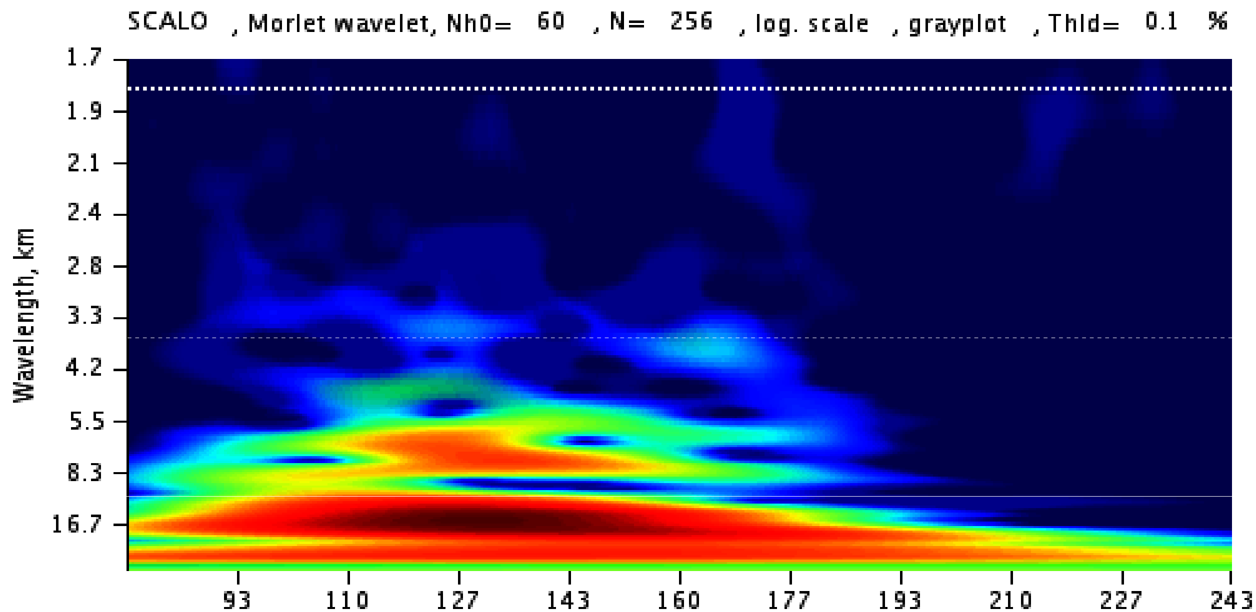
Some sort of exponential fit is possible. However:

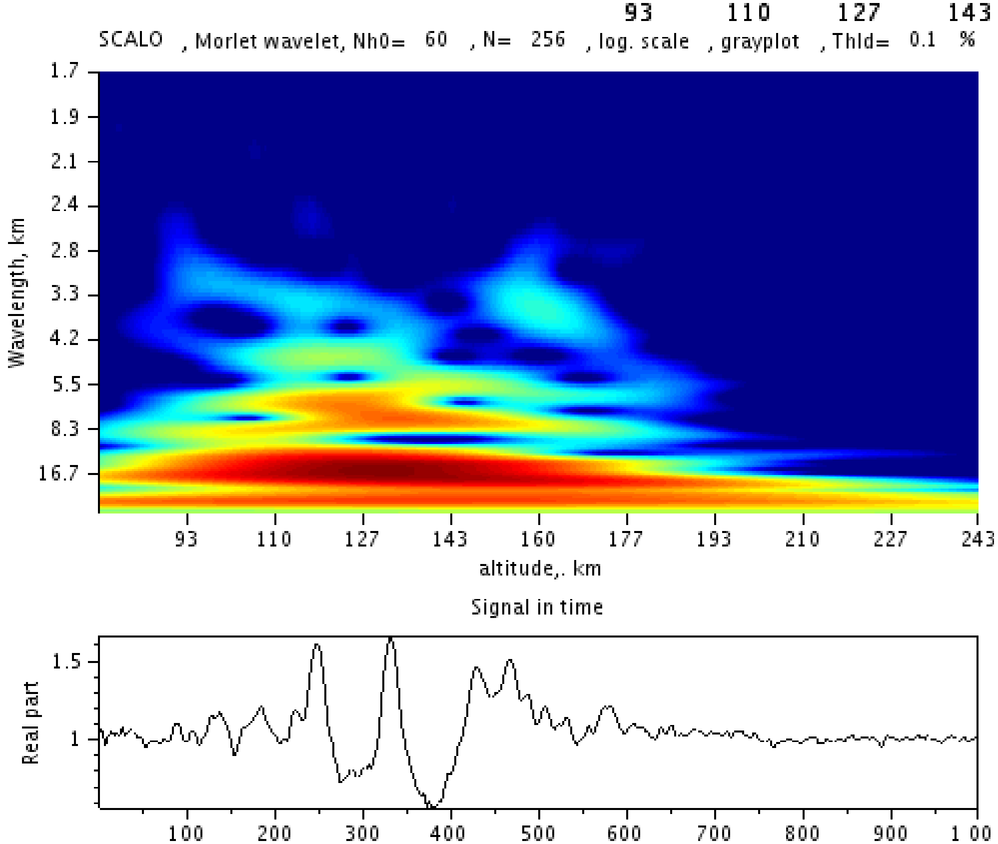
(a) we are not looking at the actual GW.
(b) the visible amplitude growth disappears approx. at the level of the lower Chapman layer – did it break there?
(c) GWs   before breaking would be likely to display saturation features.

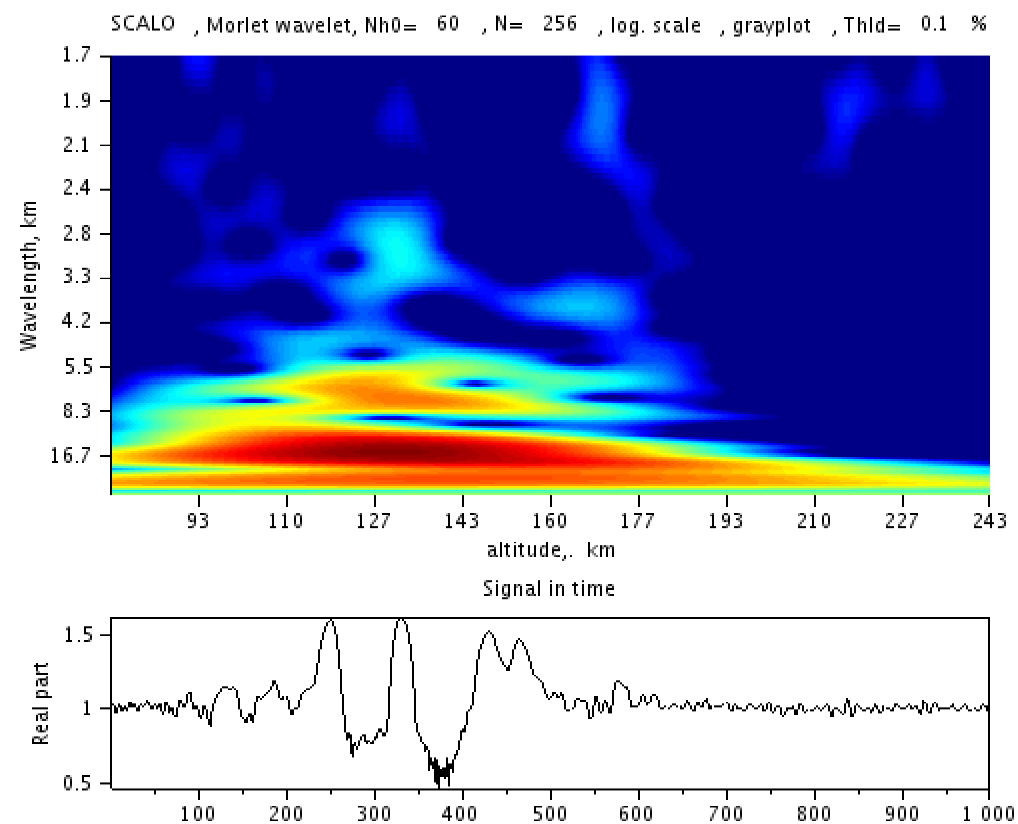
Scalogram of the dF/dt channel (14.10.1983)



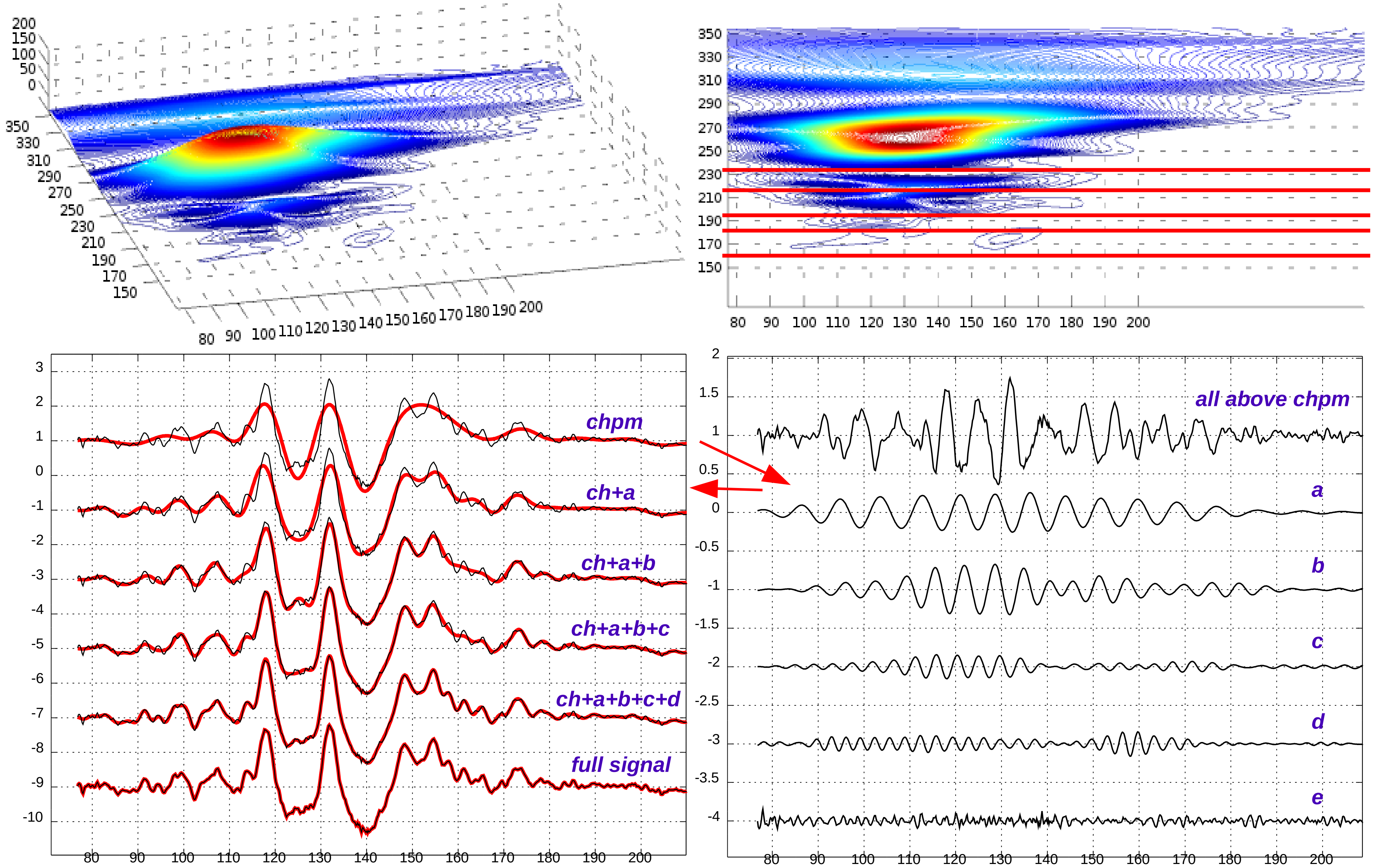
14.10.83 – finding common elements btw channels



