The Aeolus mission concept, an innovative mission to study the winds and climate of Mars

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ABSTRACT

Aeolus is a mission to provide the first set of global, seasonal, and diurnal data to characterize winds and study the climate of Mars. Aeolus measures surface and atmospheric temperatures, aerosol abundances, and Doppler shifts in atmospheric spectral lines. The payload includes a system of four of a new type of miniaturized Spatial Heterodyne Spectrometer (SHS) paired to two orthogonal viewing telescopes that can measure CO_2 (daytime absorption) and O_2 (day and night emission) lines in the Martian atmosphere. The Thermal Limb Sounder (TLS) instrument measures atmospheric temperature profiles and aerosol (H_2O ice clouds, dust) profiles, and the Surface Radiometric Sensor Package (SuRSeP) measures the total reflected solar radiance, and surface temperatures down to 140K. These combined spectral and thermal measurements will provide a new understanding of the global energy balance, dust transport processes, and climate cycles in the Martian atmosphere. The mission concept for Aeolus consists of a single sub-100 kg secondary spacecraft in a highly inclined orbit, allowing it to pass over all local times. Aeolus attains global coverage of the surface for a mission duration of one Martian year, to capture climate patterns during each Martian season. This paper gives an overview of the Aeolus payload, spacecraft, and the methodology used to mature the Aeolus mission concept.

INTRODUCTION

Aeolus will be the first mission to directly measure the winds on Mars and revolutionize our understanding of Mars climate. The Mars climate system is dynamic and characterized by the seasonal cycles of dust and water ice, which are coupled through global atmospheric circulation patterns. Winds are an important, if not the main, agent shaping the surface of Mars for the past 3+ billion years, and none of the previous or ongoing mission have provided the closure needed to understand how global-scale wind systems control these cycles. Aeolus performs systematic, global, simultaneous, direct measurements of winds, dust, and clouds at all times of day. Aeolus measurements will identify the energy sources and sinks that drive the climate system, which are critical to understand how the winds control these cycles, whether or not the cycles are closed, and the distribution of surface sources and sinks. Aeolus provides these measurements for the first time.

The Aeolus investigation is as an examination of the three most influential factors that determine climate and climate cycles: winds, energy balance, and aerosol distribution. Energy balance refers to the balance between energy inputs (mainly solar radiation) to Mars' surface and atmosphere, and energy outputs in the form of reflected energy and thermal radiation. Aerosols are simply any particles suspended in the atmosphere; on Mars, the most abundant and radiatively active aerosols are dust particles and H_2O ices. This paper gives an overview of the scientific rationale that motivates Aeolus, a summary description of the planned instrumentation, an example of a spacecraft implementation and mission concept which meets Aeolus science requirements and, lastly the structured process the NASA Ames Mission Design Center used to mature the Aeolus concept from a "cocktail napkin" to a point design.

Science Background

Wind and temperature fields are related through basic balance relationships. In atmospheres like Mars, pressure decreases exponentially with altitude at a rate inversely proportional to temperature, decreasing slowly with height in warm columns and rapidly with height in cold columns. Temperatures also change with latitude, given that solar insolation is greater in the tropics than at the poles. The combination of these two facts creates horizontal pressure gradients that in turn create winds, as mass flows from high to low pressure. On rotating planets like Mars, these winds are deflected by the Coriolis force; to the east in the northern hemisphere and the west in the southern hemisphere.

The balance between these two forces—the pressure gradient force and the Coriolis force—determines the "geostrophic wind," which is a theoretical wind that relates the temperature field directly to the wind field.

In reality, there are other forces acting on the wind field, such as mixing and friction, so geostrophy (balance) is rarely achieved in real atmospheres. A prominent form of mixing is that due to large-scale wave motions associated with weather systems and/or stationary waves forced by the topography. By directly measuring winds, we can determine just how close to geostrophic balance the winds actually are and determine the magnitude of these mixing processes, all of which play an important role in the global energy balance. Measuring aerosol profiles (dust, water ice) enables us to calculate the radiative heating and cooling rates of the atmosphere; these temperature changes are the ultimate drivers of pressure gradients and all resulting mass flows.

Our current view of the general circulation, shown in Figure 1, is based almost entirely on partly validated theoretical models. Global winds have been inferred from temperature measurements, but these are not real winds; winds are assumed calm at the surface, and certain forces are balanced (e.g., gradient winds assume that the pressure gradient, Coriolis, and centrifugal forces balance). In reality, surface winds can be strong on Mars, and wind systems can be far out of balance. Figure 1 illustrates how large the errors are for gradient winds ("derived") by plotting the difference between the zonal mean winds ("modeled") from the ARC Mars Global Climate Model (GCM) and the winds calculated from the model temperatures using the gradient wind approximation. White areas show errors that are too large to contour. In addition, to distinguish the tides (functions of local time) from the zonal mean wind, measurements must be made over a full diurnal cycle.

