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# Venus Express Radio Science Experiment VeRa

**Bernd Häusler [(1)], Martin Pätzold [(2)]**

**and the VeRa Team**

**"Venus Express Legacy Session"**

(1) Universität der Bundeswehr München,
(2) Institute for Planetary Research, RIU University Cologne

**Oxford, UK, April 6, 2016**



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# List of Contents

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# The VeRa Team and Partners

- Universität der Bundeswehr, Germany (B. Häusler, T. Andert)
- University Cologne, Germany (M. Pätzold, S. Tellmann)
- University Bonn, Germany (M. Bird)
- Stanford University (G. L. Tyler, R.A. Simpson, D. Hinson)
- Royal Observatory Belgium, Brussels ( V. Dehant, P. Rosenblatt)
- JAXA, Japan (T. Imamura)
- NASA-JPL/DSN (S. Asmar, T. Thompson)
- ESA – ESTEC/ ESOC/ ESAC (H. Svedhem, D. Titov, F. Jansen, S. Remus)

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## Funding

Financial support granted to teams of US, Belgium, Japan by their national space agencies. DLR funded partially travel costs for the German group.

**Thanks to all who have supported VeRa !**

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# VeRa – Science Topics

- Atmosphere
- Ionosphere
- Surface
- Gravity Anomalies
- Solar Corona



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# VeRa-VEX Status Early in the Mission

- First occultation season 2006
- Begin of S-band anomaly (considerable drop in radiated power) ~ August 4, 2006 DOY216

  VeRa experiments affected: SCO, OCC, BSR
- VEX thermal problems resulted in a revision of thermal rules, affecting also VeRa
- Consequence:
- No more BSR experiments (confirmation of the existence of a thin conductive layer at Maxwell Montes missing for the next decades)
- No more SCO experiments
- Limitations in further OCC experiments (sun illumination, S/C body rates)

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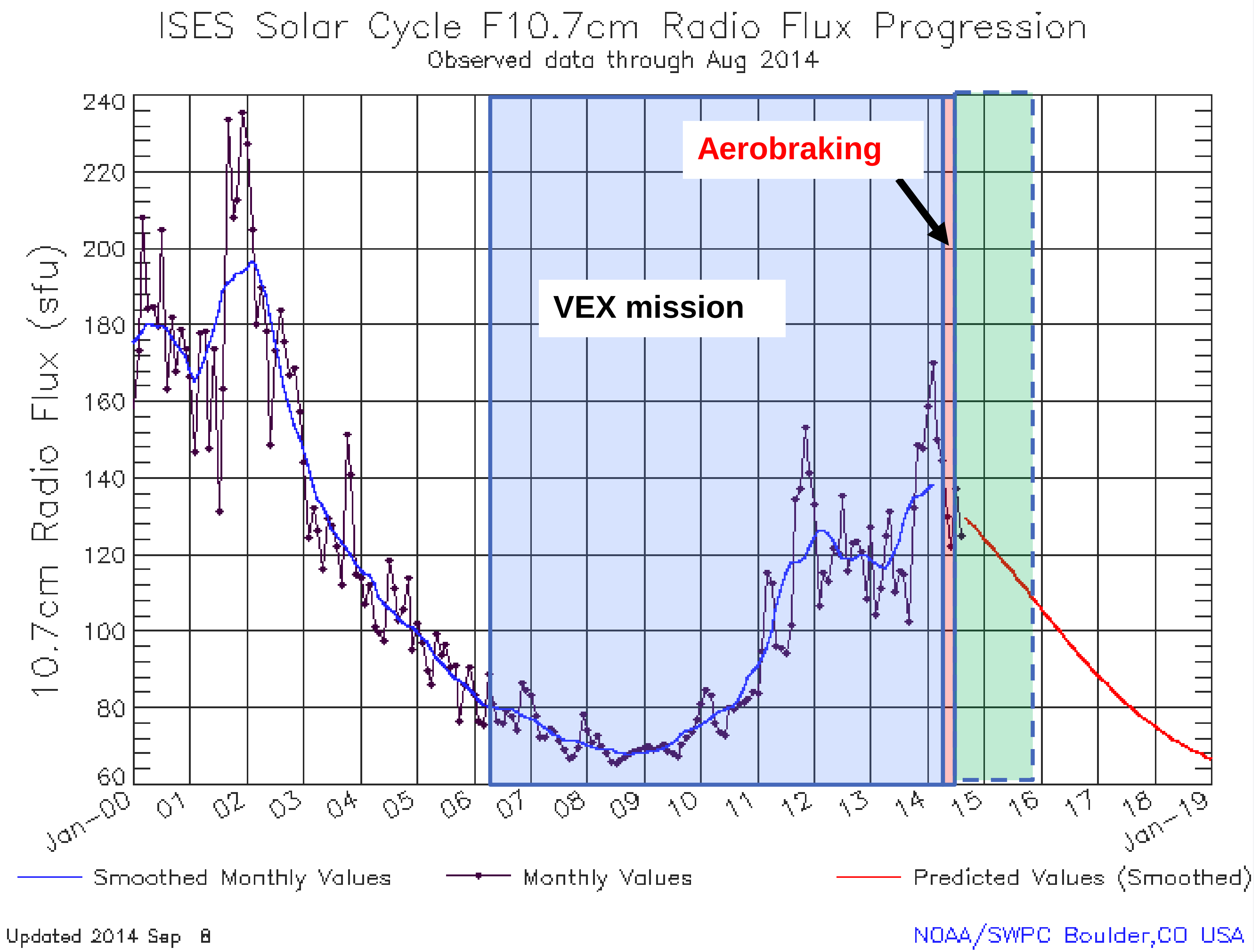
# Solar Activity in the Venus Express Mission



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# Mission Operations Summary
# Data Analysis

**CL receiver mode:**

VeRa retrieved so far more than 800 profiles of

- Temperature
- Neutral number density
- Pressure
- Electron Density

Occultation season # 16 (last radio science pass DOY 082, 23 March, 2014)

**OL receiver mode:**
- Data analysis still in progress both at RIU/Cologne and JAXA .
- Detection of very thin structures (< 1 km) in Venus mesosphere now possible.

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# Mission Operations Summary
# Archiving

- **Level 2 data archived until 2014.**
- **Selected temperature profiles available on request.**
- **Complete level 4 data set available on Saturn Server @ RIU by end of September 2016 (EURO Venus project)**

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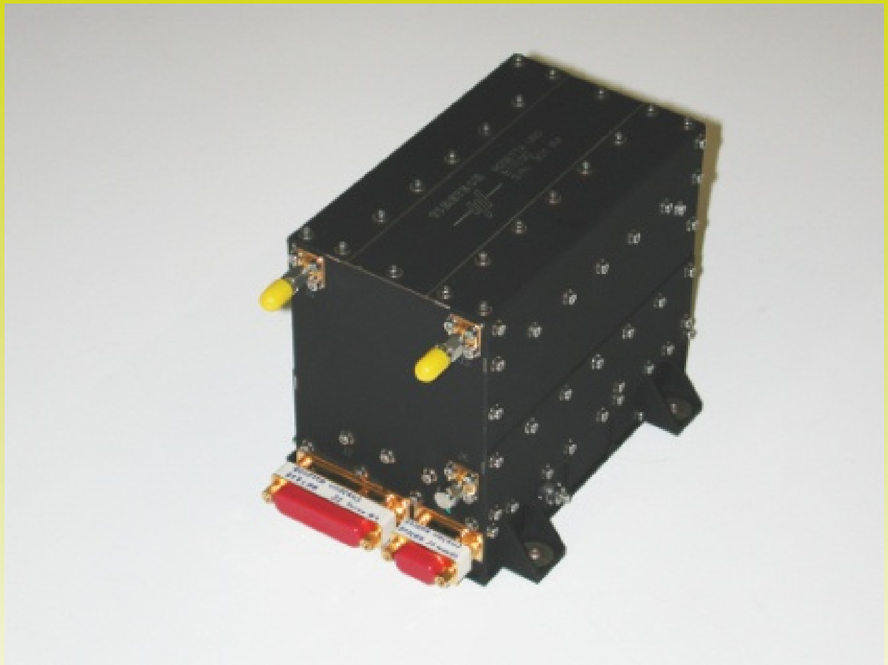
# Instrument – Experimental Techniques

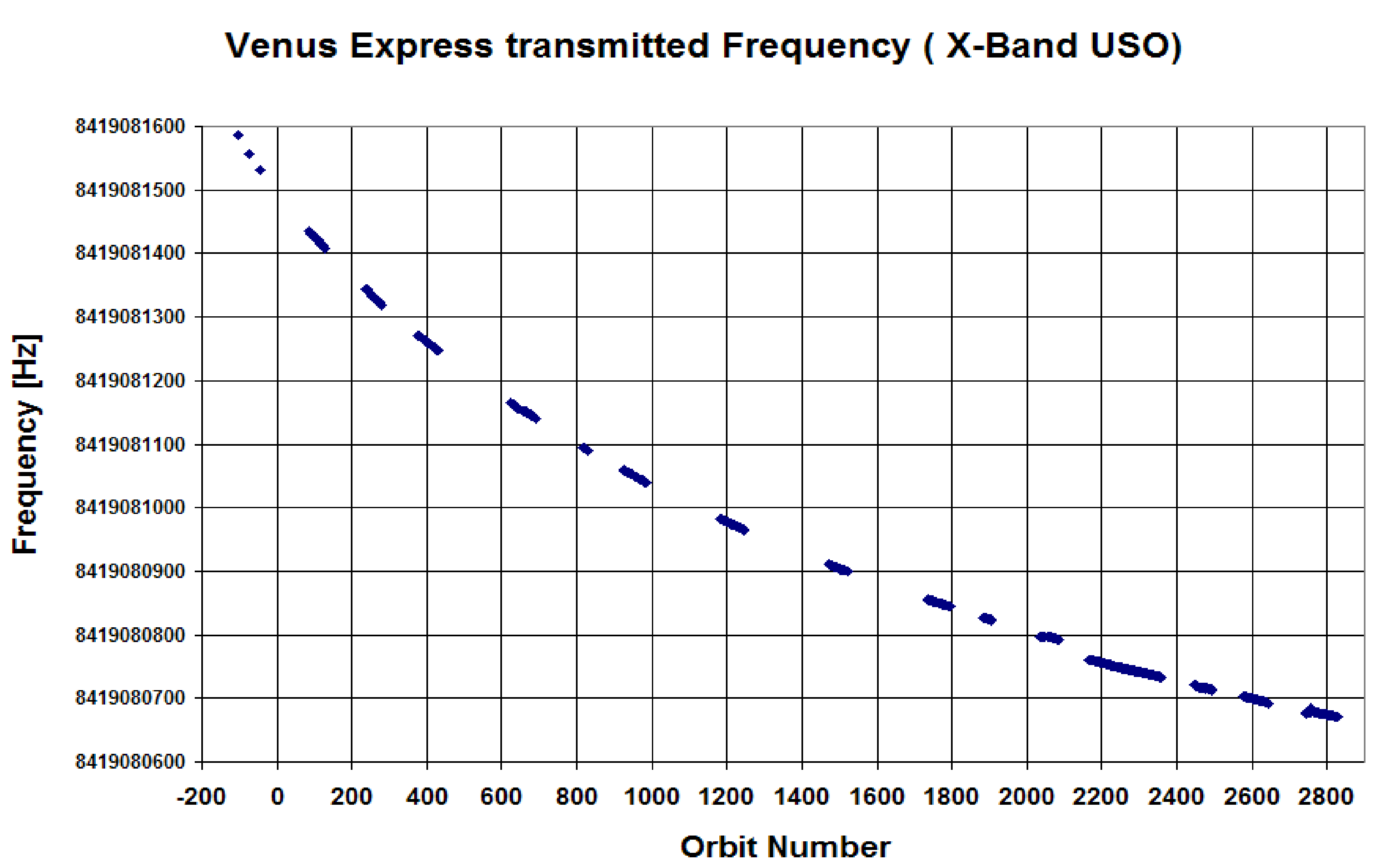
# VeRa Experiment
# Ultrastable Oscillator ( USO )



