der Bundeswehr
Universität München

Radio Science
Instrumentation and Technical Aspects

Bernd Häusler

Institute for Space Technology and Application
Universität der Bundeswehr München

Planetary Probe Workshop Short Course

Cologne, June 13, 2015

Contents

- Introduction – Our Partners

- Radio Science General

- Radio Science mission and experiments

- How to Measure…..? – The Way to Proceed

- Measurement Techniques

- Science Results

Introduction

Our Partners in Radio Science

- 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 (S. Asmar, T. Thomson)
- ESA (ESTEC, ESOC, ESAC) (S. Remus, H. Svedhem)
- DLR (DLR-Bonn)

Radio Science General

Uses ultrastable frequency sources, the precise knowledge of space and time reference systems of the space probe and ground station

Measurement accuracy: < 1 mHz @ 8 GHz

Needed frequency stability $\Delta f/f$ [illegible] 10^{-13} (Δv [illegible] 0.1 mm/s)

Signal propagation times: $\tau \approx 1$ nsec ($\Delta r = 30$ cm)

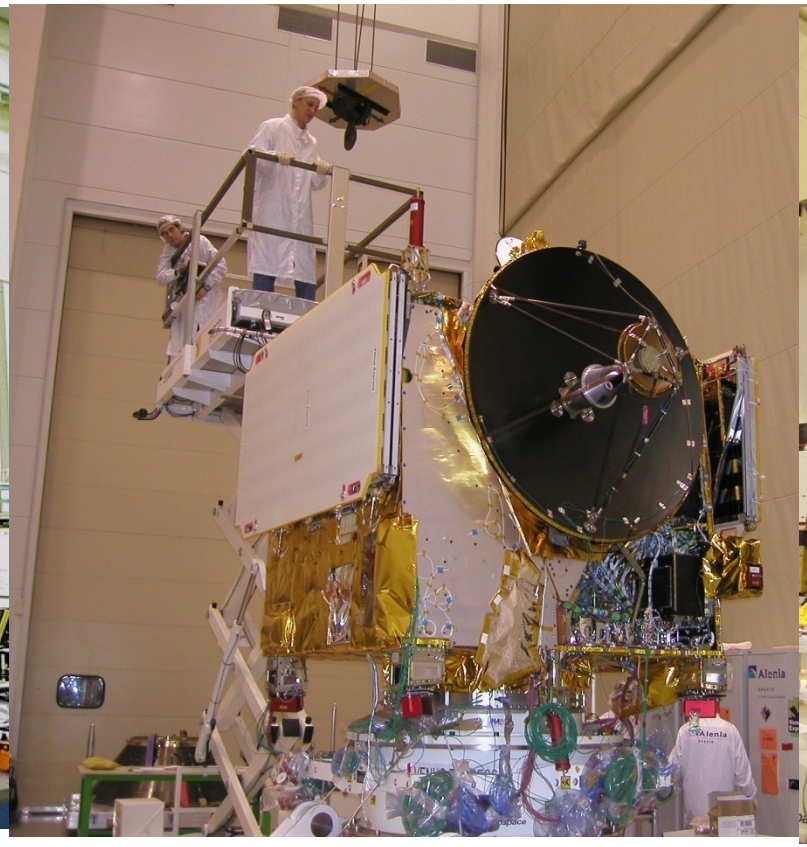
Realisation in space by ultrastable quartz oscillators/rubidium clocks
Realisation in ground station by H2 Maser

Radio Science Mission and Experiments

Universität der Bundeswehr München

Recent ESA Missions with Radio Science Involvement

Rosetta **Venus Express** **Mars Express**



How to Measure….. ?

for Example: The Structure of Planetary Atmospheres and Ionospheres

The Way to Proceed (1)

Define your observables (frequency, phase, amplitude, polarization, time resolution)

Start your work with a radio link analysis
Do you have enough C/N? (> 10dB?)
What kind of ground stations are available?

What kind of transmission and reception techniques will you select?
(One-Way, Two-Way, Dual Frequency, Closed Loop, Open Loop)

Define the reference frequency source (USO onbord, H2 Maser on ground?)

The Way to Proceed (2)

Adopt the mission concept
(Orbit and attitude dynamics, ground station coverages, time bases, reference systems, questions related to Special and General Relativity)

Dynamically simulate with high (astronomical) precision your experiment in accordance with the mission concept
(Antenna pointing angles, expected frequency shifts and power levels, ground station visibilities)

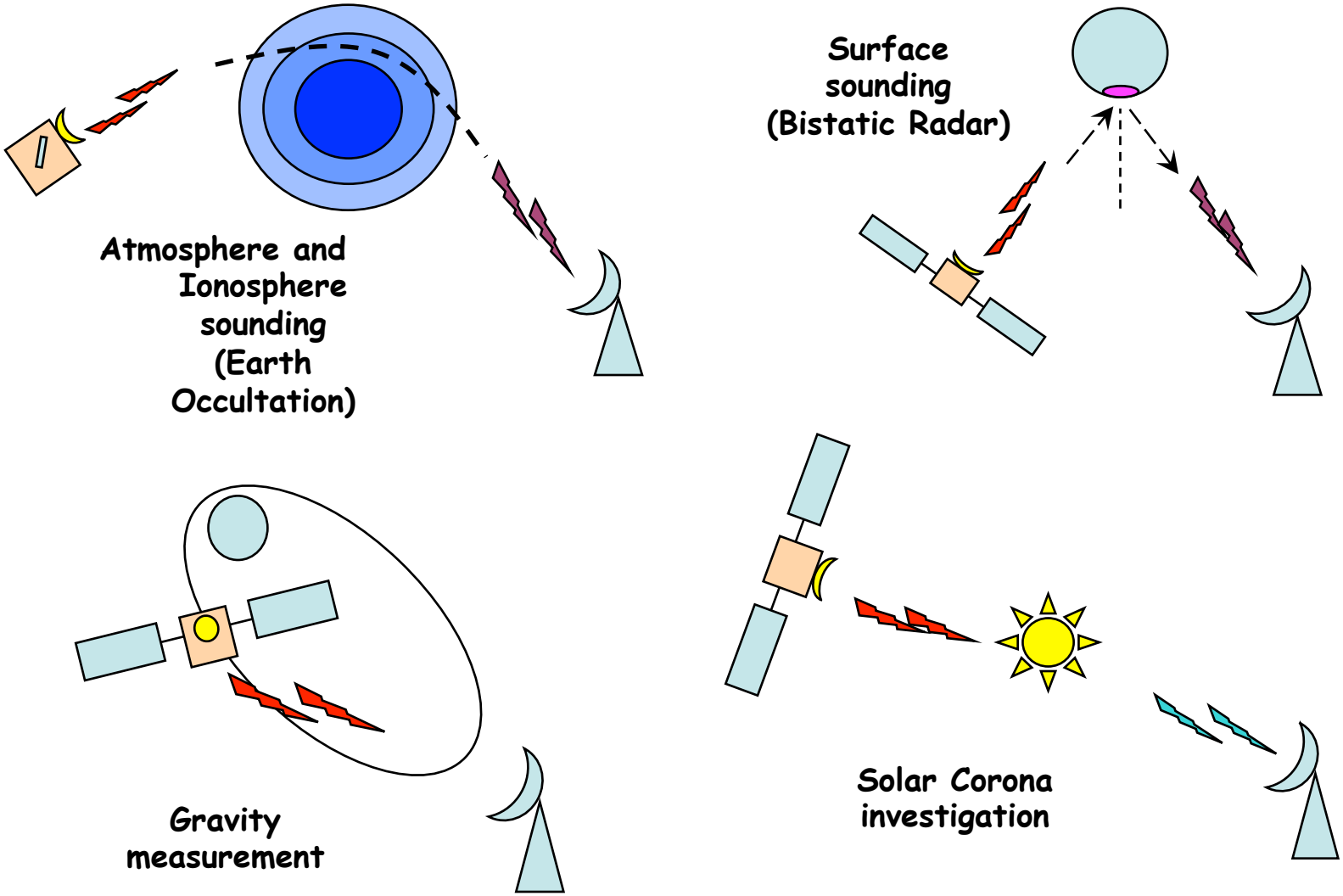
(Mission Ops will ask you!)

You will need a sophisticated software simulator tool!

You will also need a dedicated rf test/calibration station to check your instrument (ultra stable clocks, frequency generators, spectral analyzers, phase detector)

