

# Polar Traverse Rover Development for Mars, Europa and Earth<sup>1</sup>

Alberto Behar  
Avionic Systems and Technology Div.  
Jet Propulsion Laboratory  
107-102, Pasadena, CA 91109-8099  
818-354-4417  
Alberto.Behar@jpl.nasa.gov

Frank Carsey  
Earth & Space Science Division  
Jet Propulsion Laboratory  
300-323, Pasadena, CA 91109-8099  
818-354-8163, 818-354-2725  
Frank.D.Carsey@jpl.nasa.gov

Brian Wilcox  
Avionic Systems and Technology Div.  
Jet Propulsion Laboratory  
107-102, Pasadena, CA 91109-8099  
818-354-1738  
Brian.Wilcox@jpl.nasa.gov

*Abstract*— The history of Antarctic exploration is filled with traverses for scientific and operational purposes, and they continue to be conducted today. Similarly, traverses are a crucial part of planned planetary science and operations. This paper addresses the proposal for development of an autonomous rover capable of making such extreme environment traverses while accomplishing complex tasks.

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## 1. INTRODUCTION

The objective of this proposed Antarctic Traverse project is to design, build and deploy a simple, instrumented, autonomous, long-range, harsh-condition Polar Traverse Rover (PTR) which will demonstrate its value by performing a large-scale science data gathering traverse of Antarctica. Our primary goal is to test the utility of autonomous rovers to perform scientific survey and operational support work traditionally done by teams of specialists supported by logistical crews. The proposed suite of instruments include a radar system to obtain data on the ice sheet and its base, a GPS system to map ice topography and to support navigation, a camera for operational, scientific and educational use, and a simple suite of weather sensors. Terrestrial work is a necessary first step in testing the suitability of autonomous large-scale scientific traverses on planetary missions and Antarctica represents a challenging terrestrial analog for a range of planetary environments.

## 2. SIGNIFICANCE

The significance of this proposed project is that it will make long-range, autonomous, unmanned surface surveys a reasonable approach for scientific and other activities for a wide range of environmental conditions. Performing these tasks autonomously will save money, enable more aggressive scientific and operational planning, and avoid some safety constraints inherent in harsh-environment operations. Relevance to NASA programs is focused in three areas, Earth Science, Space Science, and the Human Exploration and Development of Space. Specifically:

### *Earth Science*

NASA and international Earth sciences are served through availability of rovers like the one proposed as an optimal way to conduct traverses such as validation studies of topography and topography change and examinations of regions of anomalous results from satellite sensors such as on ICESat.

### *Space Science*

Scientific investigations of icy sites are of high priority; prime examples are the Mars polar caps and Europa through the search for life in the solar system; there are also applications on the Moon. The Mars caps are especially significant in that climate history data may be readily available in the exposed layered-terrain outcroppings accessible through long-range surface surveys.

### *Human Exploration*

Transport of material over significant distances is a component of the human exploration of sites such as Mars; one particularly relevant transportation application is that of water ice from the Mars polar regions to a mid-latitude or equatorial site. On Earth, modern polar research incorporates human scientific traverses. The International Trans Antarctic Scientific Expedition (ITASE) is a multinational enterprise to study Antarctica with the goal of understanding the past 200 years of climate and environmental change. Long-range traverses provide a platform for collecting information on ice flow, snow accumulation and ice sheet history. Logistic

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considerations limit the spatial extent of measurements and in this regard, autonomous rovers can be of substantial value. An important task for the proposed PTR is to extend our measurements and understanding of the spatial variability in snow fall, a critical component of ice sheet mass balance and one of the least understood components of the global water budget.

### 3. OBJECTIVE

#### *Background*

A light-weight, long-distance rover, currently a concept with only basic established performance, is a key capability for overcoming logistical obstacles and avoiding high-risk situations in the exploration of Mars, the conduct of Antarctic studies, and the deployment of instruments on Europa and similar sites. For these areas there is a need for rapid development of a viable long-range (thousands of kilometers) robotic mobility system, demonstrated by a true test involving accomplishing a difficult traverse while performing challenging tasks that have been set forth by actual users (scientists).