**Quartz USO connected toX/S-band transponder**
**Serves as ultrastable reference frequency source**

**Allan Deviation** $\approx 3 \cdot 10^{-13}$

**1.5 kg 5 W**
**Manufact. TIMETECH**




**Note: X5.4 Flare occurred on orbit #2147 March 7, 2012**

**Oct. 9 2014 in orbit # ~ 3100**

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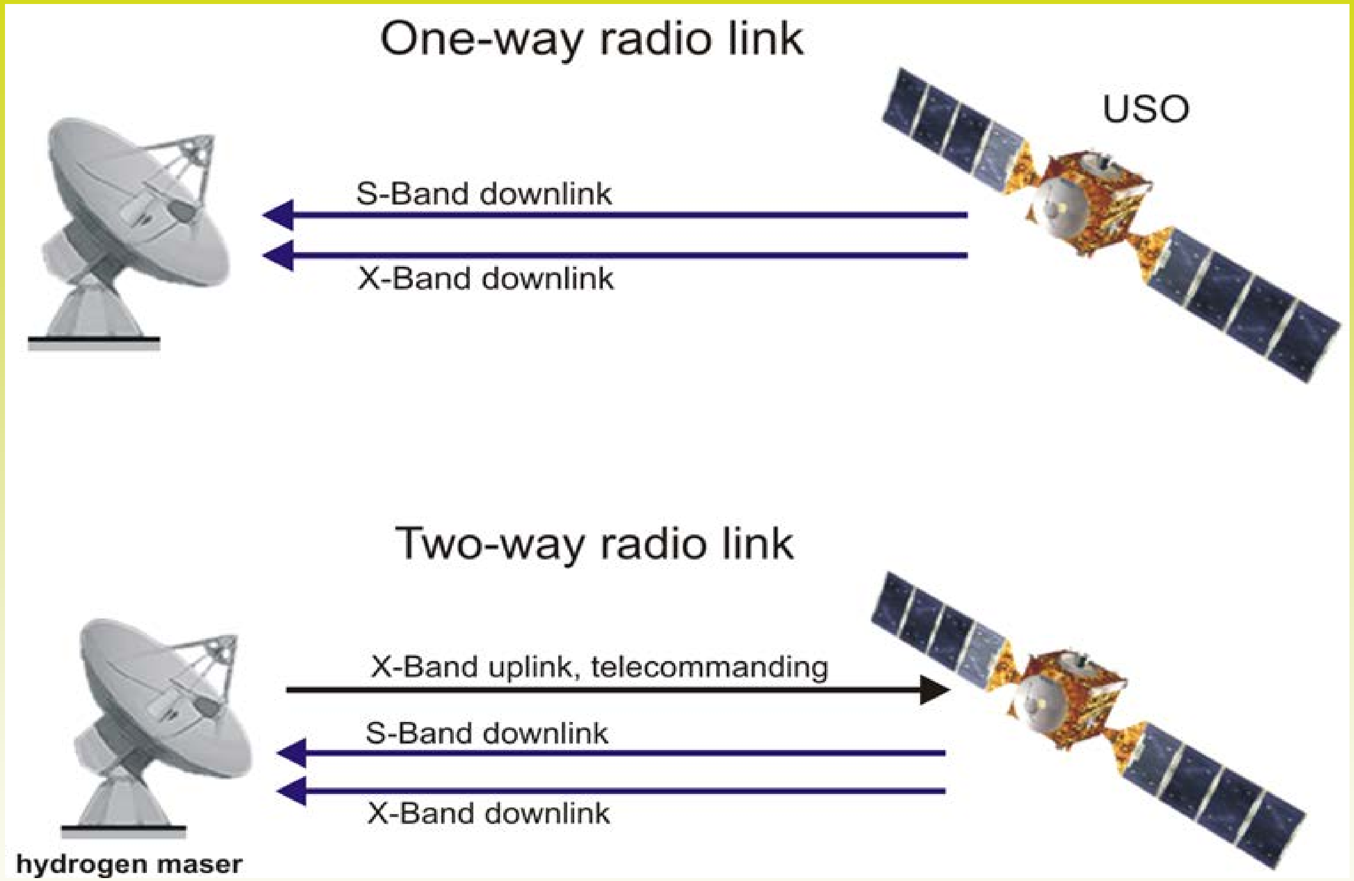
# Radio Science Measurement Techniques




**Two frequencies are needed to separate dispersive effects (plasma ) from non-dispersive effects (orbit, neutral atmosphere )**



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## Receiving Techniques Used

**Closed Loop Recording (CL):**
**Groundstation receives a dynamically limited the carrier signal with a PLL and requires S/N: ~ 12dB**

**Open Loop Recording (OL):**
**Groundstation samples incoming signal with 150 ksamples per second. Special digital processing techniques allow to recover a highly dynamic carrier signal out of noise. S/N: ~ 0 dB**
**Amount of data for a typical occultation: ~ 4 GByte**

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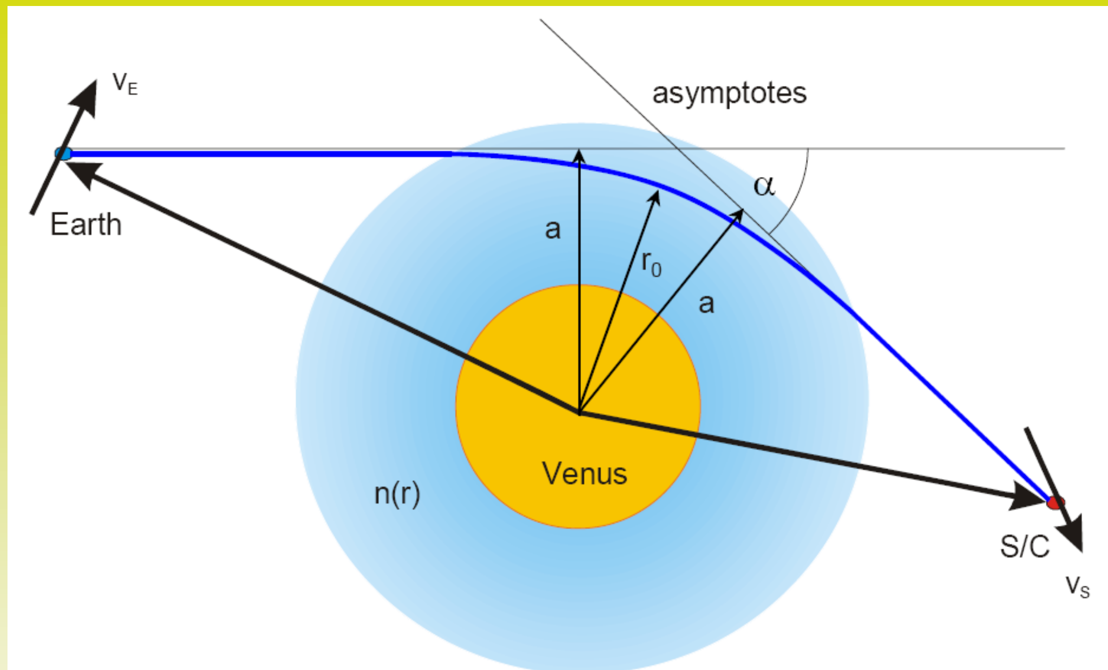
# Radio Science Occultation Technique:
# Principle: Ray Bending in Neutral Atmosphere




- $\Delta F$
- geometry

⇒ **Iterative calculation** ⇒ $\alpha(a)$ ⇒ **Abel transform calculation** ⇒ **Refraction index "$n(r)$"**

**It is the bending angle $\alpha$ which carries the information about the refraction index**

Sensitivity: $\Delta\alpha \sim 10^{-8}$ rad

**next iteration step**



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# The Radio Occultation Technique
## Conducting an Experiment

At Venus - in order to maximize receiving power - one has to dynamically steer the radio beam in 3 axes through the atmosphere to compensate for the ray bending effect (Bending angle < 7°, 3dB opening angle of antenna beam 1.7°)

Dedicated software (Matlab/Simulink based simulator) including a model atmosphere was developed for this purpose by the Radio Science team. This allowed to calculate the HGA pointing angles expressed by quaternions for the 3-axis pointing maneuvers to guide the microwave ray through the atmosphere.

Pointing had also to obey the „thermal rules“.

First done by an experiment in an ESA mission. Flawless operations.



