

# NASA/JPL Tumbleweed Polar Rover<sup>1,2</sup>

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## ABSTRACT

The Tumbleweed Rover, currently under development at the Jet Propulsion Laboratory (JPL) in Pasadena, California, is a large, wind-blown, inflated ball, which carries an instrument payload in its interior. Such rovers offer an effective and simple means of gathering data over large spatial extents of Earth, Mars, and other solar system bodies. Tumbleweeds could prove to be a safe and economical way of deploying instruments such as a ground penetrating radar or a magnetometer in numerous hostile environments. The latest version of the rover was recently deployed in Greenland, where it completed a more than 130km autonomous traverse across an ice sheet. Communicating via the Iridium satellite network, the rover in question successfully and reliably relayed live GPS, temperature, and pressure data to a ground station at JPL for nearly ten days. The follow-on rover is currently being readied for a traverse from the South Pole to the coast of Antarctica some 2000km away. The Antarctic test is set to take place in February of 2004 and will serve to verify Tumbleweed as an effective means of harvesting data in extreme and remote settings.

## INTRODUCTION

The NASA/JPL Tumbleweed Rover is a large, inflated ball that can be windblown and used to explore the surfaces of Earth, Mars, Venus, Titan, and perhaps Saturn's moon Io (via supersonic volcanic wind) and Neptune's moon Triton (as evidenced by significant surface wind erosion).

For each of these applications, various central payloads could be held in place by a series of lines that extend to the outside of the ball (see Figure 1). Various versions of this basic concept have been proposed in the past in the U.S. and France, but JPL is the first to actually develop the ball and prove its feasibility experimentally

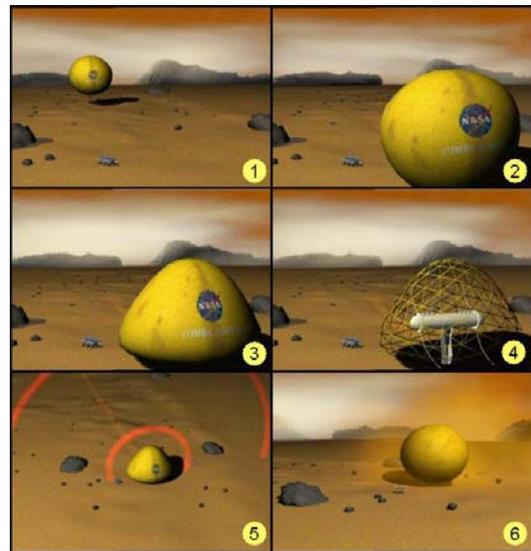


Figure 1: Potential operational scenario for Tumbleweed on Mars - (1) the wind-blown rover traverses the surface before (2 – 3) deflating to stop at an area of scientific interest. (4) Instruments and a drill are deployed to the surface to take measurements and samples. (5) Data is transmitted to an orbiting satellite, which relays the data back to Earth (6) Tumbleweed re-inflates and continues on its journey. [Image courtesy NASA/JPL]

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and analytically. In the case of Mars, a 6-m diameter ball is easily capable of climbing over one meter rocks and up 25° hills (well over 99.9% of the Martian surface) with typical global winds that occur during the southern summer. The ball could also potentially be used as a parachute on Mars (30 m/sec descent rate) and as an airbag, thus serving as its own landing system [5]. Similar large balls, but without the central payload, have also been shown to be useful as tires for an Inflatable Rover that has been successfully tested at JPL.

Field tests have been successfully conducted of scale models of the physical ball in the Mojave Desert, California, Pt. Barrow, Alaska, and a long-distance test with an instrument payload and satellite communications was recently conducted in Greenland. In the Greenland deployment, Tumbleweed covered over 130km in less than 48 hours while reliably sending back data to a ground station located at JPL every 30 minutes. While its progress across the Greenland ice sheet soon stopped due to decreasing wind speeds, the rover continued to send back instrument data for nearly 10 days. By the time this paper is presented, another Tumbleweed deployment will have taken place from the South Pole station with the objective of reaching the Antarctic coast more than 2000km away.