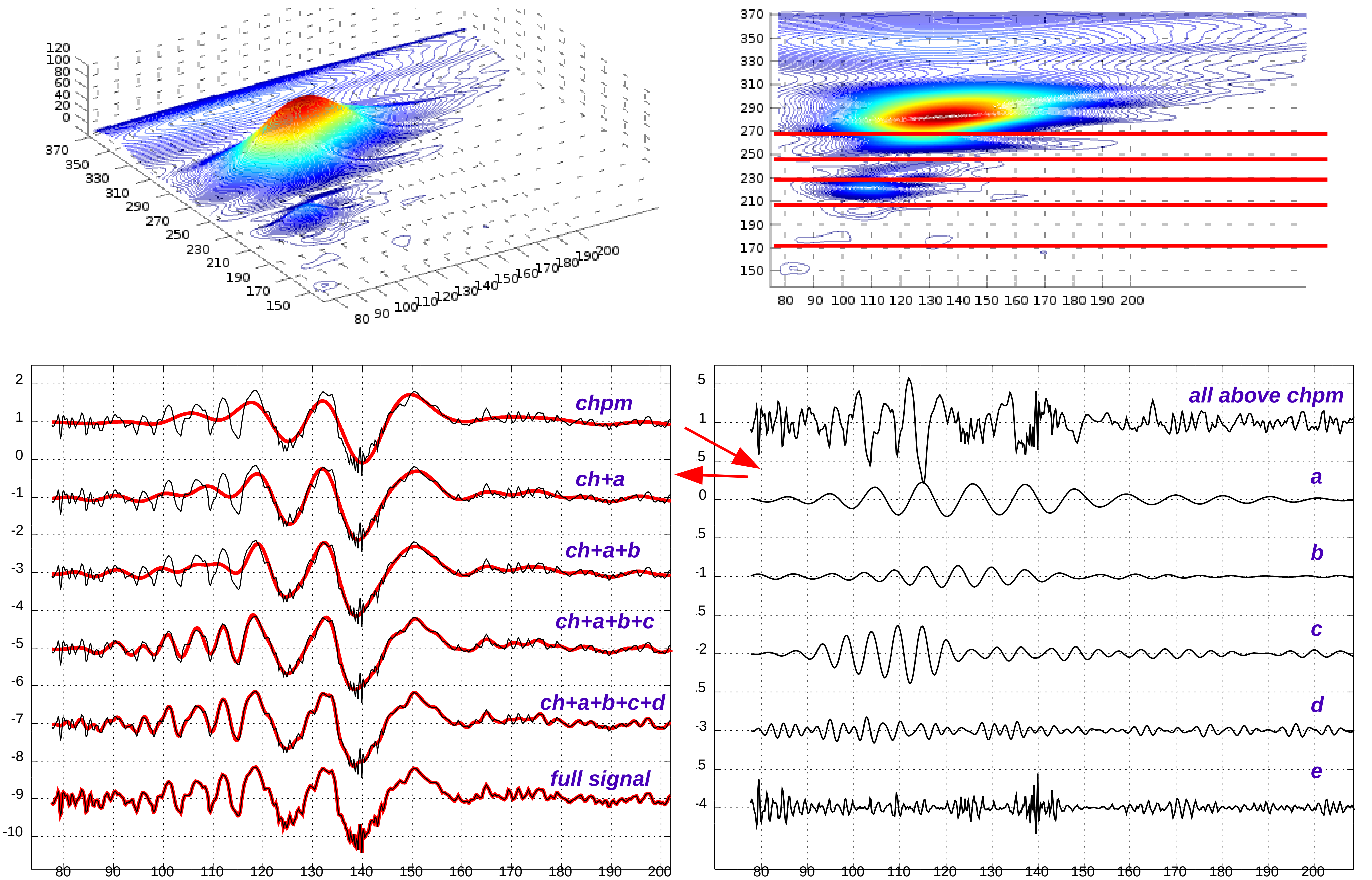




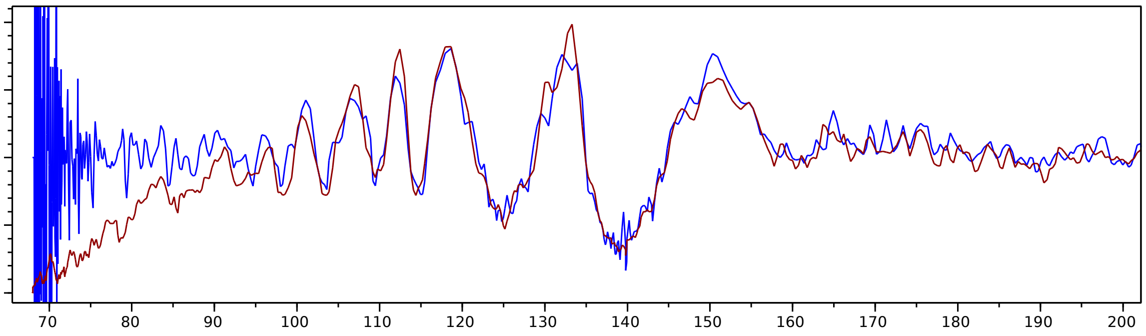
Creating signal from components provided by the Scalogram (14 oct 83 egress)

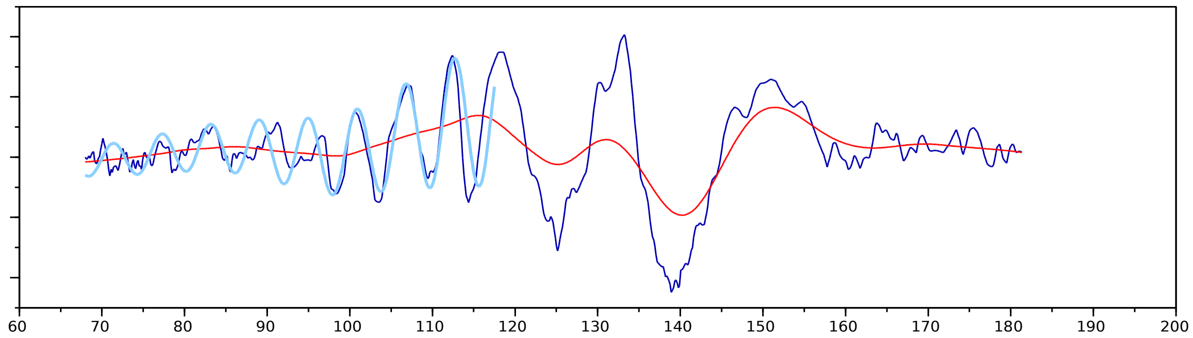


Creating signal from components provided by the Scalogram (25 oct 83 egress)



25 Oct 1983 – strong oscillations below Chapman layers





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(a) we are not looking at the actual GW.
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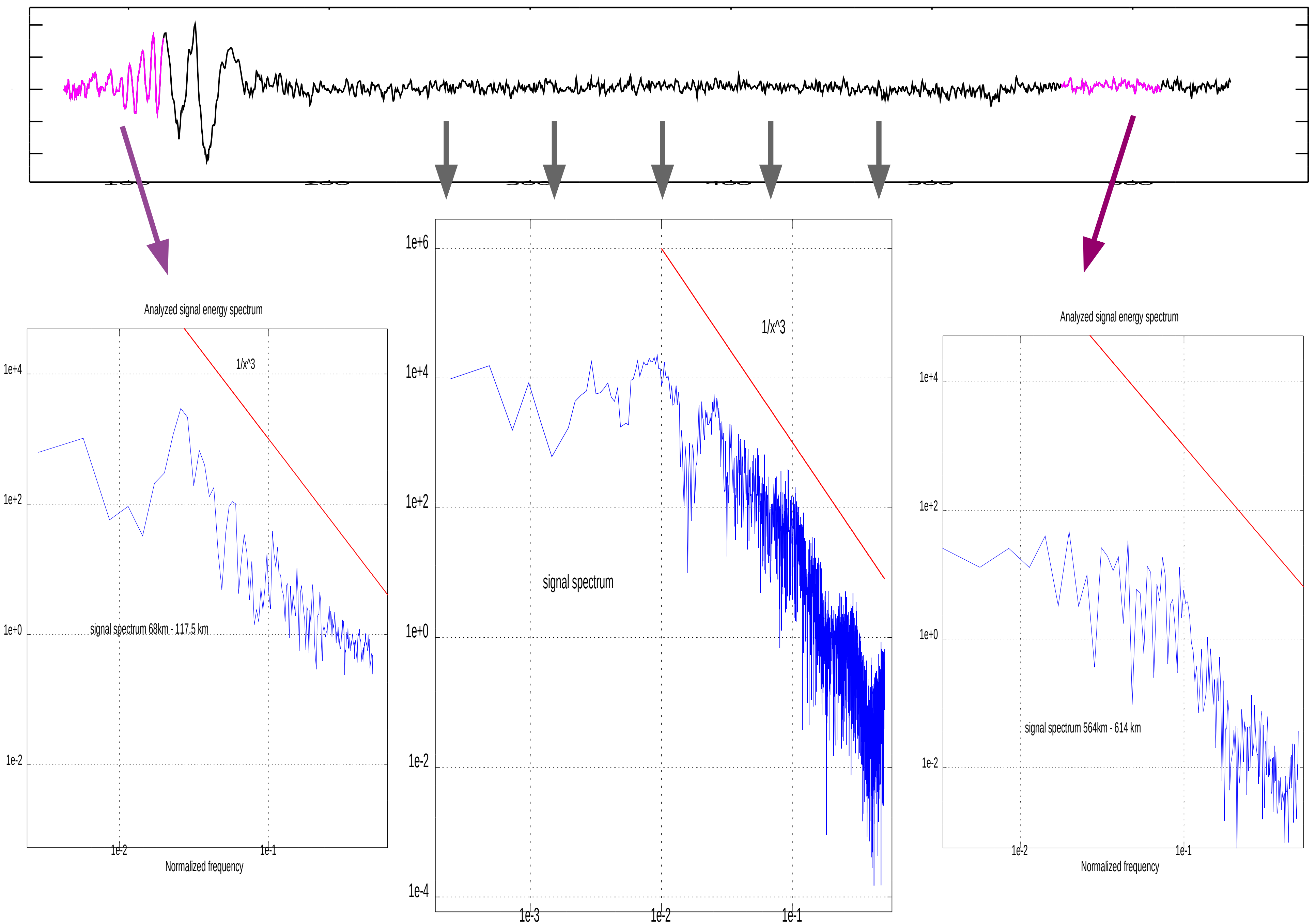
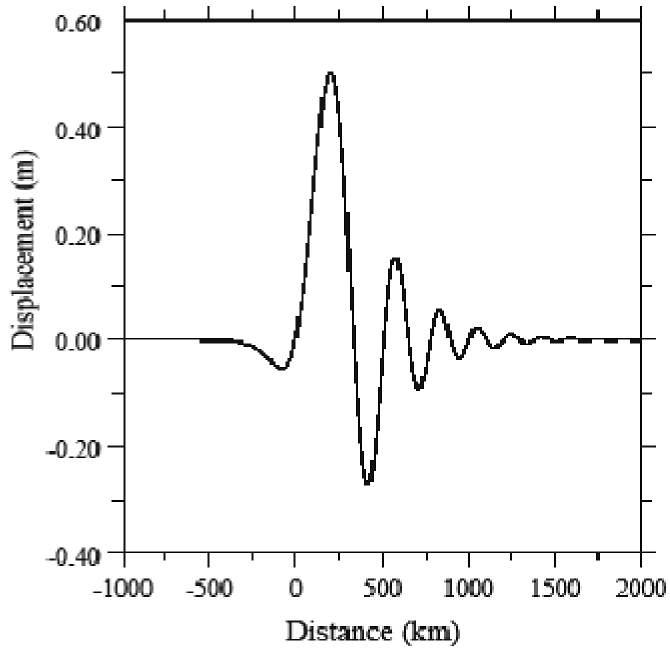
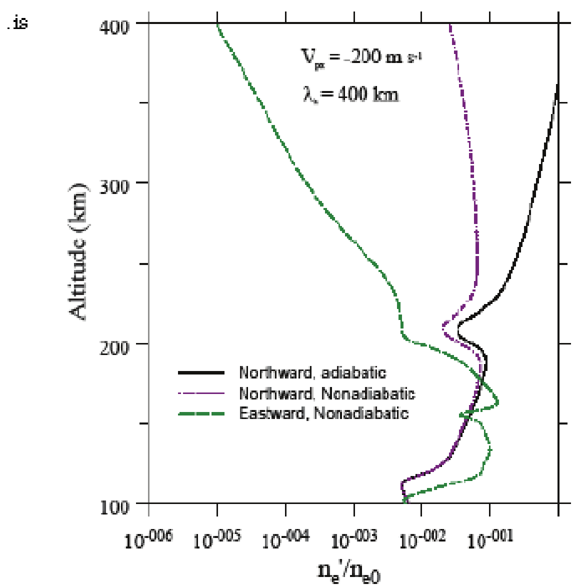
25.10.83 – power spectra of the (pwr chnl) signal and its parts