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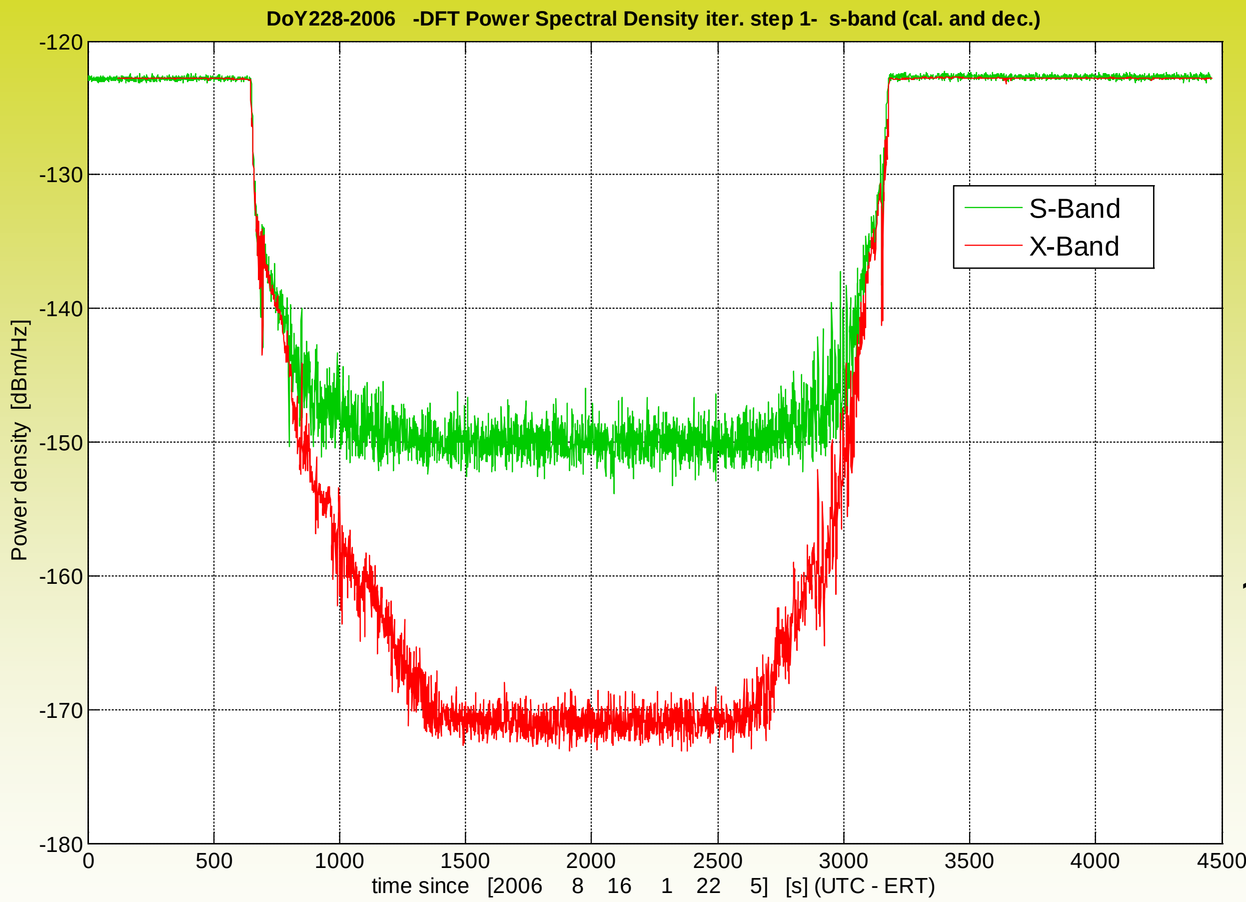
# Carrier Power in a Typical „Deep“ Occultation Pass
# CL-Receiver
## Both Channels Normalized in Power



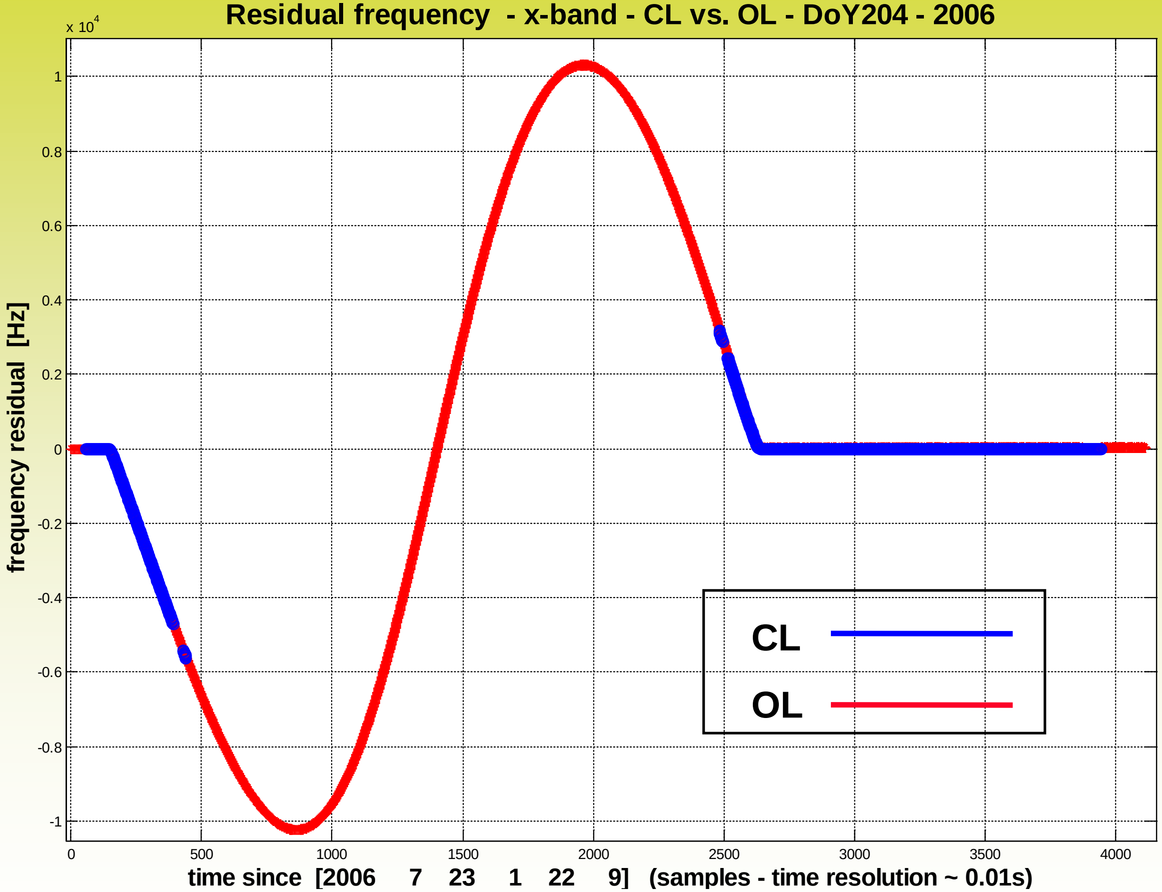

**Loss of carrier power in the atmosphere due to defocusing and absorption**

**~ - 50 dB (X-band)!**

# Atmospheric Frequency Shift of the VeRa X-Band - Carrier Signal During a Complete Occultation. CL vs. OL Technique.

**VeRa was the first planetary Radio Science mission detecting the carrier signal throughout a complete occultation.**
**The carrier could be detected during times with the planetary disk occulting completely the satellite.**

Residual frequency - x-band - CL vs. OL - DoY204 - 2006




**Loss of carrierl power in the atmosphere due to defocusing and absorption**

**~ - 50 dB (X-band)!**



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# Achievements in Science

Characterized by an excellent cooperation within in the VEX Team including the Akatsuki Team

Very competent support in the fields of mission/experiment planning  and ground station operations



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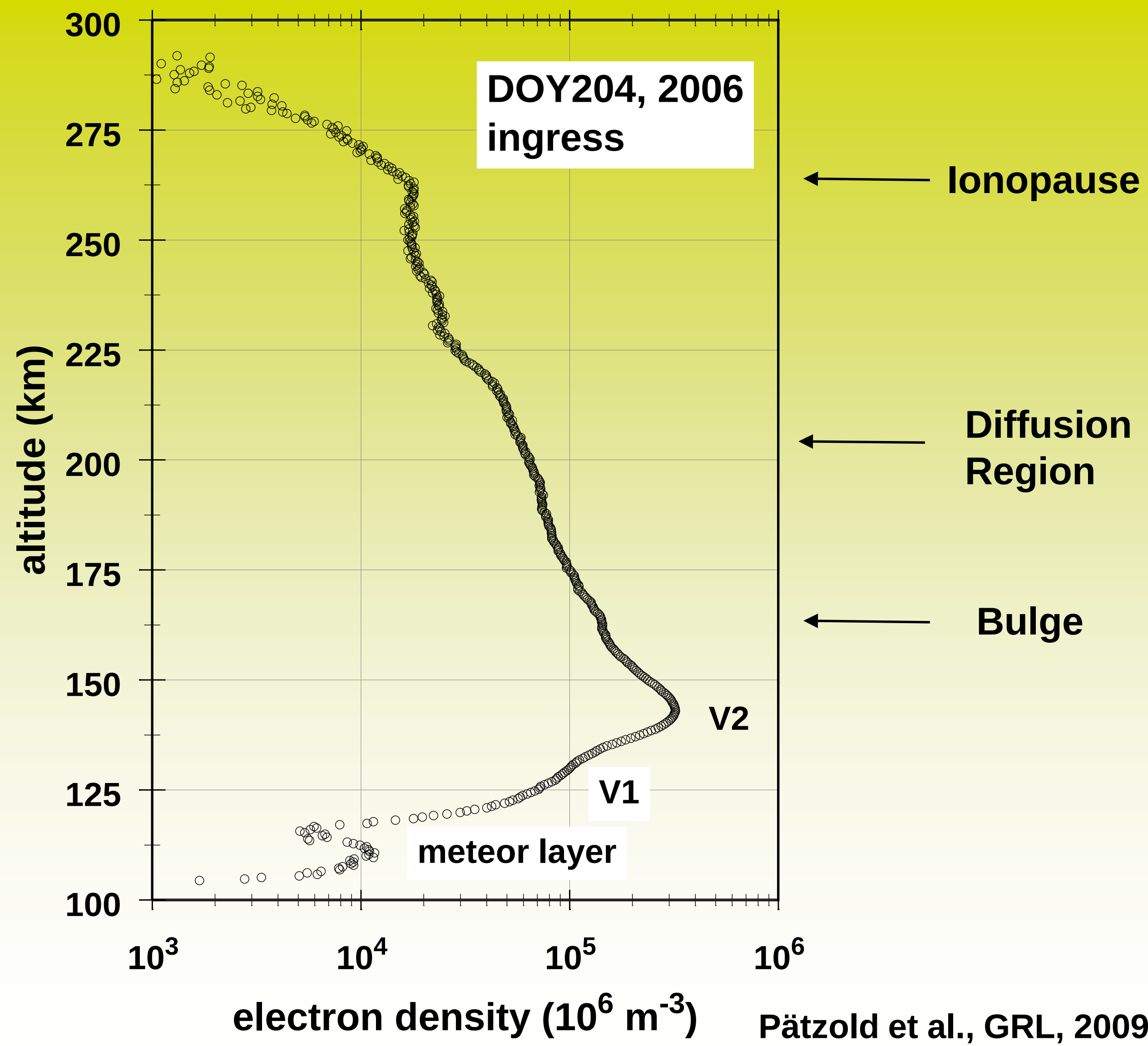
# Achievements in Science

