WEGENER: SOLID BODY DYNAMIC INVESTIGATION OF VENUS

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Orange team, Alpbach Summer School 2014

Abstract

The presence of tectonics and surface movements on Venus' surface has not yet been detected and is still an unsolved question. Plate tectonics can tell us more about the evolution of young planets, more about Earth during its earlier years, and potentially more about exoplanets.

Solid Body Dynamics Investigation of Venus, also known as Wegener, is a mission proposed to search for evidence of tectonic activity, volcanic activity, and to give understandings in geomorphological processes modifying Venus' crust. Therefore, Wegener shall contribute more knowledge in the field of tectonics and surface activity on the planet. This will be achieved by allowing the satellite to be in an orbit of 91.5 ° in inclination and using sophisticated instruments, such as an altimeter with SAR mode and SARIn mode, i.e. two 1.7 diameter antennas that will operate at a frequency of 6 GHz. A heritage Double Star magnetometer instrument (fluxgate) and a dark state magnetometer (absolute) will be used in combination to detect magnetic fields and potentially traced their origin. And lastly, a Cold Atom Gradiometer will be used onboard to give us more accurate positioning determination for orbital tracking and to improve existing gravity field models for Venus.

This low-cost mission will be launched with a Soyuz rocket and drive the satellite to its end-destination, where it will be operating for five years and most likely increase our knowledge of young and active planets.

1. SCIENTIFIC BACKGROUND

Long considered to be Earth's twin because of its similar diameter, mass and distance from the Sun, the planet Venus is turning out to be quite different from the image evoked by this analogy. For example, an impenetrable shroud of swirling clouds encircles the planet, while temperatures on the surface exceed 700 K.

Although over twenty spacecraft have examined the planet and its environment, Venus has yielded its secrets only slowly. Orbital photographs at visible wavelengths of the surface of Venus are unobtainable because of its cloud cover and our understanding of Venus is based on radar maps obtained by Pioneer Venus (1978 and 1979), Venera 15 and 16 (1984), Magellan (1990-1995) and Arecibo Earth-ground observations. We now know that Venus is an amazing place with abundant volcanoes, complex tectonic features, and relatively young terrains with few impact craters, as shown in Figure 1. Radar imagery of Venus shows large areas of lowlands, upland plateaus, and volcano-capped domes. Impact craters are not abundant, suggesting the surface is on average 0.5 billion years old. Tectonic features include tesseras, lithospheric domes cut by rifts, belts of compressional folds, ridges, and mountain ranges, distinctive volcano-tectonic features called coronae, and intensely disrupted highland plateaus. Evidence of volcanism is abundant and includes flood lavas, lava channels, shield volcanoes, and lava domes. These observations indicate the possibility that Venus has been resurfaced many times by tectonic and volcanic processes [1] and more recent emissivity measurements over Venus' hot spots from the VIRTIS instrument suggests recent volcanism [2].

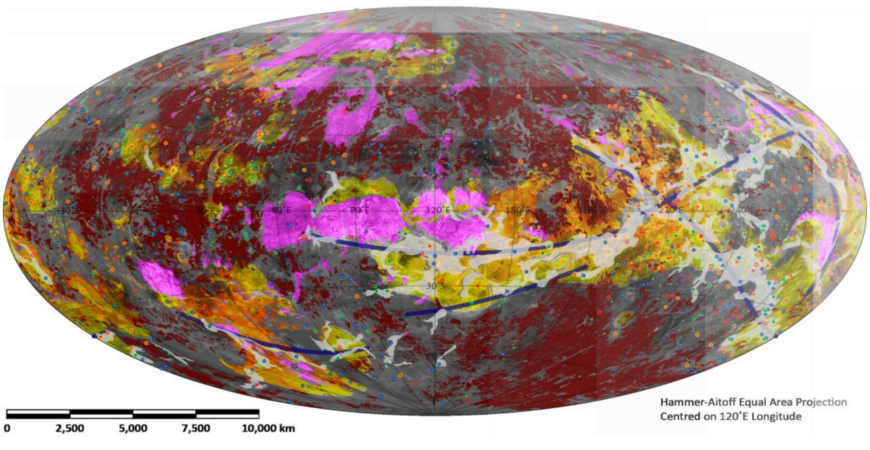

Figure 1. Venus map geological features: tesseras (pink), volcanoes (red spots), rifts valley (blue), plains (red)

Three possible hypothesis have been proposed in order to explain the observed range of geological venusian features, near random distribution of craters and inferred global heat: (i) episodic resurfacing; (ii) a plate-like movement model that implies ongoing volcanic and tectonic activity consistent with geological observations similar to terrestrial plate tectonics; (iii) dominantly plume-related localized volcanic activity.