#### *Strategy*

Our strategy in this proposed project is to accomplish a system design, development and preliminary test in a comprehensive and conclusive fashion using a team with expertise in each key area. We have elected to test in Antarctica because it is a prime Mars analog and because both NASA projects and US national Antarctic science are significantly in need of autonomous long-range scientific traverse capability. In addition the inclusion of well-chosen non-NASA science collaborators means that we have a sound broad-basis for support.

### 4. RELATION TO PREVIOUS WORK

The authors and respective collaborators have accomplished much previous work directly relevant to this proposed project. This includes the design and implementation of the Mars Pathfinder Rover (Sojourner), the development of a low-power rover radar using Caltech President's Funding, and the NASA Graduate Students Program, the successful completion of NSF funded autonomous Antarctic scientific projects utilizing satellite communications, and the development of novel rover designs within the NASA Cross-Enterprise program. The investigators also have substantial experience conducting extensive ice sheet traverses in both Greenland and Antarctica, and undertaking of large-scale ice-sheet mapping projects, in support of flight projects (ICESat) for topography determination. These activities provide a thorough background to advance this proposed work, and they also emphasize the significance of technology development in the conduct of science and operations in these environments. There have been earlier moderate-range traverse activities in non-polar environments (Wettergreen, et al, 1999; Krotkov et al, 1998), and we

will utilize developments from those experiences as well.

### 5. PROJECT OVERVIEW AND SCIENCE APPROACH

Our approach is straightforward: Gather high level requirements to define our robotic task, develop from them system level requirements; formulate a design to meet those requirements; examine this design for technology status at the component level; address required technology research and development; build the subsystems; integrate the PTR system, test the system locally; and conduct the Antarctic traverse. In parallel, we shall develop the logistical strategy including submitting proposals to national and international science agencies and funding organizations for Antarctic deployment support. The timeline concludes with an Antarctic traverse in the austral summer of 2005.

#### *The Science Task and Instrumentation*

While this is primarily an engineering project, we have given the rover system a demanding scientific task as a key part of the development of a real-world system. Specifically, we will be instructing the rover to conduct a traverse across Antarctica to collect data on the topography of the ice sheet, the thickness of the ice, the thickness of accumulated annual snow layers in the upper 200 m of the ice sheet, the depths of isochronous scattering layers in the ice, and the nature of the ice-basement interface (i.e. whether it is frozen or thawed). These data require two primary onboard systems: GPS and a sounding radar.

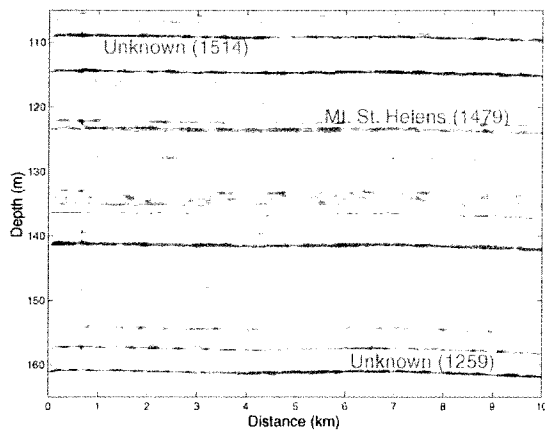
The topography of the route of the PTR is determined by GPS data analysis to be performed at JPL after the traverse. This data stream, which has been used for terrestrial testing on numerous JPL planetary rover test beds, gives the position of the rover with an accuracy of better than 10 meters, and, with carrier phase detection, further refined localization to 10 cm is planned for analysis after the completion of the traverse (Zumberge, et al, 1998). This analysis can even be made somewhat more accurate by stopping the rover for short periods a few times per day for longer averaging times, as is currently done on current US ITASE traverses (Spikes and Hamilton, 2001). The inclination of the rover will be recorded as operational data that has possible science value in determining topographic models. Finally, simple weather data will be recorded for system performance assessment.