**VeRa turned out to be an extremely versatile instrument:**
**Precise time and frequency measurements with microwaves allowed to characterize, determine, detect, discover:**

- The ionospheric structure of Venus
- Particles of meteoric origin in ionospheric plasma
- Structure of Venus middle atmosphere
- Zonal wind distribution of Venus middle atmosphere (VeRa, VIRTIS)
- Cloud top structure (VeRa, VIRTIS)
- Polar vortex
- Planetary waves
- Ubiquitous distribution of gravity waves in the atmosphere
- Saturation of gravity wave power spectra (gravity wave breaking)
- Thin-layered near neutral structure of Venus mesosphere
- Thin inversion layer at tropopause (~ 1 km, ~ 10K)
- $H_2SO_4$ g distribution in atmosphere
- Dielectric properties of surface aereas and gravity properties
- Solar corona effects

Venus Express Radio Science VeRa

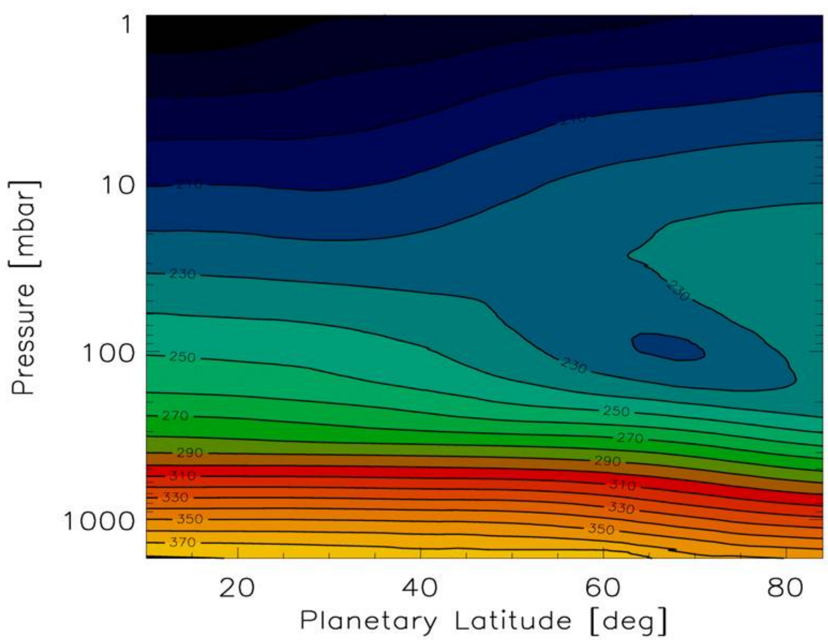
# Structure of the Venus Ionosphere
# Discovery of Meteor Layer




Pätzold et al., GRL, 2009

# Global Thermal Structure of Venus Middle Atmosphere

## Latitude vs. Pressure, Zonally Averaged




~ 80 km

~70 km

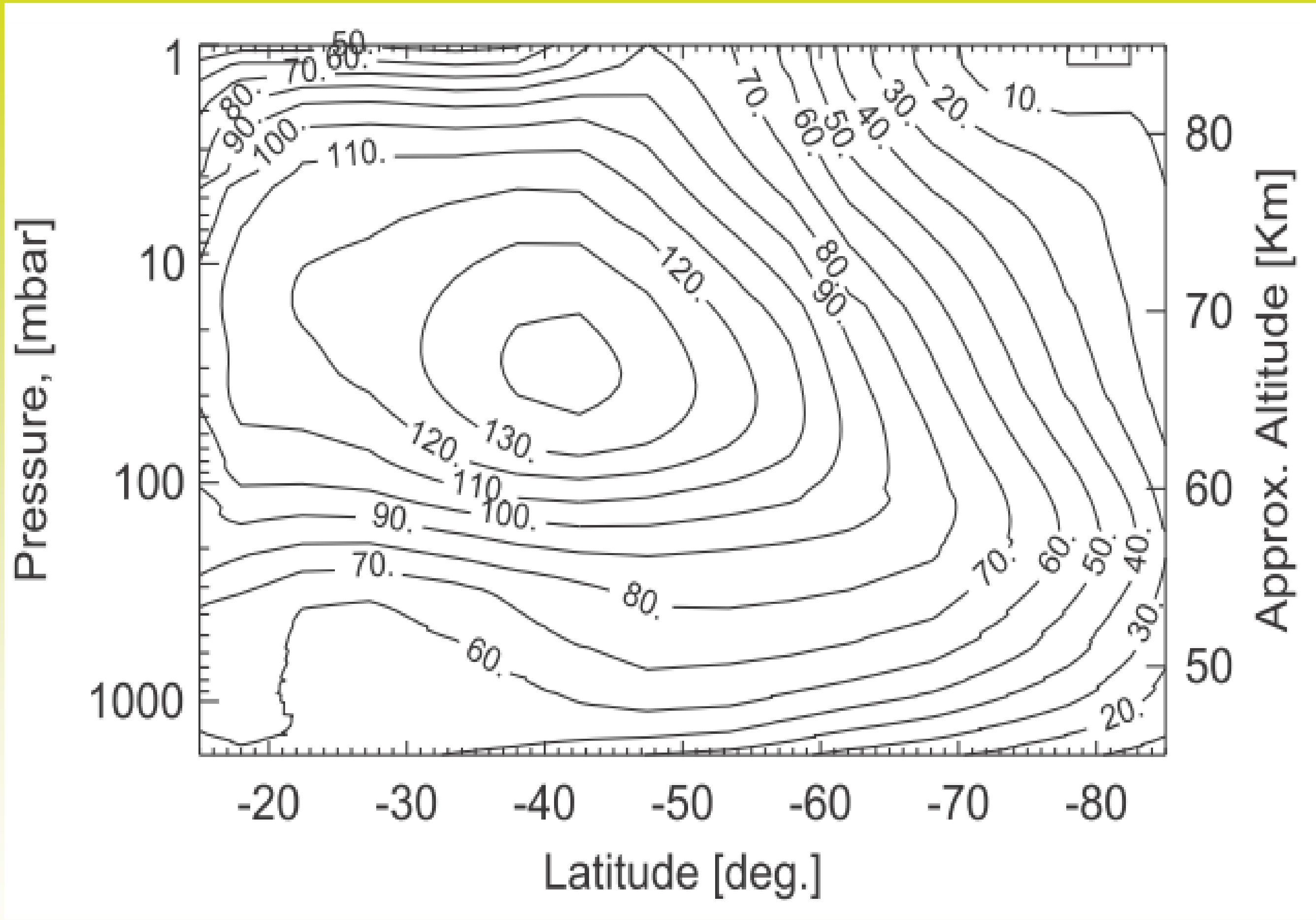
~ 60 km

**Anomalous thermal structure at high latitudes above 70 km**

**„Cold Collar“**

**Tellmann et al., 2015**

# Averaged Zonal Wind Velocity Based on Cyclostrophic Approximation. Derived from VeRa and VIRTIS Data




A. Piccialli et al., Icarus, 217, 2012





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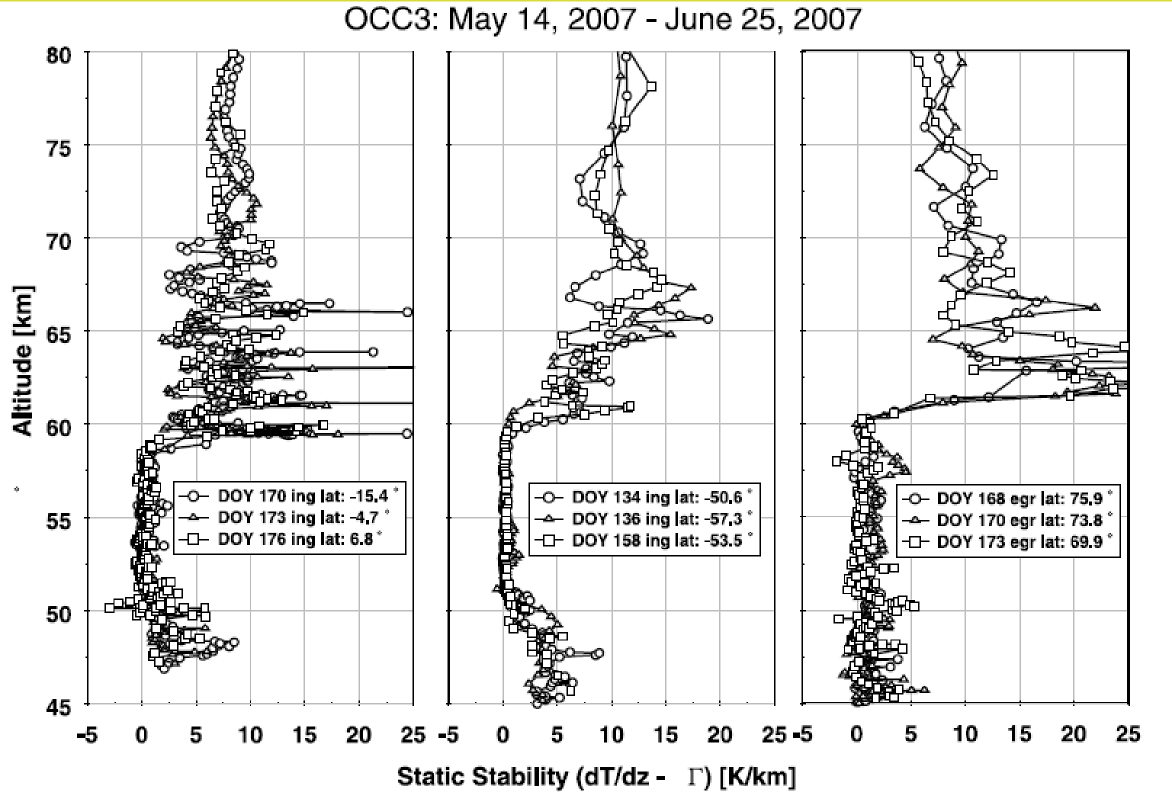
# Static Stability of Venus Middle Atmosphere as Observed by VeRa