To address these models, very precise measurements of the long term rates of surface changes are needed [3]. Although previous missions provided a major advance in our understanding of the planet, we need higher resolution repeated topographic measurements of geological features combined with gravity and magnetic field measurements in order to understand the dynamics of Venus.
Since our knowledge about Venus is currently incomplete, it is essential to send a mission that shall address basic unresolved questions about the geologic history and present state of Venus.

Wegener mission shall revolutionize our understanding of Venus by means of directly detecting and monitoring volcanic and tectonic activity.

1. SCIENCE OBJECTIVES & OBSERVATIONAL REQUIREMENTS

The aim of Wegener mission, Solid Body Dynamics Investigation of Venus, is to search for evidence of tectonic activity, volcanic activity, and to give an understanding in geomorphological processes modifying Venus' crust. The main objectives of the mission with corresponding subobjectives are as follow:

SO1. **Search for evidence of tectonic activity**
- **SO1.1** Search for evidence of resurfacing
- **SO1.2** Search for crust movement

SO2. **Search for evidence of volcanic activity**
- **SO2.1** Search for evidence of eruptions
- **SO2.2** Seach for inflation in volcanic edifices

SO.3 Understand geomorphological processes modifying the surface
- **SO3.1** geomorphological processes modifying the surface by searching for landslides and dunes

We shall detect the 3D deformation of the surface repeating topographic measurements of key surface features (tesseras, rifts, shield and dome volcanoes) movements with a target detection of 1mm/5year. Furthermore, by combining our data with topographic data from previous missions we will refine the structure of the crust.
These data will be supported by measurements of the potentially existing weak magnetic field from the core and/or remanent crust, (with a sensitivity than less 1 nT). Evidence of the presence of the magnetic field in the ionosphere could give additional information about the boundary condition of the crust (as constraints for mantle convection) and of the surface-atmosphere interaction.
By measuring our orbital position accurately we will impove our topographic measurements and we will get information concerning the gravity field. Our measurements could also improve existing gravity data
Additionally, for science objectives SO2 and SO3 we will distinguish between mass wastings, aeolian activity and surface materials that result from volcanic processes by analyzing surface measurements from the altimeter reflectivity providing data on e.g. roughness and surface brightness.

1. INSTRUMENTAL REQUIREMENTS

In order to fulfill our objectives, we list the following instruments and requirements.

OR1.1 Repeat topographic measurements of key surface features with a target detection of 0.2mm/year

We shall use an altimeter with SAR mode along-track and SARIn mode across-track with two 1.7m diameter antenna operating at a frequency of 6GHz. In order to obtain the measurements data with the desired resolution we need an almost polar orbit with an inclination of 91.5°. A high precision cross-track pointing of <10 arcsec and a spacecraft attitude maintance with a pointing accuracy of <0.2° per axis has to be ensured (CryoSat2). The Altimeter in SAR mode produces a data stream of 280kbps (560kbps in SARin mode) (SO1, SO2, SO3).

OR1.2 Map of the potential weak magnetic field from the core and/or remanent magnetic crust

We shall use a combination of a fluxgate magnetometer (heritage Double Star magnetomer) with a resolution of 156 pT ranging between +/- 512 nT and an absolute magnetometer (coupled dark state magnetometer). To operate this configuration a pointing accuracy of < 13arcsec has to be ensured (SO1, SO2, SO3).

OR1.3 Measure orbital position

Telemetry data sent via ESA's deep space network will be used to determine our orbital position to an accuracy of 6km. In post processing, this will be combined with repeated height measurements of the same spots on the surfac and crossing points of the track to obtain knowledge of the orbital position down to a resolution of approximately 5m. Optional: Cold Atom Gradiometer can improve the knowledge of the satellite's position down to the cm range (SO1, SO2, SO3).

OR1.4 Measure gravity field accurately (optional)

To measure the gravity field of the planet will improve our measurements in several ways. It will be needed to resolve the orbital position to an accuracy of few centimeters. To improve our knowledge of the deeper crustal structure and the existing gravity field, a global coverage is needed (allowed polar gap of approximately 1.5°) (SO1, SO2, SO3).