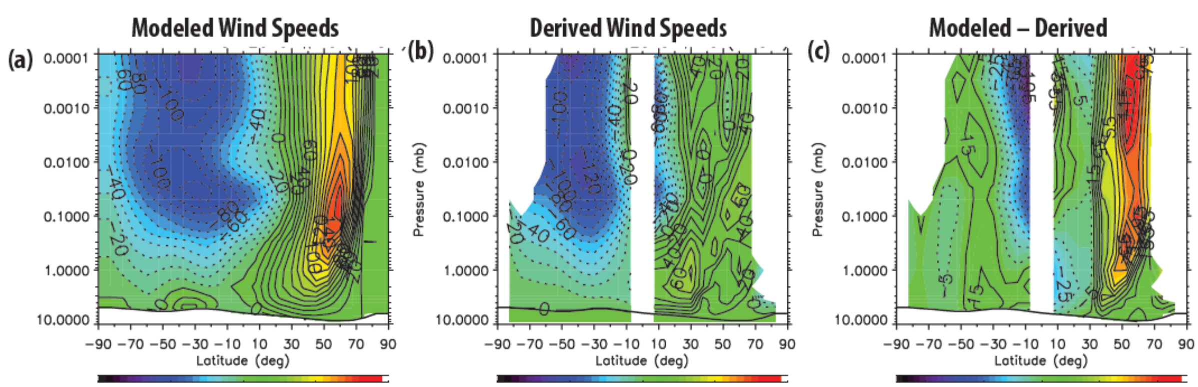

Figure 1. Wind speeds derived from thermal measurements can be in error by up to 100%. Contours show wind speeds in m/s. Solid lines are westerly winds, and dotted lines are easterly winds. (a) Global Climate Model simulated wind speeds. (b) wind speeds derived from thermal balance; (c) Difference between panels (a) and (b) shows that winds are not in balance with the thermal fields. Similarly, the actual winds on Mars are expected to be different from those derived from observed thermal fields. [1]

SCIENCE IMPLEMENTATION

The Aeolus science payload consists of three instruments: the Spatial Heterodyne Spectrometers (SHS), the Thermal Limb Sounder (TLS), and the Surface Radiometric Sensor Package (SuRSeP). The SHS and TLS point to the limb of Mars and SuRSeP looks nadir (Figure 2). The two limb-viewing instruments make vertically resolved measurements of winds (magnitude and direction), water ice clouds and dust densities and atmospheric temperatures. The nadir-viewing instrument observes total solar and thermal energy, the column densities of water ice clouds and dust, and surface temperatures.

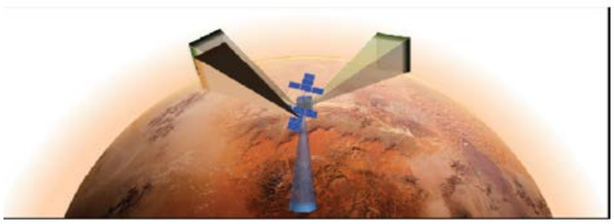

Figure 2. Aeolus Payload Fields of View. The SHS telescopes point (green) toward the limb; TLS FOV (orange) overlaps with one of the SHS FOVs; SuRSeP points nadir (blue).

Previous Mars orbiters that have fixed Sun-synchronous orbits only collect data from one morning/evening time, neglecting observations at other local times of day. Key to meeting Aeolus science is an orbit that precesses through local Mars times, allowing measurements across all local times rather than at a single fixed AM/PM time. An inclined orbit will do this, with the temporal precession of the orbit occurring more rapidly with lower inclination angles. It is important that the precession be sufficiently rapid so that seasonal changes in winds, temperatures, and aerosol distributions are not aliased into the changes caused by diurnal variations. A Mars "season" is approximately 160 Earth days; thus, a precession through all local times should be faster than this. However, lower inclination angles means that Aeolus' view of high latitudes (poles) would be restricted, which is undesirable. Therefore, the Aeolus 73-degree orbit inclination allows for Mars to rotate in local time a full Mars day (sol) in approximately 120 Earth days, or 2-hours of local Mars time in approximately 10 Earth days. This orbit also reaches high latitudes (73 degree), providing more than 80% global coverage in 10 Earth days. Every 5 days a yaw maneuver is performed to optimize limb-view relative to the Sun and also allowing for the limb instruments to view poleward of the 73-degree inclination. The Aeolus orbit is an excellent balance between polar spatial and diurnal coverage.