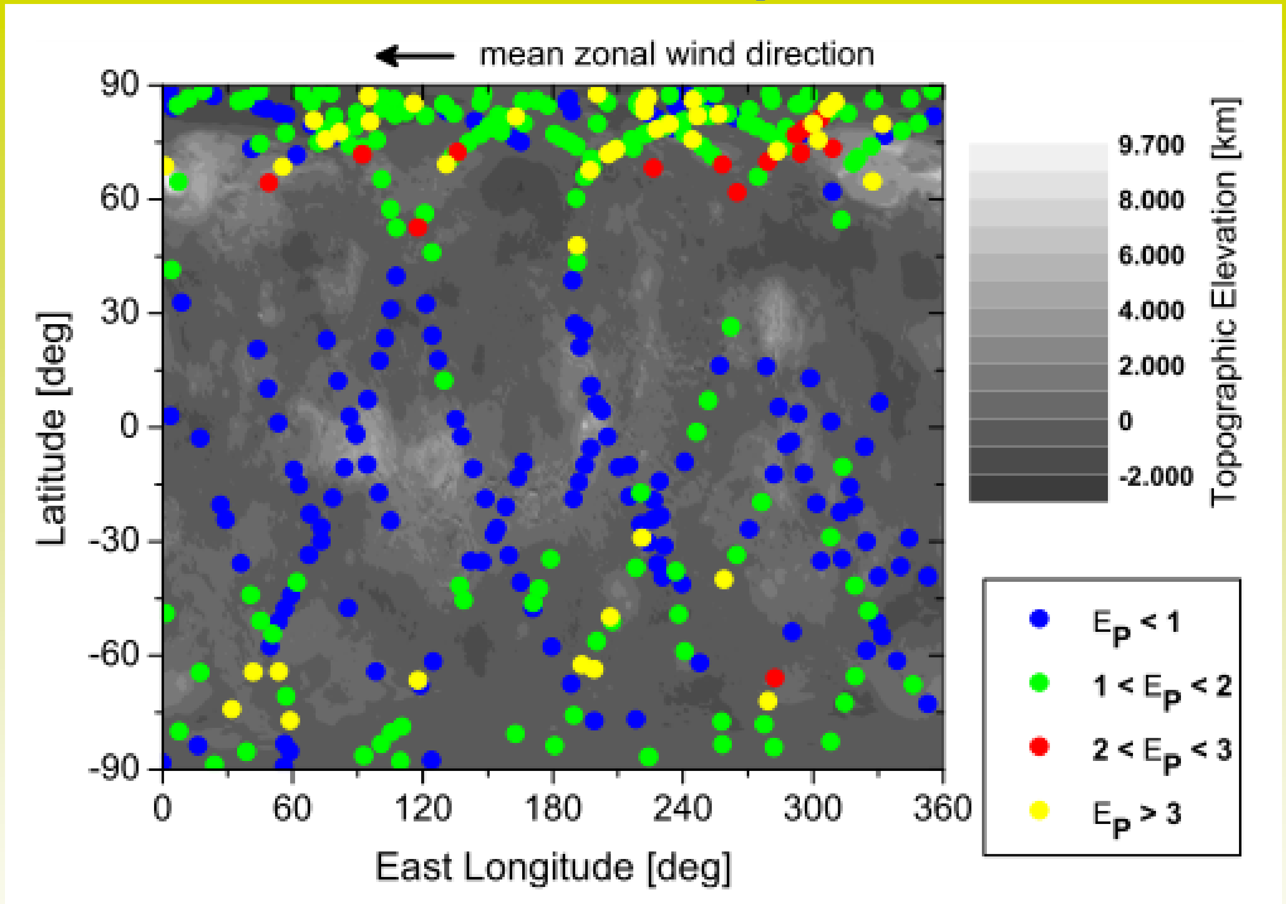

**Gravity wave propagation**
**Wave breaking**

**Thin inversion layer ~ 1 km**

**Convective region with strong vertical gradients of velocity**

**Tellmann et al., JGR 2009**

# Discovery of Globally Distributed Gravity Waves in the Venus Atmosphere




**Global distribution of the *Potential Energy Ep* of gravity waves (altitude range 65-80 km) detected by VeRa. Background: Topography measured by Magellan.**

**Tellmann et al., Icarus, 2012**



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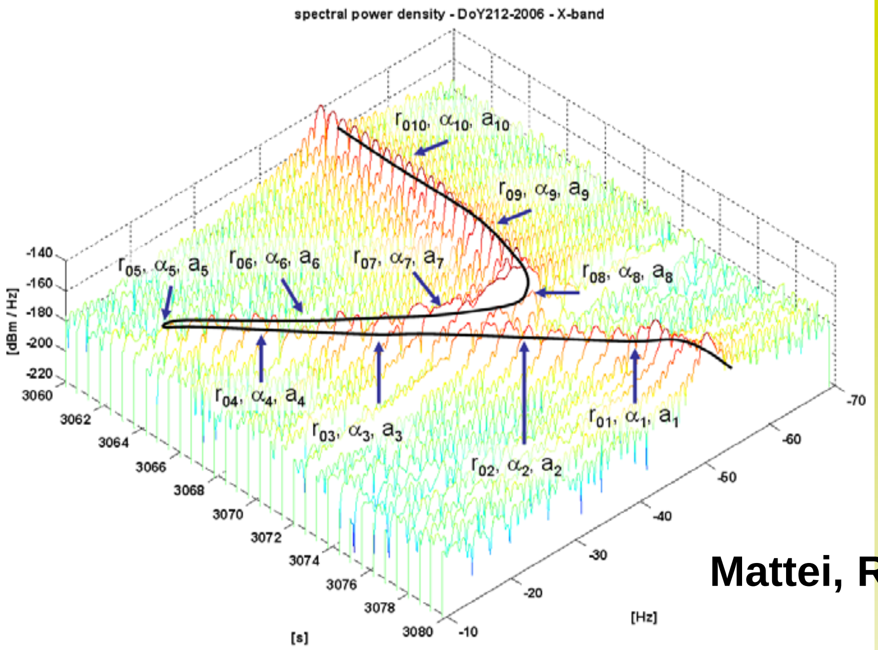
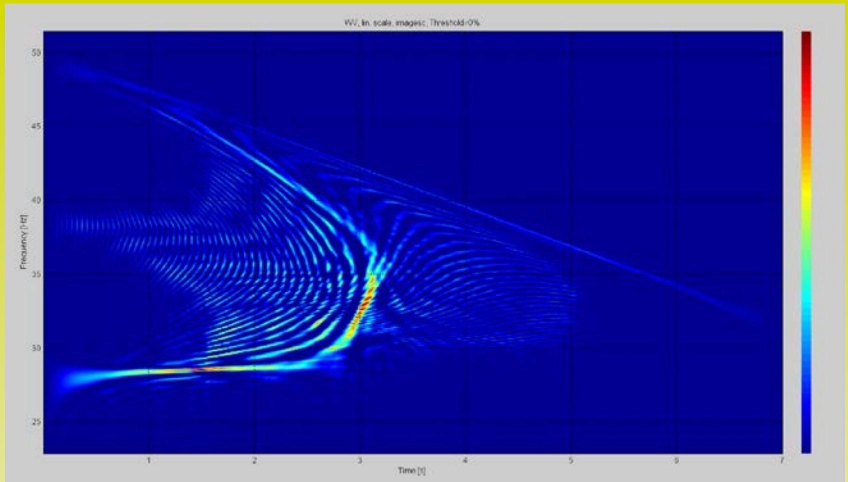
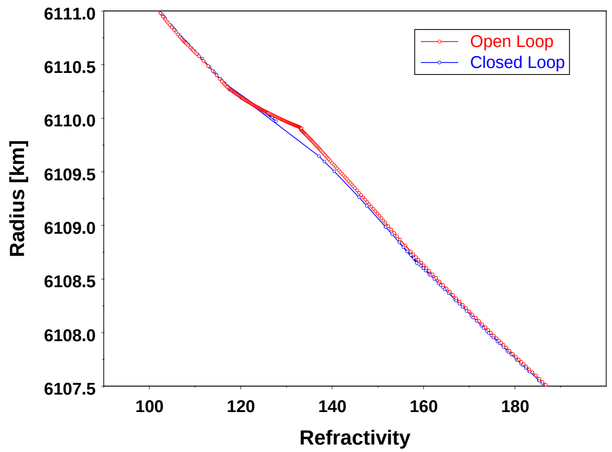
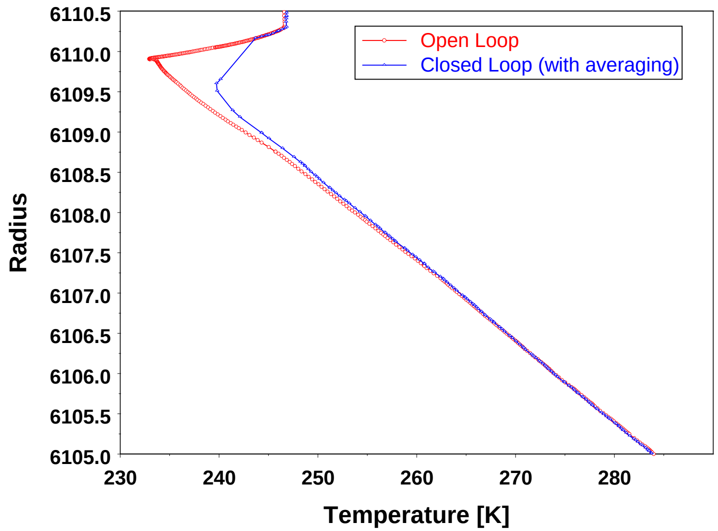
# OL Processing of Multipath Effects Based on Wigner-Ville Transformation (see also Herrmann et al. Thursday presentation)