1. INSTRUMENTATION

The spacecraft will carry a range of instruments to investigate the mission objectives explained above.

3.1 Altimeter

The science requirements demand the mission to measure dynamical a variations in the topography of the Venus surface, over several passes throughout the mission lifetime on a variety spatial scales, varying over several orders of magnitude. The altimeter design is based on the CryoSat SIRAL instrument, as the CryoSat mission had similar goals, The following specific changes were made to the SIRAL design: (i) two parabolic receiving antennas (1.7 m) forming an interferometer in the cross-track direction with a baseline of 1.84 m; (ii) the instrument is a C-band radar altimeter with an operating frequency of 6 GHz to adopt to the atmospheric transparency windows of venus; (iii) the instrument operates at a high pulse repetition frequency of 50μs (threshold 100 μs); (iv) though the return echoes are correlated, the bursts are instead interpreted using aperture synthesis data processing techniques.
The choice of antenna diameter and frequency are determined by considering the increase in antenna gain with increasing frequency and the increase in atmospheric transmission with decreasing frequency.

In SAR mode, the resolution of the radar is improved in the along-track direction. This is achieved by exploiting the Doppler properties of the echoes as they cross the antenna beamwidth. The result is equivalent to decomposing the main antenna beam into a set of 64 narrower synthetic beams in the along-track direction. The footprints of the different sub-beams over a flat surface are adjacent rectangular areas, about 50 m wide in along-track and as large as the antenna's cross-track footprint. Hence, a large number of independent measurements are available over a given area; this property is used to enhance the accuracy of the measurements over the surface. The antenna's can also be used in SARIn mode which improves the echo localization capabilities, as the cross-track direction angle of the echoes can be determined.

3.2 Magnetometer

The magnetometers are required to fulfill the mission objective to search remanent magnetic stripes in the crust and/or a weak magnetic field from the core. Two magnetometers placed in different positions on the boom. The sensor at the end of the boom (furthest away from the spacecraft body) is the absolute scalar Coupled Dark State Magnetometer [4]. The instrument is an optically-pumped vapor magnetometer which will be flown on the China Seismo-Electromagnetic Satellite mission, scheduled for launch at the end of 2016. The other sensor is a heritage fluxgate magnetometer from the Double Star mission [5]. The use of two magnetometers enables calibration of the fluxgate and provides redundancy. It is also absolutely critical to keep the magnetic noise from the spacecraft low, in order to prevent it from "drowning" the weak signals from Venus. This will enable the instruments to measure very weak magnetic fields. The low background noise distinguish separates this mission from Venus Express when it comes to magnetic measurements. To achieve the low levels of magnetic noise the spacecraft field shall not exceed 0.1 nT at the end of the 4.5 m long boom, and the variation of the spacecraft magnetic field shall not exceed 0.05 nT per 100 seconds. IN comparison, Venus Express had a noise level of ∼200 nT [6]. The resolution for the fluxgate instrument is 15.6 pT and according to first estimation even better for the absolute magnetometer. Venus Express had only an accuracy of ∼1 nT after noise characterization and calibration [7]. A comprehensive EM-noise verification and control-program (cleanness program) will be implemented. This will require modelling and testing during and after spacecraft manufacturing.

3.3 Gradiometer

To improve the gravity model and perform precise topographic measurements a gravity gradiometer will be used. By continually collecting information from the gradiometer precise data about the gravitational field can be obtained – thus fulfilling observational requirement 1.4 and 3.2. Due to limitation in the current gravity model the results could also be used in order to determine the satellite position. Without a gradiometer the highest precision of the orbital position is estimated to 0.5 m – 1 m. Although, this would allow the possibility to investigate the bigger features seen in Figure 1, the measurements could be more exact and allow an investigation of more features with a gradiometer. The proposed cold atom gradiometer is based on the principle to cool and trap atoms. When the measurement starts the cloud is released and the atoms accelerate due to gravitational effects. Finally, the position of the atoms are measured by laser interferometry and the gravitational effect deduced. Estimated noise levels for the measurements can be seen below [8].

$$\Delta\gamma = 4.7mE/\sqrt{Hz}$$

$$\Delta\omega = 35prad.s^{-1}/\sqrt{Hz}$$

When this noise level is compared to the expected gravity measurements seen in Figure 2 it can be seen that signals below approximately 0.05 Hz will not be distinguishable from the noise. Thus, a polar gap of approximately 1.5 degrees can be allowed as limit for the maximum orbit inclination since a gap less than this will not generate more precise results.

