THE RADIO SCIENCE EXPERIMENT “VERA” ONBOARD ESA´S VENUS EXPRESS SPACECRAFT

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ABSTRACT

The Venus Express Radio Science experiment VeRa is devoted to the study of the ionosphere, atmosphere and surface as well as to the investigation of localized gravity anomalies of the planet Venus and to the analysis of solar coronal plasma effects. The almost polar orbit of Venus Express provides the opportunity to investigate the atmosphere at all planetocentric latitudes, including day-night variations of its structure and signal absorption effects caused by gaseous components such as H_2SO_4 , CO_2 and N_2 [(1),(2)].

The VeRa instrument uses simultaneous One-Way radio signals at X-band and S-band (wavelengths 13 cm and 3.6 cm) for the sounding of the Venus neutral atmosphere and ionosphere and the bistatic radar experiment while the coherent Two-Way mode is used for the gravity and solar corona measurements. Using coherent measurements at the two wavelengths allows the separation of dispersive media effects from the classical Doppler shift. An Ultra-Stable Oscillator (USO) provides a high quality onboard frequency reference source (frequency stability is $\sim10^{-13}$) for the One-Way radio link. Instrumentation in the ground stations on Earth is used to record amplitude, phase and polarization of the received signals. The signals are recorded at the ground station receivers of the ESA New Norcia and the NASA DSN Canberra stations in Australia using both the Closed Loop and the Open Loop receiver systems.

The strong refraction of the microwave radio beam in the Venusian atmosphere requires custom-designed steering of the spacecraft´s high gain antenn, thereby compensating for ray-bending effects, in order to direct the beam towards Earth. Specific thermal design constraints which allow sun illumination only from certain directions required the VeRa team to develop additional sun-optimized attitude maneuvers.

We present an overview of the VeRa experiment and selected first results, including descriptions of the design of the specific attitude pointing maneuvers and the techniques developed for the analysis of Closed and Open Loop receiver data.

1. MISSION OVERVIEW

The Venus Express (VEX) Spacecraft was launched on November 9, 2005 from the Baikonur cosmodrome, Kazakhstan, by a Soyuz-Fregat rocket and successfully inserted in orbit around Venus on April 11, 2006. The mission is based on a highly elliptical polar orbit (semi-major axis a = 39494 km, eccentricity e = 0.84, height of pericenter maintained by thruster firings in the range between 250 km and 400 km). The orbit period is 24 h. The operations are directed by ESA Mission Control Center (ESOC-MCC) in Darmstadt, Germany, via the ESA ground stations (G/S) in Cebreros (Spain) and in New Norcia (Australia). Cebreros is employed for communication tasks (TT&C), while the New Norcia G/S supports the Radio Science investigation. The location of both stations ensures radio coverage during the complete VEX spacecraft orbit [(3)].

The VEX payload consists of seven instruments designed and developed by research institutes and space industries of participating countries: infrared, visible and ultraviolet spectrometers, a plasma analyzer, a magnetometer and an USO for the VeRa investigation [(4)].

2. INSTRUMENTATION

The VeRa-Radio Science investigation relies on the radio subsystem which is used for the communications between the S/C and the G/S. Two onboard transponders (TRSP´s) receive and transmit signals at S- and X-Band with an output power of 5 W and 65 W, respectively [(5)]. The ground station (G/S) hardware (IFMS 1, 2 & 3) performs transmission and reception of the TT&C RF signals as well as recording of the Doppler and range measurements. IFMS 3 is a dedicated RS receiver supporting the VeRa experiment. An onboard Ultra Stable Oscillator (USO) provides the TRSP#2 with a high quality frequency reference (frequency stability $\Delta f/f \sim 10^{-13}$ at integration time between 10 s and 100 s, see fig. 1).

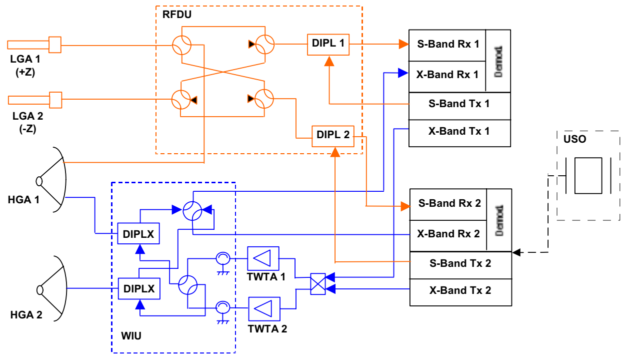

FIG 1. Block diagram of the S/C communication subsystem (courtesy EADS-ASTRIUM)

The satellite is equipped with two omni directional antennas (LGA1 & LGA2) on the spacecraft (S/C) +Z wall (top panel) and –Z wall (bottom panel), which are operated at S-band as back-up for the communication system. The VeRa operations are nominally conducted with the two high-gain antennas: HGA1 with a dish diameter of 1.3 m and two feeds for S- and X-Band, mounted on the S/C +X wall and HGA2, on the top S/C panel (+Z wall) with a dish diameter of 0.2 m and only a X-Band feed [(6)] (fig. 2). HGA2 is aligned along the –X axis in order to guarantee communications around Venus inferior conjunction when the planet is located inside the quadrature position (fig. 4). Since no solar illumination is allowed on the –X wall (which carries a “cold plate” for the remote sensing instruments), the S/C must be flipped. In a reduced way (at the cost of 12 dB of signal power), the HGA2 can also support RS observations if needed.