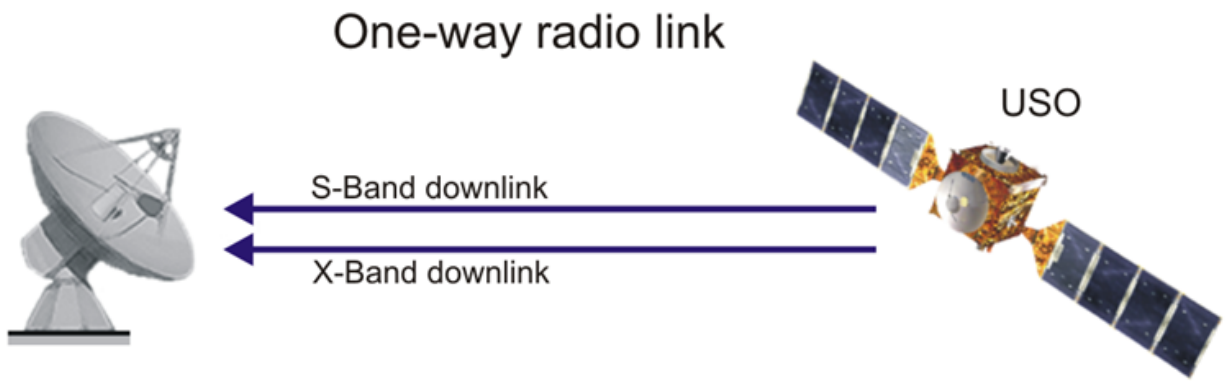
Radio Science Measurement Techniques

Radio Science Experiments Overview

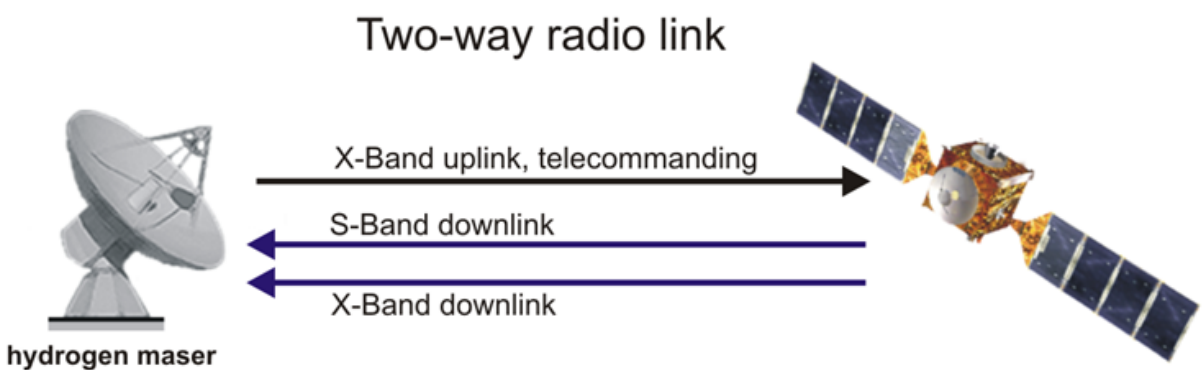


R. Mattei et al.

Radio Science Measurement Techniques



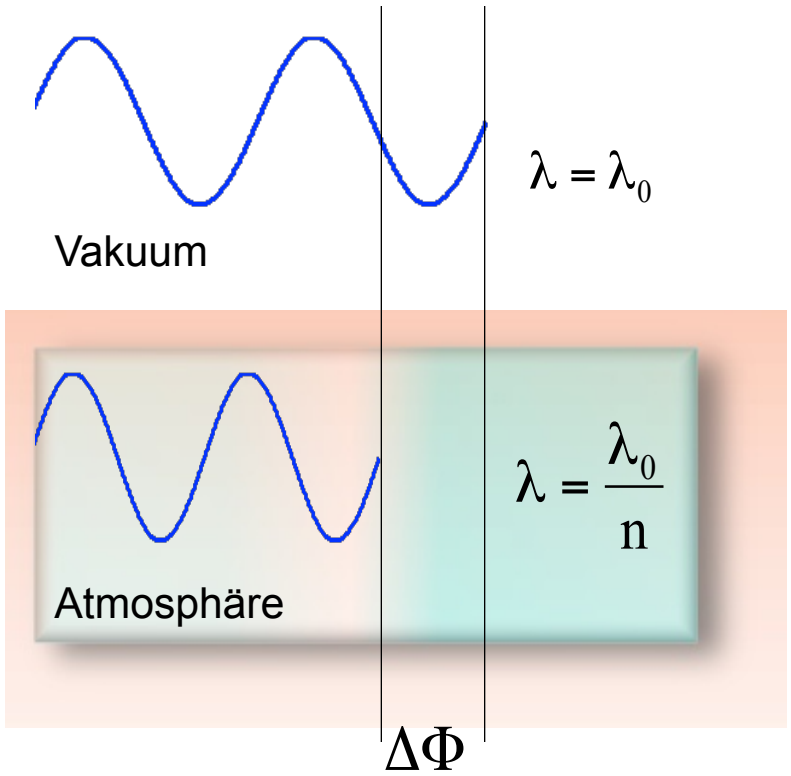
In principle an uplink experiment is also possible, see New Horizon/REX



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

Propagation of an Electromagnetic Wave through a Medium with Refraction Index n)

Change of optical pathlength as a function of time causes @ the groundstation a phase/frequency change wrt vacuum



$$\Delta l = \int n ds$$

$$\Delta\Phi = \frac{2\pi\Delta l}{\lambda_0} = \frac{2\pi}{\lambda_0}\int n ds$$

$$\frac{1}{2\pi}\frac{\Delta\Phi}{\Delta t} = \Delta f = \frac{1}{\lambda_0}\frac{d}{dt}\int n ds$$

$$n = 1 - \frac{40.3\left[\frac{m^3}{s^2}\right]\cdot N_e}{f^2}$$

Neutral Atmosphere: n > 1 Plasma: n < 1

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

How does this work? (Example: One-Way Transmission)

Refraction index of a plasma

$$n = 1 - \frac{40.3\left(m^3 s^{-2}\right) N_e}{f^2}$$

40.3 is not just a number

Group/Phase increase/ reduction

$$T_{gr/ph} = \int \frac{ds}{v_{gr/ph}} = \frac{s}{c} \pm \frac{40.3}{c\, f^2} \int_0^s N_e\, ds$$

Received phase

$$\theta_R(t) = 2\pi f_T \left[t - \frac{s(t)}{c} + \frac{40.3}{c\, f_T^2} I(t) \right]$$

Measured frequency @ ground station

$$f_R(t) = \frac{1}{2\pi} \frac{d\,\theta_R}{dt} = f_T \left[1 - \frac{\dot{s}}{c} + \frac{40.3}{c\, f_T^2} \dot{I}(t) \right]$$

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

How does this work? (Example: One-Way Transmission)

Observed frequency shift

$$\Delta f = f_T - f_R = f_T \cdot \frac{v}{c} - \frac{40.3}{c f_T} \dot{I} = f_T \cdot \frac{v}{c} - \frac{40.3}{c f_T} \int_o^s \frac{dN_e}{dt} ds$$

The observed frequency shift depends on:
Non dispersive and dispersive effects, i.e. orbital dynamics, neutral atmosphere and plasma

When using 2 *coherent* frequencies (for example X/S Band with frequency ration 11/3) we can derive on ground the so-called:

Differential Doppler

$$\Delta f_s - \tfrac{3}{11} \Delta f_x = \frac{40.3}{c} f_s \left(\frac{1}{f_x^2} - \frac{1}{f_s^2} \right) \dot{I}$$

which allows to isolate the plasma contribution

After having isolated the plasma effect
(ionosphere: typical 24 hr average 30-100 hexems
Solar corona @ 5 R_e : ~ 400 times ionosphere!)

Electron column density: 1 hexem = 10 E16 electr./sqrm

we now want to separate the neutral atmosphere effects from the orbital effects and define a „frequency residuum ΔF“ given by:

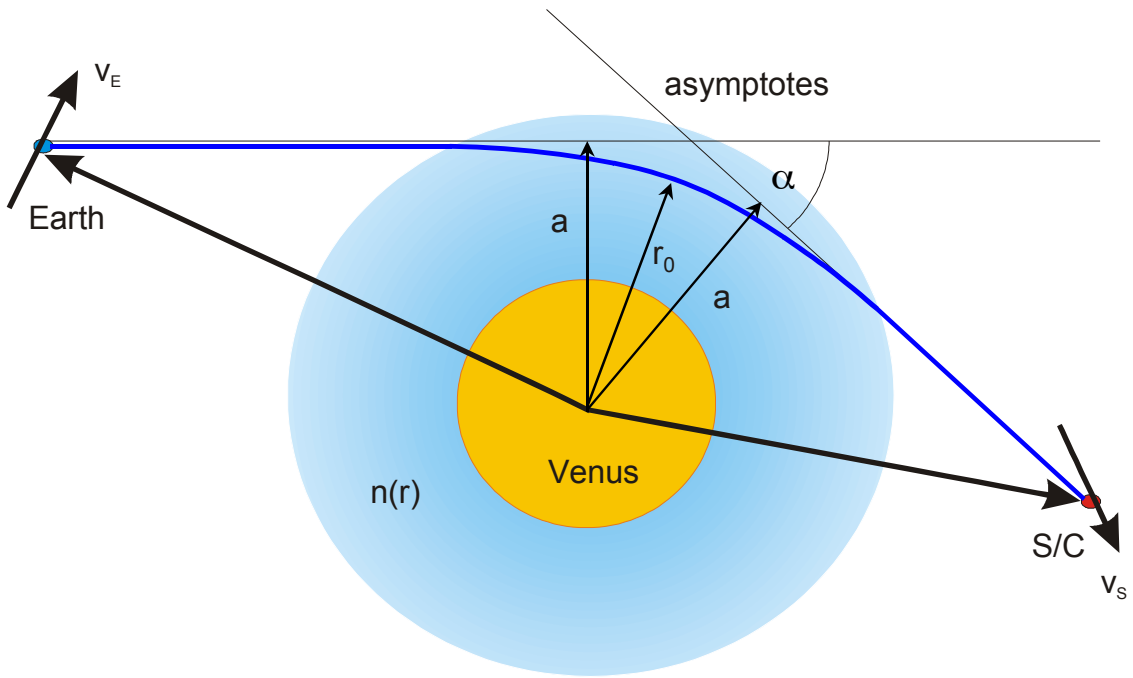
Residuum = measured frequency shift – straight line Doppler frequency shift

$$\Delta F_{atmosphere} = \Delta f_{measured} - \Delta f_{0\ (straight\,line/vacuum)}$$

It is the frequency residuum ΔF - related geometrically to a bending angle α - which carries the information about the neutral atmosphere!

The Occultation Technique

In a radially symmetric stratified atmosphere/ionosphere, the microwave ray will be bended according to the laws of optics. It is the bending angle α via the frequency residuum ΔF which carries the information on the refraction index and which will allow to derive atmospheric/ionospheric density, temperature, and pressure from.



The Occultation Technique

Prerequisits: Highly precise knowledge of positions of involved bodies, velocities, and frequencies.

Considerations of the laws of Special and General Relativity.

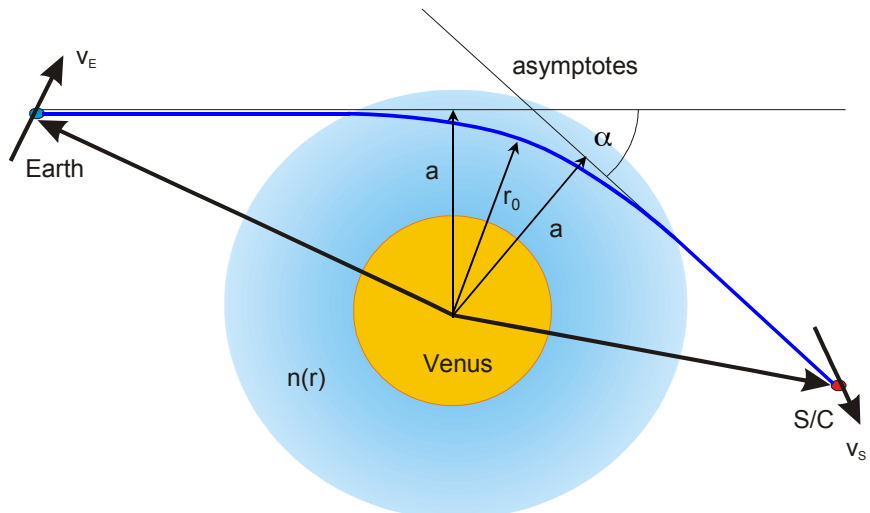
At Venus, one has to dynamically steer the radio beam in 3 axes through the atmosphere to compensate for the ray bending effect in order to maximize receiving power
(Bending angle < 10°, 3dB opening angle of antenna beam 1.7°)

Dedicated software was developed for this purpose by the Radio Science team.