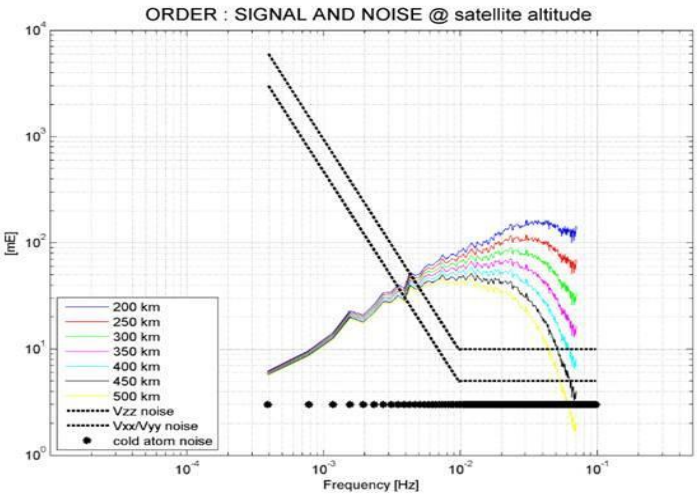

Figure 2. Expected gravity signal at different heights compared to noise levels from GOCE and cold atom gradiometer

The instrument's TRL is estimated to be 2 base on the information made available by Carraz et al., 2014. However, due to the MAIUS rocket test of interferometry with Bose-Einstein condensates in space planned in November 2014 some of the technology has the possibility to achieve a TRL at 4 [9]. Although, the TRL for the instrument as a whole remains low there are indications that a development track is in place already.

From the results from the gradiometer the position of the satellite can be deduced. It is suggested that the position for a satellite around Earth might be determined to a higher degree than what was achieved for GOCE. A conservative estimate would hence be that the position of the WEGENER satellite might be determined within 5-10 cm[8]. However; a low drag is needed in order to achieve these results. Based on the spacecraft design and the low density atmosphere of Venus at 400 km indicate that no drag compensation should be needed [10].

Thus, the gradiometer will not only fulfill the requirements of improving the data about the gravity field. As say, it will also help determining the satellite position with an unprecedented low error which will in turn increase the ability to do desirable topographic measurements.

5. MISSION DESIGN

After the determination of mission objectives (phase 0) the mission requirements were set up and the feasibility of the mission was confirmed in the PDR (phase A/B1). The more detailed analysis of the objectives was performed and precise orbital manoeuvres were simulated and confirmed in the FDR (B2/C/D), as shown in Figure 3.

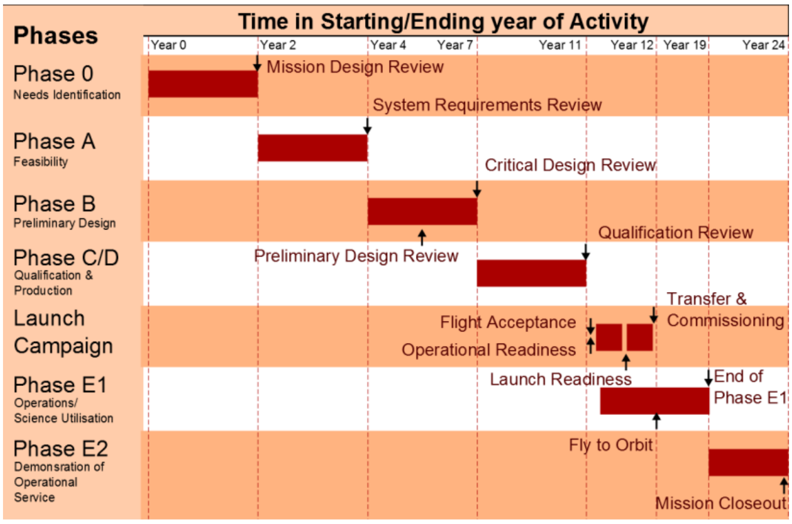

Figure 3. Mission project phases

5.1 Orbit planned

Transfer Orbit

The spacecraft is placed into a parking orbit by a Soyuz launcher. Injection into Hohmann transfer orbit is done by "Fregat" upper stage. Preferable epochs for start of Hohmann transfer are chosen so that minimize travelling time and are optimized with respect to V infinity.