Subsystems that have been tested individually at JPL, Alaska, and Greenland include a rolling Iridium satellite communications system, rolling GPS, rolling imaging, and rolling temperature and pressure instrumentation. In fact, many of these instruments, have been successfully tested on numerous, non-rolling stratospheric balloon flights conducted jointly by JPL in Antarctica-like temperatures (-40°C). Future Tumbleweed instruments that have already been tested in Tumbleweeds at JPL include a rolling subsurface radar that can determine ice thickness for global warming measurements, and a rolling magnetometer to measure local magnetic anomalies, such as buried meteorites on earth or tectonic plate shifting on Mars.

## **PROJECT OVERVIEW**

The Tumbleweed concept makes 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 saves money, enables more aggressive scientific and operational planning, and avoids 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 Tumbleweed 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. 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*

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 considerations limit the spatial extent of measurements and in this regard, autonomous rovers can be of substantial value. An important task for autonomous vehicles 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.

Tumbleweed 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).

## **ROVER DESCRIPTION**

The most recent configuration of the Tumbleweed rover can be seen in Figure 2. The body of the rover consists of a 1.5 meter diameter nylon bag with rubber studs applied to the outside. While the rubber studs were originally applied to boost traction on the 3-wheeled, inflatable rover, the studs actually help

Tumbleweed to roll along a preferred axis. Mounted inside the body of the rover along the preferred axis of rotation is a 1.2 meter long Lexan™ tube. This tube is purposefully shorter than the diameter of the ball to prevent the ends of the tube from impacting the ground when Tumbleweed fails to roll along the intended axis. Inside the Lexan™ tube is housed the electronics package of the rover. This package consists of a motherboard (with logic, instrumentation, data storage, and power conditioning elements), an Iridium modem with integrated GPS receiver, an omni-directional Iridium antenna, an active GPS antenna, a 900MHz serial transmitter, a LCD, a lithium battery pack, and a small air pump. The central tube is attached to the nylon membrane on each side by a set of Lexan™ and composite flanges and eight stainless steel bolts. Sandwiched between the Lexan™ and composite flanges with the nylon bag are pliable rubber gaskets to prevent the leakage of air.

the membrane's internal pressure), a thermocouple (for recording ambient temperature), two 2-axis accelerometers (to determine the orientation of tumbleweed at the time of acquisition), and a real-time clock (for noting the time at which the readings were made).

Also mounted on the motherboard, is a microcontroller (Stamp™ Processor), with 15 I/O pins. The microcontroller is used to communicate with the various components and instruments and store science and engineering data. The microcontroller takes temperature, pressure, accelerometer, battery level, time, position, and velocity data once every second. This data is stored as a string of 8 bit numbers in the Stamp's 512K Flash EEPROM memory. After a specified duration, the microcontroller attempts to make a call with the Iridium modem. If a connection is made, the controller begins