Measurement sensitivity of the bending angle: $< 10^{-8}$ rad

Determination of Straight Line Doppler Effect (no Atmosphere)

- Needed to Derive the Frequency Residuum -



$$\phi = -\sum_i \frac{G \cdot M_i}{r_i}$$

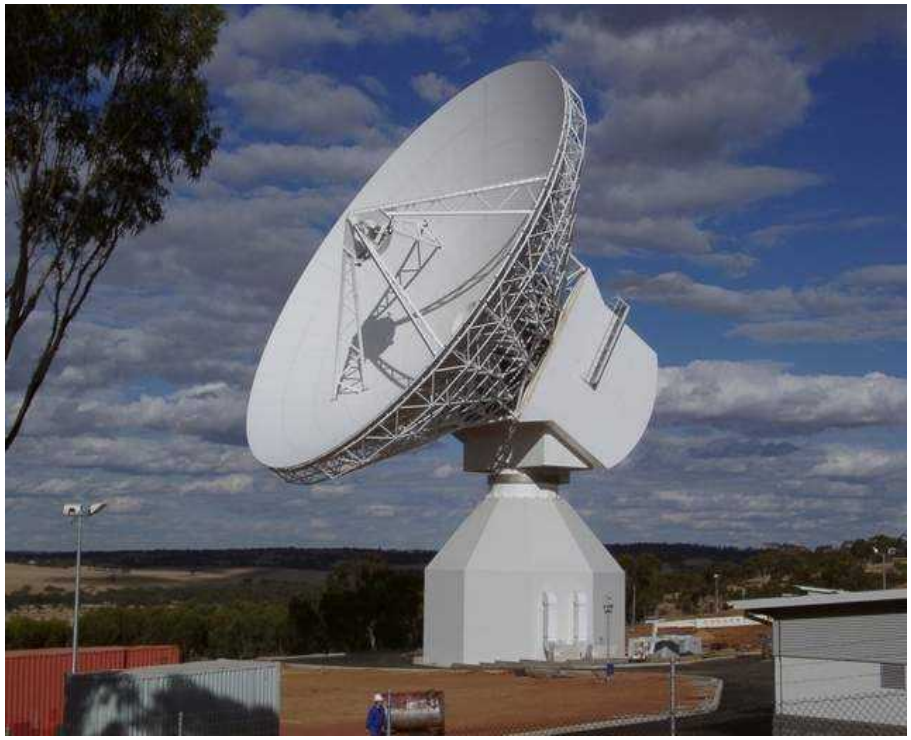
$$\beta_{S,E} = v_{S,E} / c$$

$$\Delta f_0 = f_S - f_E = f_S \left\{ \hat{\mathbf{n}} \cdot \left(\boldsymbol{\beta}_E - \boldsymbol{\beta}_S \right) + \frac{1}{2}\left(\beta_S^2 - \beta_E^2 \right) + \left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_S \right)\left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_E \right) - \left(\hat{\mathbf{n}} \cdot \boldsymbol{\beta}_S \right)^2 - \frac{1}{c^2}\left(\Phi_S - \Phi_E \right) \right\}$$

The equation is valid in an inertial, i.e. barycentric system

$\hat{n}$ **pointing unity vector from sender to receiver**

The Ground Stations



34 m station of ESA at New Norcia –Australia

70 m DSN station of NASA at Canberrra-Australia.
Used for Bistatic Radar Experiments RSI, MaRS, und VeRa

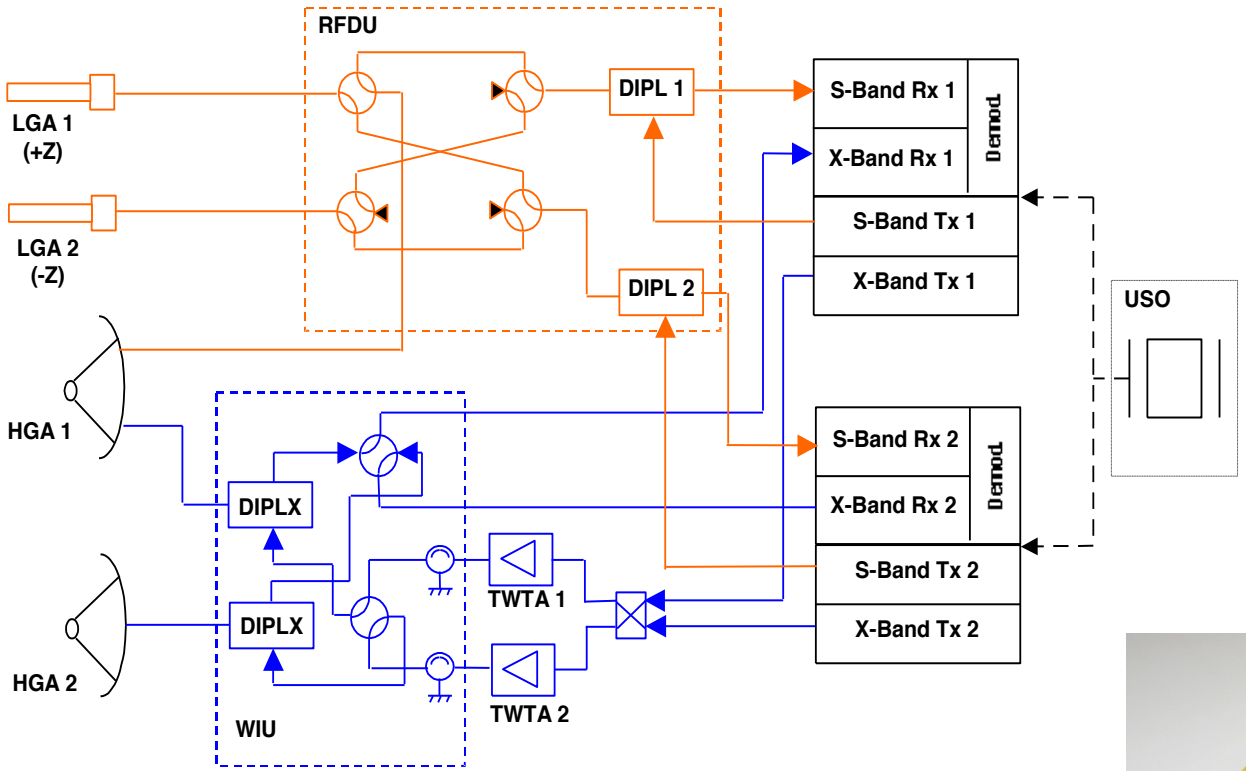
VeRa C/N Parameters for Two Ground Stations (NNO/DSS-63) as a Function of Minimum Probed Altitude for Two Venus Earth Distances, Including Losses (ONED Transmission Mode)

	S-Band 2.3 GHz		*X-Band 8.4 GHz*	
Distance (AU)	0.28	1.72	0.28	1.72
Overall C/N_0 (dBHz) NNO/DSS 63 (w/o losses)	45.1/56.4	29.3/40.3	66.8/77.6	51.0/61.8
Losses (dB) for various minimum probed altitudes r_0				
Defocusing				
40 km	26.4	26.4	26.4	26.4
42 km	24.0	24.0	24.0	24.0
50 km	18.0	18.0	18.0	18.0
Absorption				
40 km	2.1	2.1	14.7	14.7
42 km	1.8	1.8	10	10
50 km	0.1	0.1	0.5	0.5
Overall C/N_0 (dBHz) NNO/DSS 63 (including losses)				
40 km	16.6/27.9	0.8/12.1	25.7/36.5	9.9/20.7
42 km	19.3/30.4	3.5/14.8	32.8/43.6	17/27.8
50 km	27/38.3	11.2/22.2	48.3/59.1	32.5/43.3

C/N_0 can reach values ~ 0 dB at altitudes < 40km

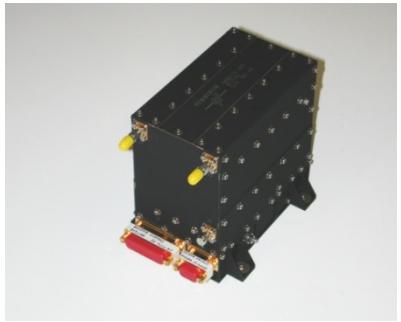
Requires special receiving techniques for carrier recovery such as Open Loop Recording

VeRa USO and the TM/TC Subssystem onbord Venus Express



$\Delta f/f \sim 3x10^{-13}$

1.5 kg
<5 W



VeRa – RSI

USO Fa. TimeTech, Suttgart

The USO

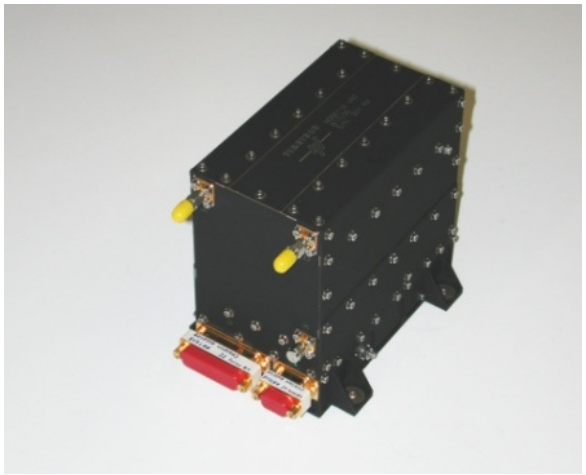
Selected as onbord reference frequency source for Rosetta and Venus Express

The inherent design of the quartz resonator guarantees an ageing rate of 1 x 10^{-11}/day after a continuous operation of 30 days.

The USO is characterized by an extreme low phase noise, resulting in an excellent frequency stability (Allan deviation ~ 3 x 10 -13 at 1-100 s).

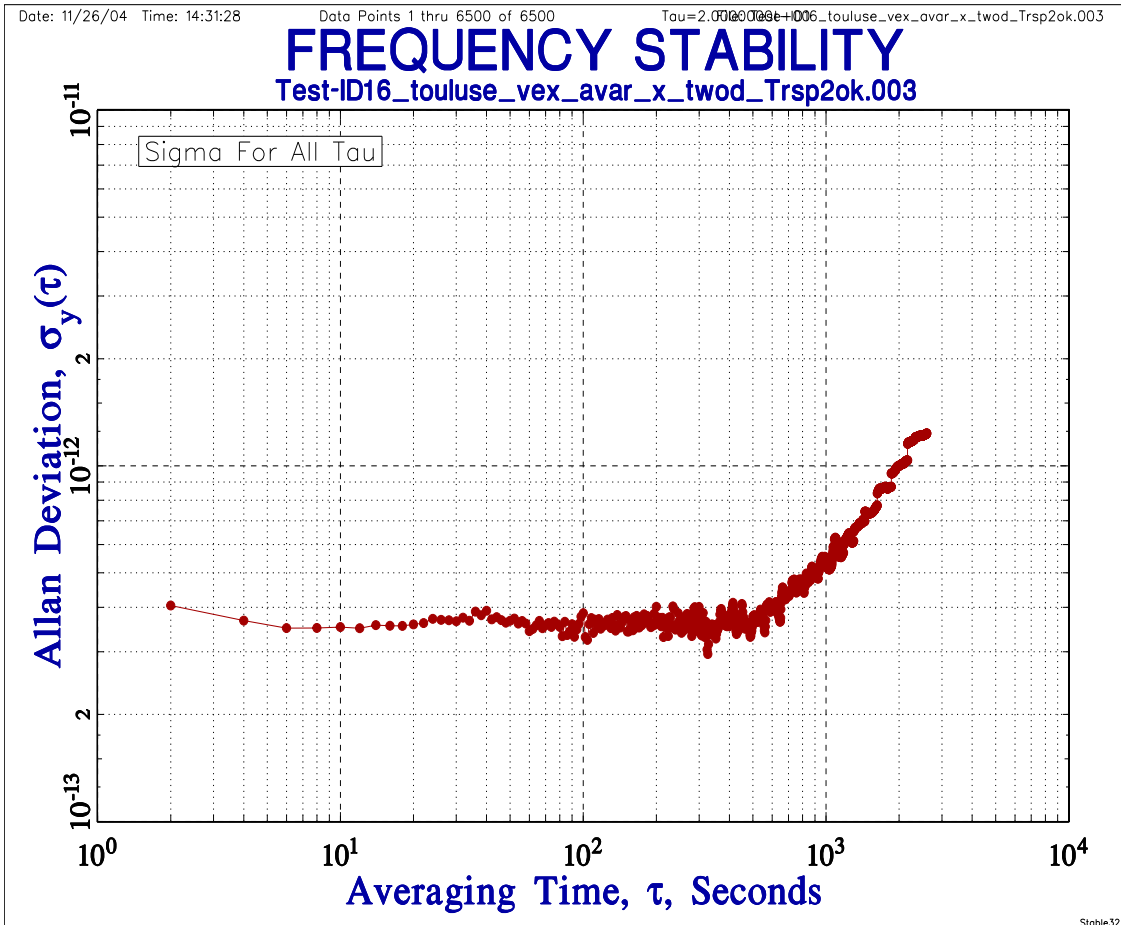
The radio frequency can be muted by a special command while the ultrastable oscillator is still powered.