Transfer from Earth to Venus is carried out by means of two impulsive transfers, the so-called Hohmann transfer. The total duration of the transfer amounts to 157.53 days. The first part of the Hohmann transfer requires a delta-V1 of 3.71 km/s. A deep space maneuver will allow the s/c to acquire an inclination of 91.5 degrees. The second part of the Hohmann transfer will be conducted shortly before arriving in the vicinity of Venus and requires a delta-V of approximately 1 km/s. Following this maneuver, the Spacecraft enters Venus atmosphere at a height of 340 km for aerobraking.

Atmospheric drag and other properties are estimated on the basis of Venus atmospheric model developed by NASA and included into STK software. Aerobraking phase continues over 47 days until an altitude of apocenter drops to the value of altitude of final orbit. As a pericenter of aerobraking trajectory gradually verges towards the Venus surface, tiny impulses are demanded in some apocenters. Delta-V of 0.2 km/s is required for ascent to final orbit, when the desired altitude is reached in apocenter of braking orbit.

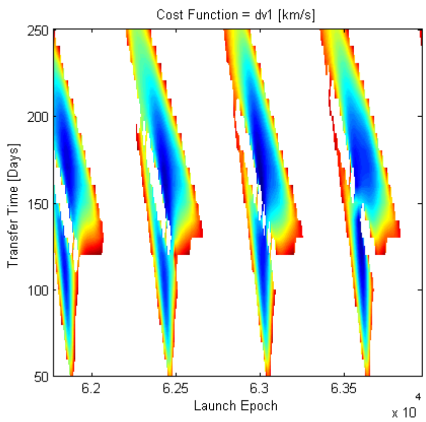

Figure 4. Cost Function Plot

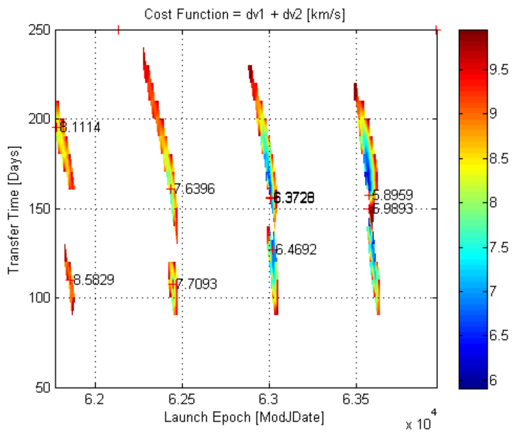

Figure 5. Cost Function Optimisation

Venus Orbit

A circular orbit with altitude 399.2 km and inclination 91.5 degree is chosen as the final orbit around Venus with the observational requirements. Circular orbit guarantees constant resolution of the image. The altitude is chosen such that after one Venus day the craft will re-enter the previous trace. At this altitude, one meter drift in altitude causes about 9 meters drift of the trace after one Venus day. With regard to the choice of inclination has two effects: values other than 90 degree create blind-zone at polar area but 90 degree inclination provides no crossing except at the poles which is indispensable for the topographical observation: Dense enough crossing points along the trace support the improvement of the orbit knowledge. As a result, an inclination close to 90 degree with small bias (1.5 degree) is chosen. For the Venus case, the largest diameter for the diamond shape holes in the trace pattern is about 5.17 km.

6. SPACECRAFT DESIGN

The general overview of the satellite is presented on Figure 7. The satellite consists of the main bus on top of which the solar panels are mounted. On the front side of the spaceraft the HGA antenna of about 1.2 m in diameter is mounted and the bench holds two altimeter antennas each 1.7 m in diameter. On the rear side of the spacecraft the thrusters and the magnetometer boom are located. The flanks are reserved for the radiators. The interior of the satellites is housing all the electronics, power supply, batteries and fuel tanks.

6.1 Thermal control system

The Wegener spacecraft is going to operate on Venus circular orbit at about 400 km altitude. It is going to be exposed to the solar flux, which is twice that experienced on Earth (2.6 kW/m2), and also a reflected flux (0.15 kW/m2). The radiation dose is estimated at approximately 20 Krad, which corresponds to 2mm of aluminium shielding. The baseline for the thermal design was Venus Express' thermal system control. The spacecraft in the fully operational mode will be generating about 750 W (including overall 20% margin), which requires 3 m2 of the radiative area. To protect the satellite from the all external heat fluxes, most of the external surfaces (except radiators, solar panels, thrusters) will be covered by MLI. Due to the high thermal stability required by altimeter antennas, their design will be based on Cryosat-2 approach, where the plates have a sandwich structure with high reflective coating for the external surfaces. In addition, the magnetometer used for the magnetic measurement requires a very stiff satellite structure. Otherwise, the MLI will detrimentally impact the measurements. This requires a redisegn of the typical MLI, for example by adding low conductive meshing to provide more stiff structure.