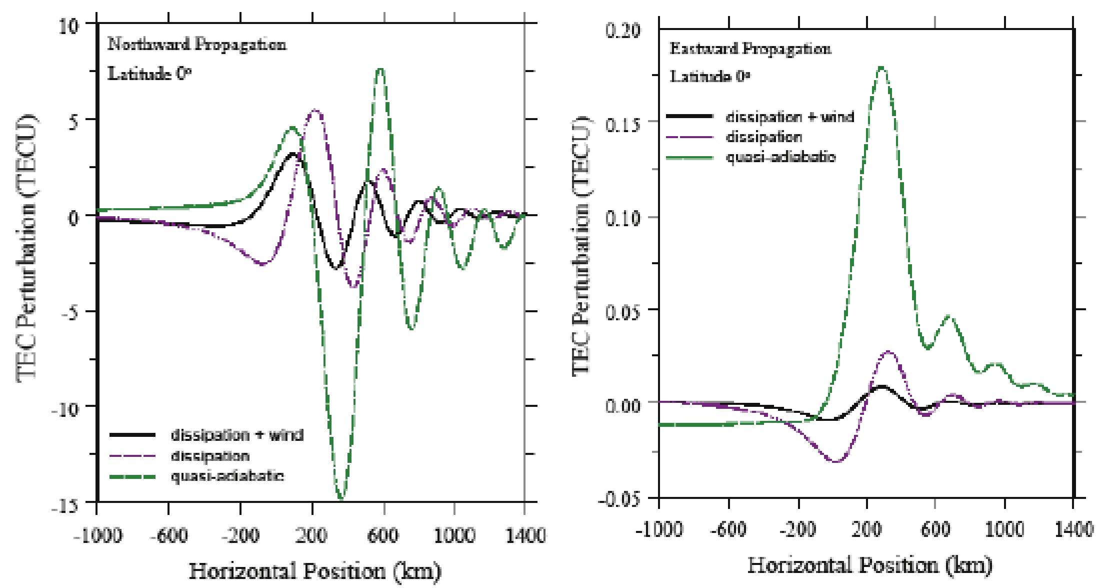




In order to simulate GPS observations, we have performed vertical integrations of the electron density perturbations to obtain the total electron content (TEC) perturbations.
The integration of the ***mean, undisturbed electron density profile*** gives a TEC value of ***17 TECU*** (where 1 TECU = 1016 electrons/m2).

For northward propagation (Figure 7a), … The inclusion of dissipation reduces the TEC fluctuation amplitude and also alters the phase of the disturbance.
The further inclusion of mean winds alters the phase again, and causes a further reduction in the amplitude ... In this latter (and more realistic) case ***the maximum TEC perturbations*** are about 3 TECU, which corresponds to an ***approximate 20% perturbation about the mean.***

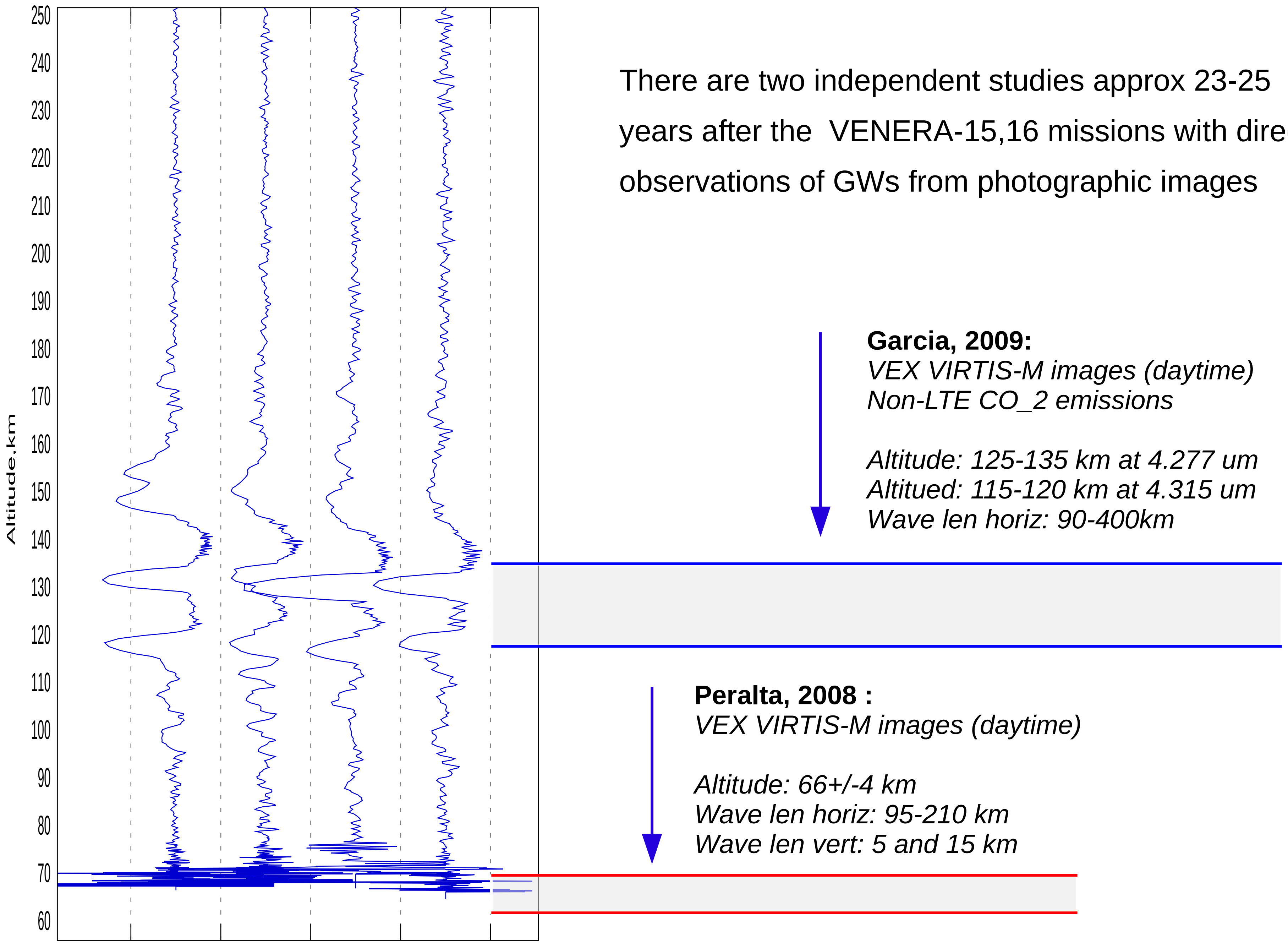




(a) (b)

Fig. 7. (a) TEC fluctuations for northward propagation (after Hickey et al., 2009). (b) TEC fluctuations for eastward propagation (after Hickey et al., 2009).