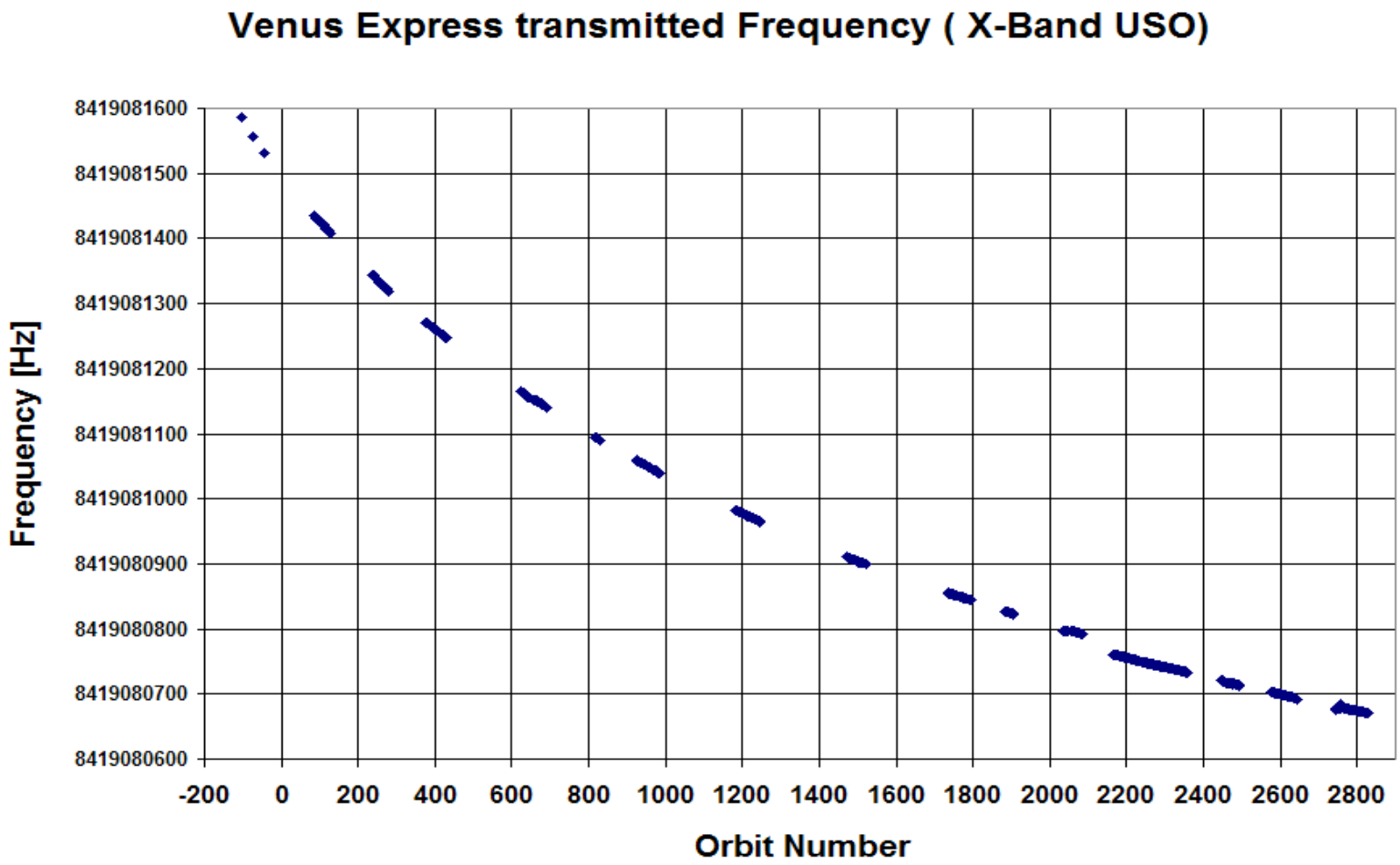
Mass: 1.5 kg, Power < 5 W, Dimensions 16 x 13 x 13 cm