Table 1 Instrument Performance Summary

Instrument Attributes	Performance Requirement	Actual Performance	Margin
SHS			
Sensitivity	0.5 W/m2/sr/ µm	0.1 W/m2/sr/ µm	500%
Wind Speed Range	10-160 m/s	5-230 m/s	100%
Wind Speed Accuracy	10 m/s	5 m/s	100%
Spatial Coverage	±70 degrees latitude, Global coverage in 10 sols	±80 degrees (with yaw), Global in 10 sols	14%
Spatial Resolution	10km	<5km	100%
TLS			
Sensitivity	SNR > 40 in 15.1 µm channel at 140K	123	300%
Temperature Range	140-300K	130-350K	7% low end, 17% high end
Temperature Accuracy	±5K	±3K	40%
Spatial Coverage	±70 degrees latitude, Global coverage in 10 sols	±80 degrees (with yaw), Global coverage in 10 sols	14 %
Spatial Resolution	10km	<5km	100%
SuRSeP			
Surface Temperature Range	140-300K	120-350K	
Surface Temperature Accuracy	±10K	±5K	100%
Spatial Resolution	<150km	100km	50%

Spatial Heterodyne Spectrometers (SHS).

The SHS consists of four stacked Spatial Heterodyne Spectrometer modules coupled to two orthogonal viewing telescopes. The SHS modules are ideal for space-based Doppler shift measurements because of their very high resolution and thermally compensated design. A single SHS module is similar in configuration to a Michelson interferometer, except that the mirrors in the arms of a Michelson are replaced by reflection diffraction gratings, tilted at an angle with respect to the optical axis. The tilt of the gratings can be adjusted to target certain wavelengths of observation. Unlike conventional Fourier transform spectroscopy, the SHS requires no moving parts to operate at full theoretical resolving power over its full spectral range. It can thus be readily formed into a monolithic block, making it well suited to the rigors of launch and space operations. For Aeolus, two identical SHS-O_2 modules measure the Doppler shift in atmospheric O_2 airglow emission (1270 nm) in day and night observations. Likewise, the other two identical SHS-CO_2 modules measure the Doppler shift in atmospheric CO_2 absorption (1430 nm) during daytime observations. Identical modules are optically connected to one telescope each, so that each spectral line is observed with two orthogonal views. This allows line-of-sight (LOS) wind speeds to be converted to wind vectors during ground processing.

To increase the signal-to-noise ratio (SNR) and lower the spectral resolution requirement of the wind instrument, the difference in emission/absorption line position is derived. This takes advantage of the change in line position along the LOS, convolved with the instrument spectral function, rather than solely relying on a line center measurement. The absolute radiance of the lines is not needed; the wavelength calibration need only be stable across a series of measurements. Slow drifts are also allowed as they typically have systematic signatures that can be filtered out. Therefore, instrument calibration is relatively simple; with only occasional (every 10 days) views of a stellar source for spectral calibration.

The SHS telescopes have a full FOV of 10 degrees and a pixel instantaneous FOV (IFOV) of 5 milli-degrees providing a projected footprint at the limb of 250 km and spatial resolution per pixel of ~ 0.5 km. Ten vertical spatial elements are summed onboard the instrument to increase SNR, providing a measurement resolution of approximately 5 km. The FOV has been deliberately oversized to relax spacecraft (S/C) pointing requirements; the S/C pointing is allowed to drift as much as 1 degree before the sensor FOV drifts off the atmospheric limb.

Thermal Limb Sounder (TLS)

The TLS is a limb-pointed instrument for measuring atmospheric temperatures and aerosol distribution. It is comprised of a modified commercial-off-the-shelf (COTS) uncooled micro bolometer thermal camera with a series of on-sensor optical filters. Similar instruments have flown at Mars, including the THEMIS instrument on Mars Odyssey. For Aeolus, six filters are applied with each filter being 95 detector pixels across, with 10 buffer pixels between each filter set. The array has a ~5- degree FOV at the nominal S/C altitude, allowing it to capture the same altitudes as the SHS instrument, and like the SHS, is deliberately oversized to relax S/C pointing requirements.

For calibration, the TLS has an internal shutter just before the sensor that closes once every 10 measurements. This shutter is maintained at a fixed temperature and allows for radiometric calibration and flat fielding. For full instrument calibration (including optics beyond the internal shutter) the TLS is periodically (once every 10 days) pointed to deep space.