Supporting evidence? - VEX VIRTIS-M images at two altitudes



There are two independent studies approx 23-25 years after the VENERA-15,16 missions with direct observations of GWs from photographic images

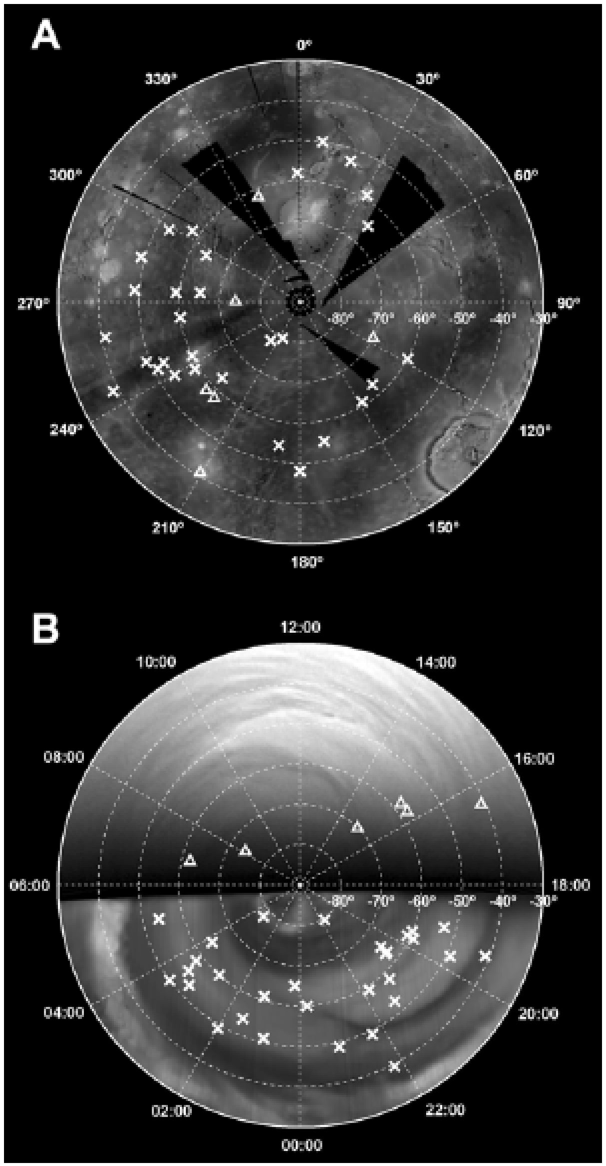
Garcia, 2009:
VEX VIRTIS-M images (daytime)
Non-LTE CO_2 emissions

Altitude: 125-135 km at 4.277 um
Altitued: 115-120 km at 4.315 um
Wave len horiz: 90-400km

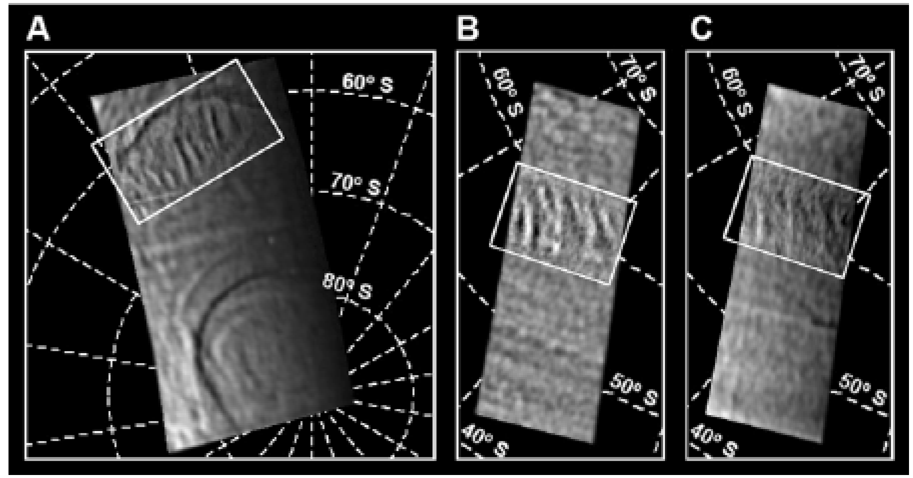
Peralta, 2008 :
VEX VIRTIS-M images (daytime)

Altitude: 66+/-4 km
Wave len horiz: 95-210 km
Wave len vert: 5 and 15 km

Peralta 2008: Mesoscale GWs from VEX-VIRTIS images (1)



A - geographical locations
B – local time



Observed wave trains:

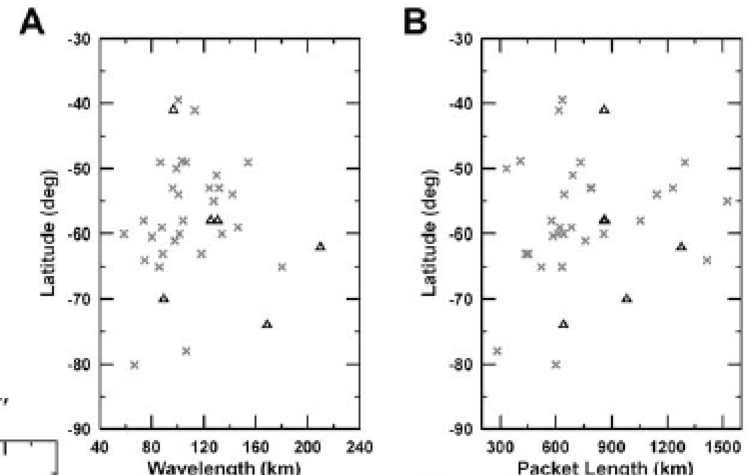
A, B – reflected UV (380 nm), day side; 66+/-4 km

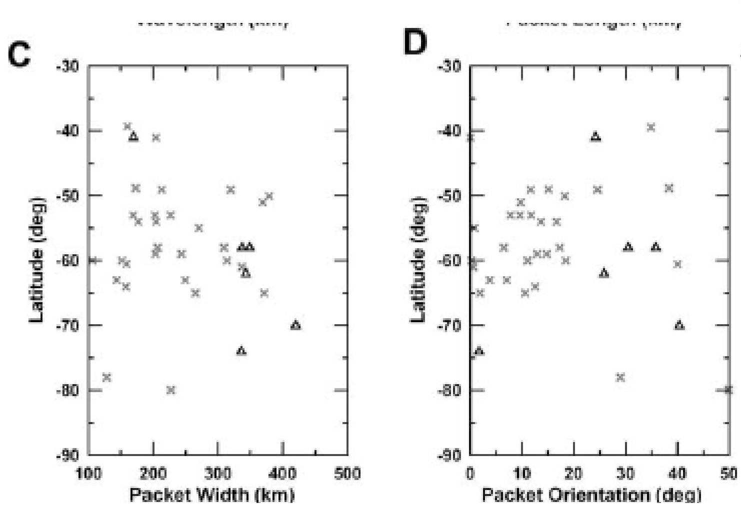
C - NIR (980nm), 61+/-3km

Characteristics of waves:

A - wavelength,
B - packet len

(triangles = UV)



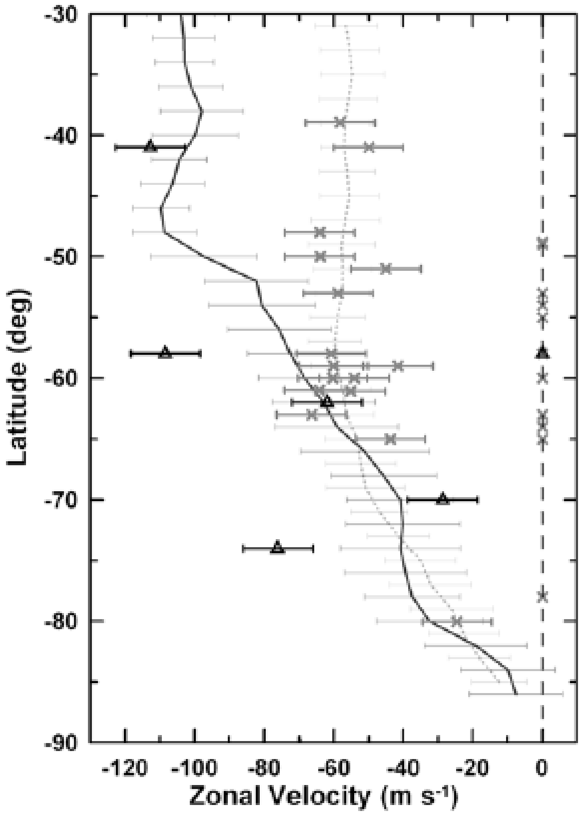


Characteristics of waves:

C - packet width,
D - packet orientation

(triangles = UV)

Peralta 2008: Mesoscale GWs from VEX-VIRTIS images (2)



(left) observed horizontal wave velocities plotted against background wind profile

(bottom right) dispersion relation for observed UV waves

(bottom) summary tables with wave parameters (UV)

Tables: observed wave properties

Table 2a. Summary of Wave Properties From UV Images by VEX-VIRTIS

Orbit	Latitude (deg)	Number of Crests	Wave Length (km)	Crest Width (km)	c_r (m/s)	$\|\bar{c}\|-u$ (m/s)
59	−41	8	95	45	−113	−12
59	−58	7	115	60	−108	−40
170	−62	5	210	125	−62	0.5
255	−70	11	90	45	−29	14
388	−74	4	170	100	−76	−36

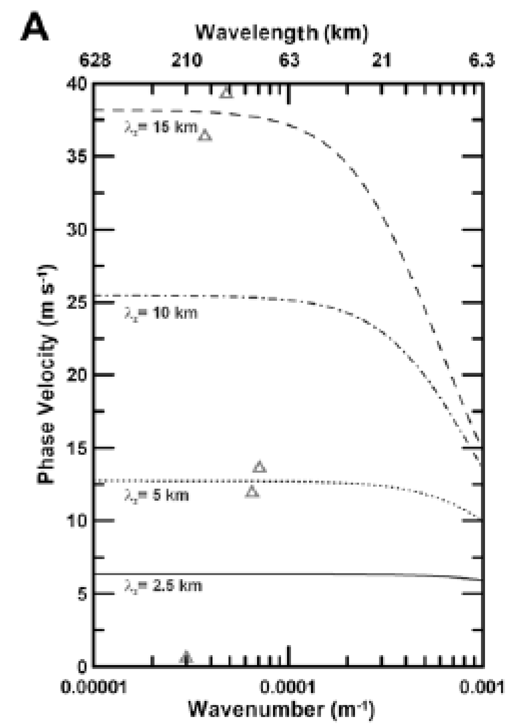
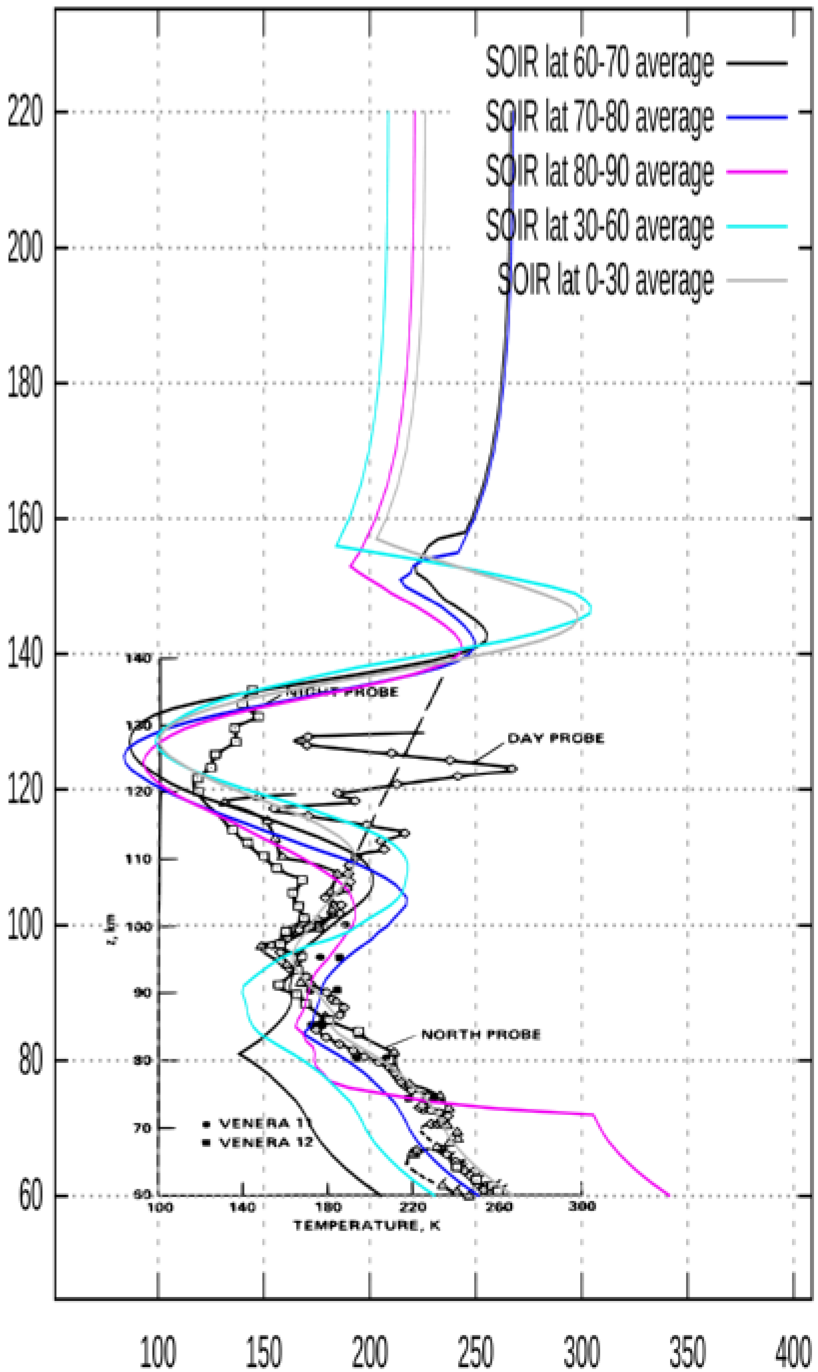