A major portion of the scientific measurements, including ice thickness and mapping of layers, will be executed by a radar system. In particular, radar would be used to measure ice thickness and map deep internal layers, as well as to map near-surface layers with high resolution. We are confident of significant results due to previous successful studies that used conventional ultra-wideband Ground-Penetrating Radar (GPR) to determine basal conditions along a line in previously documented research

(Gogineni, et al, 1998)

We propose to develop a compact, lightweight and efficient wideband radar to characterize the subsurface along the traverse; such radars have been deployed, in the past, in aircraft and surface vehicles, but these early systems were not suited to remote autonomous application. Observations required are the depths of both near-surface and deep internal scattering layers, the result of deposition of snow following significant volcanic eruptions as well the thickness of the ice sheet and the basal topography and thermal state (Siegert, 2000; Uratsuka et al, 1996). We propose to develop this radar to operate in two modes: the Wideband Layer Mapping Radar, an ultra wideband (200- 2000 MHz) Frequency Modulated Continuous Wave (FMCW) radar for mapping internal layers in the top 500 meters of ice with high resolution (< 20 cm); and a Deep Ice Radar, a narrowband (100-150 MHz) stepped-frequency pulse system for measuring ice thickness and mapping deeper layers with resolution of about 2 meters in ice.

The current status of radar design for this type of use has been lead by a group at Kansas University (KU). The KU group has developed an inexpensive wideband radar and successfully demonstrated its performance by mapping of internal layers with fine resolution at the North Greenland Ice Core Project (NGRIP) drill site in spring, 1999 (a sample of data is shown in Figure 1). The system proposed here is a more advanced version of this system, which will be implemented using latest Radio Frequency Integrated Circuits (RFICs) and digital technology in a miniaturized and ruggedized system.

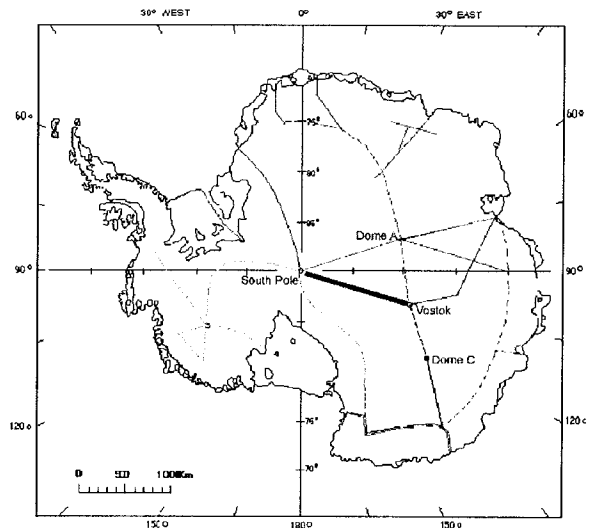


**Figure 1.** Sounding Data Over Ice. Radar data taken in spring, 1999, from the NGRIP site in central Greenland to illustrate the location of isochronous internal scattering layers which are the result of volcanic material, largely sulfuric acid, in the accumulated snow. The tracking of these layers between sites where ice-coring analysis has been done has been shown to be valuable in the chronometry of the ice cores (Dahl-Jensen, et al, 1997) (Image courtesy of Univ. of Kansas).

### The Traverse

The proposed Antarctic traverse will be conducted during an upcoming Antarctic summer season after extensive pre-testing. Prior to the Antarctic deployment, we plan a two-stage field-testing process. The first stage will occur early in rover development and will involve mobility/autonomy testing in cold and/or glacierized environments in Alaska. Towards the end of the rover development, we propose a thorough test of all systems (mobility, autonomy, scientific, communication) by conducting a relatively short (~100 km long) traverse of Austfonna, an ice cap in the High Arctic archipelago of Svalbard. This site is attractive because it is a small-scale analog for polar conditions, yet is easily reached by regular commercial transportation links thereby keeping logistics to a minimum.

The Antarctic traverse route will be chosen, after considerations of engineering and scientific issues, from a selection of targets interesting from polar scientific or autonomy perspectives (see Figure 2); these include traverses along the major ice divides, along flow lines of major ice streams and drainages, along ice flow lines across Lake Vostok, from South Pole to Dome A, across subglacial volcanoes, and across Dome C.