Surface Radiometric Sensor Package (SuRSeP).

The SuRSeP is a radiometer package originally built at ARC for the lunar Resource Prospector Mission. SuRSeP is based on a design that is currently at TRL 6, having gone through environmental qualification testing. For Aeolus, SuRSeP measures surface temperature, total surface solar reflected and thermal emitted radiance, and total dust and water cloud column densities, using eight uncooled thermopile sensors with spectral band pass filters. The approximate energy balance of Mars is calculated using the “open” channel minus the “solar” channel. Surface temperatures are derived from two channels dedicated to “warm” and “cold” surfaces, while three channels near 15 microns are used to derive atmospheric column temperatures between 10-25 km and 25-45 km. Lastly, two more filters measure the column densities of atmospheric dust and water ice clouds. These two aerosols are critical to characterize atmospheric radiative heating.

The SuRSeP instrument monitors internal detector temperature to calibrate for changes in instrument temperature over time, but requires periodic (once every 10 days) deep-space looks to calibrate. This calibration requires the S/C to roll so that the sensors are off the limb of the planet. Given that the polar CO_2 ice is at a sublimation temperature of approximately 145K (south pole), additional nadir calibration checks are made over the seasonal CO_2 frost cap. It is understood that these are simply checks for significant offsets as the actual and apparent CO_2 ice temperature will vary by ±5 degree or more. Together with wind speed measurements, Aeolus can determine, for the first time, the global energy balance in Mars’ atmosphere.

MISSION CONCEPT

Aeolus uses a single sub-100 kg S/C to accommodate the three science instruments and launches as a secondary payload with the Next Mars Orbiter (NeMO), which is scheduled for launch in the 2022-2024 timeframe. NeMO carries Aeolus to Mars and into NeMO's 320 km operational orbit. Following deployment from NeMO, Aeolus initializes operations and transfers from the 320-km orbit to a 383-km average-altitude orbit at 73-degree inclination to conduct science operations. This orbit transfer requires a ΔV of ~153 m/sec. Aeolus' orbit provides continuous viewing of the Mars limb, which meets the science requirements. Since Aeolus is powered off during launch and cruise, NeMO's interface to Aeolus during cruise allows battery maintenance, heater control, and S/C commanding, up to and including separation from NeMO. Separation sensing and confirmation is provided by Aeolus. Initial command telemetry communications are performed using X-band via the Deep Space Network (DSN). UHF crosslink via NeMO is used for science data and high data rate up-link/ downlink. After a commissioning and calibration period, Aeolus performs its primary science mission over a 2-year period (1 Mars year). The instruments are body-pointed by the S/C. Aeolus' science orbit yields approximately 12 orbits per Martian day, where at least 10 of the orbits are dedicated science operations. During science orbits, Aeolus takes 40 science measurements, one every 2.5 minutes with each one lasting 30 seconds. This cadence is driven by the volume of data to be downlinked and available crosslink data rates to NeMO. To maintain maximum solar coverage and minimize jitter during the science measurements, Aeolus gimbals the solar arrays to track the Sun between each science measurement. The remaining two orbits are reserved for daily S/C activities which include: a) crosslink to NeMO once every 8 days, lasting approximately 5-20 minutes; b) direct-to-Earth communications via the DSN once every 7 days, lasting approximately 1 hour; c) reaction wheel desaturation via the cold-gas thrusters once every 3.5 days, lasting approximately 1 minute; d) a 180 degrees yaw maneuver using the three-axis reaction wheels once every 6 days, lasting approximately 15 minutes ; and e) instrument calibration activities once every 10 days. The 180-degree yaw maneuver is required to adequately capture both Martian poles. Two orbits are conservatively reserved for occurrences when multiple daily S/C activities occur on the same day; however, if no daily S/C activities are scheduled, Aeolus continues taking science measurements. Figure 3 shows a nominal two weeks operation cycle for Aeolus.