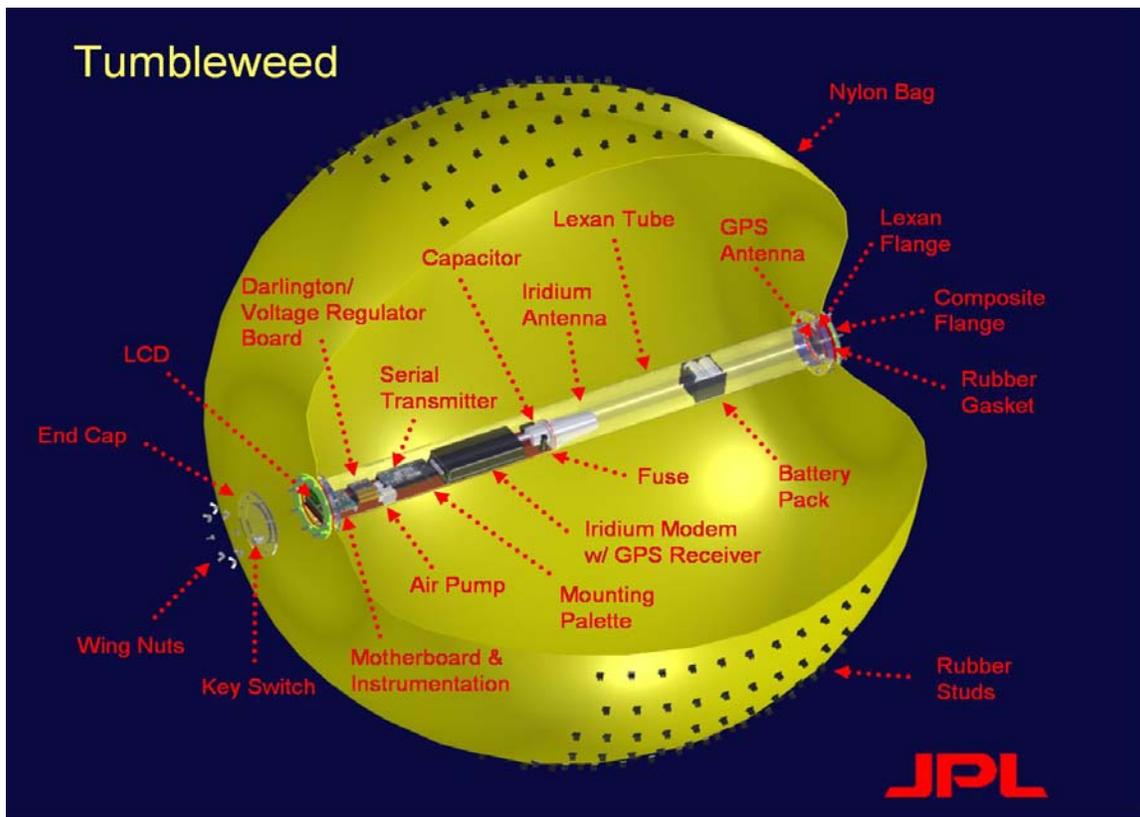


Figure 2: Exploded view of the Tumbleweed system.

As mentioned, a GPS receiver is integrated into the Iridium modem, while the remaining instrumentation is mounted on the motherboard. It consists of: two pressure transducers (one for ambient pressure and the other for monitoring

sending the stored strings of data. If the connection is unsuccessful, the controller will try once more. If the second attempt is unsuccessful, it will continue taking new data and wait another duration before making the next call attempt.

Each time the controller acquires a new set of data (i.e. – every 4 seconds) it transmits the information locally via the 900 MHz serial transmitter. This transmitter has about the same range as the average household cordless phone (300 m). This capability is extremely useful for the development phase, but is not used on the long-distance deployments. The serial transmitter also allows for the remote updating of the onboard software. It is therefore possible in the field to change the software that is running on the microprocessor without removing the electronics package from the rover. The same information that is sent to the serial transmitter is also sent to the LCD. Again, this capability helpful for local field tests but is not necessary for the long-distance deployments.

What really makes Tumbleweed unique is the long range communication subsystem based on the Iridium modem. This component allows data to be sent from anywhere on the planet. Further, because the Iridium constellation is polar orbiting, the performance of the modem improves with latitude, thus making it the ideal system for use in the Arctic and Antarctic.

#### *System Description*

The Tumbleweed communication system architecture is described in Figure 3. After acquiring science and engineering data from anywhere in the world (1), Tumbleweed transmits its data to the Iridium satellite network (2). Using inter-satellite links, Iridium passes the data to the waiting ground station (3) - also located anywhere in the world. Next, the ground station receives, parses, saves, and displays the incoming data. The main ground station also runs a web server. The web server ensures that the live incoming data is made available for anyone to see via the internet (4).

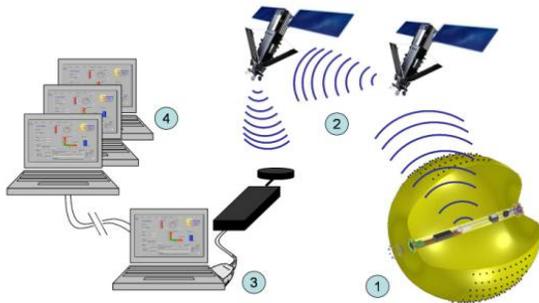


Figure 3: The Tumbleweed communication system architecture

## RELATION TO OTHER WORK

The Tumbleweed rover of this paper is not the only example in existence. Various aspects of the concept are being researched in other institutions in the United States as well as internationally. These activities range from full-scale prototyping, to performance modeling, to materials testing.