**Figure 2.** Map of Antarctica showing locations mentioned in the text. The routes being taken by various nations as part of the International Trans Antarctic Scientific Expedition (ITASE) as shown in color. The proposed autonomous rover traverse from South Pole to Vostok is indicated by the thick black line (Map courtesy of Gordon Hamilton).

The baseline candidate traverse is from South Pole Station to Lake Vostok Station (a Russian station at 78.4S, 107E). This first traverse has logistical convenience in that the terrain is simple, the conditions are relatively benign, and flights to these sites are common during the Antarctic summer. The traverse is interesting in that it

bridges accumulation and ice layering data between the West Antarctic and East Antarctic data sets being acquired by the International Trans Antarctic Scientific Expeditions (ITASE) program (Mayewski and Goodwin, 1997). Of the US ITASE investigators, G.S. Hamilton (Spikes and Hamilton, 2001) is a collaborator on this proposed project. The proposed baseline traverse distance is about 1200 km, and it could be modified from a straight line or lengthened to collect extra sounding radar data, e.g., over the subglacial lakes near the South Pole as well as Lake Vostok (see Siegert et al, 1996). Alternative modifications include the possibility of the rover traveling simultaneously with a future ITASE traverse for the purpose of cross-calibration between instruments and close support by project personnel.

The PTR will be assembled in Antarctica, and tested briefly on a nearby site of interest (ice shelf or subglacial lake). If mishaps occur on the traverse a small aircraft, (e.g., a Twin Otter) can be used to fly support personnel to the PTR for diagnosis and repair. Satellite communication links will be maintained from the rover to Antarctic and to a US based operations center.

## 6. POWER AND COMMUNICATIONS

For long-term unassisted operation, rovers must have self-sufficient power sources, with solar power as the most likely option. Solar power arrays must be kept relatively free of snow, ice, and dirt, and a large, near-vertical array will increase the rover's sensitivity to wind. Minimizing system power consumption is thus critical to making the array small for improving rover robustness. We will investigate the use of antennas that are omni directional—cylindrical or conical—rather than actively steered to reduce mechanical complexity. A fixed array will require more total area. We will investigate the use of five to 15 kg of lithium ion batteries for backup power needed to stabilize sensors thermally and also support movement of rovers to prevent them from being buried during low-light blizzard conditions.

Power management is performed by 1) acquiring energy from the solar power array, 2) predicting the solar panel available power output, 3) measuring the current power draw of the electronic system, 4) predicting the power requirement of any anticipated action of the navigation or command parsing system, 5) matching the available power against the projected need, 6) returning a status flag to the command parser and/or navigation/hazard avoidance software to indicate a binary "go/no-go" power availability, and, if "no-go", a subsequent recovery/abort action by the algorithm requesting the power, customized for the particular command being requested.

Communications management is performed in a fashion similar to the communications strategy originally designed for the Athena Mars rover (Athena is a 70 kg Mars rover designed for the '03 and '05 previously planned launches; it is designed to select and load samples for return to

Earth). At specified times, the vehicle will stop and establish a communications link with a satellite. Pre-queued engineering, health, and science data will be burst up to the satellite for a preset duration. Even though the satellite system may accommodate a highly flexible communications strategy (more like a cellular phone), such a strategy will not be used so that we will closely match actual planetary missions. In Antarctica, previous projects have used a variety of geosynchronous satellites (largely satellites no longer needed by their original owners such as NASA, NOAA and the Pentagon), and there is, in the timeframe of the proposed traverse, the possibility of commercial communications using low Earth orbit systems.

## 7. PTR DESIGN AND TECHNOLOGY

Several autonomous and semi-autonomous rovers have been developed in the past decade (see, e.g., Wettergreen, 1999). Notable among them are Nomad, a large autonomous system that was used in Antarctica to search for meteorites, and Sojourner, a small semi-autonomous system that was successfully deployed on Mars in 1997. The proposed rover is a distinct third branch utilizing a mixture of new approaches and materials along with some successful elements of past rovers (some built at JPL and discussed below). The PTR is specifically conceived as optimized for autonomous long-range operations in a remote site. The design stresses simplicity, robustness, lightweight, low volume (for spacecraft delivery), low power, and thoroughly tested autonomy. Additionally, the first long traverse is to cover a simple, smooth route on the Antarctic polar plateau, a region that is surprisingly benign.