Orbit Design

Currently available trajectory plans for NeMO include a 10-month low thrust transfer from Earth to Mars vicinity, at which point NeMO performs a 15-month low thrust orbit insertion to a final operational orbit of 320 km. NeMO carries extra propellant to perform large plane changes that include destination inclinations between 75 to 93 degrees. The Aeolus science orbit is constrained by the science requirements, planetary protection regulations, NeMO's operational orbit into which Aeolus is initially deployed, and the inherent mass limitations of a small spacecraft. For the orbit trade study, the Aeolus team conducted various simulations involving a high-fidelity propagator with the following assumptions:

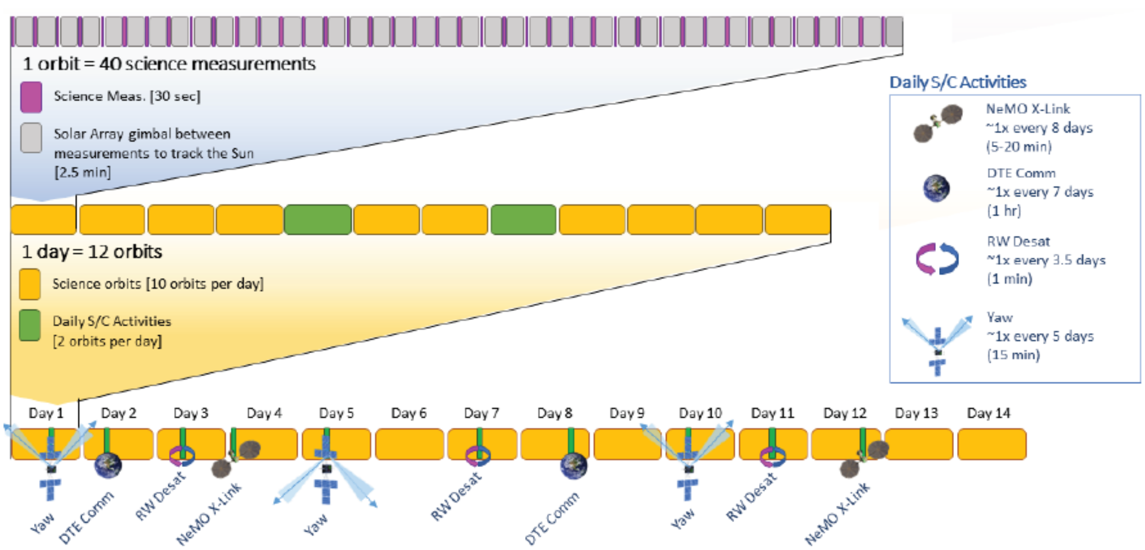

Figure 3. Aeolus 2-weeks ops cycle shows science measurement and daily S/C activities

- Mars GRAM 2005 atmospheric model [2]
- NASA GSFC GMM2B Mars gravity model 20x20 [3]
- Sun third body mass
- Spherical model for solar radiation pressure
- Solar flux index F10.7 assumed to be constant and with a value of 100.

Due to the limited propellant mass available on a small S/C, the Aeolus orbit must be achievable with a small ΔV budget. The main science requirements driving the mission design are the following:

1. To prevent seasonal aliasing in Aeolus measurements, the orbit must precess over all local times at least once every 2 months.

2. The inclination of the orbit must be 70-75 degrees to sufficiently measure Polar Regions.

The science objectives include measurements at all local times. This is achievable through natural orbit precession due to the oblateness effects of Mars. Therefore, the orbit ground track covers all longitudes at all times during the Mars day. In terms of precession, this is translated in a requirement to achieve one full precession every 2 months. This number can be halved since each orbit includes passes at two different local times, depending if the orbit is passing through the ascending or the descending node. Therefore, the orbit needs to precess fully every 4 months, or 120 days.

As part of the orbit trade study, our team analyzed the time required to achieve full precession with respect to the initial orbit altitude and inclination. The blue shaded region in Figure 4 shows the available trade space for orbit altitude and inclination that meet Aeolus' ground coverage and precession requirements. Aeolus' orbit parameters must also meet the following requirements:

1. Aeolus science requires 10 orbits per day to achieve sufficient mapping resolution, with orbital velocity between 3 and 4 km/s.

Figure 5 A/B shows that any of the achievable orbits for Aeolus, after taking into account propellant mass limitations and precession requirements, comply with the orbit velocity and orbit period requirements.

2. Planetary Protection regulations require Aeolus' orbit to be stable for at least 50 years.

Planetary protection regulations require an orbiter in the vicinity of Mars, such as Aeolus, to be in a stable orbit for at least 50 years. Due to Aeolus' propellant mass limitations, the ΔV available to transfer to a different altitude is limited, which constrains the range of achievable altitudes. Low initial orbit altitudes result in an orbital decay over time due to atmospheric drag effects, while a high orbit altitude, even in the low Mars orbit environment, translates to a slow precession rate. High-fidelity, long-term propagation was conducted with conservative assumptions in the ballistic coefficient and the solar weather forecast. The analysis shows that Mars perturbations alter the orbit shape, producing periodic changes in the eccentricity that result in periapsis as low as 310 km. These perturbations do not present a risk to planetary protection since these altitudes do not encounter high-density regions of the atmosphere, avoiding orbit decay.