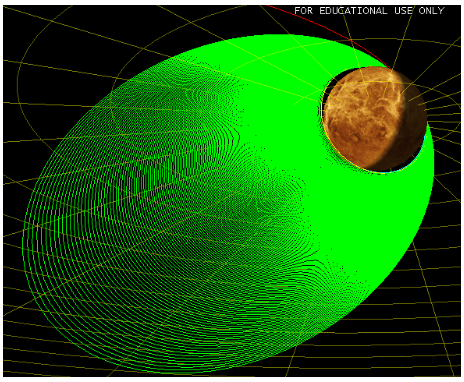

Figure 6. Aerobraking model

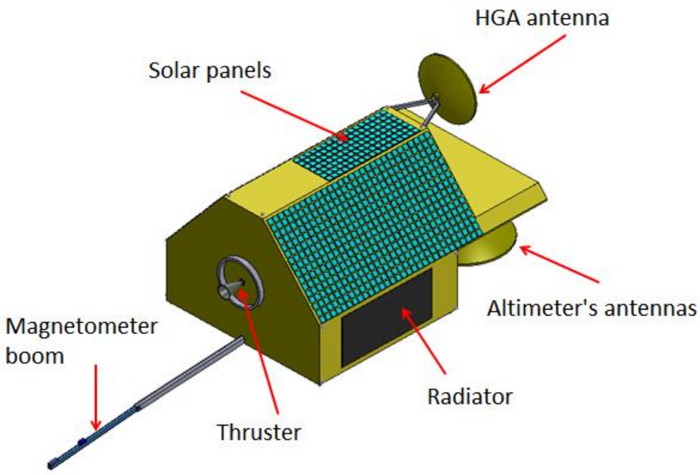

Figure 7. Spacecraft design

6.2 Mass budget

Table 1 and 2 summarize the mass budget for the WEGENER mission.

Payload	Mass [kg]	Margin [%]	Mass with margin [kg]
Altimeter in SARIn mode	70	10	77
Fluxgate Magnometer	2.86	5	3.0
Cold Atom Gradiometer	15	50	22.5
Absolute magnetometer	1.2	20	1.44
Total	**89.1**		**103.9**

Table 1. Payload mass budget

	Mass - nominal [kg]	Subsystems' margin	Mass with the margin [kg]
Payload	171	n/a	171
Subsystem			329
Propulsion	51	5%	54
AOCS	12	5%	13
Communications	15	5%	16
C&DH	11	5%	12
Thermal	25	5%	26
Power	52	5%	55
Structure & mechanisms	140	10%	154
<u>Total with 20% margin (S/C dry mass)</u>	<u>500</u>		<u>566</u>
Total with Propellant mass			**937**
Mass of the Soyuz launcher [kg]			**1650**
Mass for the Venus orbiting [kg]			**1100**

Table 2. Subsystem mass budget

6.3 Power

The maximum power requirement of Wegener satellite of power is about 1265 W, the effective solar panels area of 3m2 is required (assuming 25%, EOL). Due to the fact, that on Venus' orbit the solar heat flux is twice as on Earth (2.6 kW/m2) and radiation dose is about 20 krad, the design of the solar panels be made of solar cells used for the Venus Express solar arrays. They are made of Gallium Arsenide cells, which are more resistive for the higher heat flux and radiation dose. To operate during the eclipse, the satellite requires 2 batteries (Li-ion, 24Ah, 518 Wh) – heritage from Venus Express.