A spherical, inflatable micro rover system for Mars has been proposed by a group from Uppsala University, Sweden [3]. The concept uses an internal motor and a jumping mechanism to increase mobility, and micro-electromechanical systems (MEMS) to increase science return. The device is currently in design phase and a prototype has been fabricated and lab tested. Other Tumbleweed systems that are blown by the wind, but not inflated, have been proposed by NASA Langley Research Center [1]. These concepts are generally envisioned to be about 6-m in diameter with a mass of 20 kg, similar to the JPL Tumbleweeds. They have various means to catch the wind and be propelled along the Martian surface. A working model of a "box kite" design has been fabricated and tested by a student group at North Carolina State University.

The Tumbleweed currently under development at JPL has a rather serendipitous origin. While researchers in JPL's Inflatable Technology for Robotics Program were testing a three-wheeled, inflatable rover in the Mojave Desert, one of its 1.5 m diameter nylon tires was detached by a gust of wind. The runaway tire quickly picked up speed in the moderate wind and seemed relatively unimpeded by the desert's rough terrain. The renegade ball was able to climb steep slopes, over large boulders, and through the jagged brush without hesitation. This seemingly unlucky incident produced a rather lucky discovery and was the inspiration for the current Tumbleweed rover.

## GREENLAND TEST RESULTS

In the spring of 2004, by the time this paper is presented, the JPL Tumbleweed will have undertaken an attempt at a 2000km traverse from South Pole Station to the Antarctic coast. Antarctica has been selected for Tumbleweed's final deployment because it is a prime Mars analog and because both NASA projects and US national Antarctic science are in significant need of autonomous long-range scientific traverse capability. In anticipation of the Antarctic deployment, Tumbleweed components were tested in the Mojave Desert, California and Pt. Barrow, Alaska. In July of 2003, the entire Tumbleweed system was put to the test in a long-range deployment from the Greenland

Summit camp. Summit is located at the apex of the Greenland Ice Sheet near the center of Greenland (see Figure 4).



Figure 4: Tumbleweed just before being deployed from Summit Camp, Greenland.

Figure 5 depicts the ground track that Tumbleweed followed across the Greenland Ice Sheet. After 19 hours and 45 minutes, the lightweight inflatable sphere came to a rest some 131 km from its release point and failed to move again for the duration of the test. It is hypothesized that lower wind speeds cause the rover to stop progressing.

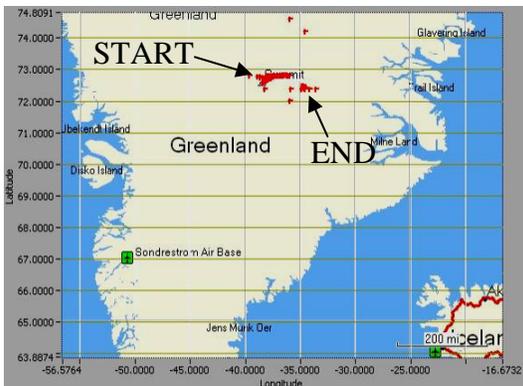


Figure 5: Greenland deployment ground track.

Despite the harsh operating environment, Tumbleweed reliably sent back data to a ground station located at JPL every twenty minutes (the hole in the data was caused by an overnight crash of the ground station computer and is not attributed to a rover malfunction). While its progress across the ice sheet came to an early end, the rover continued to send back science and engineering data for nearly 10 days.

Figure 6 is a more detailed view of the rover's position history over the course of the

deployment. The reason for the rover's discontinuance is perplexing because it successfully came to a rest several times during the deployment and continued again when winds increased. However, because Tumbleweed is designed to be inexpensive (and therefore expendable), there are no plans to recover the rover from its remote location to determine the cause behind its immobility.