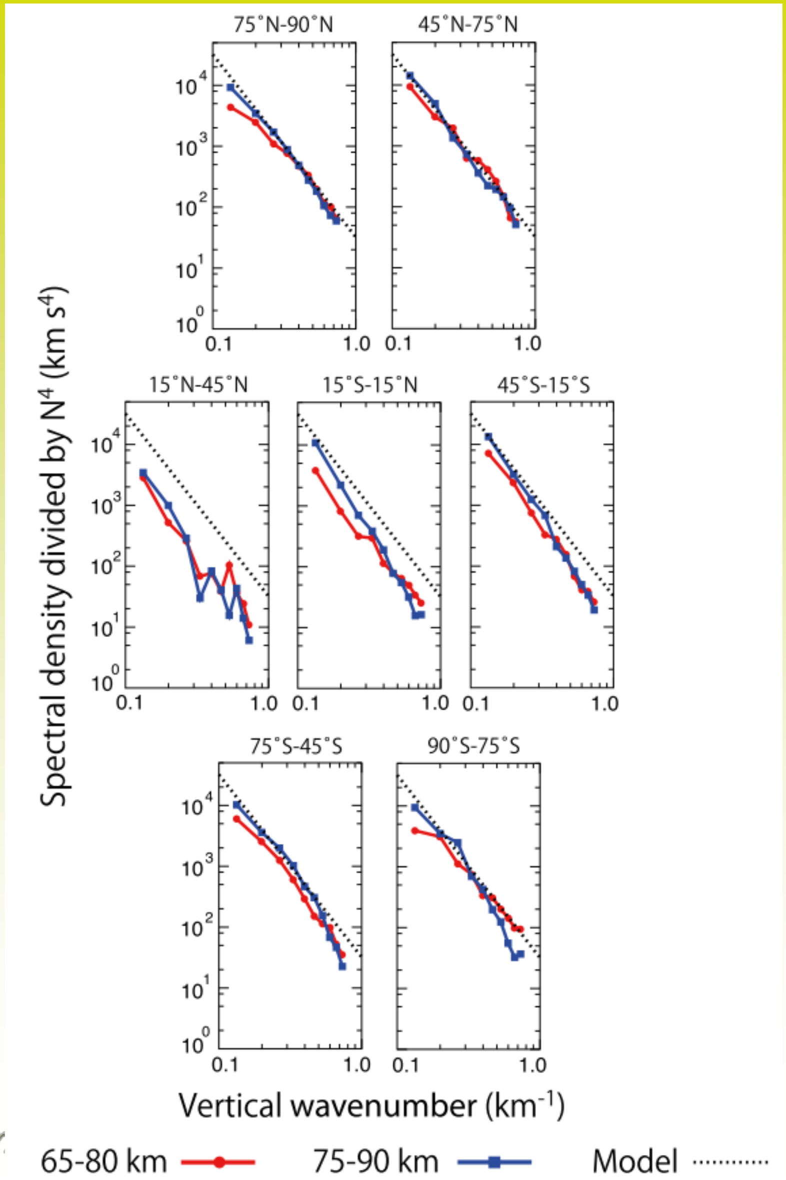
Mattei, Remus, 2010




**1 km" thick" Inversion layer not detected every pass – but almost.**

# Discovery of Saturated Gravity Wave Spectra and Turbulence in the Upper Mesosphere




***Power Spectral Density of vertical wave number spectra divided by $N^4$ in the altitude interval 65-80 km and 75-90 km in selected latitude intervals .***

**Shown also semi-empirical saturation curve (dotted).**

**Vertical diffusion coefficient : 2.7-31 (m2s-1)**

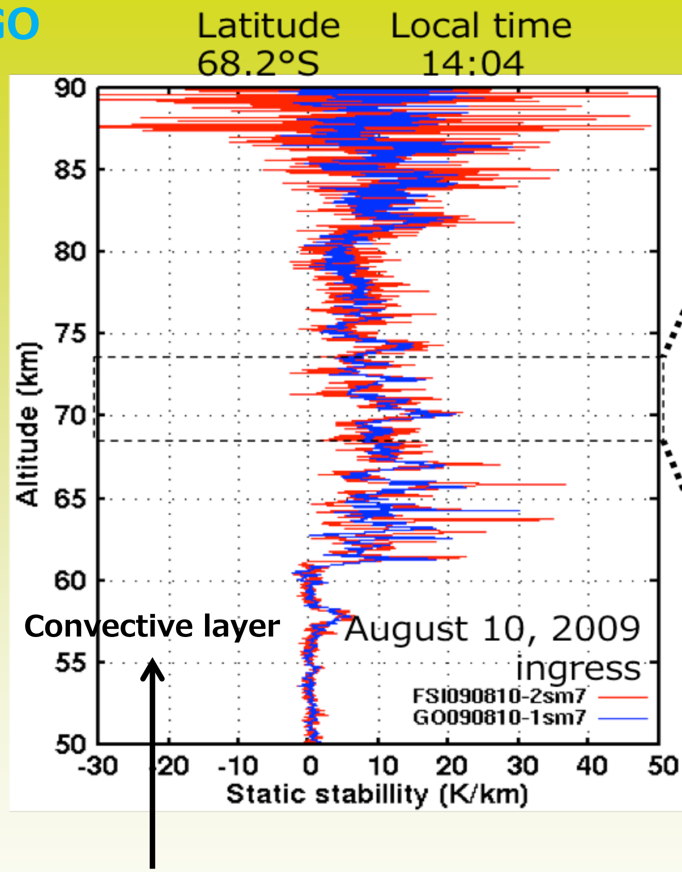
**Ando et al., JAS, 72, 2015**

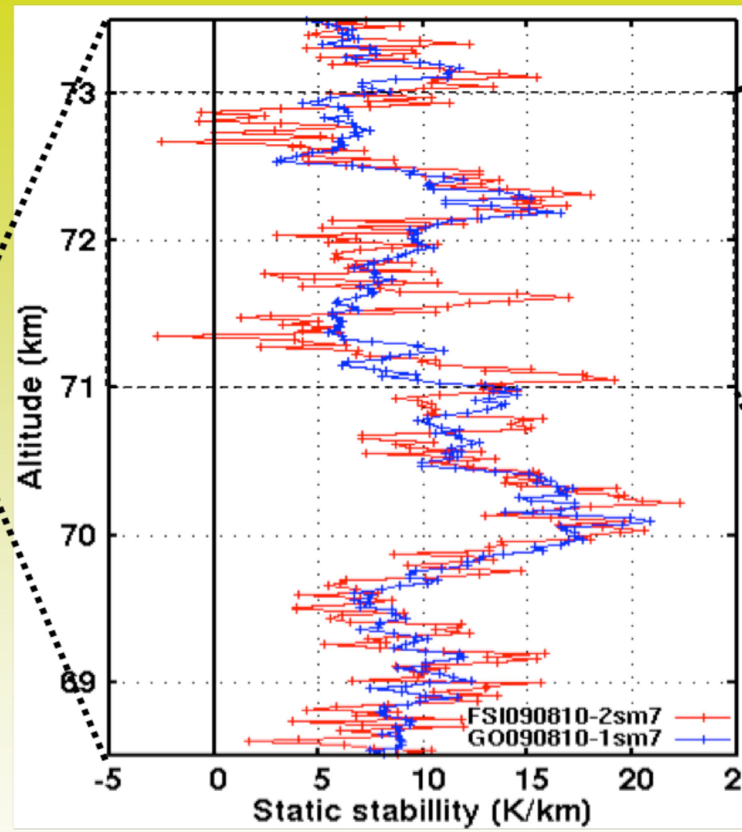
# Static Stability Profiles Analyzed with the OL – FSI Technique
# Small Scale Fluctuations – Thin Near Neutral Layers