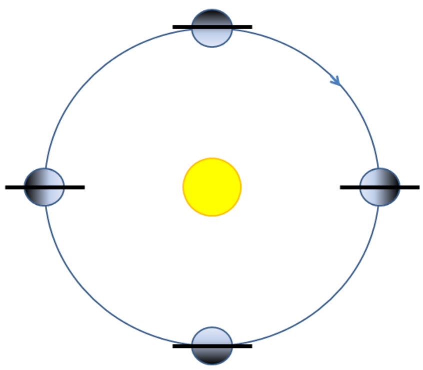

Figure 8. Orbital position of the spacecraft with respect to the Sun

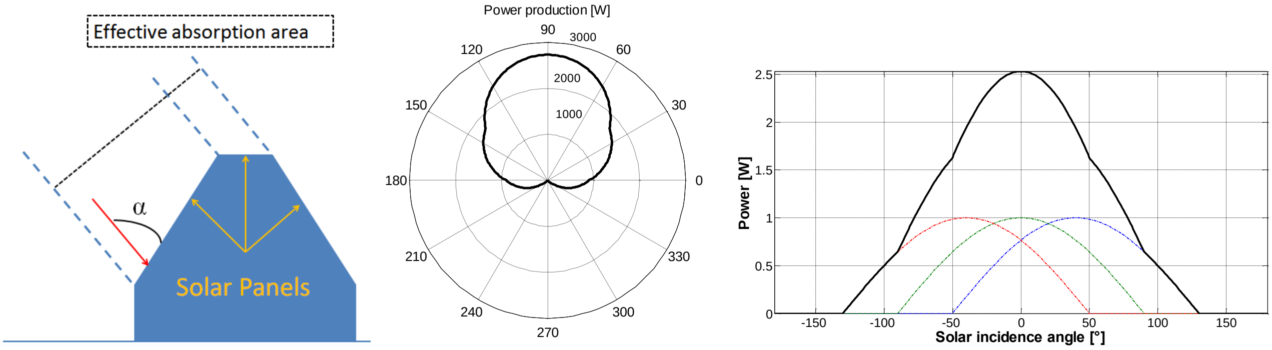

Figure 9. The solar panels are located on the top of the spacecraft on the three walls creating roof shape cover (a). This geometry allows heat to be absorbed with respect to the incident angle of the incoming solar flux (a). (b) and (c) present the absorbed solar heat flux with respect to the incident angle.

Payload	Power [W]	Margin [%]	Power with margin [W]
Altimeter in SARIn mode	295	10	325
Fluxgate Magnetometer	3	5	3.2
Cold Atom Gradiometer	10	50	15
Absolute Magnetometer	4	20	4.8
Total	317		350

Table 3. Power Payload

	Subsystems' margin [%]	Power - nominal [W]	Power - including margin [W]	Transfer Scenario [W]	Science and Communication [W]	Science [W]	Eclipse [W]	Maintenance [W]	Safe mode [W]
Payload	n/a	345	347	0	347	347	347	0	0
Subsystems									
Propulsion	5%	60	63	63	0	0	0	0	0
AOCS	5%	39	41	41	41	41	41	41	0
Communications	5%	65	68	0	68	0	0	68	0
C&DH	5%	42	44	0	44	44	44	0	0
Thermal	5%	55	58	0	58	58	58	58	0
Power	5%	412	433	0	433	433	0	0	0
Total [W]		**1018**	**1054**	**104**	**991**	**923**	**490**	**167**	**0**
With overall 20% margin		**1221**	**1265**	**124**	**1189**	**1107**	**588**	**200**	**0**

Table 4. Power Subsystem

6.4 Attitude control

Based on the requirement to align the spacecraft with an accuracy of 10 arcsec, Wegener will use twelve 10-N thrusters as actuators. In addition, five reaction wheels, mounted in a tetrahedral configuration and two Inertial Measurement Units (IMU) are used as attitude sensor. The thrusters are also used to off-load the momentum of the reaction wheel. Based on the Three Star-Trackers (STRs) which directly provide position information, the integration error of the IMU will be periodically corrected. The attitude control in the basic design uses a feedback control with PID controller.

6.5 Onboard computer and data handling

Data handing on the satellite is important due to a high data input, mainly from the altimeter, and low transfer speeds to Earth. When the SIRAL is used on the Cryosat-2 a data rate of around 11 Mbps is generated; a lower value than this is expected since this mission primarily needs altimeter measurements. Also, data compressing on the system would severely decrease the amount of data to be transferred. As described before, the communication link to the Earth allows data to be sent at a speed of around 380 kbps approximately 8 hours a day. A maximum data transfer of 9 Gb/day is thus reasonable to consider.
Data will be sent using the movable antenna. In this phase no measurements are possible since the movement of the antenna will disturb the center of gravity and introduce magnetic noise. Due to this temporary storage of the data is needed as well as access to a flexible onboard computer.
Wegener will use a compact computer based on ESA's microprocessor LEON4 or LEON3. LEON3 has high performance (1.4 DMIPS/MHz) and estimated power consumption of 30 W and a mass of 4 kg. The system will have to be adapted to the radiation and thermal environment around Venus. Regarding suggestion to the onboard storage one might consider a MMU based on the NEMO Flash SSR though with similar environmental adaptations as the onboard computer. Estimated specifications for this type of MMU could be summarized to 10 W, 6.5 kg, 0.5 Tb [2].