The VeRa investigation is supported on the ground by the ESA Ground Station in New Norcia (Australia) which consists of a 35 m parabolic antenna with a gain of 68.2dBi at X- Band and 55.8dBi at S-Band. The system temperature of the receivers are 74 K and 47.9 K, respectively. For many observations the Radio Science experiments also rely on the ground stations of NASA-JPL Deep Space Network (DSN). Some of these stations are equipped with 70 m dishes and the state-of-the-art receivers have a very low system noise temperature (25 K and 20 K at X- and S-Band, respectively).

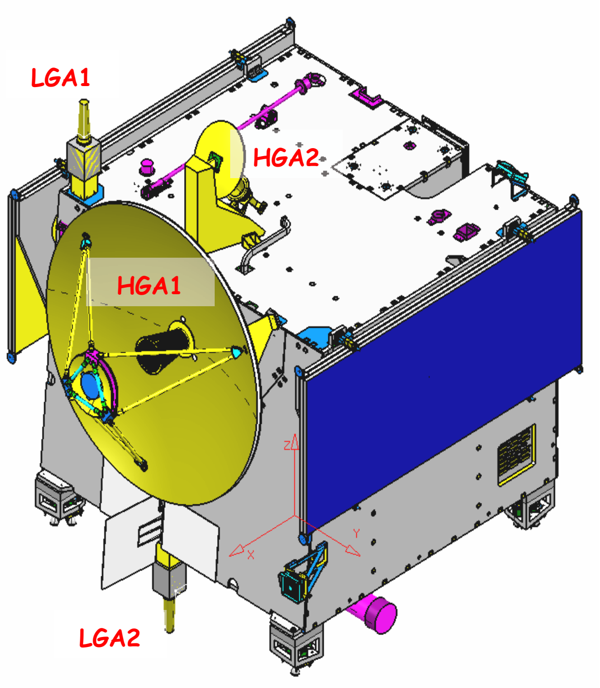

FIG 2. Spacecraft overview (courtesy EADS-ASTRIUM)

3. EXPERIMENTS

The VeRa Radio Science investigations work on the principle that a RF carrier signal propagating through media will experience variations of some of its parameters because of its interaction with planetary and interplanetary media and gravity fields. Modifications of such signal parameters as frequency, amplitude, polarization, group delay, etc. allow to draw conclusions about the nature of the propagation medium and the gravity fields.

As mentioned, VeRa utilizes the same RF carrier signal otherwise used for the communications with Earth. When used for science, however, the carrier is not be modulated by TM or TC data, in order to preserve spectral purity.

When a RS observation is performed, the most important information to be evaluated is contained in the variations of the signal frequency. In addition to a low system noise temperature at the G/S, it is thus very important to minimize the phase noise of the frequency source on the S/C. This is achieved by implementation of an Ultra Stable Oscillator (USO) onboard, whose Allan Deviation has proved to be better than 4×10^{-13} for integration times between 10 s and 100 s [(7)]. At a Venus-Earth distance of 0.28 AU and for minimum ray path altitudes from 60 km down to 40 km, this leads to a carrier frequency noise (standard deviation of the phase error, including receiver thermal noise) varying from ~1 mHz to ~8 mHz at S-Band (2.3 GHz) and from 2.5 mHz to ~4 mHz at X-Band (8.4 GHz). These values apply for measurements performed at the NNO station)[(2)]. Observations are conducted with different spacecraft and ground segment configurations, depending on the science case to be investigated. Four different transmission modes are implemented (fig. 3):

1) ONES (One-Way Single) in which the S/C sends a downlink (D/L) signal at one frequency (S- or X-Band). In this mode the USO is the frequency reference source.
2) ONED (One-Way Dual). The same as ONES, with D/L signal sent on both frequencies.
3) TWOS (Two-Way Single). This is a "coherent" communication mode, by which an uplink (U/L) signal is sent from the G/S, received onboard, frequency converted and transmitted back by the S/C. This mode is called "coherent" because the TRSP acts as a mirror, conserving the phase information. In this case, the stability of the frequency reference source is governed by the G/S H_2–Maser, whose frequency stability is ~ 10^{-15}.
4) TWOD (Two-Way Dual). The same as TWOS, with D/L signal sent on both frequencies.

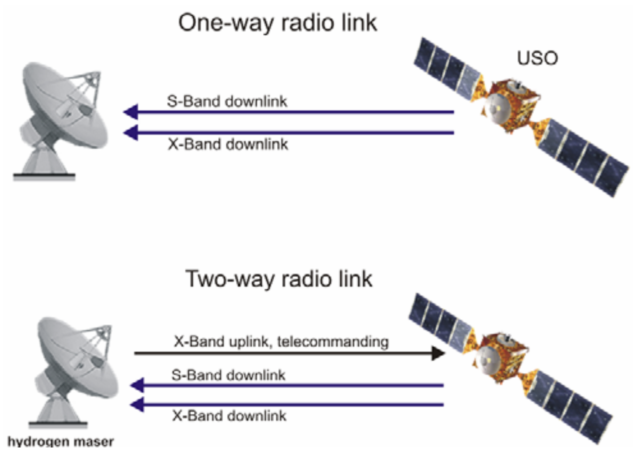

FIG 3. Transponder configurations and transmission modes of the satellite. The Ultra-Stable Oscillator (USO) serves as onboard reference frequency source in the One-Way mode. In the Two-Way mode the reference frequency is generated by a H_2 – Maser.

The VeRa Radio Science investigation is comprised of four categories of observations:

3.1. Atmosphere and Ionosphere sounding

The experiment to study the planetary ionosphere and atmosphere is performed in so-called "Earth occultation" constellations. It exploits an observational geometry in which the spacecraft to Earth communication is occulted by the planet. Throughout the mission the relative position of Earth and Venus vary continuously leading periodically to so-called "Occultation Seasons". Each occultation season lasts about two to three months depending on the planetary constellation, as shown in fig. 4 and fig. 5.