FSI

GO

**Vertical Resolution 70 m**

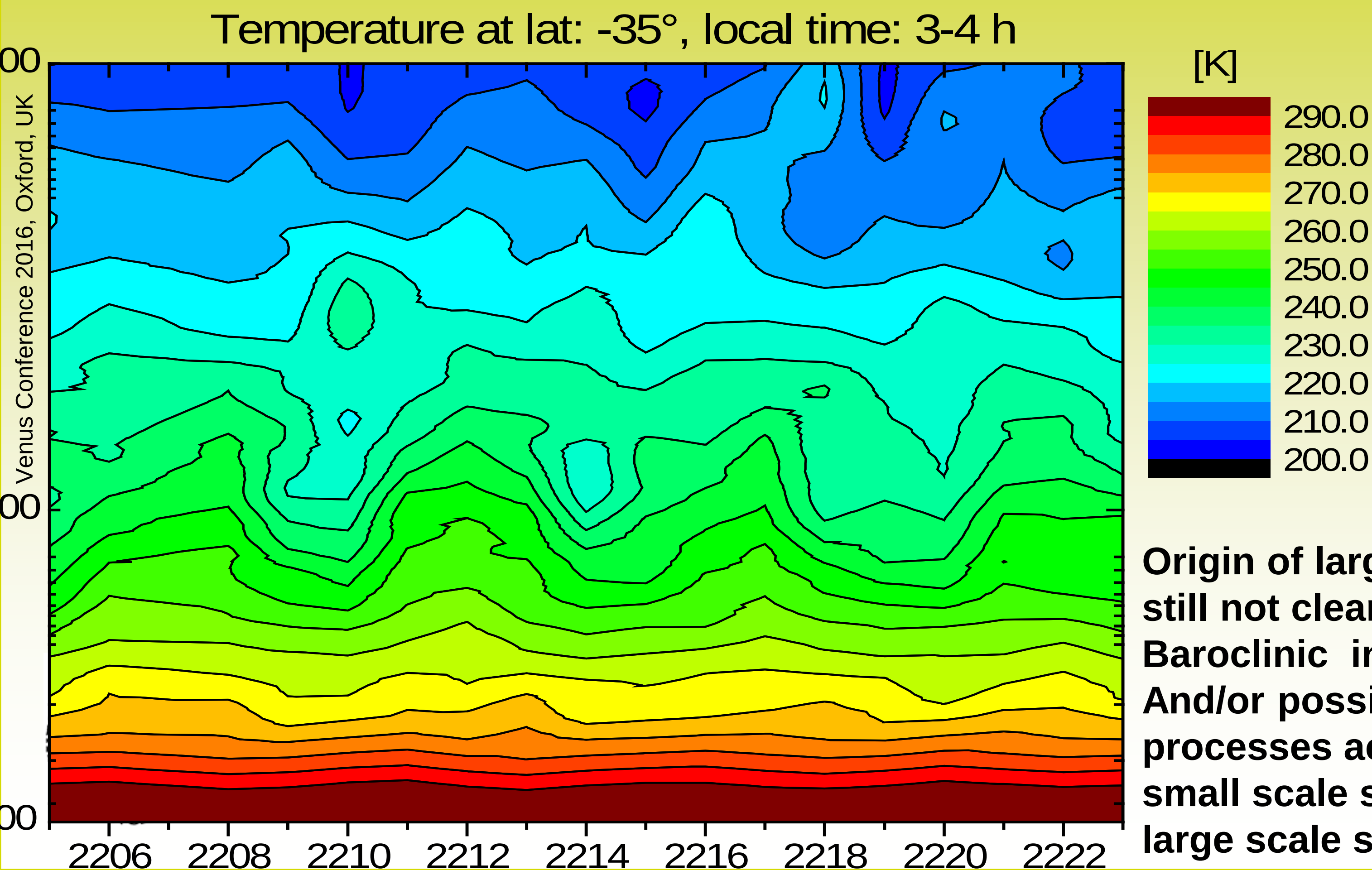



**Thin, near-neutral layers are frequently found above ~60 km altitude in the high-resolution static stability profiles obtained by FSI in the middle and high latitude. Indication for turbulence.**

**Miyamoto et al., 2015**

# ~ 4 Day Variations at Constant Latitude and Local Time
# Presence of Planetary Wave
# (possibly vert. propag. Rossby/Kelvin Wave)
## - see Presentation by Tellmann et al. (Thursday) -






**Origin of large scale structure still not clear:**
**Baroclinic instability?**
**And/or possibly turbulent processes acting transfering small scale structures into large scale structures?**

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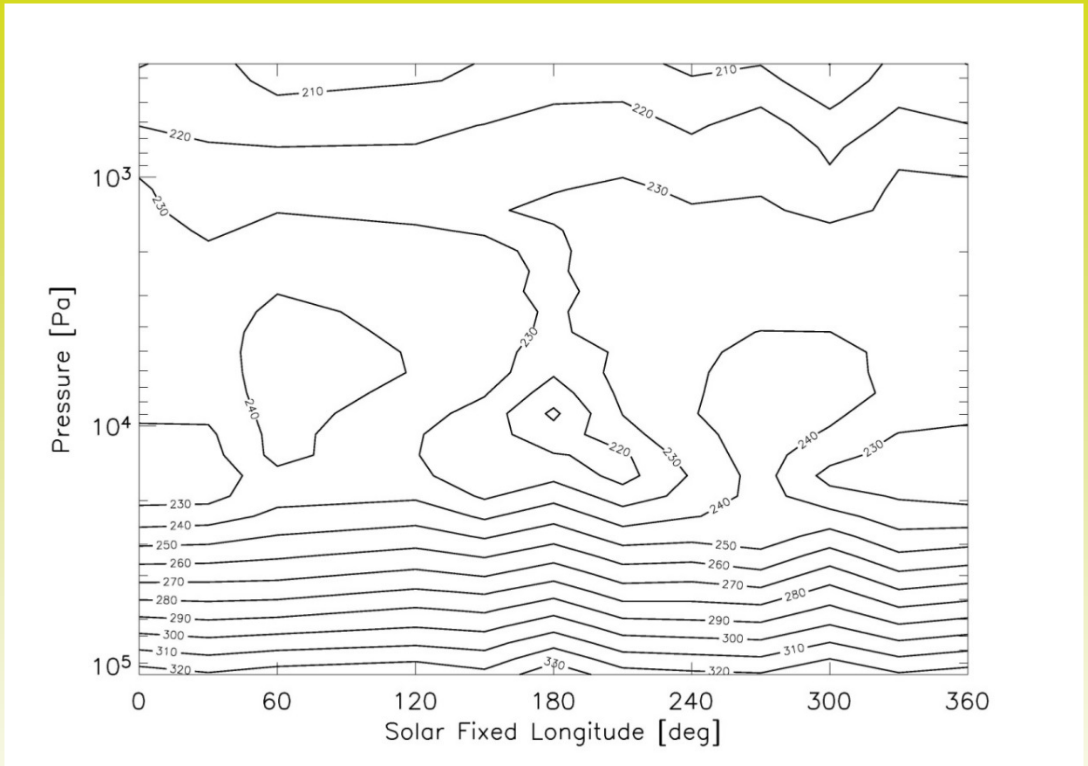
# Solar Induced Effects above Tropopause at 75° - 85° Lat.
# Presence of Wave # 2 Structure




Noon

Evening

Midnight

**Coldest temperatures located at the subsolar and antisolar points.**

**Tellmann et al., JGR, 2009**



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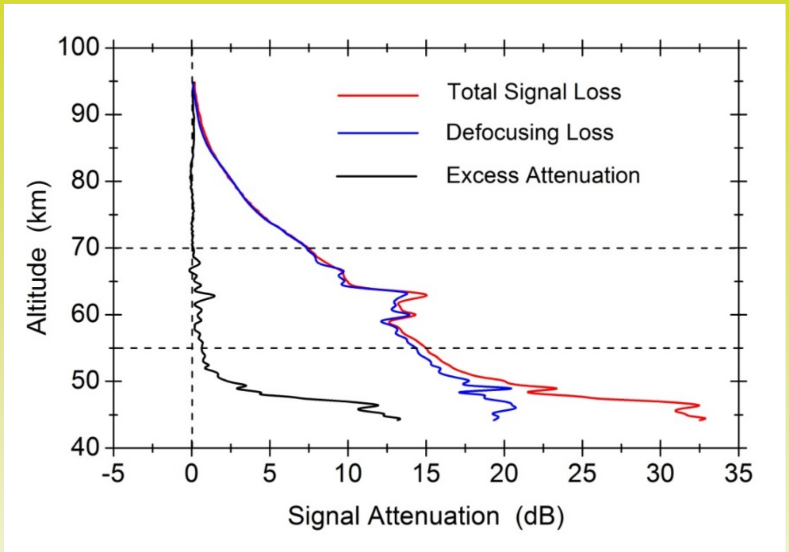
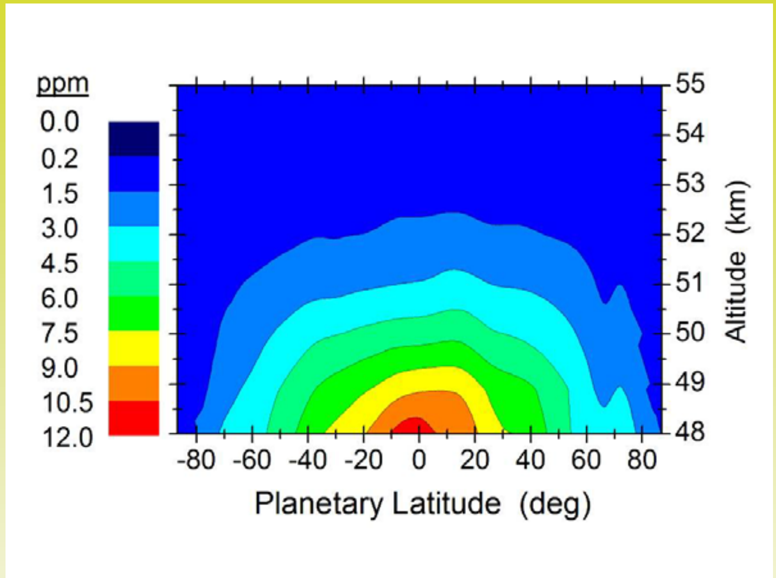
# $H_2SO_4$ g Absorption Effects Observed by VeRa
# - Presentation by J. Oshlisniok this Tuesday -




**Model is being developed supporting the picture of a meridional transport of H2SO4 g condensing into droplets in the upward branch and evaporating again in the downward branch of the Hadley cell assuming a significant polar depression.**