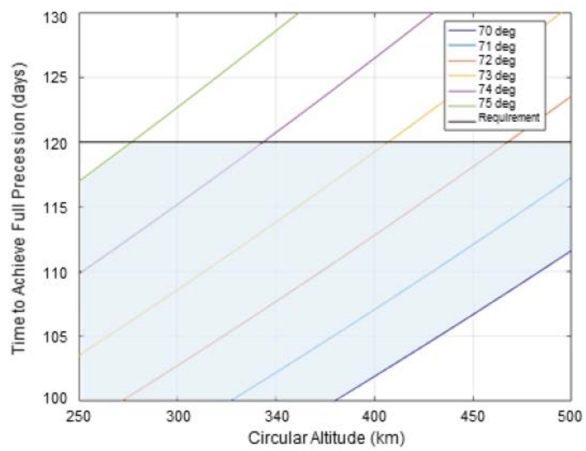

Figure 4. Time to Achieve Full Precession with respect to Orbit Circular Altitude and Inclination. Inclination is the largest contributing factor to the time it takes the S/C to complete a full cycle over the 0-360 degrees spectrum of the right ascension of the ascending node (RAAN). High inclinations yield slower precession, while low inclinations yield faster precession. The same applies for high altitudes; however, the dependency is less extreme. The light blue color highlights the region that complies with the spatial and temporal science requirements for observing the Mars weather. The black horizontal line corresponds to the 120-day requirement.

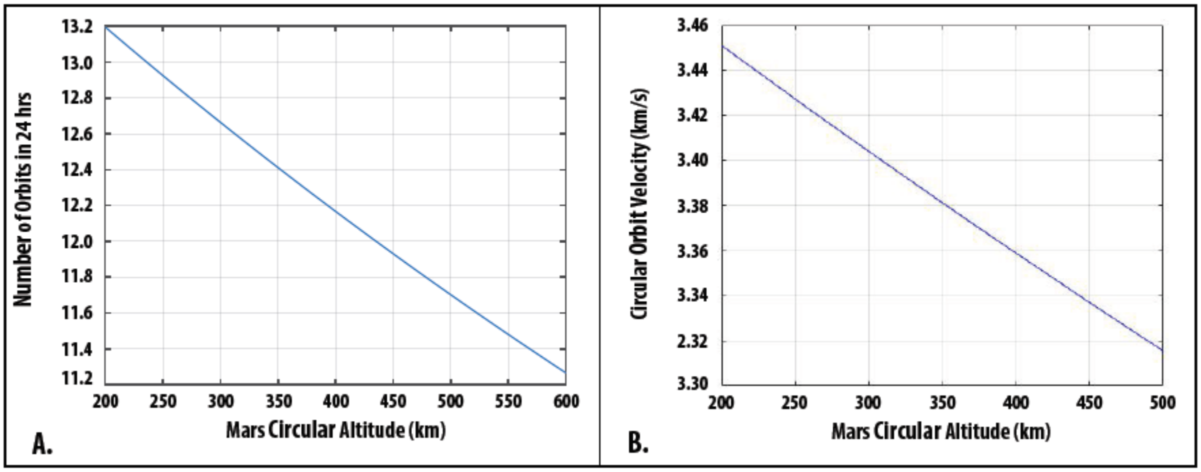

Figure 5. A) Relationship between circular orbit altitude at Mars and the number of orbits in 24 hours. B) Relationship between circular orbit altitude at Mars and circular orbit velocity. Higher altitudes give lower number of orbits and lower orbit velocity. All orbit altitudes in Aeolus' trade space comply with the mapping resolution and instrument requirements.

FLIGHT SYSTEM CAPABILITIES

Aeolus is a small 3-axis stabilized spacecraft, approximately 35 x 35 x 37 cm in volume with a 13-cm rear thruster protrusion with healthy margins (See Table 2). The SHS telescopes are each symmetrically 45 degrees off of cross-track, allowing SHS to view the Martian limb from perpendicular angles. The TLS is oriented along the same axis as the rear SHS telescope, also viewing the limb. The SuRSeP is on the bottom of the S/C, viewing nadir. Figure 6 shows the field of view for both the instruments and the star trackers. The reflectarray antenna is stowed on the bottom of the S/C during launch. Once Aeolus is safely deployed from NeMO, the reflectarray unfolds from the main structure by 90 degrees and then unfolds its side panels, with the final deployed configuration shown in Figure 7. The reflectarray feed then rotates down pointing at the array ready for signal transmission. The two solar arrays are attached to separate two-axis gimbals that rotate about the x and z axes.