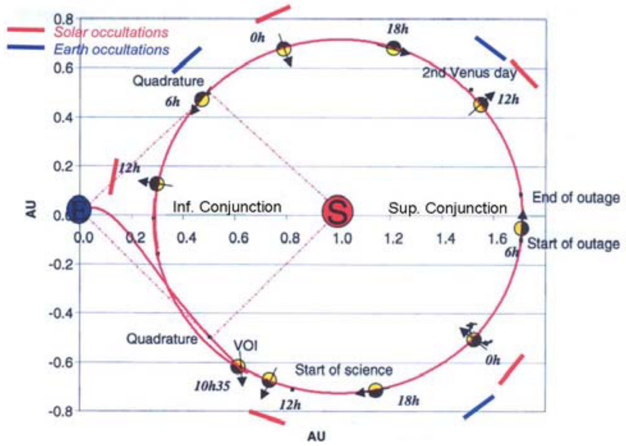

FIG 4. Venus position and observation geometry throughout the mission in a Sun-Earth fixed coordinate system.

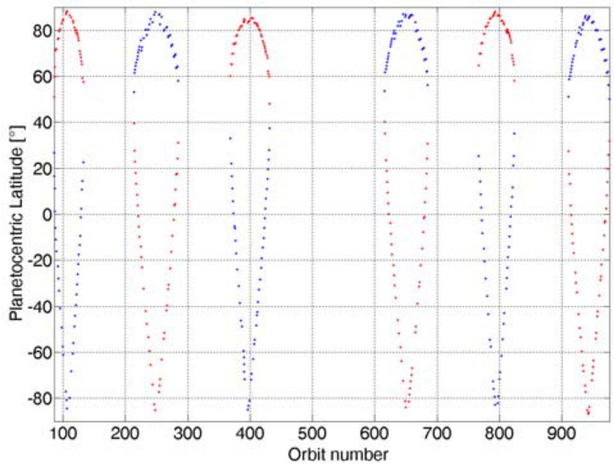

FIG 5. Distribution of planetocentric latitudes for occultation ingress and egress (assumed to be at the planetary surface) for nominal and extended mission (red dots mark occultation ingress, blue dots mark occultation egress) [(1)].

In a typical occultation pass, as the satellite approaches the planet, the down link signal from S/C to the G/S consecutively penetrates interplanetary space, planetary ionosphere, and neutral atmosphere. This represents the "ingress" phase of the pass. The reverse sequence, as the S/C emerges from behind the planetary disk is called the "egress" phase. As a consequence, the observed signal variations allow one to derive vertical profiles of planetary atmospheric and ionospheric parameters. The very dense atmosphere of Venus with its associated strong density gradients has the effect that its atmosphere can only be sounded to a minimum height of approx. 33 km (so-called "superrefraction height"). Throughout any occultation, however, the transmitted signal – when beamed in the proper direction – is always refracted around the planet and can reach the G/S even when the S/C is completely occulted by the planetary disk.

3.1.1. The Measurement Principle

The optical path covered by an electromagnetic wave while propagating through a medium is different from the optical path experienced in vacuum. The difference between the optical path length in the medium and in vacuum is given by:

(1) $$\Delta l_m = \int (n-1)\, dl_o$$

The increase in path length due to the medium can be expressed as a difference in phase:

(2) $$\Delta \phi_m = \frac{2\pi}{\lambda_o} \int (n-1)\, dl_o$$

This in turn leads to a change in frequency with respect to the vacuum case:

(3) $$\Delta f_m = \frac{1}{2 \cdot \pi} \frac{d(\Delta \phi_m)}{dt}$$

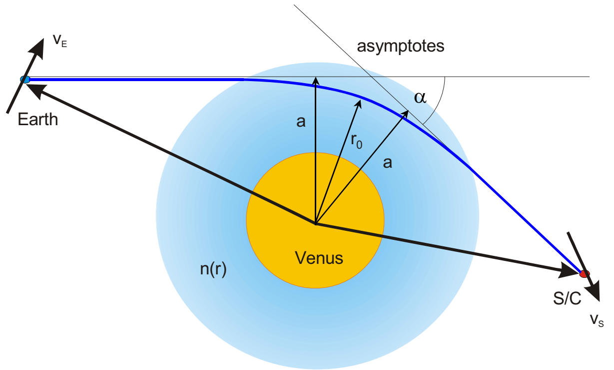

FIG 6. Ray bending in the Venus atmosphere. Ray path closest approach distance r_o and deflection angle α are related to the impact parameters *a* (asymptote closest approach distance) and index of refraction *n(r)*. The *(x,z)* coordinate system is a planetocentric coordinate system. [1]

In addition to the medium-related frequency change given in (3), the frequency measured at the G/S will contain contributions from the classical Doppler effect, which must be accounted for in the data analysis. The difference between the observed frequency and the frequency predicted without the intervening propagation medium is called the "frequency residual". The ray bending angle α can be determined from the frequency residual and from the knowledge of the occultation geometry (s. fig. 6). Assuming radial symmetry of the atmosphere and applying appropriate inversion techniques (inverse Abel transformation), it is possible to relate the refraction index *n*, to the bending angle α and the asymptote closest approach distance *a* [1], [2]. By further assuming validity of the ideal gas law, vertical profiles of density, pressure and temperature can then be derived from the refractivity μ:

(4) $$\mu = (n-1) \cdot 10^6$$

Where μ is proportional to the number density of the summed constituents of the atmosphere and can be considered constant over a wide range of frequencies.