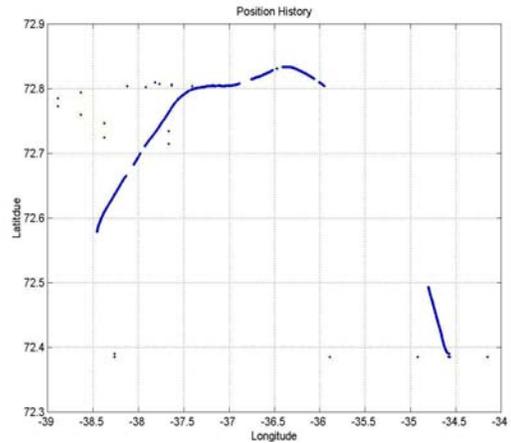


Figure 6: Position history of the Tumbleweed deployment in Greenland.

Figure 7 depicts the altitude change over the path of the deployment. While some post-processing remains to be done to make this data more precise and thus scientifically more useful, this figure is an example of what might be accomplished with a Tumbleweed rover. The total altitude change from start to finish is estimated to be 80 meters.

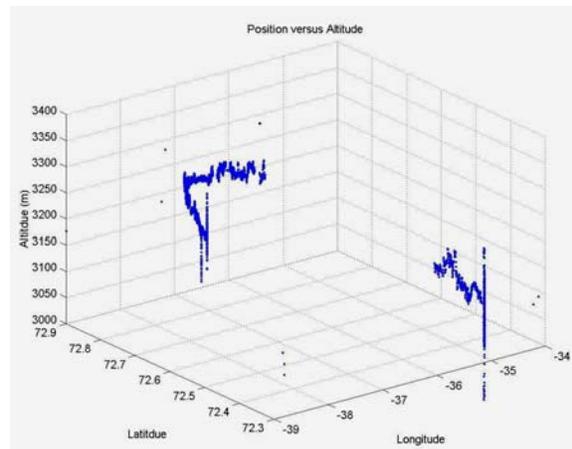


Figure 7: Altitude along ground track.

Figure 8 depicts the speed of Tumbleweed over the course of the deployment. The rover reached a maximum rate of 17 km/h and averaged

roughly 7 km/h. The wind speed at the time of deployment was 28 km/h (15 knots) which propelled Tumbleweed at roughly 6 km/h.

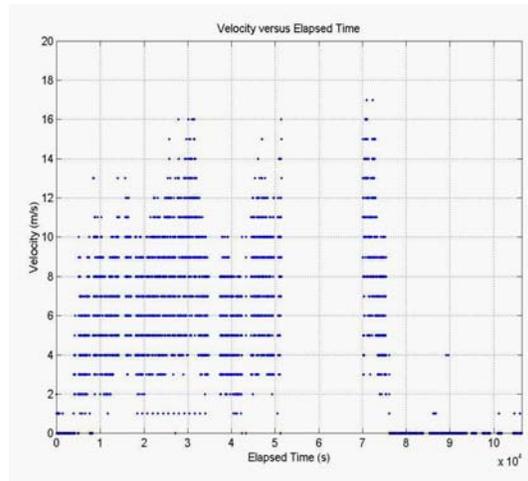


Figure 8: Speed of Tumbleweed over the first 24 hours of the Greenland deployment.

Figure 9 depicts the temperature recorded by Tumbleweed over the first 24 hours of the deployment. The thermocouple is located inside the central Lexan™ tube. The temperature in this area reached surprising extremes, with a max of 64 °C and a min of -13 °C. It is believed that heat loss from the electronics and a greenhouse effect account for the high temperatures recorded. Future designs will likely have an externally mounted thermocouple.