The z rotation is limited to prevent blocking instrument FOVs. The UHF antenna is stowed during deployment and deploys via spring mechanism to 10 cm off the front face. Aeolus uses a non-toxic monopropellant system as main propulsion system, which provides 5 N of nominal thrust and up to 250s of Isp. In addition, it employs four 25 mN cold-gas micro thrusters for Attitude Determination and Control System (ADCS).

The S/C is cold biased (See Figure 8) so components do not exceed maximum operating temperatures. To prevent components from exceeding lower temperature limits, trim heaters are added to select components.

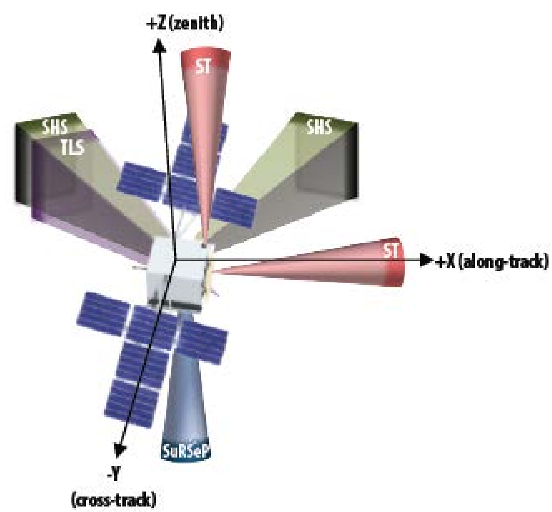

Figure 6. Field Of View for Aeolus's instruments and Star Trackers.

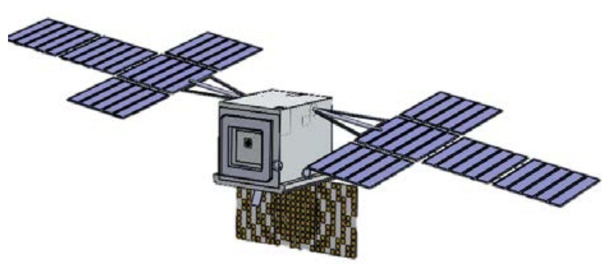

Figure 7. Aeolus in final deployed configuration

Table 2 Aeolus System Margin Allocation

SC resource	CBE	Allocation/Req.	Margin
Dry mass	32 kg	54 kg	41 %
Wet mass	38 kg	63 kg	41%
Tot power	53 W	112 W	53%
Pointing	± 0.007 deg	<0.5 deg	+ high
Attitude Knowledge	<0.00167 deg	< 0.05 deg	+ high
Delta-V	237.5 m/s	153.4 m/s	35%

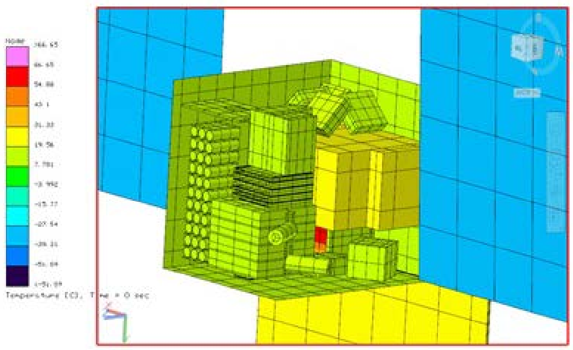

Figure 8. Aeolus thermal model showed during the highest elemental heating science orbit. S/C components are within their prescribed temperature range.

SCIENCE MISSION MATURATION PROCESS

Introduction to CML approach

The Concept Maturity Level is a framework created by NASA JPL to define mission concept maturity, and to specify steps for increasing the maturity of those concepts. It draws heavily from the well-established framework of TRL, Technology Readiness Level. The MDC team at Ames implemented its own approach to CML, drawing from the early JPL foundation [4]. CMLs structure the concept development process from the early "cocktail napkin" stage (CML1) all the way to Critical Design Review (CML9). For Aeolus the team stopped at CML 4, a point design.

Aeolus CML 1

Led by the PI under guidance of the MDC engineering team. The outcome/product is a one-page document that identifies scientific knowledge gaps and the uniqueness of the concept, states broad science objectives, and provides a one-sentence description of measurements. Also, a cartoon with a graphical description of how the PI envisions the measurement is provided. At this maturity level, the cartoon is an artifact to help the PI explain their concept to the engineering team.

