ATROMOS: A Mars Companion Mission Enabled by Advanced EDL Concepts

Marcus S. Murbach[(1)]
Periklis Papadopoulos[(2)]
Bruce White[(3)]
Erin Tegnerud[(4)]

(1) NASA Ames, MS 213-13, Moffett Field, CA 94035, Marcus.S.Murbach (at) nasa.gov
(2) San Jose State University, ENG Bld. Rm 30B, San Jose, CA 95192, Periklis.papadopoulos (at) sjsu.edu
(3) NASA Ames, MS 213-13, Moffett Field, CA 94035, bwhite (at) arc.nasa.gov
(4) NASA Ames, MS 213-13, Moffett Field, CA 94035, etegnerud (at) mail.arc.nasa.gov

ABSTRACT

The ATROMOS mission proposes to develop two small 10-kg class entry probes on future U.S. and European Mars missions. The effort attempts to solve core issues regarding the development of small piggy-back class missions that have thus far not been successful (e.g., DS-2, Beagle-2) yet could yield very important Mars investigative elements. This is of particular interest in that most of the planned missions in the next decade are orbiter missions that could be greatly enhanced with the inclusion of a surface element. The initial mission is proposed as a two-point network that would land one probe on the North pole and a second several 100s kilometers south in order to measure key atmospheric gradients. Key to the mission is the development of a self-stabilizing entry probe (the SCRAMP – Slotted Compression RAMP probe) that will be flight tested on the SOAREX VI flight experiment in the 4th quarter of 2007. In addition, a simple entry, descent and landing (EDL) sequence is proposed requiring a minimum number of pyrotechnic events, allowing the technology to be more facile to develop and qualify. Having such an entry system with simple spacecraft interfaces could help 'compartmentalize' the riskier technology /instruments, and greatly enhance the science capability of future orbiter and lander missions. Larger, more capable versions of the Atromos mission will be further discussed, with the suggestion that this may lead to future network and other complementary missions.

INTRODUCTION

For the past several years, ARC has been investigating Mars Entry/Descent/Landing (EDL) strategies that would permit simple, low-cost 'companion' missions as 'Missions of Opportunity' (MoO) for various classes of small surface missions. As part of the recent Mars Scout solicitation, a 20-kg dual-probe companion mission was put forth that would form a simple 2- point network intended to study the Mars polar atmosphere dynamics. While the Mars Scout solicitation specifically required the use of non-U.S. carrier spacecraft (e.g., the European Agency EXOMARS), the mission/technology concept was intended to be applicable to future U.S. missions as well. One of the principal arguments put forth was that after the Mars Science Lander (MSL) mission of 2009, there would be a dearth of landed missions for a good part of the following decade. This was deemed unfortunate because as the secrets of the geo/hydrological history of Mars slowly unfold, there are no planned U.S. in-situ missions that would continue adding to and corroborating orbital data until later in the decade. In addition, it was also argued that by developing a series of relatively inexpensive 'companion' missions – with a set of very simple interfaces to the carrier spacecraft – high risk/high return technologies could attempted that would present minimal risk to the +1B class carrier spacecraft. This would add a 'companion' ground element to all future orbiter missions as well.

THE MISSION CONCEPT: 2-PT NETWORK

The proposed mission and EDL sequence are depicted in Figure 1. At 20-30 days (depending on opportunity and orbit mechanics), two probes are ejected from the Mars carrier spacecraft leading to a direct atmospheric entry. The interface between the probe and spacecraft is extremely simple as the probes do not have to be spun to several rpm in order to ensure proper orientation of the heatshield/TPS (Thermal Protection System) at the Mars atmosphere interface. Upon entry, the probes quickly self-orient due to the unique SCRAMP (Slotted Compression RAMP) geometry discussed in a following section. At a prescribed low supersonic flight condition, the probe flare separates and acts as a high speed drogue, pulling the payload canister and parachute system out of the forebody entry body envelope. Attached to the payload canister is a set of spring-loaded spokes forming the SPIDR (SPool with Inertial Damping Radii) and is oriented by the locked spokes in both the radial and axial directions, forming the landing 'cocoon' which envelopes the payload canister. After the measurement of the initial landing impact by an on-board accelerometer, the long parachute riser line is cut such that the parachute drifts away from the eventual landed spot (i.e., the difference in the horizontal momentum component allows the desired separation). The science station resides protected within the payload canister envelope. Through the canister wall, there is mounted the descent imaging camera, the antennas (three at 120 degrees; semi-deployed) and segmented solar cells which augment the internal power generation system. Other design variants have included a electric motor at one end of the SPIDR 'wheel' permitting improved orientation to the sun as well as a 1 m high mast.