Table 1a. Summary of Wave Packets Properties From UV Images by VEX-VIRTIS[a]

Orbit	Date (mm/dd/yy)	Latitude (deg)	Local Hour	Packet Length (km)	Packet Width (km)	Orientation (deg)
59	06/18/2006	−41	16,4	>860	170	25
59	06/18/2006	−58	15,7	>865	340	30
170	10/07/2006	−62	06,8	1275	340	25
255	12/31/2006	−70	15,0	980	420	40
388	05/13/2007	−74	08,1	640	335	2

[a]Visible and InfraRed Thermal Imaging Spectrometer (VIRTIS).

VEX SOIR – Terminator Profiles (Temp, Pressure, Density, ...)



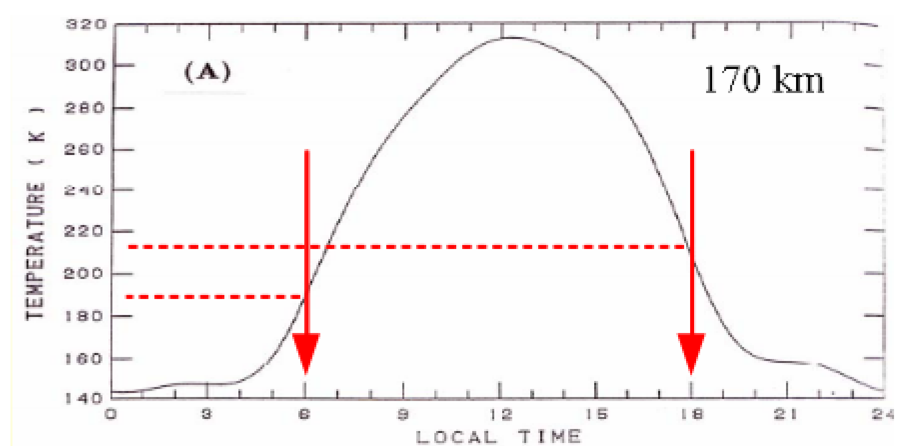
(1) VEX VAST SOIR (see [4]):
High-res. Spectrometer measurements of CO2 vertical density profiles using solar occultation of the Venus high atmosphere (i.e. at terminators, 70 – 170 km)

These measurements are unique at such altitudes and will provide the necessary background figures for the GW parameter estimations.

(2) "Permanent temperature minimum" at 125 may be a terminator feature no present in daytime ionosphere, as the superimposed PVO probes' temperature profiles suggest.

This will affect the subsequent estimation.

Mengel et al 1989 (model based on PVO data):
Temperature versus local time at 170 km alt.



Obtaining GW parameters from its breaking height and frequency

From theory:
the dissipation altitude depends of the kinematic viscosity

(1) At the dissipation altitude

$\nu_{diss} = \frac{\omega_i}{H_\rho m^3}$ where H_ρ is the density scale height,

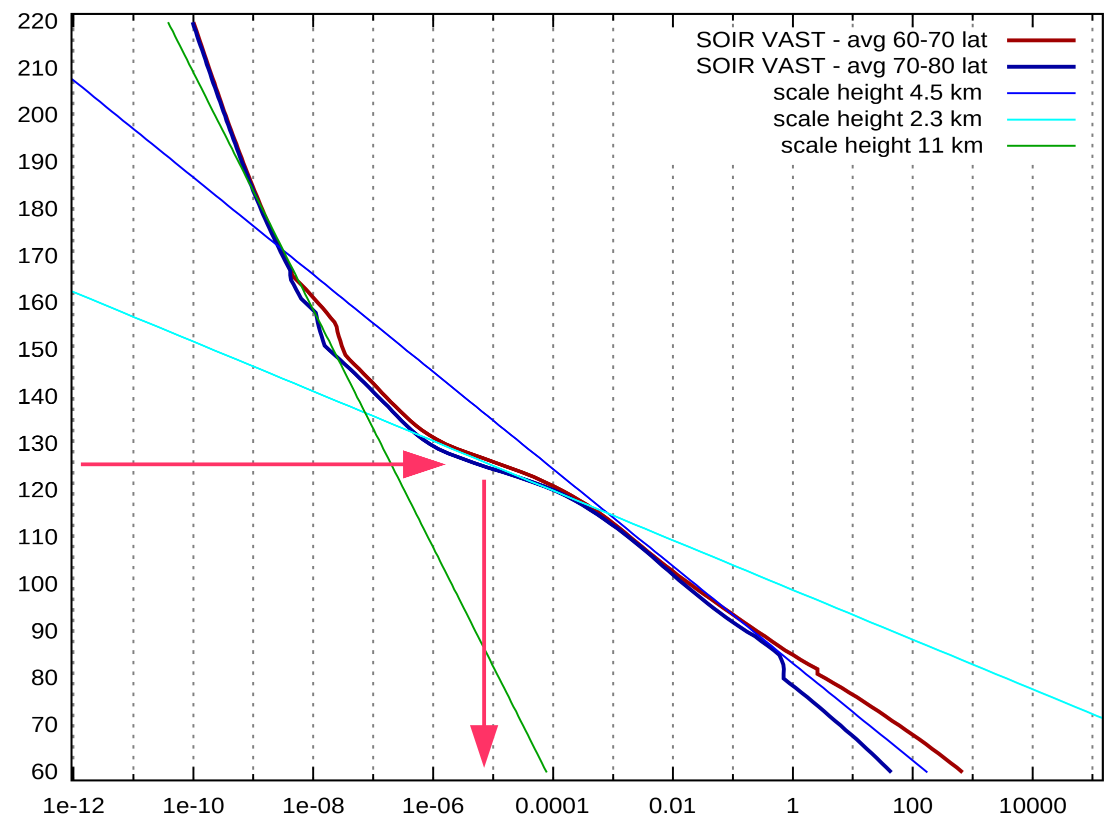
ω_i is the GW's intrinsic frequency and

$m = \frac{2\pi}{\lambda}$ is the vertical wave number

(2) At the same time it is defined as

$\nu = \frac{\mu}{\rho} = \frac{\mu R T}{M P}$ from the gas laws.

where R is the gas constant and M is the molar mass



(3) The viscosity itself, μ, depends on temperature according to the Sutherland's formula

$\mu = \mu_0 \frac{T_0 + C}{T_0^{3/2}} \frac{T^{3/2}}{T + C}$ (where C is a known constant and

for CO_2 the viscosity $\mu_0 = 14.8 \mu Pa \cdot s$)

Or: $\mu = \beta \frac{T^{3/2}}{T + C}$ where $\beta = \mu_0 \frac{T_0 + C}{T_0^{3/2}} = 1.572 \frac{\mu Pas}{\sqrt{K}}$

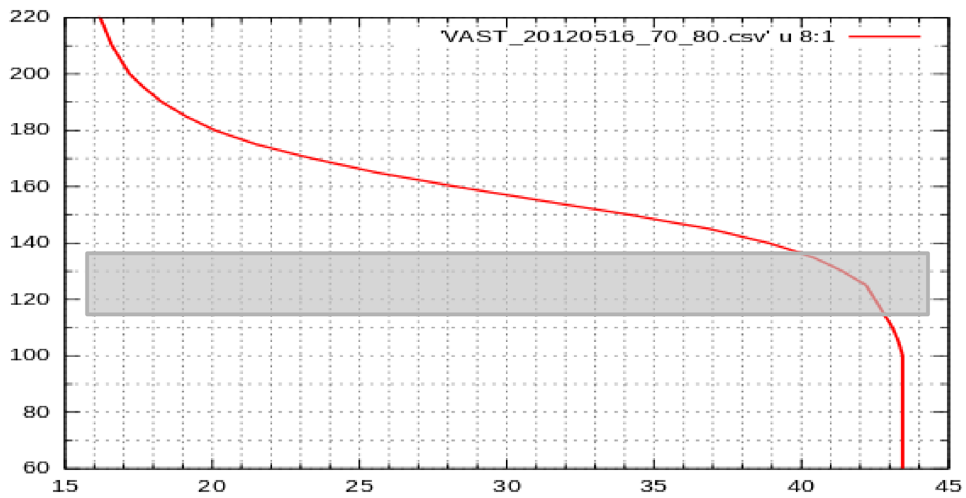
for the CO_2 293 K. For 250 K we obtain $\mu = 12.68 \mu Pa \cdot s$

(4) Therefore eliminating ν we obtain

$$P = \mu R \frac{m^3}{M \omega_i} H_\rho T \quad \textbf{(1)}$$

which includes observable or known values and allows us to estimate GW's intrinsic frequency (and therefore all its parameters) from the known breaking altitude using the SOIR profiles.