Fig.7 shows two temperature profiles from the northern and the southern polar latitudes in orbit # 400 on May 26, 2007 (DOY 146). The analysis assumed for the radius of planet Venus R_V = 6051.8 km.

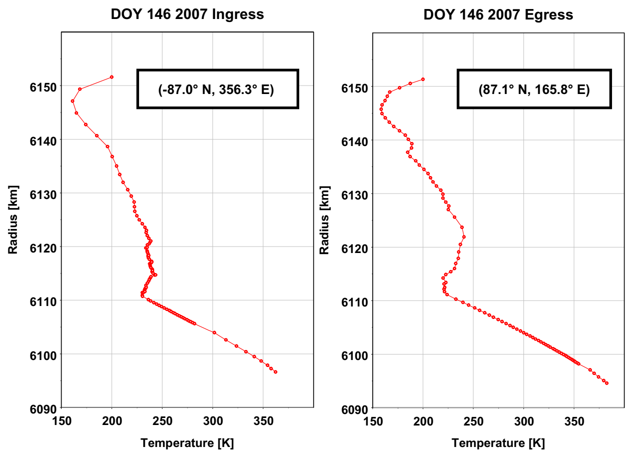

FIG 7. Temperature profiles (ingress and egress) from VEX-VeRa Occultation Season #3.

For an ionized medium, the refraction index *n* (*n*<1) is related to the electron number density N_e [m^{-3}], to the plasma frequency, and to the signal frequency *f* (dispersive medium):

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

Fig.8 shows an electron density profile in altitudes ranging from 120 km to 290 km derived from data taken in orbit #270 on January 16, 2007 (DOY 016).

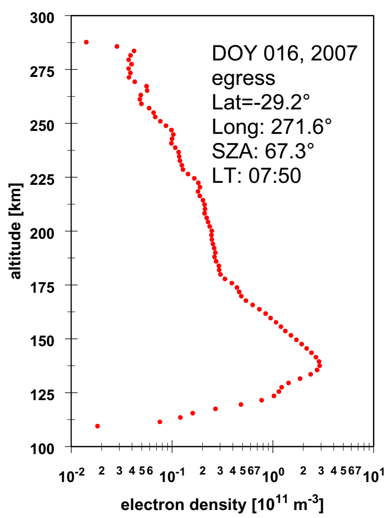

FIG 8. Ionospheric electron density profile from VEX-VeRa Occultation Season # 2.

The received RF signal power during an occultation experiment is also a parameter of great interest. When propagating through the planetary atmosphere, the electromagnetic wave is affected by atmospheric *defocusing* and atmospheric *absorption* effects that can together reach magnitudes > 40 dB at Venus.

Defocusing is the consequence of a gradient in the atmospheric refraction index as a function of the radial distance from the planet. The refractive defocusing spreads the antenna beam in the plane of occultation so that a part of the electromagnetic energy does not reach the Earth. Referring to the parameters shown in fig.6, the defocusing loss can be calculated as developed by Eshleman[(8), (1)].

(6) $$\tau = 10\log(\cos\alpha - D\frac{d\alpha}{da}) \text{ (dB)}$$

where *D* is the distance of the S/C from the crossing of the asymptotes.

Atmospheric *absorption* loss is caused by the interaction of an electromagnetic wave with major constituents of the atmosphere such as, CO_2, H_2SO_4 and N_2. Subtracting the free space and the atmospheric defocusing losses from the received signal power, one obtains an atmospheric absorption profile that may be interpreted in terms of the atmospheric structure and composition.

3.1.2. Experiment Operations

The atmospheric refraction index *n* increases stronglytoward lower altitudes. The deeper the microwave signal penetrates in the atmosphere, the larger the local value of the refraction index. This causes the ray bending shown in fig.6. Special S/C attitude maneuvers must therefore be executed with high time precision ($\leq$1 s error in absolute time, pointing error $\leq$0.1°), in order to steer the antenna beam continuously through the atmosphere, and thereby compensate for the atmospheric bending effect. Ray-tracing techniques based on an atmospheric model derived from Magellan data [(9)] were implemented in a Radio Science Simulator (RSS) whose architecture is based on a MatLab/Simulink platform [(10), (11), (12)]. This dedicated software tool was developed by the VeRa team for mission planning and data analysis. Based on the JPL/DE405 ephemeris program and using as inertial reference frame the J2000 reference frame, it can predict favorable conditions for RS experiments, compute proper S/C attitudes profiles, and simulate expected Doppler shifts. The program takes into account also relativistic effects.

The quality of the predicts generated by the RSS can be seen for example in a comparison of a measured and predicted frequency shift as shown in fig. 9. We recognize here the comparison between the frequency shifts ΔF caused by ray bending in the planetary atmosphere/ionosphere. Differences between both graphs represent differences between the actual ionosphere from the modelled ionosphere including a possible small time shift between the prediction and the execution of the slew maneuver.