**350 Profiles between 2006 and 2014**

**J. Oschlisniok et al., 2016**

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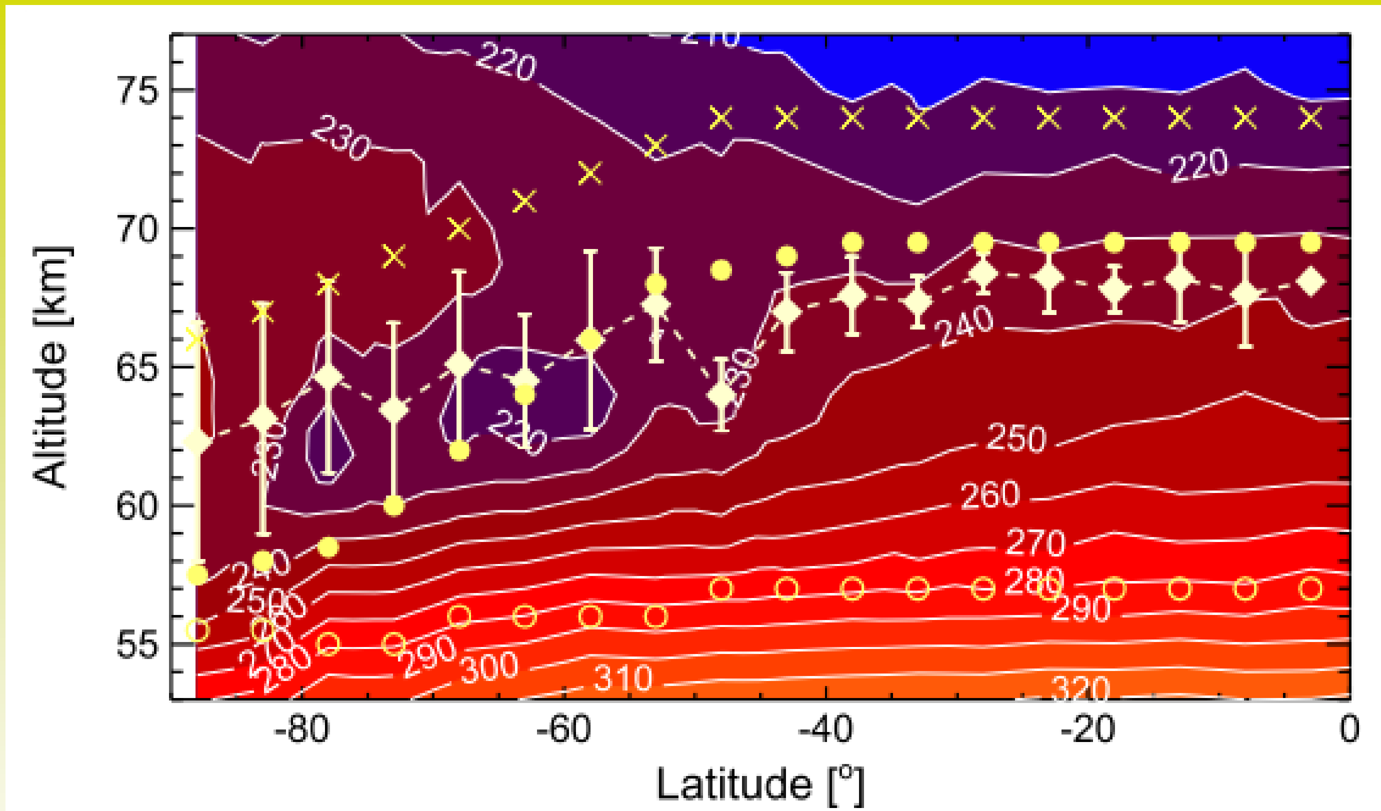
# Latitude Dependence of the Cloud Top Altitude

## - Presentation by D. Titov this Tuesday -



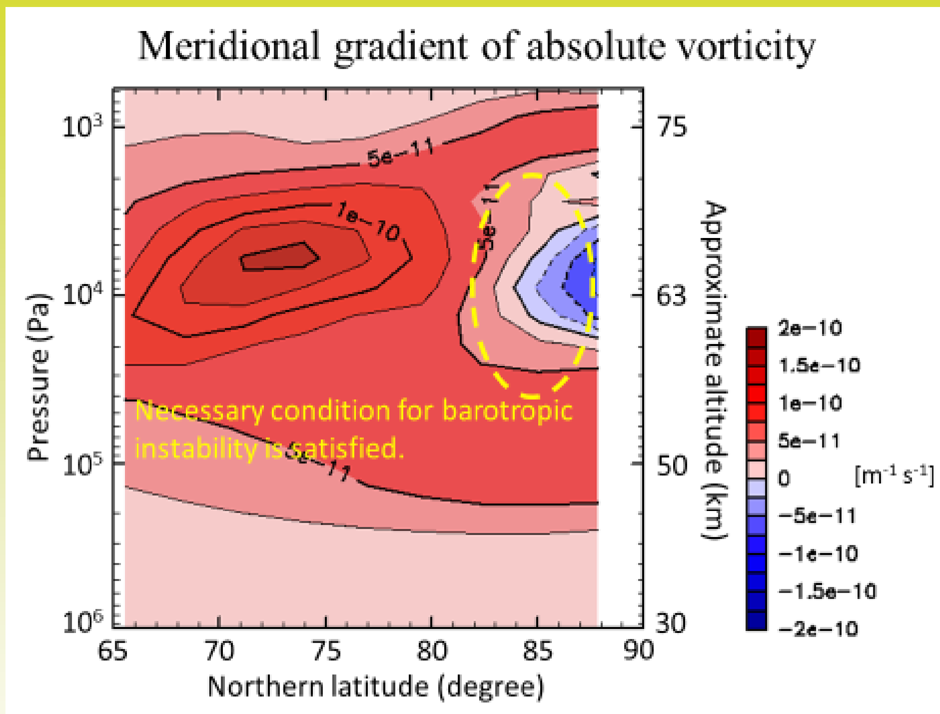

**Background: VeRa temperature field**
**Crosses: VIRTIS (near IR)**
**Filled and open circles: Venera 15 (mid-IR)**

**Data suggest an increase of particle size in the upper cloud from equator to pole**

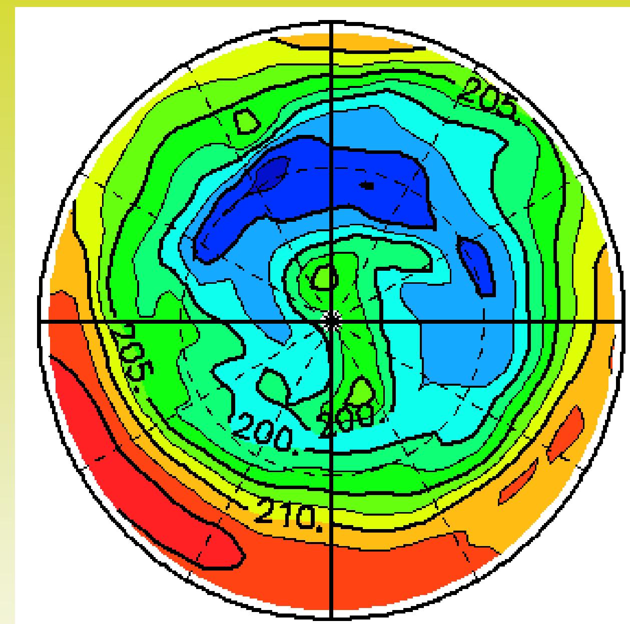
**Lee et al., Icarus, 2012**

# Simulation of Barotropic Instability in the Venus Atmosphere - Polar Vortex

## - Presentation by H. Ando this Thursday -




**Instability criteria met**
**Change of sign of dq/dφ**




**Circumpolar temperature distribution as simulated by AFES**

**Verical temperature structures from VeRa used qualitatively**

**Ando et al., 2016**

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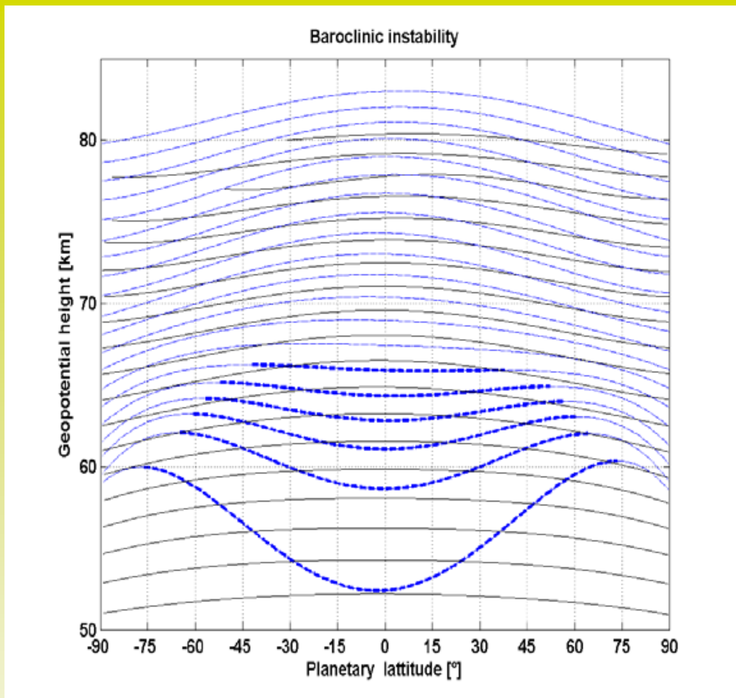
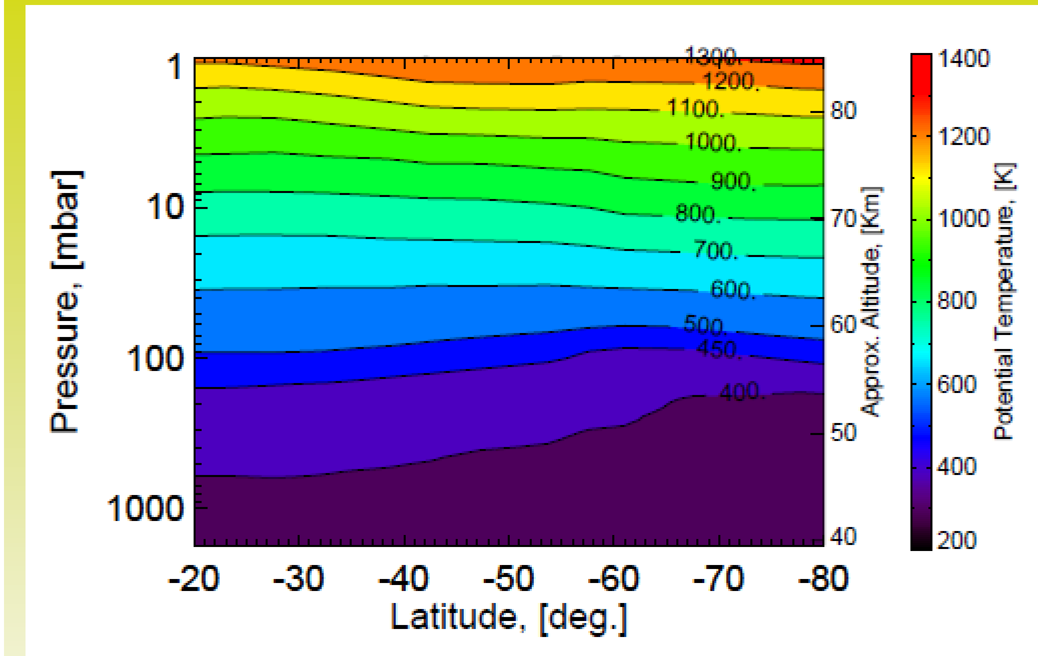
# Baroclinic Structure of Venus Atmosphere in the Cloud Layer




----- potential temperature
—— pressure

**Picciali, 2010**

**Häusler, Andert, 2010**

**Instability criteria must be met.**
**Unstable modes can develop in regions of low static stabillity with large gradients of zonal velocity creating planetary scale waves.**

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# Thank You
# For Your Attention



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