Manufacturer: Time Tech Stuttgart, Germany

USO Frequency Stability
Allan Deviation

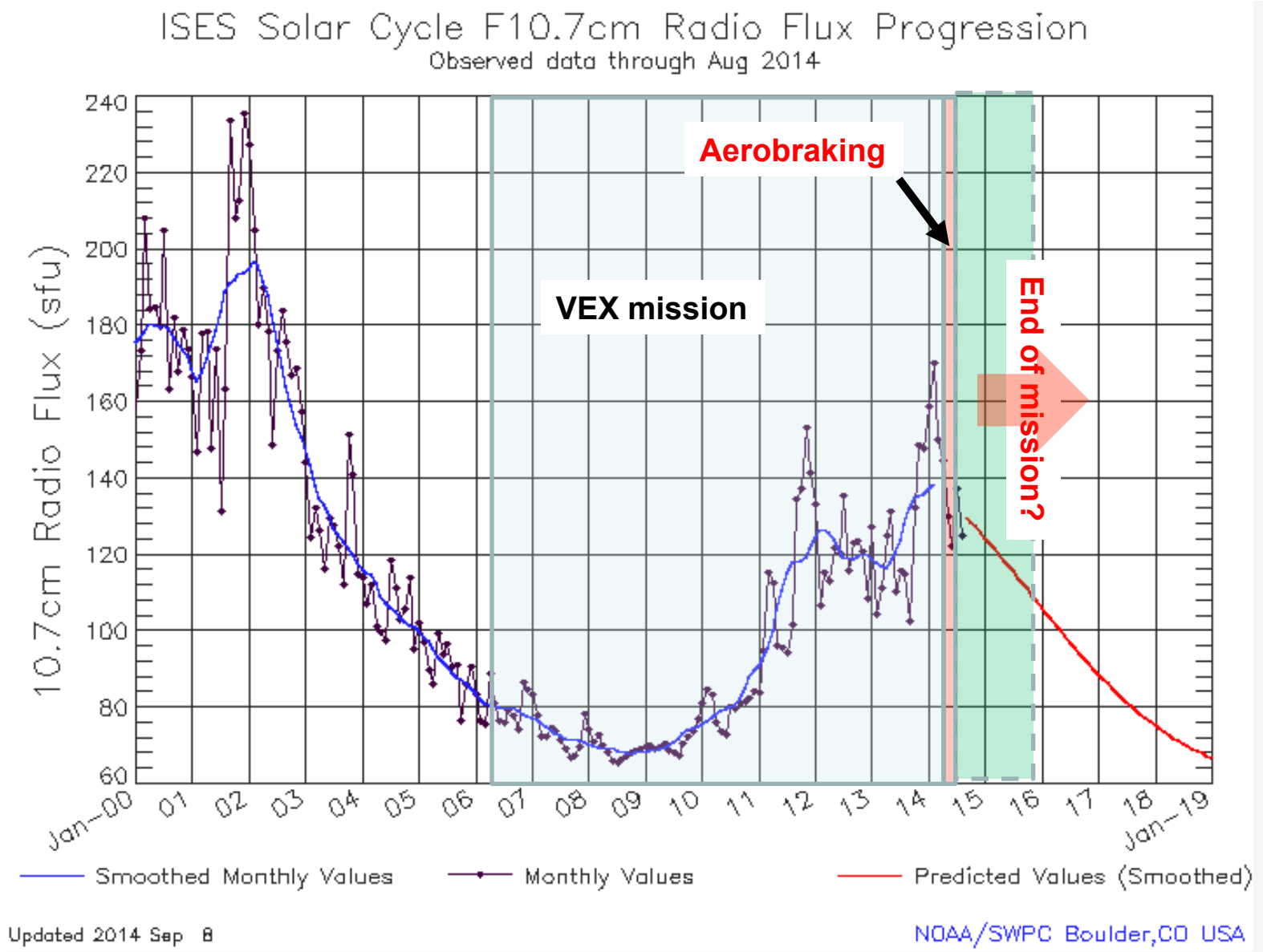




Note: X5.4 Flare occurred on orbit #2147 March 7, 2012

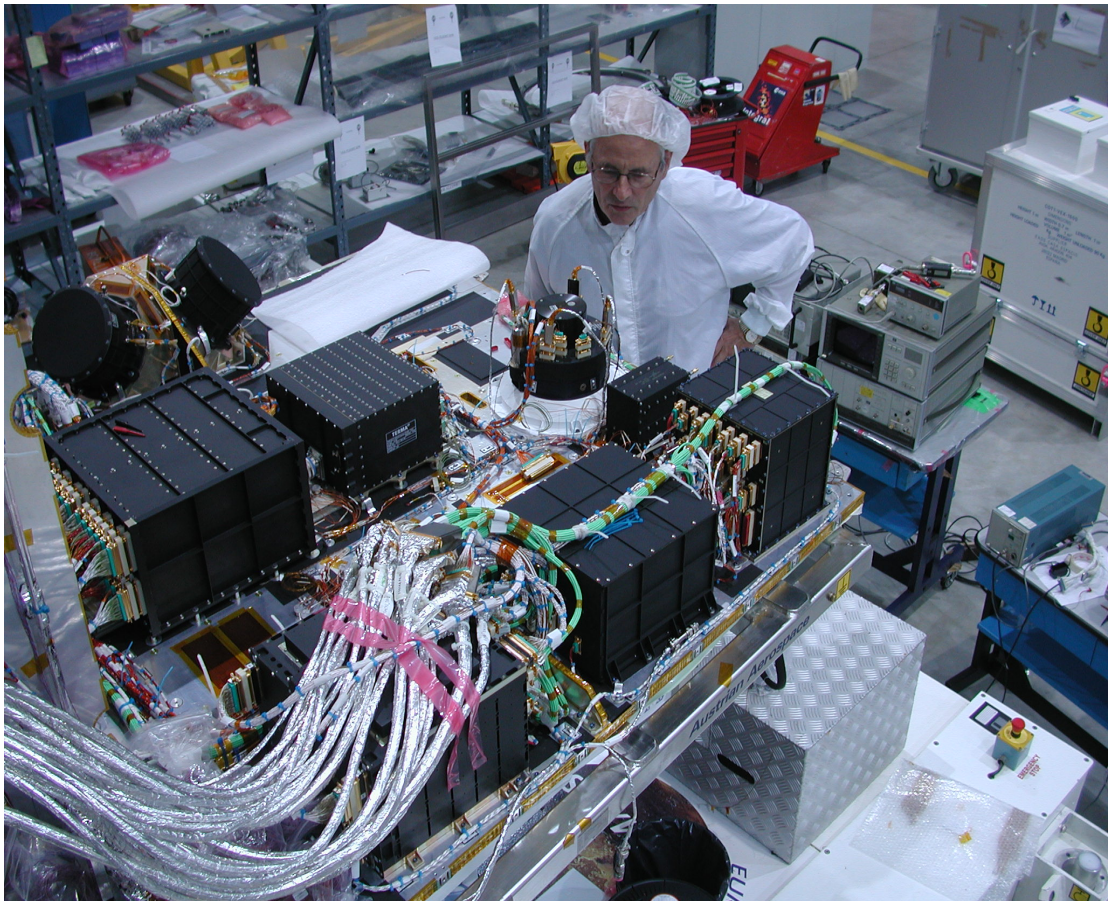
We are today (Oct. 9 2014) in orbit # ~ 3100

Solar Activity in the Venus Express Mission

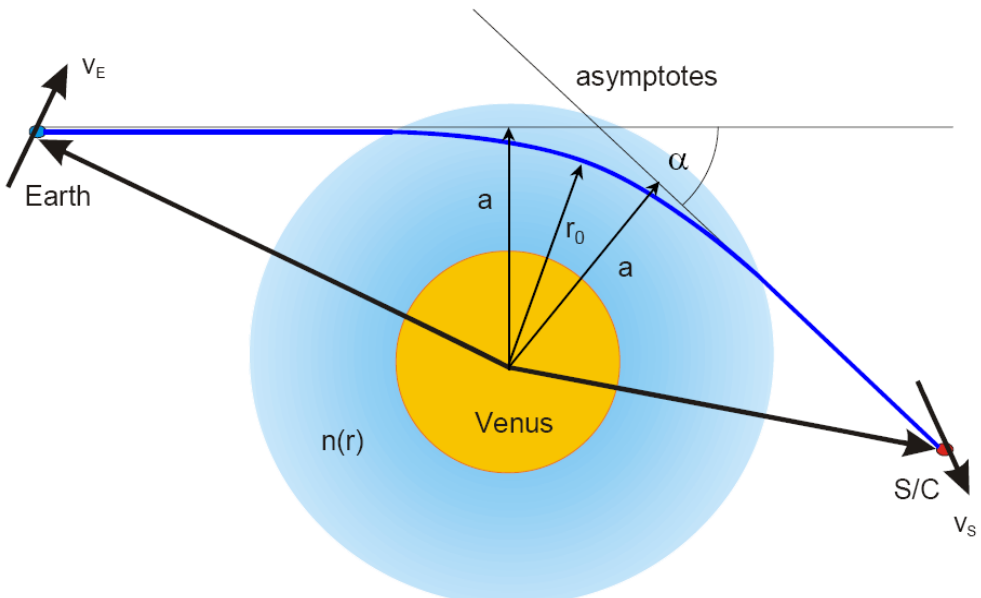


der Bundeswehr
Universität München

Integration of the USO „VeRa“ into the Venus Express Satellite, Turin, Juni 2004



Radio Science Earth Occultation Experiment: Physical Principle and Observation Geometry



• *ΔF*
• geometry

⇒ **Iterative calculation** ⇒ ***α(a)*** ⇒ **Abel transform calculation** ⇒ **Refraction index "*n(r)*"**

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

The Abel Transformation for a Radially Symmetric Atmosphere

$$\alpha(a) = -2a \int_{r=r_o}^{r=\infty} \frac{1}{n} \frac{\partial n}{\partial r} \frac{dr}{\sqrt{(nr)^2 - a^2}}$$

Abel Transformation

$$r_o = \frac{a}{n(r_o)}$$

Bougher´s law

$$\pi \ln n(r_0) = -\int_{a=a_0}^{a=\infty} \frac{\alpha(a)}{\sqrt{a^2 - a_0^2}} da$$

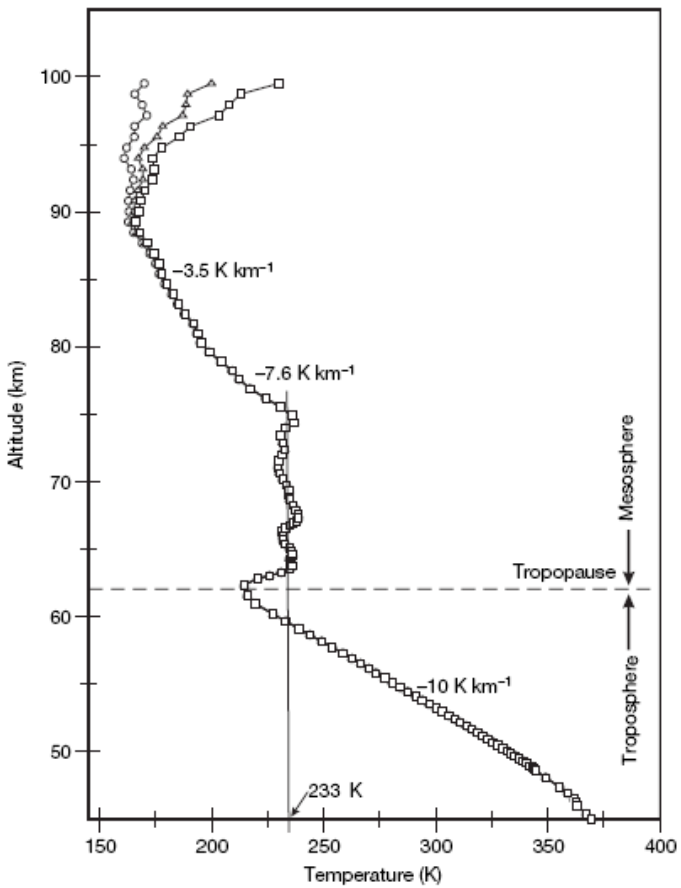
Inverse Abel Transformation

Radio Science Experiment VeRa

Derivation of atmospheric vertical profiles of *Temperature*, *Pressure*, *Density*

Refraction index ***n(r)*** ⟹ **Refractivity** $\mu(r)$ $\mu = (n-1)\cdot 10^6$ ⟹ **Ideal gas law** ⟹

- $T(r)$
- $p(r)$
- $\rho(r)$



Temperature profiles on DOY 234, 2006 at 71° N

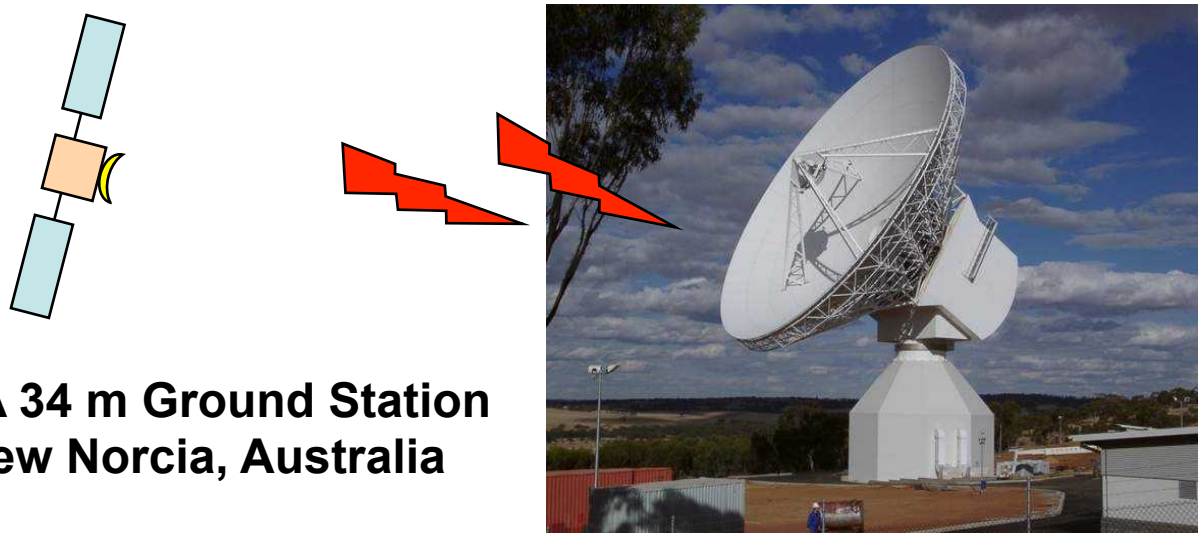
Three different boundary conditions for the temperature at 100 km (170K, 200K, 230K) lead to identical profiles at altitudes < 90 km in the atmosphere of Venus