The simplicity of the EDL system is comprised of a). a very simple carrier spacecraft interface and operation, b). two pyrotechnic functions (an additional point is that no mortar required for parachute deployment), c). the replacement of a complex airbag system with a spring deployed mechanical impact attenuation system (e.g., the SPIDR).

THE SCIENCE MISSION

Science Goals

The proposed science goals are:

- Acquire in-situ simultaneous measurements at the critical polar regions that will provide ground truth for remote sensing instruments as well as characterize critical polar atmospheric transport processes and phenomena.
- Use the entry data to reconstruct atmospheric structure at the unique polar locations.
- Emplace small, robust science stations that will constitute a Network Science test-bed by providing pressure, relative humidity, temperature, opacity and radiation dosimetry for the period of 90 sols (level I) or 1 Martian year (level II).

Importance of Mars Polar Science

The goals addressed by the Third Mars Polar Science Conference (S. Clifford, et al) were to determine:

- Current mass balance (mechanisms, rates, temporal and spatial variability, and sources and sinks) of CO_2, H_2O, and dust.
- Causes of the north/south asymmetry in the evolution and physical characteristics of the polar deposit.
- Origin of inter-annual variations in dust storm activity and general circulation of the atmosphere.
- Evidence for or against feedback between climate and polar insolation.

In addition to the specific science objectives of the mission, the technical goals are:

- Develop the necessary technical elements to enable future 'companion' spacecraft on later Mars missions.
- Develop and prove critical technologies supporting a Network Science Mission proposed for 2016.

The Phoenix Polar Mission

The Phoenix mission was selected by the Mars Scout Program and will land a large science station during June 2008. It will soft-land at high northern latitudes between latitude 65 and 75 degrees north. The key operational period is initially planned for 90 sols with an additional operational phase, should the solar panels continue to operate. The suite of on-board instruments will include a meteorological station. One of the objectives will be to enable climate studies that will provide horizontal and vertical transport of water vapor during polar summer. The mission proposes to correlate the humidity with wind direction to understand the rates at which the vapor is moved northward and southward near the seasonal cap boundary.

While Phoenix is intended to be the first successful polar lander and meteorological station (note that the DS-2 micro-probe missions and the Mars Polar Lander were both intended to land in the scientifically interesting polar regions, both unfortunately failed), it is nonetheless of fairly short duration. The Atromos mission would complement Phoenix and extend its Mars climatology objectives by a) extending the range through at least part of a polar winter (level II performance would extend for 1 year), and/or b) measure the comparable antipodal climate properties simultaneously at or near the other pole . While the data set would be preliminary in comparison to a full Network Mission, it would begin to provide critical information as to whether the water cycle is closed on an annual basis and the extent to which transport processes occur across the northern/southern hemispheres. The latter has much to do with hemispheric asymmetry in the polar caps (e.g., the northern water-ice dominated cap is three times larger than the southern CO_2-dominated ice-cap), and the suggestion that water-ice clouds provide the mechanism to retain and transport water to the northern hemisphere

(Clancy, 1996). A brief comparison of the intended/proposed polar science missions is provided in Figure 2.

Relevance of Companion Missions

The development of small 'companion' probes has remained very attractive, both as an augmentation to larger missions/projects as well as eventual elements contributing to the development of a Network Mission. However, such development has been fraught with risk, in part based on the technology selections that may not have been appropriate at these smaller scales. As examples of earlier 'companion' missions, the DS-2 and Beagle-2 missions are briefly summarized below.