6.6 Telemetry

All data is sent via telecommunications to the ground station on Earth. The ESA Deep Space Network will be used for 8 hours each day. We can downlink in average 380kbps, depending on the relative position of Venus and Earth. Our spacecraft possesses one 1.7 diameter parabola antenna that is movable to allow pointing in earth direction. It can operate at X-Band at 60W and 8500MHz frequency and, as backup over short distances, at 5W and 2296MHz. The link budgets are a heritage of the systems on Venus Express and Magellan.

7.. GROUND SEGMENT

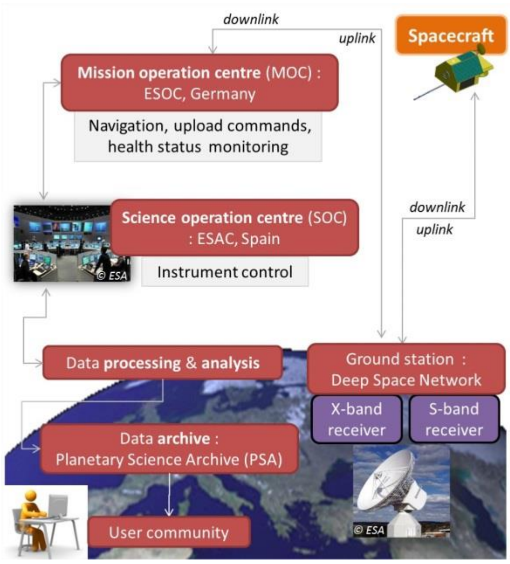

Figure 10. Ground segment

Figure 10 depicts the path of the mission data, between the reception by the Deep Space Network to the data archive. The data will be released after 6 months and made available for the community, after various processing steps.
These processing steps include first levels data correction (time ordering, merging, calibration), onboard calibration (e.g. potential improvement of magnetic field detection by lowering the orbit) and processing (e.g. altimeter data products, based on a CryoSat Mission algorithm).

Outreach projects for the Wegener Mission data products are considered for various audiences (media, students…) and for distinct phases of the Mission (e.g. Venus ground observation, workshop sessions for sharing specific data tools).

. RISK MITIGATION

The Wegener mission has a possibility to encounter some possible risks during the design process. Below are some scenarios presented, which might occur during the mission. Each risk is mentioned by its severity, the consequence that follows, and the mitigation plan.
Very low: (i) Malfunction of one radar channel. The consequence is no SARIng, but out primary mission goal is still

possible; (ii) Scalar magnetometer failure, which leads to loss in accuracy during the measurements. This will still not endanger the primary mission goal.
Low: Malfunction of the absolute vector magnetometer, which leads to no detection of remnant magnetic crust. The primary mission is still possible to continue.
Medium: (i) More than one reaction wheel fails during the five-year mission. The consequence is reduced pointing quality of the instrument; (ii) This in turn leads to a redundant system with five reaction wheels; (iii) Gradiometer not flight ready. Instrument is not needed for reaching the threshold of the primary mission objective.

9. COST ANALYSIS

Wegener is a M-class (Medium size) mission that will be launched with a Soyuz rocket since it is a reliable and low-cost vehicle. The overall estimated budget is ~ 750 M€ for a 5 year long mission. The total costs excluding the payload will be ~570 M€.

10. DESCOPE OPTIONS

An option for descoping the mission involves removing the coupled dark state magnetometer. With the remaining payload it would still be possible to detect magnetic striping but it will not be possible to improve the magnetic field model data. Descoping the gradiometer will significantly reduce the development cost without impacting the primary mission objective.

11. CONCLUSIONS

The Wegener mission will provide a unique opportunity to study Venus and its solid body dynamics. The ideal combination of topographic, magnetic, and gravity measurements will lead to a significant improvement of understanding plate tectonics, volcanism, and crustal structure of an Earth-link planet. The improved knowledge of the solid body dynamics of Venus will also improve general understanding of planetary geophysics and evolution of terrestrial planets.

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