$$p(r) = kN_t(r)T(r)$$

$$N_t(r) = \kappa \cdot \mu(r) \qquad \kappa = 8.21\cdot 10^{22} \quad m^{-3}$$

$N_t(r)$ = total number density of the neutral atmosphere

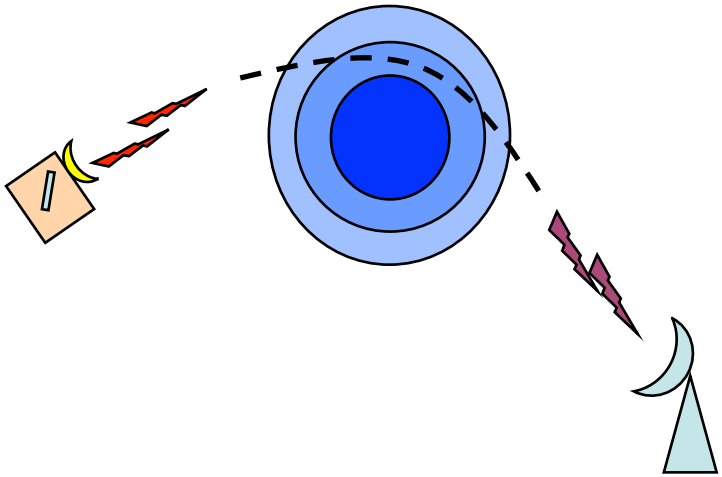
Data Acquisition and Data Processing

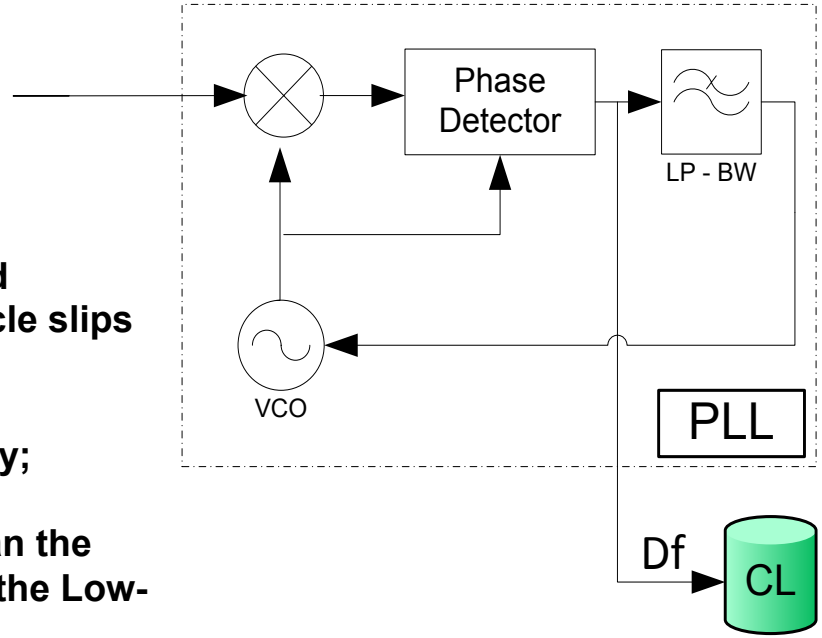


ESA 34 m Ground Station
New Norcia, Australia

- Data from Occultation Experiment have been recorded by „Closed Loop“ as well as by „Open Loop“ techniques.
- In „Closed Loop“ the received signal is tracked at the G/S by making use of a PLL.
- In „Open Loop“ mode voltage samples of received signal are collected.
- The „Open Loop“ technique allows to cope with:
  - atmospheric absorption effects and defocusing (signal attenuation can reach up to 50 dB)
  - strong frequency dynamics (up to 200 Hz/s)

Closed Loop Data Acquiring: Principle Scheme





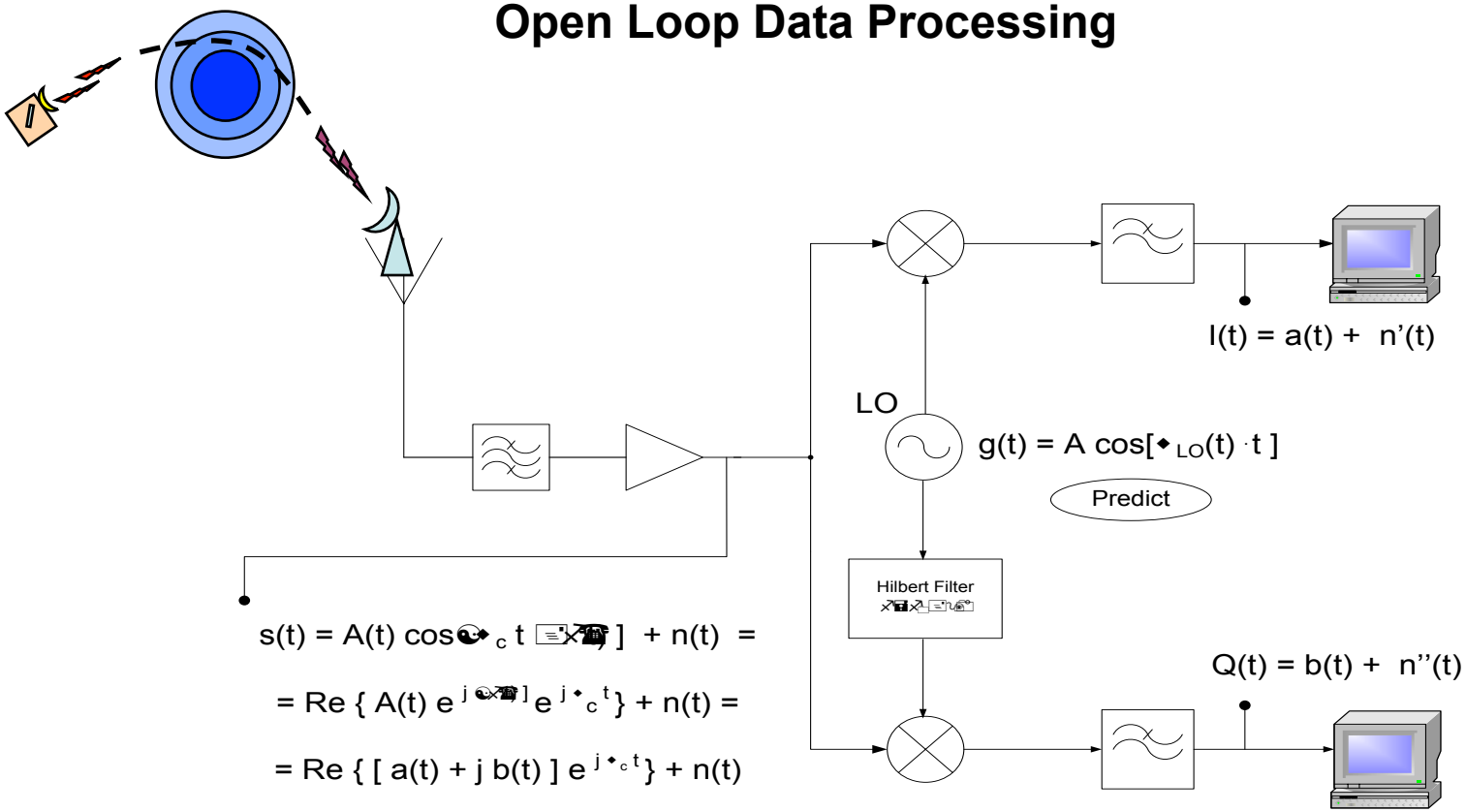
Absolute frequency shift, shift rate and attenuation become larger causing cycle slips and loss of lock in the PLL because :

1) VCO reaches its maximum frequency;

2) signal dynamics becomes larger than the system band width (which is given by the Low-Pass filter);

3) SNR value drops making signal undetectable

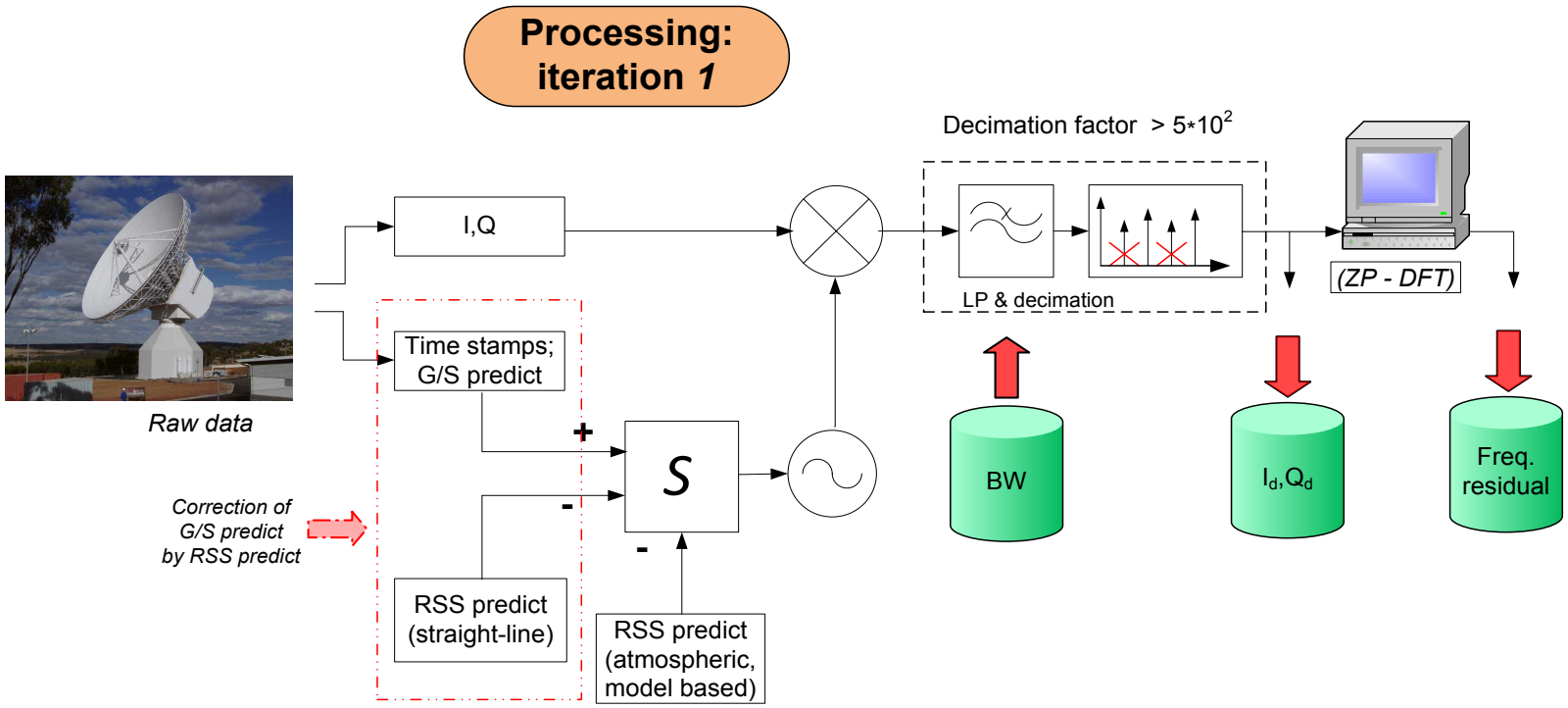
Open Loop Data Processing



The received base band signal is represented in complex form as <u>V</u>(t) = I(t) + jQ(t), where I(t) and Q(t) are its base band analogue components, which differ in phase by 90° . This allows phase coherent signal processing.