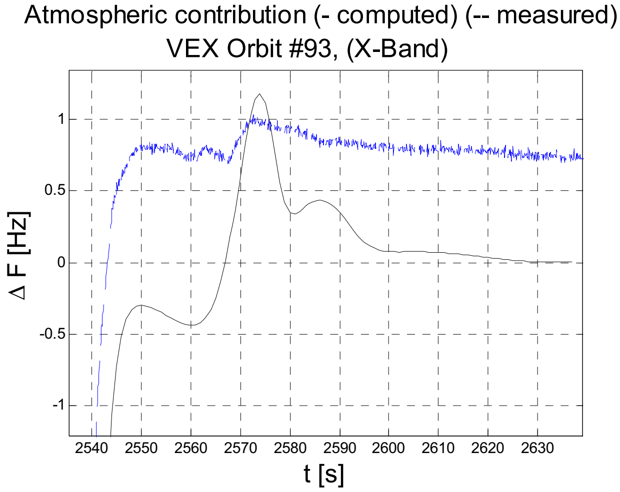

FIG 9. Comparison between the frequency shifts caused by ray bending in the planetary atmosphere and ionosphere of Venus. The dark line shows the predicted signal while the measurements are indicated in blue[(13)]

3.2. Bistatic-Radar

In a bistatic-radar configuration the transmitting antenna and the receiving antenna are located at different places. This is the case for the Bistatic Radar experiments (BSR) of the VeRa investigation, for which the S/C antenna is pointed toward the planet´s surface and the reflected echo is collected on Earth. The precise prediction of the S/C attitude required for this experiment is performed in the planning phase with the RSS. Under the assumption of specular reflection, the incidence angle of the radio beam is determined such that the reflected beam is directed at Earth.

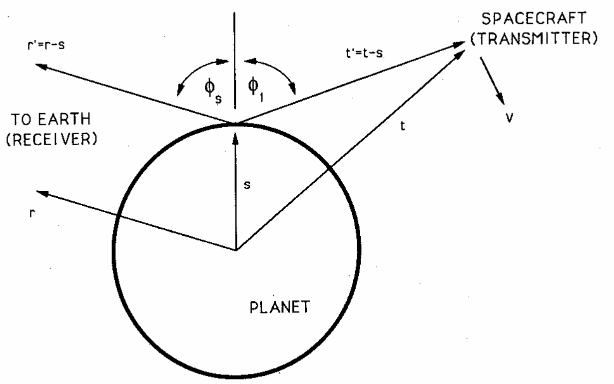

FIG 10. Geometry for the Bistatic Radar Experiment **[(14)]**

The BSR experiment is devoted to the study of surface properties in regions of special interest. Besides roughness and slope, two quantities which can be determined with a resolution of the same order of magnitude of the radio wavelength, the surface composition of the investigated area is the main object of interest of the experiment. Composition analysis can be carried out by investigation of the dielectric constant, which is derived from the Fresnel voltage reflection coefficients [14]:

$$(7)\quad R_H = \frac{\cos(\phi) - \sqrt{\varepsilon - \sin(2\phi)}}{\cos(\phi) + \sqrt{\varepsilon - \sin(2\phi)}}$$

$$(8)\quad R_V = \frac{\varepsilon \cdot \cos(\phi) - \sqrt{\varepsilon - \sin(2\phi)}}{\varepsilon \cdot \cos(\phi) + \sqrt{\varepsilon - \sin(2\phi)}}$$

where R_H and R_V are the reflection coefficients of the horizontal and vertical component of the incident wave, respectively and ϕ is the incidence angle. The VEX S/C transmits a right circular polarized wave (RCP), echoes are generated in both circulation senses, RCP and LCP. It is possible to define reflection coefficients for circularly polarized waves as [14], [15]:

$$(9)\quad R_{SC} = \frac{R_V + R_H}{2}$$

$$(10)\quad R_{OC} = \frac{R_V - R_H}{2}$$

where R_{SC} is the reflection coefficient for the same sense circular polarization and R_{OC} is the reflection coefficient for the circular sense opposite to the incident polarization.

The RCP echo power equals the LCP echo power at a special angle of incidence called the Brewster angle, where R_{SC} equals R_{OC}. Since the incidence angle is known, the dielectric constant can be obtained from the ratio of average RCP echo power (same circulation sense) to the average LCP echo power (opposite circulation sense), which is proportional to $|R_{SC}|^2 / |R_{OC}|^2$. It is also possible to derive magnitude and phase of the cross spectrum from the complex quantity $\langle R_{SC} \cdot R_{OC}^{*} \rangle$. The dielectric constant can be then estimated by relating the information gained from data analysis with model calculations (fig.11).

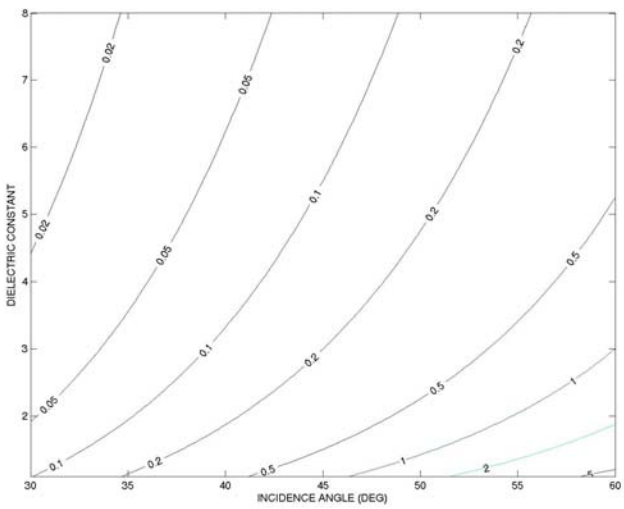

FIG 11. Relation between incidence angle, dielectric constant and echo power ratio [15]

Fig.11 shows first results from a Bistatic-Radar observation after the first processing step, which brings Open Loop data from level 1 (raw data) to level 2. The echo signal was acquired on orbit #55, June 15, 2006 from a BSR experiment over Maxwell Montes [15]. This target constitutes a point of particular interest for planetary science because the nature of its surface composition is not yet fully understood. The four plots show the frequency spectrum of the received signal over the time in both polarization (left side) and magnitude and phase of the cross-spectrum (right side) over the duration of the experiment.