The first of the small probe missions was Deep Space 2 (DS2), a set of companion probes on the ill-fated 1998 NASA Mars Polar Lander. The probes consisted of two parts, an aftbody and a forebody. The aftbody was a short 1.737 kg cylinder, 105.3 mm high and 136 mm in diameter. The aftbody was designed to remain above the surface after impact to provide radio communications. The forebody, or penetrator, was a long thin cylinder (105.6 mm long, 35 mm in diameter) with a mass of .670 kg. The forebody fit in the aftbody in its stowed position and was designed to separate on impact with the surface. The aftbody and forebody were connected after impact by a flexible cable. Both parts of the probe were designed to withstand extreme decelerations. The probes carried meteorological, thermal, and water vapor instruments as well as a drill for soil sample collection. There was no system in place for EDL telemetry, such that when telemetry contact was lost, the probes disappeared after entering the Martian atmosphere. Unfortunately the moment and cause of the failure was nearly impossible to deduce (hence leading to the use of semaphore 'signals' during subsequent missions).

The second was Beagle 2, a companion mission on the 2003 ESA Mars Express orbiter. With a probe mass of 69 kg and 66 cm in diameter, the principle objective was to detect extinct or extant life, or at the very least establish if the conditions at the landing site had ever been conducive to supporting life. The craft carried an extensive instrument suite capable of geochemical, mineralogical, petrological, and meteorological analysis. Beagle flew the highest mass ratio of payload-to-support systems of any prior Mars mission, and did so by employing minimal or zero redundancy. Similar to DS-2, no system was in place for EDL telemetry, and the probe/lander was lost after being released from Mars Express.

Atromos, while still a small companion probe, is different from the two aforementioned missions. The craft is not a penetrator like DS2, so it must only withstand the impact of a parachute descent (300 g's vs. 50,000 g's). Smaller in size than Beagle 2, less kinetic energy has to be dissipated during ground impact such that alternative attenuation designs can be considered. (The Beagle 2 airbag contributed significant complexity to the EDL sequence, and perhaps was a cause of mission failure).

Unlike both prior small probe missions, Atromos has a redundant power generation system consisting of both solar power and the RHU-powered MilliWatt Generator (or MPG). Risk is further reduced by a passive science payload with no electromotive parts, in contrast to the robotic arm and soil collection mechanisms present on Beagle and DS2. Finally, Atromos carries a telemetry system that will transmit a semaphore signal during EDL (using the carrier and sub-carrier frequencies as done on MPF) after critical events, including, as a minimum: probe deployment, probe 'wake-up' prior to entry, parachute/SPIDR deployment, initial surface impact, parachute detachment, and cessation of surface motion. In summary, from the historical antecedents, it is necessary to build small companion probes as simple and as robust as possible. With such a development, the relevant technologies may contribute directly to a larger Network Science Mission as well as permit more complicated Beagle-class mechanisms/instruments during subsequent missions.

Science Measurements

For basic meteorological data, the most important measurements are surface temperature and pressure. The Martian atmosphere, being 95% CO_2, seasonally condenses and sublimes on the poles. This alters the mean global pressure by 25-30% and causes a much larger signature in surface pressure than the terrestrial counterpart. The pressure and temperature measurements are relatively easy due to both low power requirement and omni-direction (i.e., the surface probe does not require a particular orientation). The abundance of water in the north polar region shows a typical concentration gradient that would drive the water transport. The measurement of water vapor on the polar cap or at a latitude further south would provide important data regarding flux. The measurements that constitute the basic sets of measurements are atmospheric structure, water vapor, atmospheric opacity. In addition, descent imaging would provide detailed local context of near geological/topological features.

The next sections will discuss the implementation of a 2-point polar science network based on suggested technologies.

THE SCRAMP: A SELF-ORIENTING ENTRY PROBE

During the initial Mars network studies performed at NASA Ames over a period of several years, a variety of traditional atmospheric entry probe concepts were explored in detail. The initial candidate was based on the DS-2 (Deep Space 2) probe based on a 45° Newtonian Sphere Cone (NSC) shape. It was found that the probe geometry only worked if the probe static margin (the distance between the center-mass and center-of-pressure) was sufficiently large to permit rapid self-orientation. However, for applications other than penetrators (the original application in which the CM is far forward inside the narrowing conical volume), the packaging constraints were such that it rendered the DS-2 geometry infeasible. Relatedly, the common 70° probe geometry provided very little static margin and required spin-stabilization to ensure proper heatshield orientation. In the PAET variant, a hemispherical back cover was intended to help if the spin stabilization malfunctioned (in this case, and the similar AESOP shape from the Aerotherm Corp., the restoring moment of the probes was such that re-orientation occurred after many cycles, such that major heating occurred at the probe shoulder area).