Sampling rate 150 ksamples/s for VEX

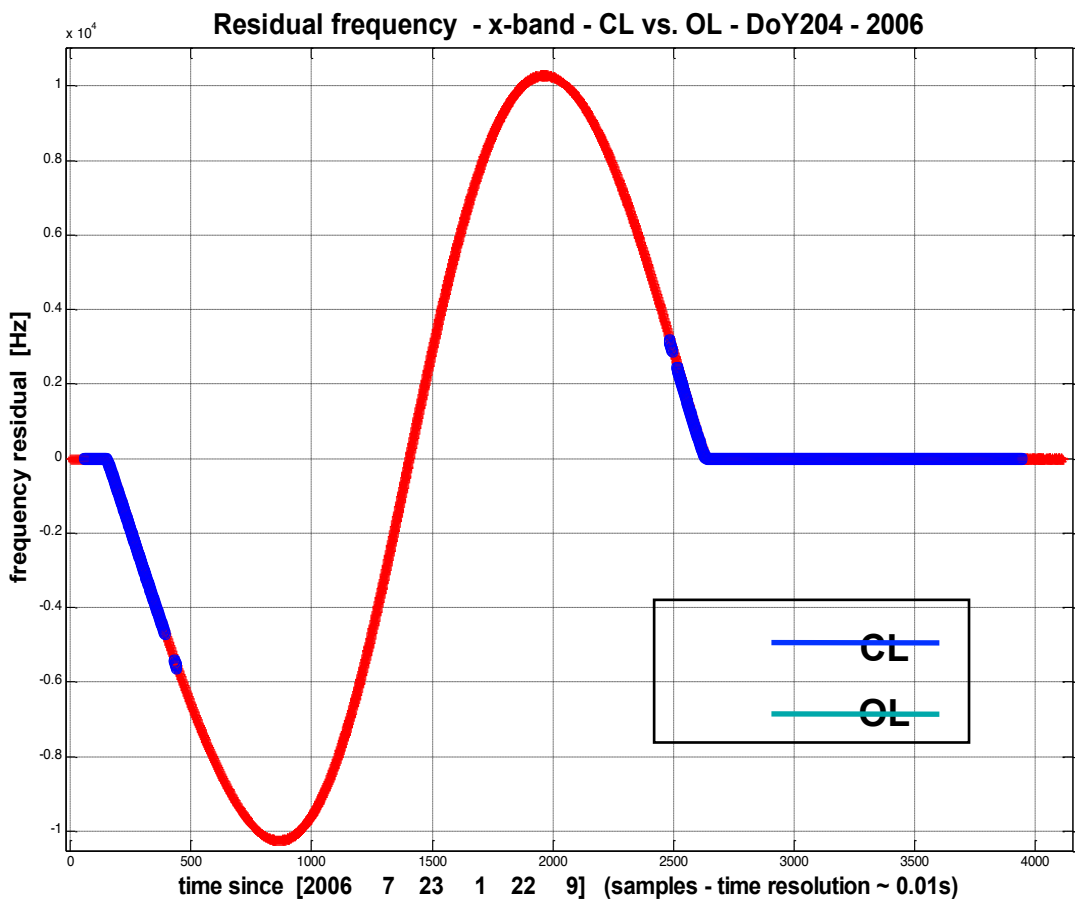
Data collection during a typical occultation pass at Venus ~ 4 GBytes



OL – Processing allows phase coherent reconstruction of the carrier signal at C/N_0 ~ 0 dB, at a frequency shift of 100 Hz/s with a resolution of ~ 5 mHz

Atmospheric Frequency Shift of the VeRa X-Band - Carrier Signal during a Complete Occultation.

VeRa was the first planetary Radio Science mission detecting the carrier signal throughout a complete occultation, i.e. it was possible to detect the carrier during times where the planetary disk was occulted completely the satellite.

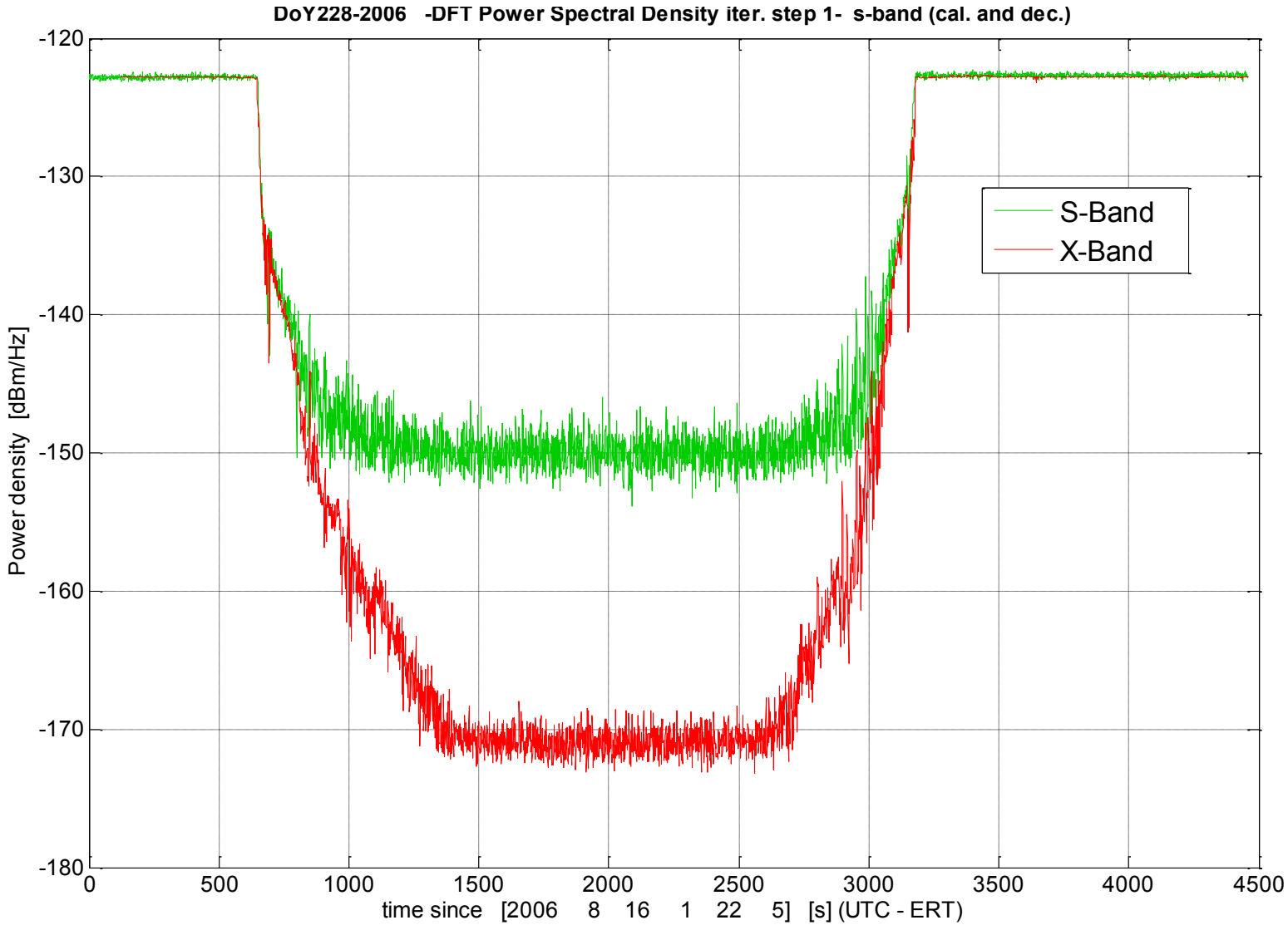


Loss of signal power in the atmosphere

~ 50 dB!

Universität der Bundeswehr München

Loss of VeRa X-Band - Carrier Power during a Complete Occultation.