Polar ice sheets may be less challenging than other terrain explored by mobile robots: for the most part, they are relatively flat, although small-scale (~ 1m) roughness features (sastrugi) caused by blowing snow might be encountered periodically. A rover with large-diameter, compliant tires will be able to climb over large rocks (up to 0.7m) and should be capable of driving over and along 30° slopes. Crevasses present a bigger challenge. Relatively lightweight rovers (< 50 kg) with large areas of terrain contact may be able to cross some bridged crevasses safely (which would require sensing of snow-bridge thickness), but in any case autonomous identification of open and bridged crevasses is essential.

### *Mobility Subsystem*

The rovers' mobility subsystem will likely use four or six compliant, large-diameter, independently driven and steered wheels. While tracks are traditionally used on vehicles designed for low-strength terrain such as snow and mud, they are mechanically more complex, heavier, and must support much more weight (at the minimum, the weight of a person and a two-cycle engine) than the expected mass (roughly 30-50 kg) of one of the rovers.

Compliant, large-diameter wheels provide high mobility for low mass, enabling power-efficient locomotion and simplifying the hazard detection task—which in turn reduces computation and power requirements. Payload mass and expected terrain will determine the number of wheels and suspension type. Depending on total vehicle mass and wind conditions, the rovers will use either an inflatable or wire mesh wheel design, both of which provide a large contact area to prevent sinking in soft soil or snow. Hard spikes or other aggressive treads may be required for operation on ice. Whole-vehicle parametric optimization will be performed to determine the best configuration for stability, mobility, power efficiency, and sensor visibility.

The environmental and mission requirements, including wind and self-sustained power source generation, pose many challenges that constrain the design of the mobility system. Large-diameter wheels have advantages in terms of efficient mobility over rough terrain, but they also pose a risk in windy conditions because of their large surface area. Wheel size and type (e.g., low-pressure inflatable vs. wire-mesh) are representative of the types of trade-offs that we must investigate to guarantee an optimal and efficient design. For a systematic exploration of the trade-space we will leverage Darwin2K at JPL, which automates the design and evaluation of a large number of vehicle designs using an inventory of parameterized mechanical parts (Leger, 2000). Darwin2K uses a distributed evolutionary algorithm that can synthesize and optimize robot kinematics (topology and dimensions), dynamics, components, and controller parameters with respect to multiple user-selected performance metrics. We plan to conduct detailed design studies in the early phases of the proposed project to converge to a suitable design that meets all mission operations and environmental requirements.

#### *System Electronics and Software*

The Polar Traverse Rover will have an electronic and software architecture derived from the flight rover designs created by the JPL Robotic Vehicles Group for the MUSES-CN asteroid rover (Jones and Wilcox, 1999), and for the Athena Mars rover (Maimone et al, 2001). Software Development Models for both of these rovers have been completed at the time of this writing. Both of these rovers use the R3000 32-bit processor (available in both commercial and flight versions) and VxWorks real-time operating system. Both rovers use a software architecture developed for flight, which automatically generates command dictionaries and interfaces to the ground data system software at the time of compiling of the flight code. This flight code is modular and can be adapted easily to rovers having different complements of motors, cameras, and other sensors and I/O. The flight version of the electronics has been qualified for thermal extremes from -180C to +110C, so the Antarctic summertime thermal environment of -50C to -30C is not a

concern.

The electronics and software architecture is a direct outgrowth of the Sojourner vehicle, which explored a small part of Mars in the summer of 1997 and was implemented by many of the same team as on this effort. Sojourner, MUSES-CN, and Athena all have extensive health monitoring, diagnostic, and fault protection features. The system can, for example, operate with or without a battery. Sojourner was specifically designed to operate in a solar-only mode following the expected failure of the battery, and performed flawlessly in making that transition in the fifth week on Mars. (The Pathfinder lander was unable to negotiate that transition ending the mission on the 83rd Mars day.)