The above limitations in the NSC designs are what lead to the invention of the SCRAMP probe geometry shown in Figure 3. The payload cylinder resides in front of the flare, which is the major drag and stabilization producing element. In order to mitigate the flow recirculation which otherwise causes an undesirably steep effective aerodynamic surface, there is a series of slots at the compression ramp corner (hence the name). This feature was found to greatly improve the contributed drag coefficient. Also, for certain flare/forebody ratios, there is a shock-shock interaction during the high Mach portion of the entry which further increases the drag and stability. Due to the controlled oscillations (by unique geometrical features), the high local heating effects have been found to be adequately designed to ensure sufficient TPS margin. The latter is a key measurement during the current flight test described below.

THE SPIDR: A 'MECHANICAL AIR-BAG' ANALOG

During the network studies, the objective of which was to land 10-24 independent probes on the surface of Mars, it was also found that developing alternatives to the air-bag impact attenuation system was highly desirable. In brief, it was found that the air-bag concepts did not scale very well to the smaller scale, in particular if a similar number of pyrotechnic events had to be utilized. Also, air-bags are difficult to separate from the final landed configuration, or at minimum, are difficult to deflate and maintain a proper science station orientation. Finally, air-bag concepts are expensive to develop in that there is a great sensitivity to geometry, air-pressurization and de-pressurization. In contrast, a mechanical system such as the previously described SPIDR offers certain advantages over airbag systems (Figure 4). In particular, relative ease of deployment as well as a fairly inexpensive design/development cycle (i.e., unique manufacturing capabilities are not required nor expensive and hazardous gas generation chemicals) made a SPIDR system the leading candidate for the current study effort (Figure 5). Lastly, the packing geometry of the SPIDR fits very well within the SCRAMP cylindrical forebody, providing a high packing efficiency.

ATROMOS SCIENCE SYSTEM DESIGN

Power Tube

The Surface Science Station is designed to provide: a) the appropriate thermal environment throughout mission phases, b) a simple structural system to survive impact loads, c) ease of test and integration, d) minimum mass. The basic design is referred to as a PowerTube which is a ruggedized set of concentric canisters into which the RHUs (Radioactive Heating Units)are integrated into the core. The RHUs provide both thermal input as well as the source for the Robust Milliwatt Power Generator (MPG). The as breakdown is provided in Fig. XX.

Mechanical and Thermal Design

The backbone of the station is a hexagonal structure, mounted within a vacuum jacket, to which all major science station electronics are packaged (see Figure 6,). This is the 'warm box' for the electronics. In the interior of the hexagon, the 'robust' RHU-MPGs are housed, and designed such that the RHUs are typically incorporated several days/weeks before launch. Through the vacuum jacket/wall, the instrument I/F protrusions extend to the outer wall/cylinder of the station/SPIDR. This outer cylinder provides the mounting for the 2 photovoltaic bands, the descent/surface camera, the stowed antenna and TC mast. At the end of the SPIDR cylinder are the spring-loaded/locked spoke mounts that serve as the primary means of impact attenuation.

The science station power system is comprised of two energy generation systems, both redundant, that 'trickle-charge' the ultra-capacitor bank (Figure 7).

Power for the 'floor' operations is 15-18 mW (includes leakage current effects). The baseline generation is provided by two RHU-powered MPG sources that produce 20 mW each at BOL (this is a structurally robust version of a previous 40 mW design). In addition, there are two cylindrical In-P photovoltaic arrays that provide augmented power generation during daylight/summer operation. The arrays are multi-directional and can provide 6 mW/cm^2. Thus 8 hr of illumination on 10-15 cm^2 would recharge the system for a sol for minimum operation. Should the thermopile/generator break, the thermal energy of the RHUs provide sufficient thermal stability to survive a polar winter. The polar summer, on the other hand, offers greater margin due to long hours of illumination such that the MPG power is not essential (though the RHUs are essential for thermal control). The system thus has a potentially large energy margin with respect to the minimum operation mode.