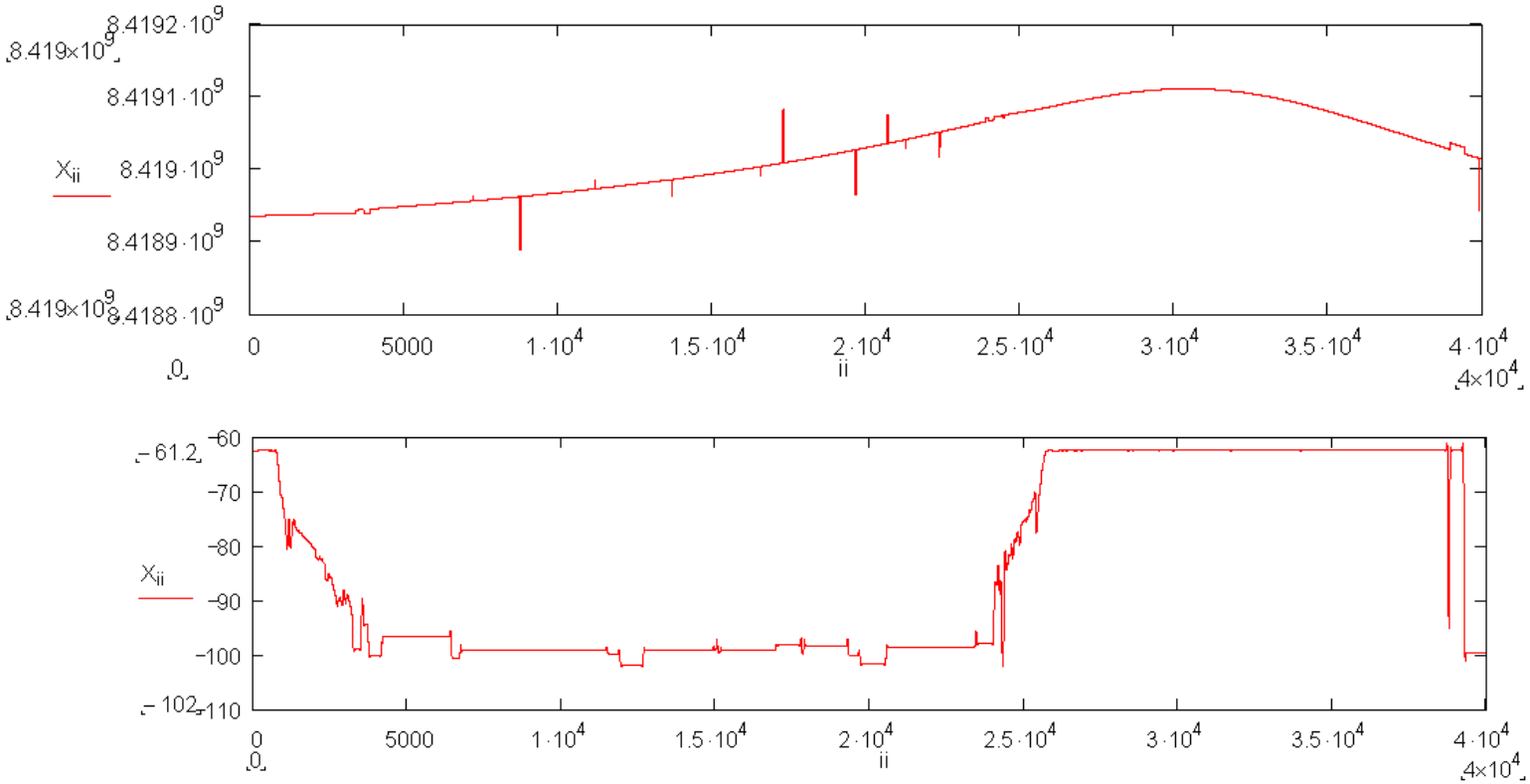


Universität der Bundeswehr München

First light through atmosphere - Closed Loop Data Processing

Occultation Pass # 93 DOY 204

IFMS 1 X-band sample rate : 10sample/s
Measured frequency and AGC values

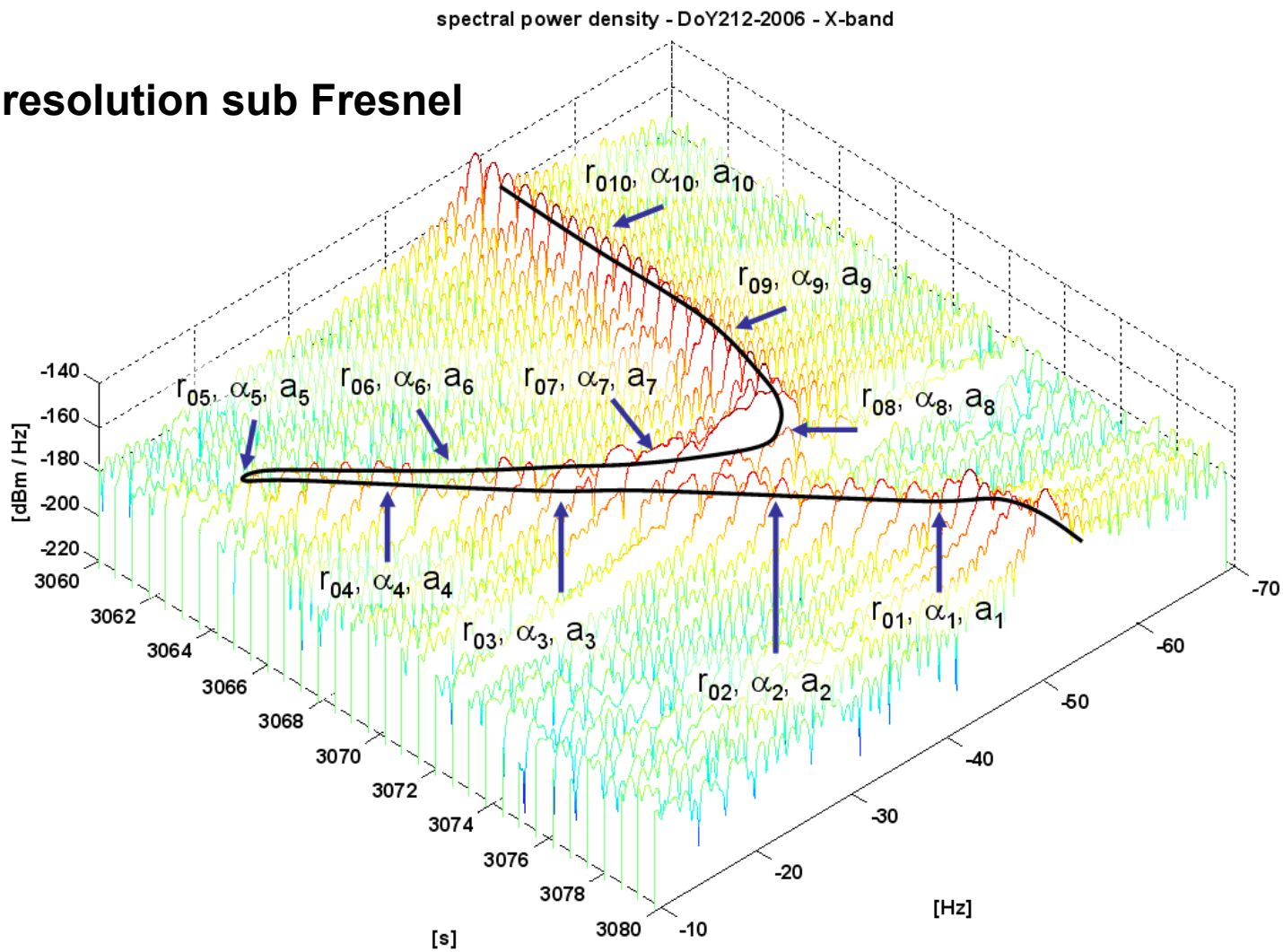


Occultation start-end at 250 km altitude of ingress/egress points.
Duration 43 minutes = 2580 seconds

Len: „You will find out“

VeRa - OL Processing of Multipath Effects

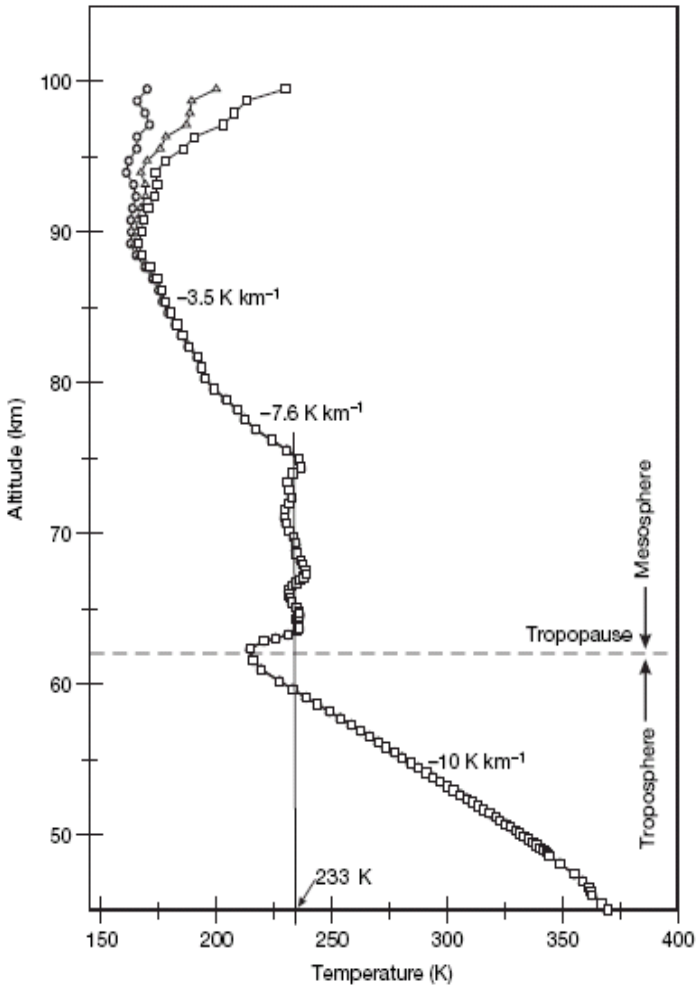
Altitude resolution sub Fresnel



R.Mattei et al.

Science Results

Venus Express – VeRa Ergebnisse



Pätzold, Häusler et al., Nature, 2007

Temperatures at the surface ~ 737K
CO_2- green house effect!

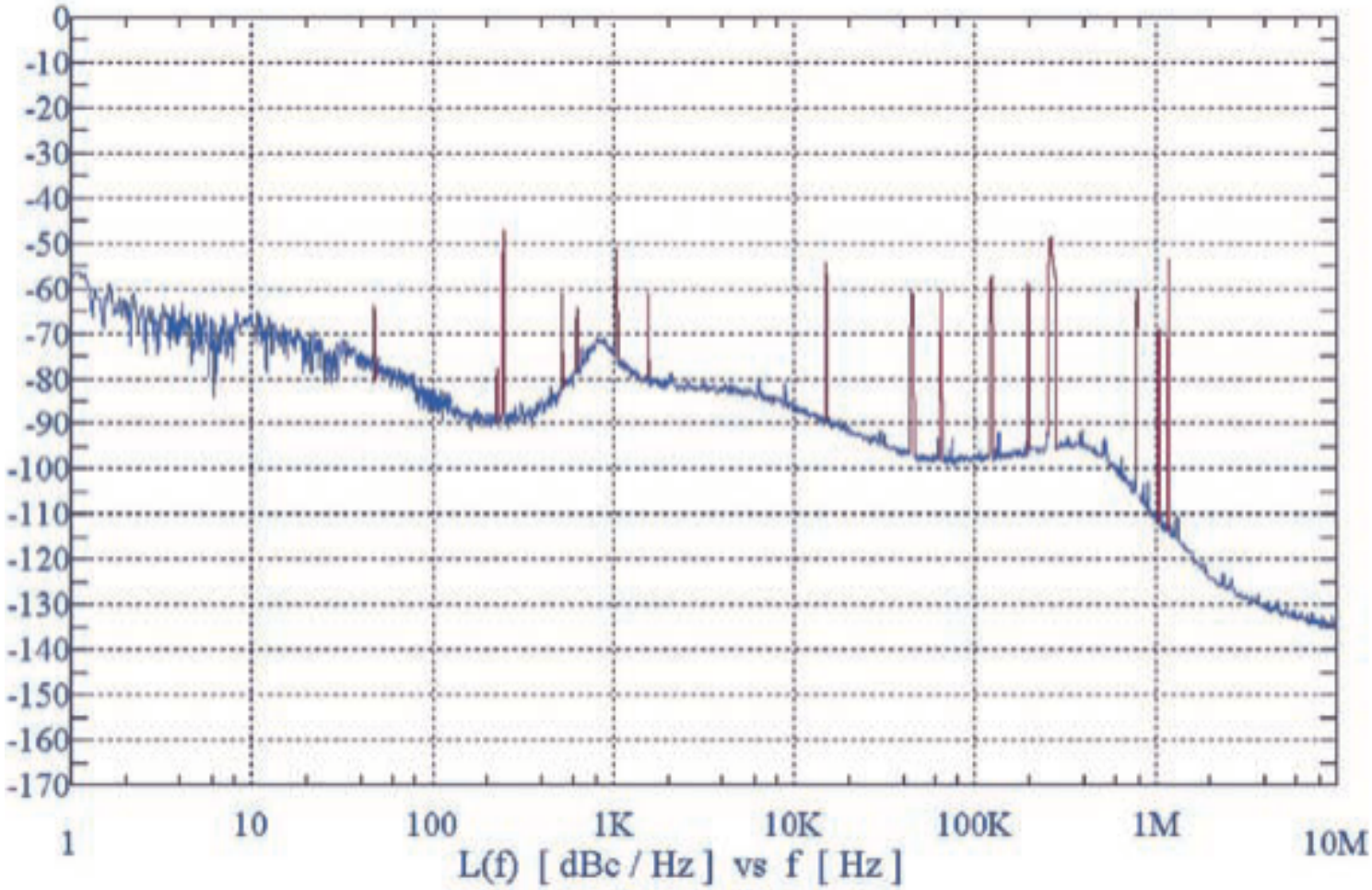
Radio Science measurement technique allows high vertical resolution at the temperature profiles

Example: Rosetta

Start of the Journey to Comet „Churyumov Gerasimenko“:

Lauch of Ariane 5
March 2, 2004, 07:17 UTC
Kourou

Observation Types, Scientific Objectives, Radio-Frequency Transmission Modes, and Ground Station Configurations

Observation Type	*Science Objectives*	*Spacecraft Mode*	*Receiver Mode*	*Radio Links*
Occultation	Atmospheric density, temperature and pressure profiles. H_2SO_4 absorbing layer Ionospheric structure Atmospheric waves	ONED USO driven Carrier only	OL CL	X and S down
Bistatic Radar	Planetary surface dielectric properties and roughness	ONES USO driven Carrier only	OL	X and S down both polarizations
Solar Corona-Solar Wind	Solar corona structure, Solar wind acceleration region, electron density, CME	TWOD coherent	CL, OL Ranging mode	S up X and S down both polarizations
Gravity	Gravity anomalies	TWOD coherent Carrier only	CL	X up X and S down

Phase Noise Spectrum of USO and Transponder 02 in the ONED Mode at X-Band