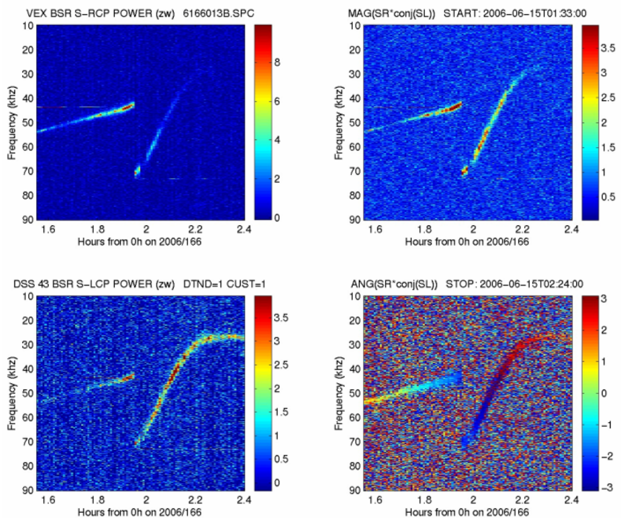

FIG 12. Echo signals from Venus surface during a BSR experiment over Maxwell Montes: frequency spectrum of right and left circular polarization (left side) and cross spectrum (magnitude and phase, right side) [15].

3.3. Experiment Conduction

There are different techniques to perform a BSR observation, "specular pointing", "inertial pointing" and "spot pointing".

In the specular pointing mode, the strategy implemented for the VeRa experiment is to direct and continuously steer the antenna beam toward the planet´s surface in order to follow an ideal track of "specular points" on ground. The transmitted radiation illuminates each specular point with the predetermined incidence angle so that the specularly reflected beam reaches the Earth.

In the spot pointing mode, the antenna beam is pointed to one target for the whole duration of the experiment.

In the inertial pointing mode, the antenna beam is directed towards the surface of the planet into an inertially fixed direction at the beginning of the experiment which is then kept constant throughout the experiment.

For Venus, the specular point method was used in all cases. The success of the experiment depended critically on the accuracy of the HGA1 pointing. Pointing angles had to be delivered to ESOC several months before the experiment took place. The pointing profiles derived by the RSS were referenced to the time of perigee passage and the time-tagged commands could be executed therefore with a minimum timing error. This method relies on the knowledge of the onboard time and its offset with respect to absolute time (ephemeris time - TBD). VeRa required a pointing accuracy of 0.1 ° with a timing error of $\leq$ 1 s. ESA Mission Control assured that S/C maneuvers were performed with the required precision.

3.4. Gravity measurements

The objective of the Gravity experiment (GRV) is the investigation of anomalies in the planet´s gravity potential in particular regions. The experiment is conducted in the two-way coherent mode, thereby relying on the G/S H_2 –maser as the frequency reference source. The targets are located in the proximity of the orbital pericenter for experiment sensitivity reasons (minimum S/C altitude). The most important target of the VeRa GRV experiment is "Atalanta Planitia", a low basin which measuring ~1500 km in diameter and 2 km in depth [(1), (2)]. Suitable orbits for GRV observations must be occultation free and well separated in time from solar conjunction periods. The study is performed by evaluating the measured Doppler frequency shift while the S/C is flying over the selected target area. The experimental method is sensitive to velocity changes as small as ~ 10 µm/s which can be interpreted as localized gravity effects and can contribute to the understanding of effects like mantle dynamics [(1),(2)].

3.5. Solar Corona

The solar corona is the outer, highly ionized part of the Sun´s atmosphere, extending millions of kilometers into space. The coronal structure is highly variable over time and characterized by coronal "holes", coronal "streamers" and rapid outburst events like Coronal Mass Ejections (CME´s).

The Solar Corona experiment (SCO) is executed to investigate the structure of solar coronal plasma during the planetary superior conjunction phase (Fig. 4). In general, this configuration degrades the S/C–G/S communications link due to the increased background noise (equivalent enhancement of the antenna noise temperature) when the G/S tracking antenna is pointed close to the solar disk.

The combination of equations (1), (2), (3) and (5) yields for a ionized medium :

$$(11)\quad \Delta f_m = \frac{-40.3\left[\frac{m^3}{s^2}\right]}{c \cdot f} \cdot \frac{d}{dt} \int N_e dl_0$$

The quantity on the right side of (11), $\int N_e dl_0$, is called the Total Electron Density Content (TEC): It represents the electron content of a column with a base surface of 1 m^2 and extending between transmitting and receiving antenna for the length of the optical path of the signal. Making use of two coherently transmitted downlink frequencies allows one to separate non-dispersive effects (motion-related Doppler shifts and neutral atmosphere frequency shifts) from the plasma-induced frequency changes. The dual frequency measurement thus provides the derive time of TEC and by integration the variations of the plasma density. Information about the coronal plasma density is also derived from the differential group delay between both D/L frequencies (ranging signals) [(1),(2)].

4. MISSION CONSTRAINTS

Several constraints have to be respected during the planning of the VeRa experiments. First of all are the thermal constraints, imposed by the direction toward the Sun. Certain S/C panels are designed for heat exchange and must be kept in the shadow throughout the mission or are allowed to be directly illuminated by solar radiation only for a certain amount of time under certain angles. Other walls hosting payload parts, sensitive to solar heating. These walls can not be exposed to the Sun at all. In consequence, the only panel which can be fully illuminated by the Sun is the +X panel, (HGA1 panel). The minimum incidence angle allowed for the incoming radiation on the +Z panel is 10° because of the presence of sensible optical instruments. The +Y and –Y panels (attachment points of the solar arrays) can be exposed within an incidence angle of 80° but for no longer than 1 h time duration (s. fig.13).