SOAREX VI: SUB-ORBITAL FLIGHT VALIDATION

Key to the development of the 'companion' mission technology has been the use of sub-orbital sounding rocket technology for critical re-entry experiments.
The SOAREX (Sub-Orbital Aerodynamic Re-entry Experiments) flight test series was developed at NASA/ARC specifically to advance novel and next-generation EDL concepts for future missions. The SOAREX I and II included SCRAMP probe shapes with certain important geometric design characteristics (e.g., flare/forebody ratio, slot vs. no-slot cases). The aft flare pyrotechnic separation and parachute deployment were successfully tested during these initial flights. In general, the flight tests were used to augment or validate data obtained in the ballistic range, arc-jet, and through computational fluid dynamics (CFD).

The current SOAREX VI flight configuration is shown in Figure 11 and is scheduled for launch in October, 2007. The SCRAMP configuration has a .56m flare, with an entry mass of 20kg. The re-entry velocity will be over 4 km/s at an entry angle of -30°. While this does not represent the typical 6 km/s Mars entry, it is a 'hot' entry permitting the validation of TPS design techniques as well as critical measurements (e.g., pressure ratios, recession sensors, thermocouples, probe dynamics) of the SCRAMP flare. The maximum convective heating rate is of the order of 50w/cm2 with localized, periodic shock-interaction heating on the outer flare region of 200-300w/cm2. The pressure, thermocouple and recession sensor data obtained from flight will permit direct comparison to the CFD solutions.
In addition, supporting arc-jet work permits the development and validation of TPS designs at the sub-orbital and Mars direct entry conditions. A shock generator and unique translation device has been installed in the AHF arc-jet at NASA Ames which will permit further comparison of the shock-shock heat transfer/ pressure increase and effect on candidate coupon materials (Figure 12). Some of these coupon materials will be flown on sections of the flare geometry. The coupons will also be tested at the higher heating conditions simulating the Mars case (150w/cm2 at the nosetip stagnation point and 600-800 w/cm2 on the outer flare radius; Figure 13). Initial tests of the coupons have been extremely encouraging, in part due to the oscillatory nature of the shock movement on the flare TPS.

SUGGESTED DEVELOPMENT SERIES

What is proposed is a series of companion missions, beginning with earth sub-orbital launches via piggy-back opportunities, and eventually being incorporated on Mars missions. It is argued that the DS-2 was essentially a good idea, as it 'compartmentalized' risk on the mission – the most unfortunate part was that the probes did not work and thus discouraged future similar endeavors. A more evolutionary approach may provide confidence in the approach and yield more capable science missions after the initial series were successfully implemented.
A suggested development series beginning with the SOAREX flights, may appear as:

2007 SOAREX VI (4km/s; instrumentation core development)
2009 SOAREX VII (6km/s; TPS and EDL validation)
2011 Simple Atromos (Mars EDL; TM only)
2013 Initial Atromos science mission (science station; high TRL instruments)
2016 Advanced Atromos Stations or Network Mission

CONCLUSIONS

The argument for the development of Mars companion missions was further outlined. The Atromos mission was presented as a 2-point Polar Network that could provide compelling surface science as well as the incentive to develop the enabling technologies for this class of mission. The critical technologies are identified as a) a self-stabilizing entry probe (e.g., the SCRAMP), b) a mechanical impact attenuation system (e.g., the SPIDR), and c) an on-board electrical/thermal power system that would complement an externally mounted photovoltaic panel (e.g., the PowerTube). The development of the critical EDL technology is being aided by the SOAREX flight series, which has permitted the exploration of unique and advanced probe designs. With further modest investment, the enabling technologies could mature such that a variety of scientifically compelling, high risk missions could be accomplished during the early part of the next decade.