Results/Conclusion



VEX SOIR – molar mass vs height: evidence of turbopause at the altitudes where most of gravity waves break

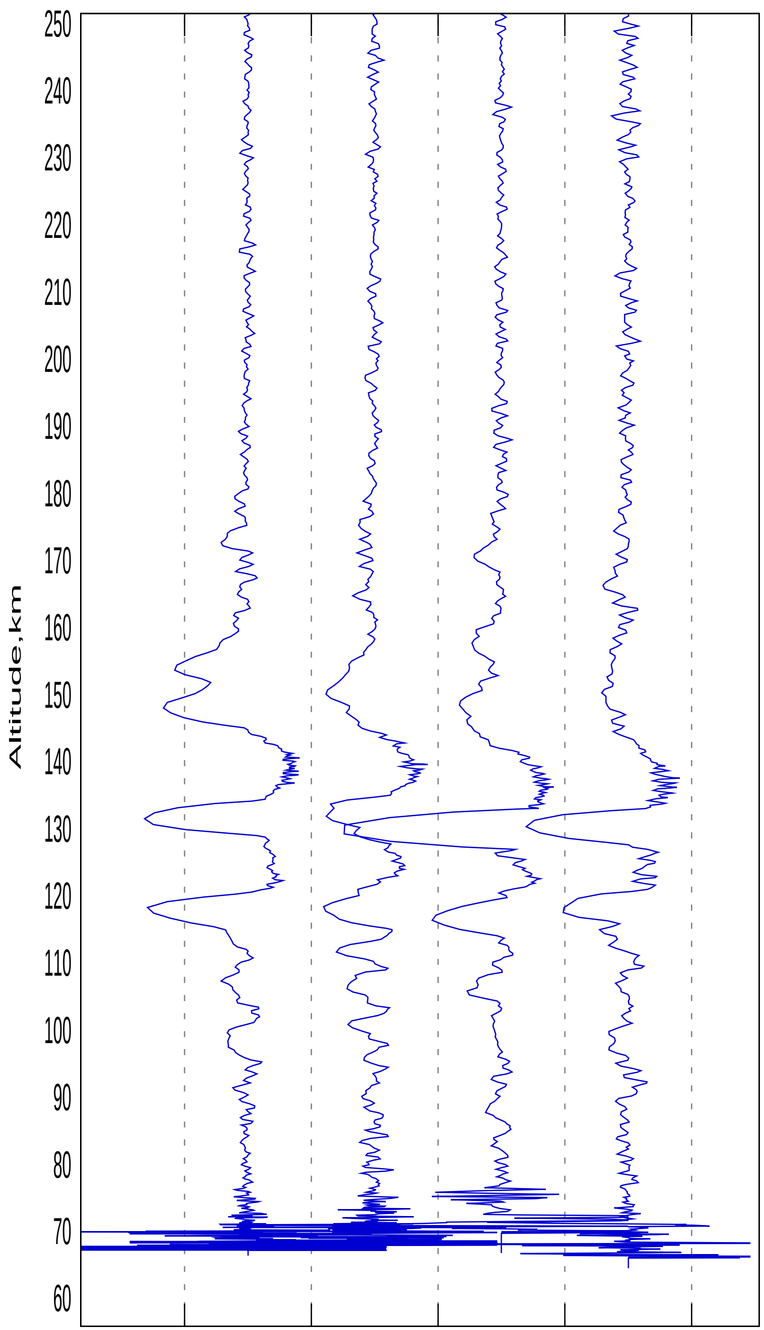
1. One has to be careful in interpreting the results because our signals and their Scalograms are static “snapshots” of dynamic processes. GWs can generate other waves and turbulence when breaking, and it is not obvious if observed oscillations are connected

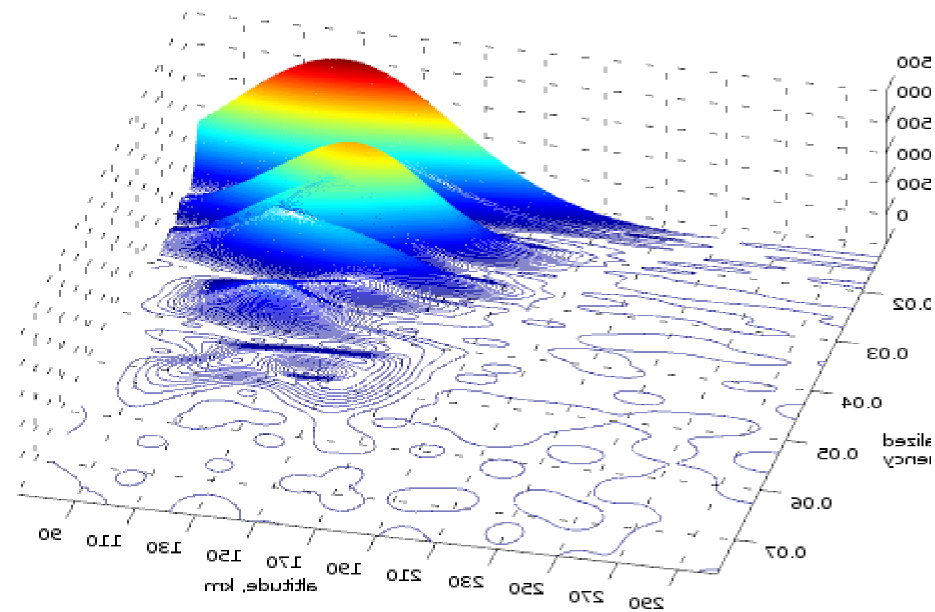
2. Most of wave breaking occurs between 120 and 140 km (with some events between 110 and 120km). This is in good agreement with numerical estimates. Two checks can be conducted: (a) At what altitude the GWs observed by Peralta (2008) will occur? (b) What are the intrinsic frequency and horizontal parameters of the waves from VENERA-15,16 signals?
Preliminary estimates indicate waves with very similar parameters (10s of m/s horizontal speeds, 5-10km vertical wavelengths, hundreds of km horizontal wavelengths), which identifies VENERA-15,16 observations as GWs of the type reported by Peralta. Ours are “first order of magnitude” estimates, based on approximate knowledge of background parameters obtained in another mission.

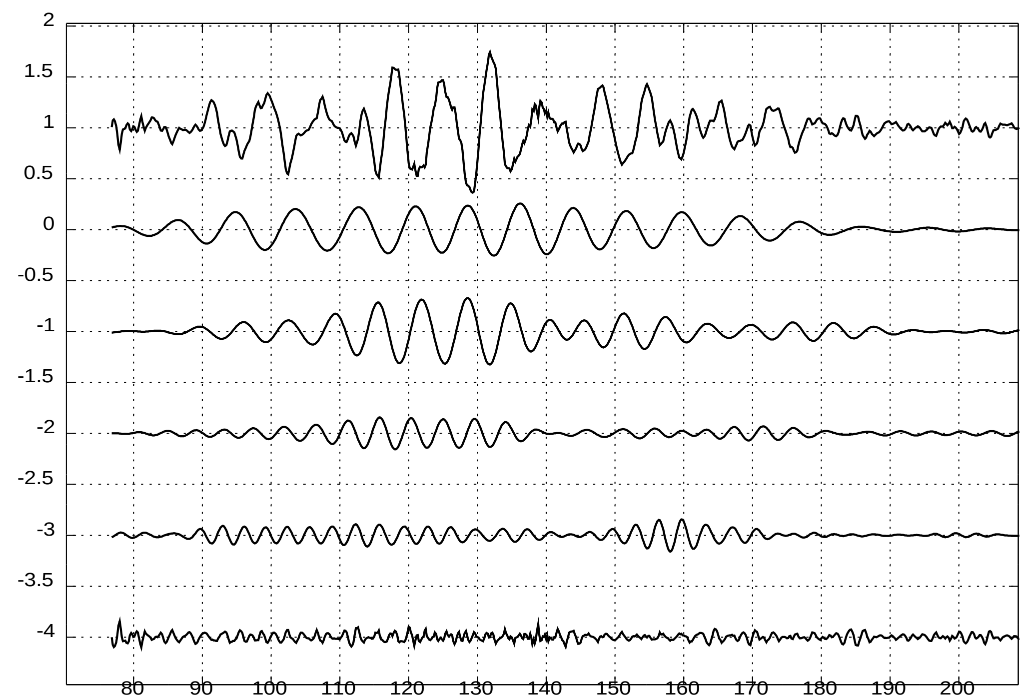
3. The range of breaking altitudes falls to the area identified as the turbopause, where “the well-mixed atmosphere” ends. This also confirms physical plausibility of the obtained results.

4. The proposed method of analysis
demonstrates possibility of using radio occultations as a remote sensing technique for the study of GWs at ionospheric altitudes, in addition to the traditional use for the calculation of N_e profiles.

Results/Conclusion



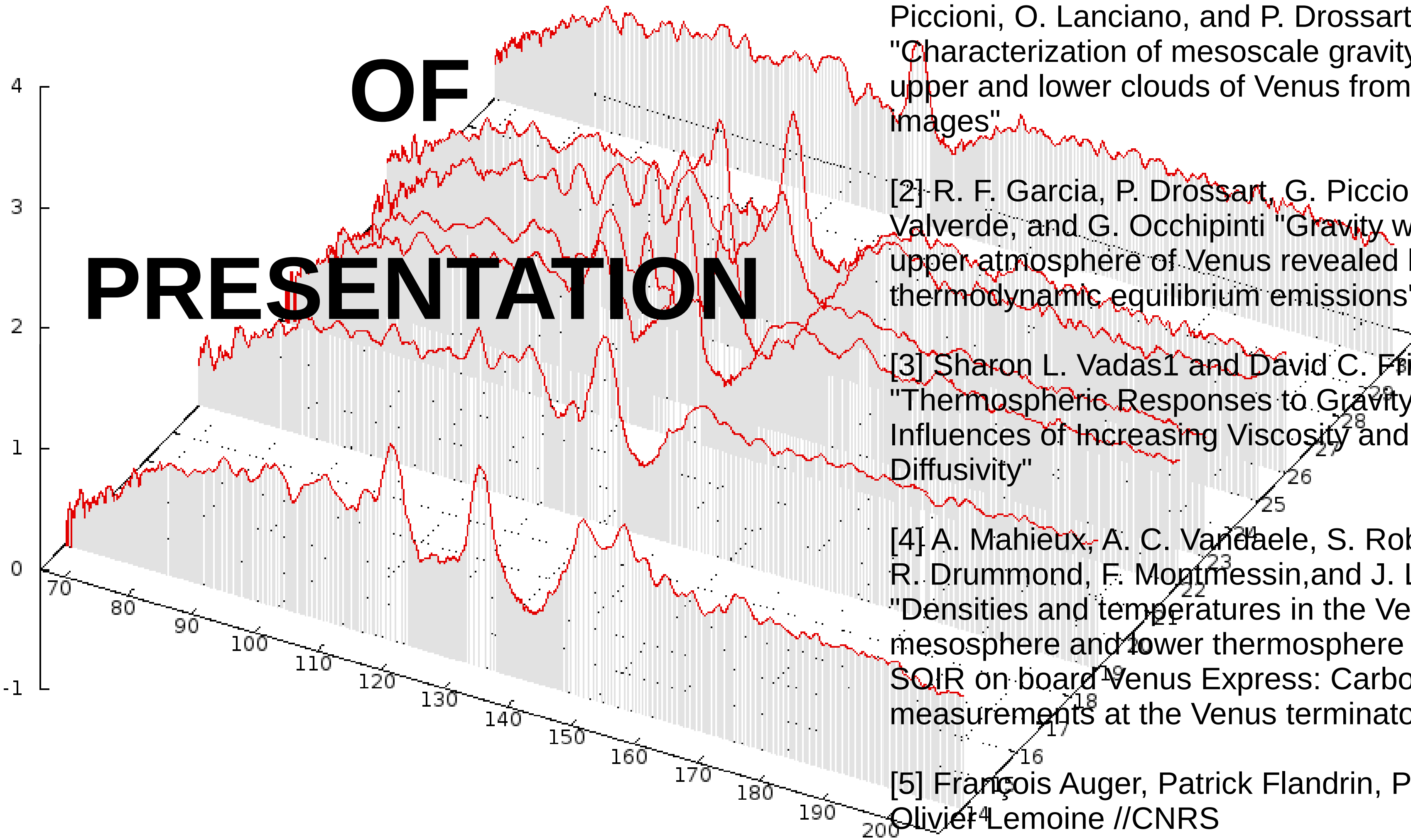




END

OF

PRESENTATION



References:

[1] J. Peralta, R. Hueso, A. Sanchez-Lavega, G. Piccioni, O. Lanciano, and P. Drossart "Characterization of mesoscale gravity waves in the upper and lower clouds of Venus from VEX-VIRTIS images"

[2] R. F. Garcia, P. Drossart, G. Piccioni, M. Lopez-Valverde, and G. Occhipinti "Gravity waves in the upper atmosphere of Venus revealed by CO2 nonlocal thermodynamic equilibrium emissions"

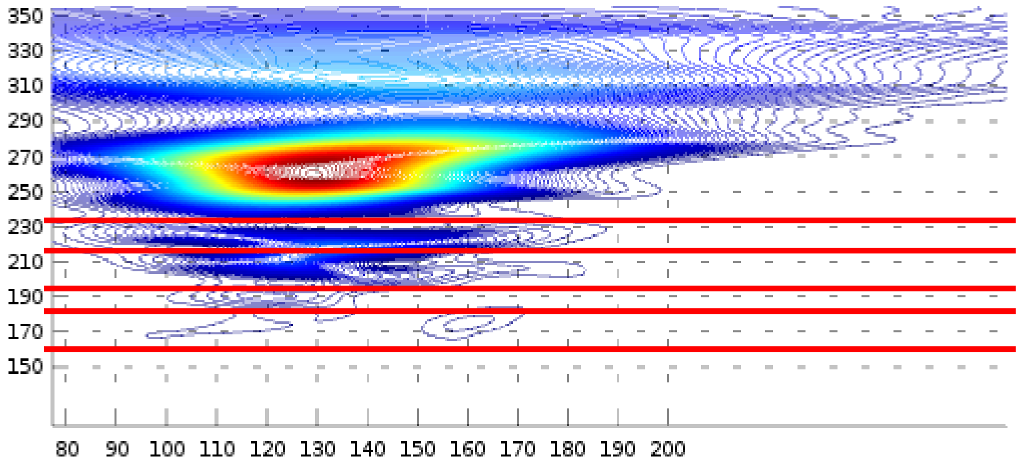
[3] Sharon L. Vadas1 and David C. Fritts "Thermospheric Responses to Gravity Waves: Influences of Increasing Viscosity and Thermal Diffusivity"

[4] A. Mahieux, A. C. Vandaele, S. Robert, V. Wilquet, R. Drummond, F. Montmessin,and J. L. Bertaux "Densities and temperatures in the Venus mesosphere and lower thermosphere retrieved from SOIR on board Venus Express: Carbon dioxide measurements at the Venus terminator"

[5] François Auger, Patrick Flandrin, Paulo Gonçalvès, Olivier Lemoine //CNRS (France) and Rice University (USA)//, 1995-1996 "Time-Frequency Toolbox"

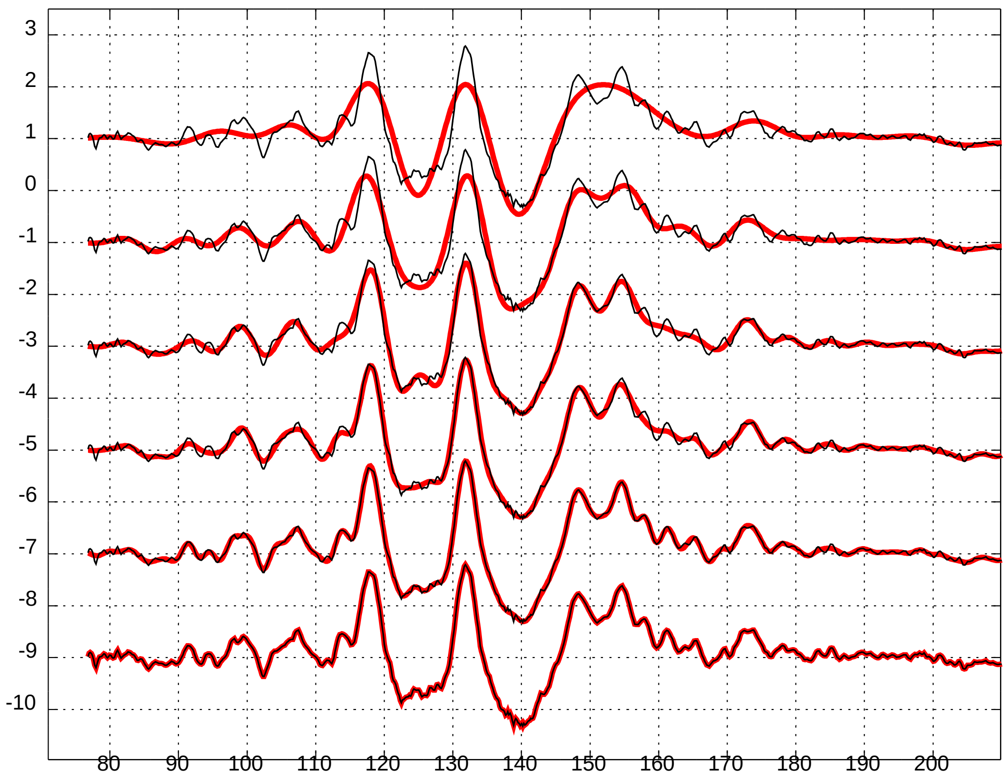
End of presentation

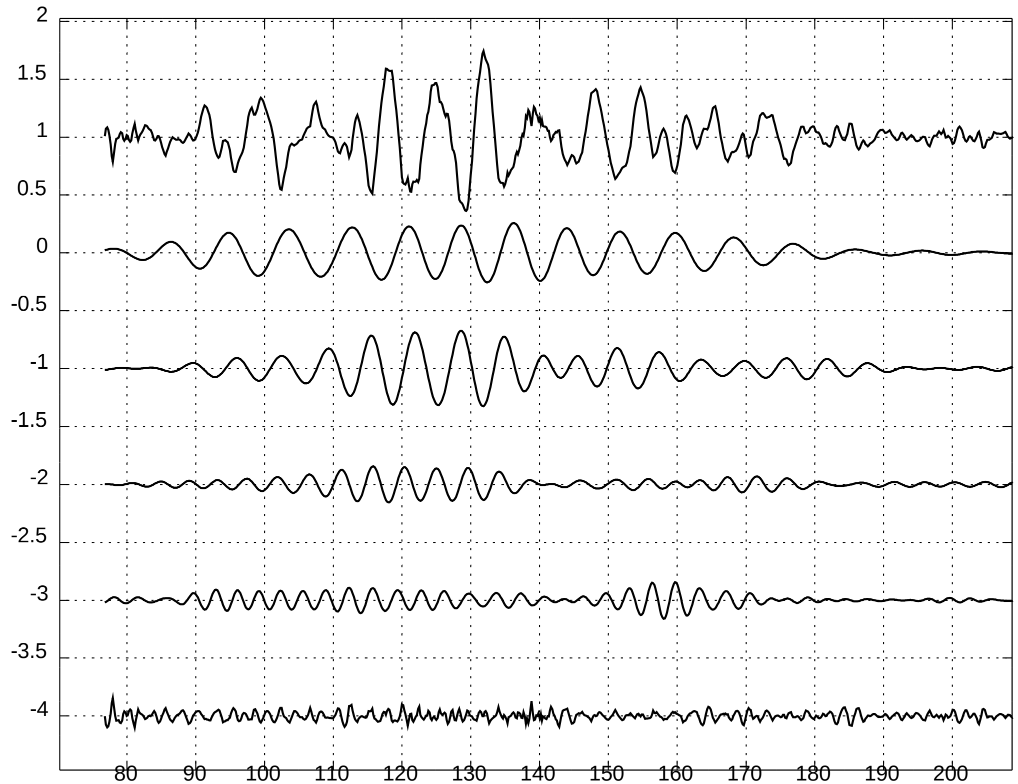
Creating signal from components provided by the Scalogram (14 oct 83 egress)



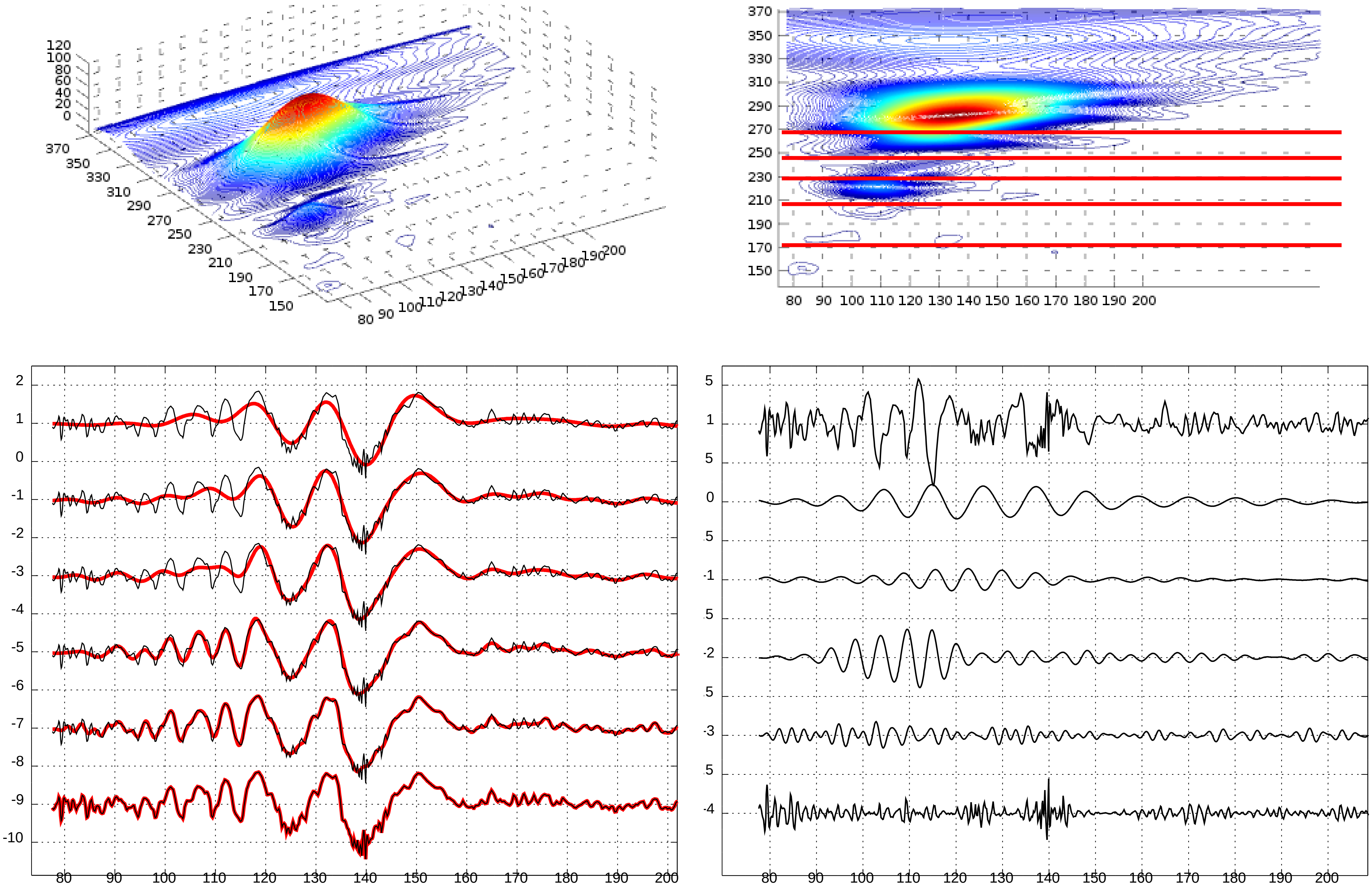
- Signal consists of the lower-frequency “Chapman Layer” and a few superimposed quasi-harmonic oscillations
- Two or three strongest lower-frequency components are responsible for the overall signal shape