#### *Autonomy, Guidance, Control, and Navigation*

The autonomy for this vehicle is a direct extension of that incorporated in the Sojourner, MUSES-CN, and Athena solar system rovers. Even Sojourner was capable of cross-country autonomous navigation, although this was not exercised during the mission, due to the scientists' desire to perform detailed examination of nearby rocks. Autonomy involves several elements: mission objectives, navigation, hazard avoidance, power management, communications management, and health monitoring. For autonomy software we plan to leverage existing and concurrent technology development at JPL. Current rover testbeds will serve as platforms for software development and field tests and will provide engineering design rules, experience, and tools for long-range rover design. Control, hazard detection, sensor data processing, and operations software can also be inherited from JPL testbeds like the Field-Integrated Design & Operations (FIDO) rover, while cooperative autonomy algorithms and software are available from the current Robot Work Crew's task (Schenker et al, 2001).

The fundamental navigation sensor input for the Polar Traverse Rover is the GPS, which can be used to localize the rover with a refined accuracy of 10 cm as mentioned earlier. The GPS data will be used to update odometry and sun-sensor-based heading similar to other flight and testbed planetary rovers. The essential traverse headings will be maintained as the global "goal" locations for the autonomous hazard avoidance sensing and control.

The rover will also include a standard planetary rover camera system designed to aid in navigation and operations, as well as providing images for outreach. In a preliminary concept the camera system can consist of a compact ring of eight small hard-mounted cameras with overlapping fields of view, as well as an upward-looking all-sky camera. The cameras will be interfaced to a small computer system that will control their operation and acquire image data over a Universal Serial Bus (USB) interface. The computer system will process, compress and format the combined images and transmit them to the rover's main computer. The use of several small cameras

allows for flexibility of operation and without the need for moving parts. Imaging modes include full 360-degree color panoramas, high-resolution color images of designated targets, compressed monochrome images to validate rover navigation, and stop-action movies to demonstrate rover mobility. The forward-looking camera will serve as the hazard avoidance camera.

Finally, we are considering the possibility of testing true scientific autonomy with this project; that is, we can program PTR to examine the radar data for signals characteristic of sub glacial lakes, and instruct it to alter its course to perform a mapping of the lake before returning to its traverse.

## 8. CONCLUSIONS

This research is of vital importance in ultimately gaining more knowledge about the Antarctic ice sheet environment as well as enabling us to develop new technology to explore the icy environments of other planets.

The proposed research addresses issues related to exploration in remote regions that are otherwise dangerous, difficult, repetitive or expensive to access in any other way. We believe that successful deployment of an instrumented rover that can operate autonomously will allow us to obtain key glaciological parameters that are difficult or impossible to measure otherwise. The technologies and tools developed as a part of this project will reduce future operational costs and risks associated with polar research and allow a path to develop future systems to explore environments such as the Mars polar caps and possible the surface of Europa.

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**Alberto Behar** has been a member of the Robotic Vehicles Group at the NASA Jet Propulsion Laboratory since 1991. His group designs the rovers and in-situ surface systems for several planetary missions. His previous studies earned him a PhD in EE (Astronautics Minor) from USC, an ME from Rensselaer and an MS with Specialization in Robotics from USC. His primary interests are developing, testing and deploying architectures for planetary surface spacecraft.



**Frank Carsey** received the PhD in physics from UCLA in 1971 and has been active in polar research for most of the intervening years, specializing in scientific application of satellite data in polar oceanography and ice sheet glaciology. He is currently developing means for monitoring processes in the sub glacial domain using remote sensing and in-situ measurements and is interested in the overlap of Earth and planetary science and technology. He is Team Leader for Polar Oceanography in the Earth and Space Science Division of JPL.



**Brian Wilcox** is the Supervisor of the Robotic Vehicles Group at the Jet Propulsion Laboratory. The group is partially responsible for the Mars Exploration Rover planned for launch in 2003. Brian was personally responsible for conceiving and developing the stereo camera and laser ranging system used on the Sojourner rover. He received the NASA Exceptional Engineering Achievement medal in 1992 and the JPL Award for Excellence in 1999 and 2001. He holds four US patents in the areas of robotic vehicles and VLSI for robotic perception, with three more pending. He graduated with highest honors with a B.S. in Physics and a B.A. in Mathematics from the University of California at Santa Barbara, and has an M.S. in Electrical Engineering from the University of Southern California.