ACKNOWLDEGEMENTS

In order to carry out these diverse endeavors, there were significant contributions from a number of people too numerous to name. The SOAREX team included H. Morgan, M. Cropper, Phil Eberspeaker, C. Brodell, G. Scott, M. Guerrero, T. White, T. Tragesar; The CFD/Computation team included M. Wright, D. Prabhu and P. Papadopoulos, G. Allen; The arc-jet/ballistic range team included I. Terrazas-Salinas, C. Cornelison, D. Bagdanov, and D. Holt.

REFERENCES

[1] Murbach, M., et al, "ATROMOS – A Polar Science Mission of Opportunity," NASA Ames Research Center conceptual study report, August 1, 2006.
[2] Murbach, Marcus S., "The SCRAMP – The Development of an Advanced Planetary Probe from CFD to Re-entry Test Flight," International Planetary Probe Workshop III, Anavisos, Greece, June 28- July 1, 2005.
[3] Murbach, M., et al, The SPIDR (Spool with Inertial Dampening Radii)- an omni-directional system for shock attenuation, Invention Disclosure, October, 2006.
[4] Bertin, J., Hypersonic Aerodynamics, AIAA Education Series, American Institute of Aeronautics and Astronautics, Washington, D.C., 1994.
[5] Davies, C., Planetary Mission Entry Vehicles: A Quick Reference Guide, Space Technology Division, NASA Ames Research Center, Version 1.0, June, 2002.
[6] Lees, L., and T. Kubota, "Inviscid Hypersonic Flow over Blunt-nosed Slender Bodies," Journal of the Aeronautical Sciences, vol. 24, 1957, pp. 195-202.
[8] Canning, T., Seiff, A., and C. S. James, Ballistic Range Technology, AGARD-AG-138-70, August, 1970.
[9] Seiff, Alvin, Reese, D. E., Sommer, S. C., Kirk, D. B., Whitting, E., and H. B., Niemann, "PAET, An Entry Probe Experiment in the Earth's Atmosphere, ICARUS 18, 535-563 (1973).
[10] Walters, R., Slack, D., Cinnella, P., Aplebaum, M., and C. Frost, "A User's Guide to GASP," Virginia Polytechnic and State University, Research Report NASA Grants NAG-1-766 and NAG-1-1045, November, 1990.
[11] Wright, M.J., Candler, G.V., and Bose, D., "Data-Parallel Line Relaxation Method for the Navier-Stokes Equations," *AIAA Journal*, Vol. 36, No. 9, 1998, pp. 1603-1609.
[12] Edney, B. E., "Effects of Shock Impingement on the Heat Transfer around Blunt Bodies," AIAA Journal, Vol. 6, No. 1, pp. 15-21 January, 1968.
[13] Micheltree, R., DiFulvio, M., Horvath, T., and R. Braun, "Aerothermal Heating Predictions for Mars Microprobe," AIAA Paper 92-0170, 36th Aerospace Sciences Meeting, Jan., 1998, Reno, NV.
[14] Micheltree, R., Moss, J., Cheatwood, F., Greene, F., and R. Braun, "Aerothermodynamics of the Mars Microprobe Entry Vehicles," AIAA Paper 97-3658, August, 1997.
[15] Braun, R., Micheltree, R., and F. Cheatwood, "Mars Microprobe Entry Analysis," Proceedings from the 1997 IEEE Aerospace Conference, February, 1997.
[16] Cliffor, S., et al, "Third Mars Polar Science Conference."