Atmospheric gravity waves can frequently be described with a simple linear theory that treats them as small departures from a stably stratified background state varying only in the vertical.
[Fritts, Alexander 2003]

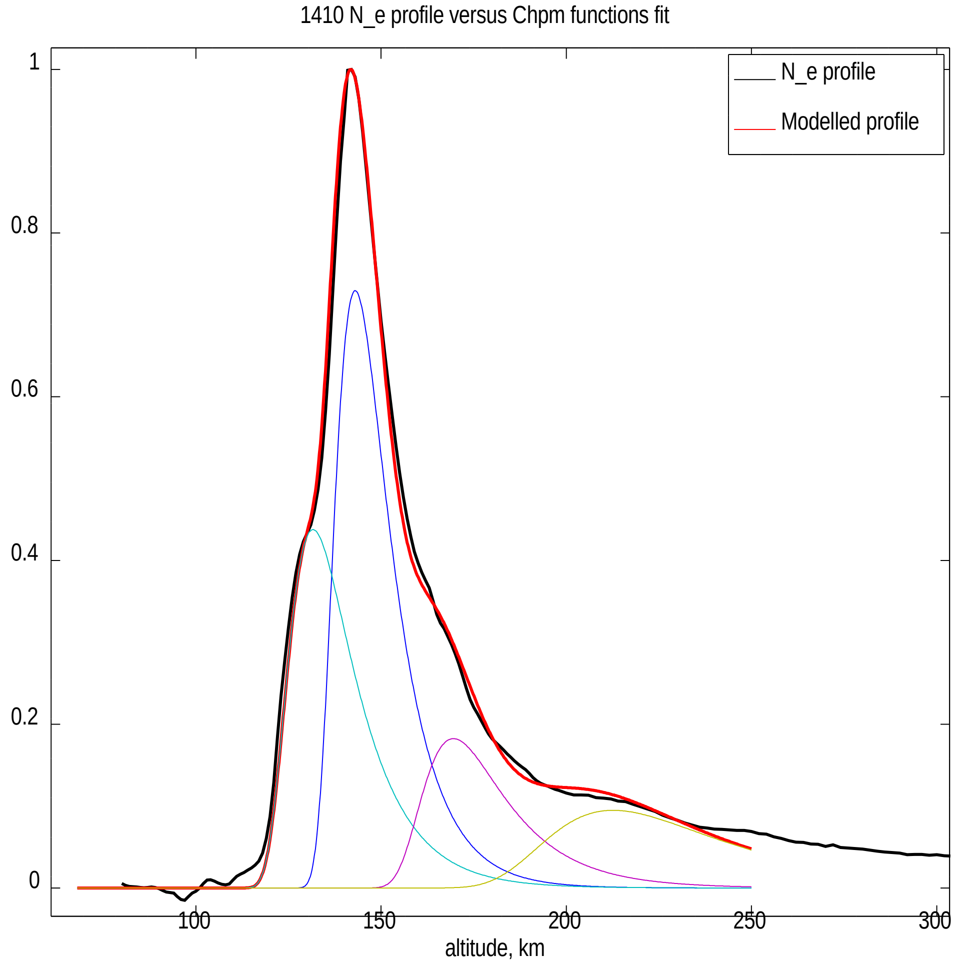


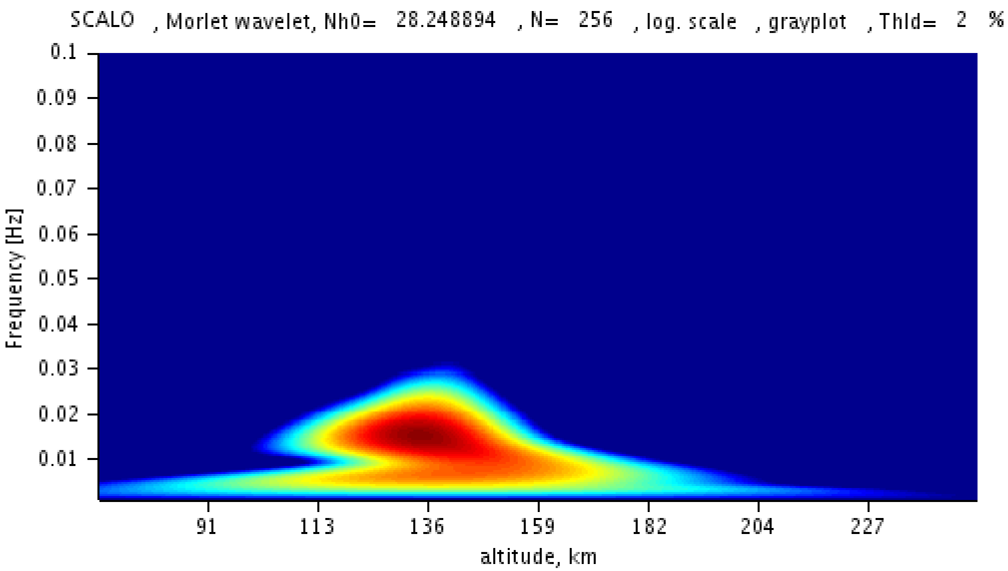


Creating signal from components provided by the Scalogram (25 oct 83 egress)

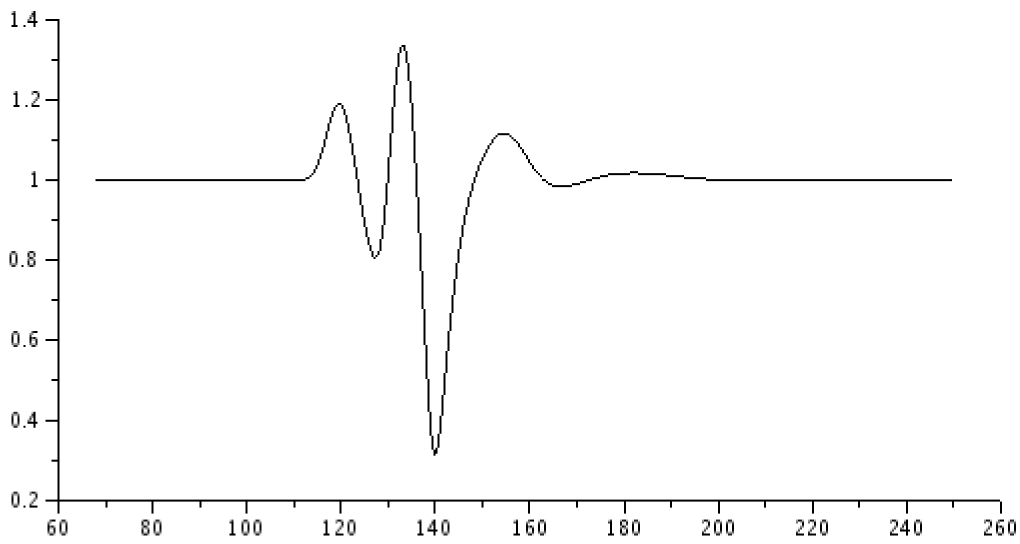


14.10.83 Signal: Chapman Layers on Time-Frequency Plane





Chapman layers are separated on the time-frequency plane.
They can mask waves longer than approx. 11-12 km

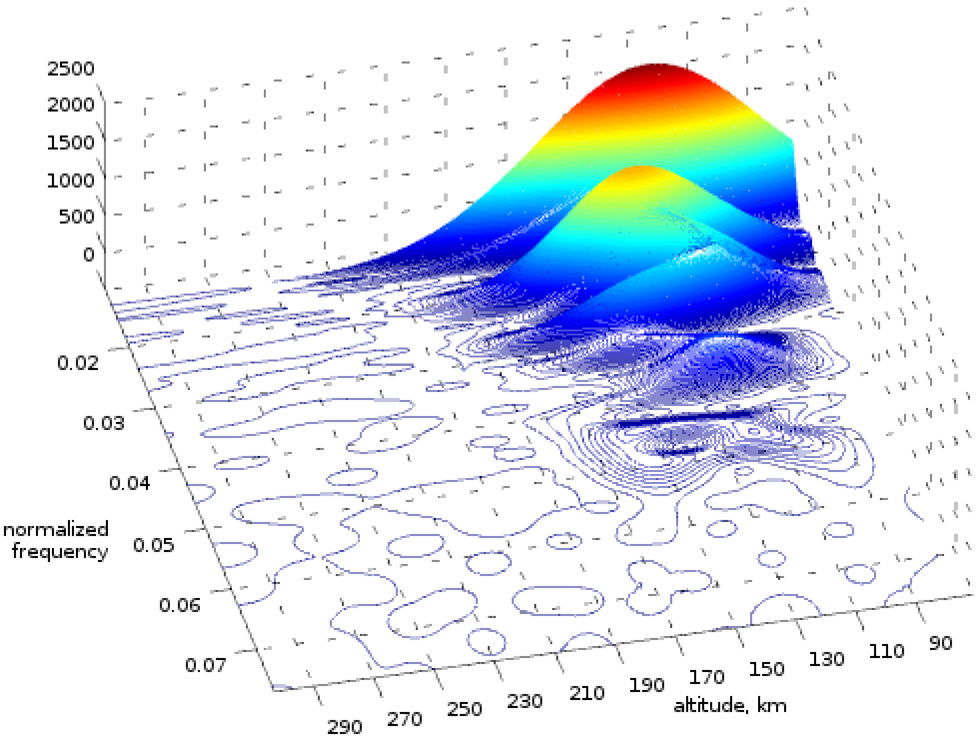


(top) approximation of the N_e profile with Chapman functions

(right) second derivative of the approximated signal

(right top) Scalogram of the above (as a function of normalized frequency

Creating signal from components provided by the SCALOGRAM



- Synthesized signal begins to resemble experimental data even when components' match is rough

- Which proves that “linear theory” is correct and that we understood the nature of the observed effects correctly

Atmospheric gravity waves can frequently be described with a simple linear theory that treats them as small departures from a stably stratified background state varying only in the vertical.
[Fritts, Alexander 2003]