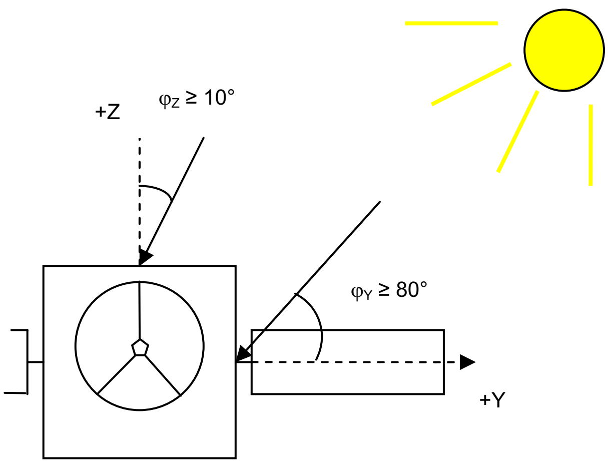

FIG 13. VEX S/C sun illumination - thermal constraints

Sun-optimization routines were implemented in the RSS in order to cope with thermal constraints. The nominal attitude profile required for an OCC or a BSR observation is "corrected" by turning the S/C around the antenna beam direction by a specifically computed angle in order to meet the thermal constraints. In cases where no angle was found meeting the requirements the experiment had to be cancelled. Without the implementation of these maneuvers about 60% of all VeRa experiments would have been subject to cancellation. Furthermore, mechanical constraints allow a maximum S/C angular rate of 0.15 deg/s.

5. MISSION PLANNING

The various experiments of the mission have to be coordinated in order to properly share common resources such as observation time slots, memory allocation, etc. This task is accomplished by ESA in cooperation with all investigation teams. Experiments and relevant observation modes are combined in ten "science cases", which are arranged in the Science Activity Plan (SAP)[(4)]. The mission scheduling is articulated in Medium Term Planning (MTP) periods of one month duration. Three months before the period of concern, each experiment team must deliver to ESA the timing and (if necessary) the calculated S/C attitude files for the observations scheduled in that month. Each period contains four "commanding weeks" (Short Term Planning, STP). In each commanding week the operations to be conducted over that week are scheduled. The planning information is implemented in a file containing all TC for the S/C. The TC file is uploaded in advance in the S/C mass memory, so that the operation will be automatically executed at the right time [(16)].

6. DATA ACQUISITION AND DATA PROCESSING

Two different techniques are used for the signal acquisition on ground in the framework of the RS investigation: the "Closed Loop" (CL) mode and the "Open Loop" (OL) mode.

In the CL mode the ground receiver makes use of a Phase Lock Loop (PLL) to track the RF carrier signal. Two kinds of data files are delivered for processing: the phase recording over time, from which is possible to evaluate the received frequency, and the received signal power (AGC). The first step of the CL data processing consists in the calculation of frequency residuals by subtraction of motion-related effects from the measured "sky frequency". Corrections for the effects of the terrestrial troposphere and ionosphere which are located between transmitting and receiving antenna are included in this calculation. The computation of the Doppler frequency predict (including relativistic contribution) as well as S/C attitude profiles, are based on ephemeris calculation and require a proper handling of reference systems and time bases in the RSS. Detailed insight on this topic is given in [(10),(17), (18)].

Signal reception by a PLL receiver is implemented for all VeRa experiments except BSR. For deep atmospheric and surface sounding the absorption and loss effects described above can cause a dramatic reduction of the received signal. Signal to Noise (S/N) degradations > 45 dB are observed in some cases. It is thus necessary to use a different reception technique, the "spectrum analyzer" or Open Loop mode necessary. In this case, the local oscillator (LO) which is used to downconvert the "sky frequency" (frequency of received RF signal) to the Intermediate Frequency (IF) is specifically tuned such that the down-mixed carrier signal stays always within the recording bandwidth defined by the sampling frequency (typically 100 ksamples/s). The digitized carrier signal is sampled and stored in raw files (s. fig 14).

The frequency generated by the LO at the G/S compensates for the expected Doppler shift caused by the relative motion between S/C and G/S ("straight line Doppler"). At the NASA DSN stations, however, the LO tuning can be augmented so it additionally compensates for the frequency shift caused by medium, which can reach ~ 100 KHz in special cases.

The expected frequency shift induced by the medium is of central importance for a proper setting of the sampling frequency at the receiver. The Nyquist criterium requires that the sampling rate be greater than twice the signal bandwidth.

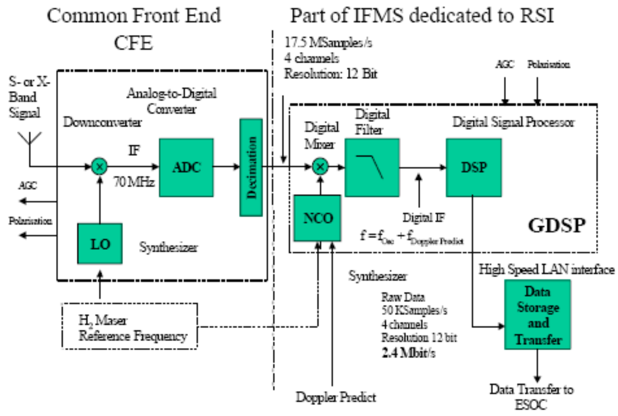

FIG 14. Principle scheme of the New Norcia IFMS Open Loop receiver **[(18)]**.

On the other side, the sampling rate cannot be increased arbitrarily, because it directly determines the generated data volume. As an example, an occultation experiment of one hour duration generates a binary data volume which exceeds 1.5 GB.