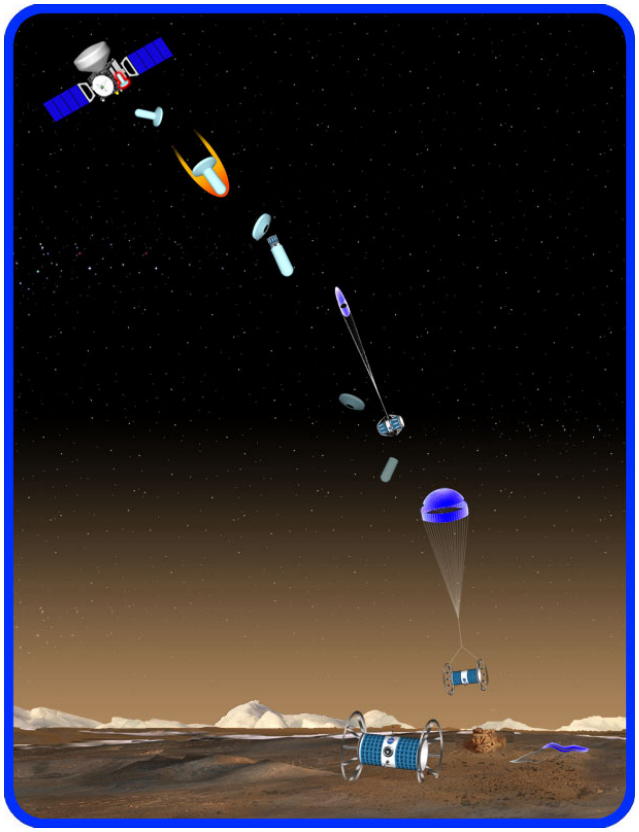

Figure 1. Atromos mission sequence (S/C separation, entry, descent and landing).

	Type	Mass	Technical challenge	Power	Intended Duration	Surface Contamination	MET Capable
DS-2	Penetrator (Hard Lander)	3.67 kg	High	Batteries	8 Sols (Failed)	No	No
Phoenix	Soft Lander	100's kg	Medium	Solar Array	90 Sols (Launch '07)	Yes	Descoped?
Atromos	'Firm' Lander	**9kg**	**LOW**	Arrays/ Robust MPG	**90-668 Sols**	**NO**	**YES**

The Atromos Program will develop a low risk, long duration polar measurement capability. It will provide a new EDL paradigm for a unique class of Companion and Network missions

Figure 2. Mars polar science mission comparison (not to scale).

Figure. 3. The basic SCRAMP probe geometry.

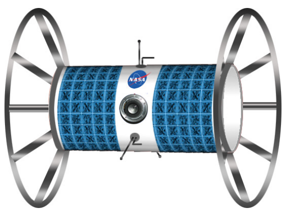

Figure. 4. The SPIDR impact attenuation system.

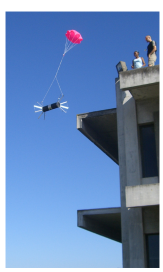

Figure 5. Initial SPIDR drop tests.

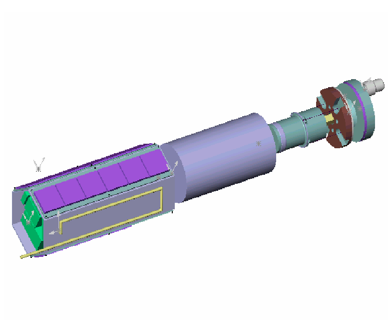

Figure 6. Power-tube internal instrument design

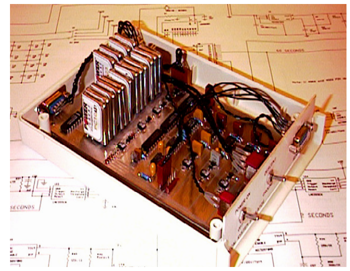

Figure 7. Science station protoboard.

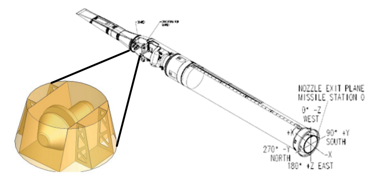

Figure 11. SOAREX VI Payload Ejection System.

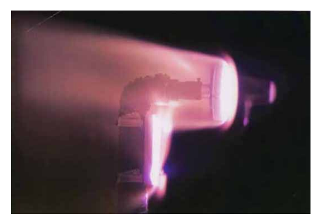

Figure 12. Arc-jet test of shock interaction and translation stage at Mars entry conditions.

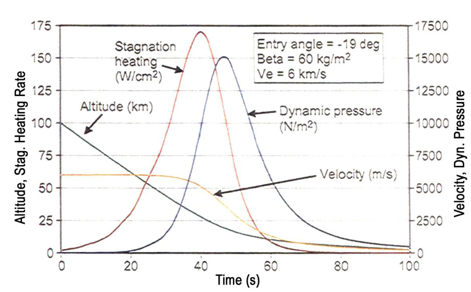

Figure 13. Entry heating calculations for Mars entry case.