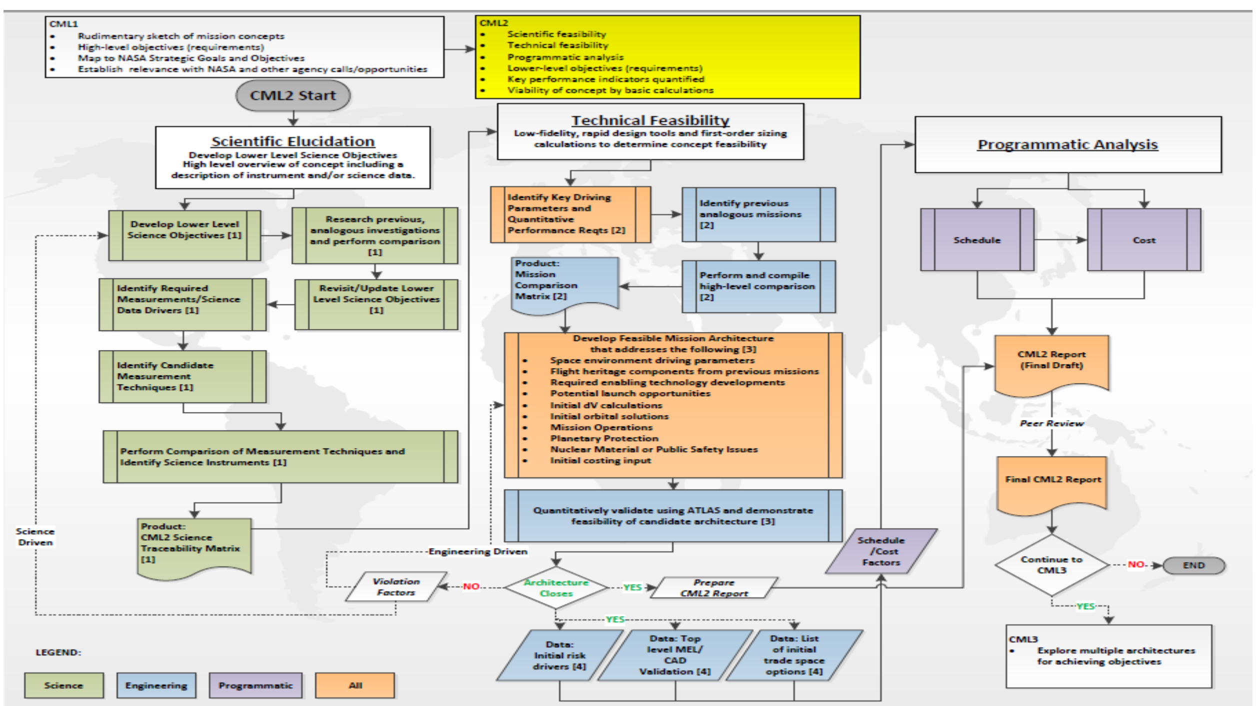

Figure 9. NASA Ames Mission Design Center Concept Maturity Level 2 process flow

Aeolus CML2

During CML2 development, the engineering team works closely with the PI to assess the initial feasibility of the concept. The goal is to find a solution that closes; at this level, the mission is not optimized for cost since the emphasis is on the technical feasibility. The Ames MDC team developed a process flow (See Figure 9) to help facilitate the feasibility assessment. This process is divided in three main areas: science, engineering and, programmatic. At the end of this maturity level the team can assess if the concept is technically feasible and gain an initial idea of the cost, schedule and risks.

Aeolus CML3

During CML 3 development the engineering team continues to work closely with the PI to expand the trade space of potential feasible architectures. This "out of the box" phase of divergent thinking is closely followed by a convergent process that leads the team to assess and rank the architectures identified. The selected options are then vetted and discussed with management before agreeing on moving further in the concept development process.

Aeolus CML4

During CML 4 the team continued the technical iteration on the architecture selected at the end of CML 3. During this phase the team performs further analysis and refines the preliminary ones. The outcome of CML 4 is a point design with a grass-root cost estimate, a more detailed schedule, ~1400 lines for Aeolus, a clear identification of the technology development needed to mature low TRL items, a set of initial risks and potential mitigation strategies identified.

CONCLUSION

Aeolus offers a potential opportunity to perform a much needed science mission to determine the wind on Mars leveraging a cost effective approach. Aeolus reliance on NeMO both for transfer and communication relay represents both its major asset and hindrance. Therefore, the team is currently pursuing other alternative architectures options that emerged during CML 3.

ACKNOWLEDGMENTS

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