The received base band signal is represented in complex form as $\underline{V}(t) = I(t) + jQ(t)$, where $I(t)$ and $Q(t)$ are its base band analogue components, which differ in phase by 90°. Extraction and recording of base band analogue components is called "coherent reception" and allows preserving the phase-related information of the signal (fig.15),

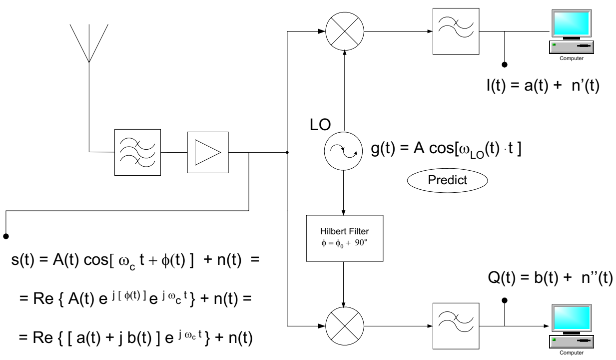

FIG 15. Principle scheme of a coherent receiver. The analogue base band components are extracted from the signal and stored separately.

During an occultation experiment, CL recording is always implemented parallel to OL recording, in order to complement the information. CL data will therefore provide very valuable information for high and medium altitude atmospheric sounding. Open Loop reception guarantees prolonged signal recording and a reconstruction of the RF carrier signal for altitudes extending below the Venus cloud deck (~ 40 km altitude). Here the noise contribution to the signal is substantial and CL recording is not any longer possible because of carrier lock loss. Figs. 17 and 18 show an example of a reconstructed carrier signal with data obtained by OL recording. These data were recorded during Occultation Season 3 on orbit #381, May 7, 2007 at the NASA DSN station DSS 43 in Canberra, Australia.

Figs. 19 and 20 show the simulation of the expected frequency shift and RF power level for the same pass. The accuracy of the frequency prediction made it possible to receive the carrier signal at the G/S with a significantly reduced bandwidth.

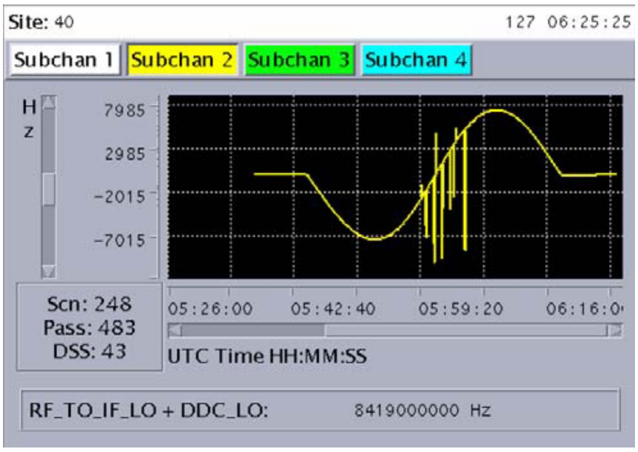

FIG 16. Results of OL recording at DSS 43, Canberra, Australia. Only atmospheric/ionospheric media contributions to the total frequency shift remain. Occultation pass in VEX orbit #381.

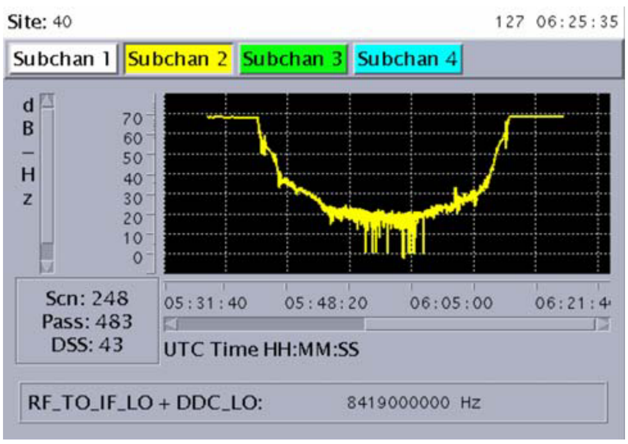

FIG 17. Results of OL recording at NASA DSS 43, Canberra, Australia. Received RF carrier power (spectral power density) vs. time. VEX occultation pass, orbit #381.

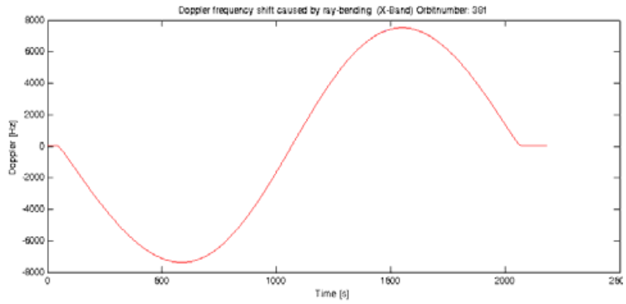

FIG 18. RSS predicted frequency shift caused by the atmospheric/ionospheric media for the same pass shown in fig. 17.

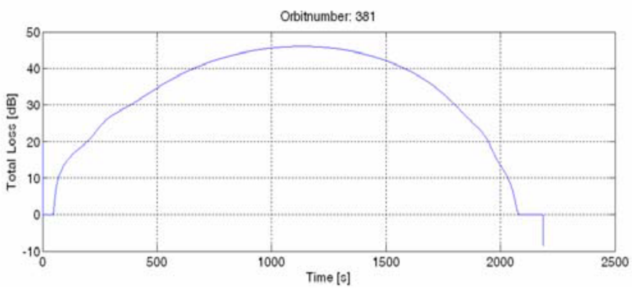

FIG 19. By the RSS predicted RF carrier power spectral density vs. time for the pass shown in fig. 18.

7. ACKNOWLEDGEMENTS

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