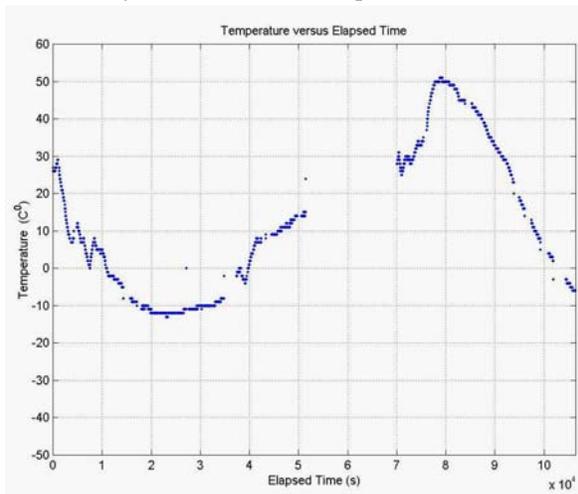


Figure 9: Temperature variation recorded by Tumbleweed in the first 24 hours of the Greenland deployment

Figure 10 is a plot of both the internal and external pressure recorded during the Greenland deployment. Tumbleweed's onboard software

activates a pump located in the central tube when the internal pressure drops below a critical level for a specified period of time.

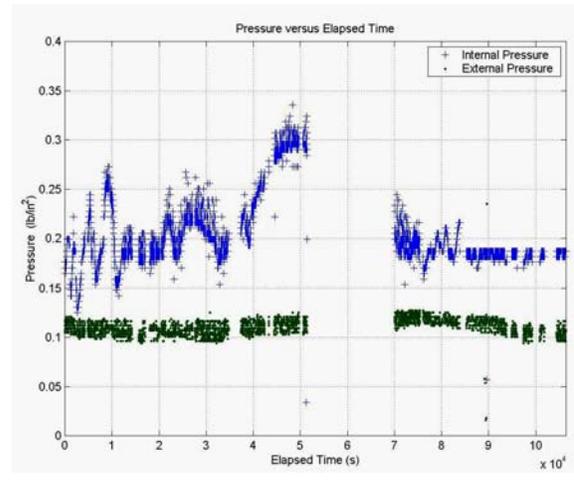


Figure 10: Internal and external gauge pressure recorded in the first 24 hours of the Greenland deployment.

## FUTURE WORK

After hopefully demonstrating Tumbleweed's ability to successfully traverse Antarctica in the spring of 2004, we will likely work towards a traverse across Antarctica with a more significant science package. The primary objective of this deployment likely being the collection of 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. As in previous tests, the topography of the route of Tumbleweed is determined by GPS data analysis performed at JPL after the traverse.

The 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 [4]. In addition, rolling subsurface radar tests have already been conducted via Tumbleweed at JPL.

The 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 (~1 m) roughness features (sastrugi) caused by blowing snow might be encountered periodically. Tumbleweed's large-diameter compliant membrane enables it to climb over large rocks and over and along steep slopes. Crevasses present a bigger challenge; though Tumbleweed's lightweight construction and large area of terrain contact may enable it to cross some bridged crevasses safely.

While this deployment will likely focus on GPR and GPS measurements, it is foreseeable that other instruments such as a magnetometer or UV sensors may be utilized. In addition, side-facing cameras could provide significant public outreach potential while returning useful engineering and science data. This is especially true because of the ability of Tumbleweed's ground station software to publish the live incoming data to the internet.

## CONCLUSION

Tumbleweed as conceived and built is optimized for long-range autonomous operations in remote and hazardous environments. The design stresses simplicity, robustness, lightweight, low volume (for spacecraft delivery), and low power. This research is of vital importance in ultimately gaining more knowledge about the Antarctic and Arctic ice sheet environment as well as enabling us to develop new technology to explore the icy environments of other planets. Tumbleweed addresses issues related to exploration in remote regions that are otherwise dangerous, difficult, repetitive or expensive to access in any other way. The eventual deployment of a fully instrumented rover 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.

Additional documents and test results for Tumbleweed can be found at:

<http://robotics.jpl.nasa.gov/~behar/JPLTumbleweed.html>

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## BIOGRAPHY

Alberto Behar has been a member of the Robotic Vehicles Group at the 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.



Jaret Matthews joined the Robotic Vehicles Group at the Jet Propulsion Laboratory in 2003. He holds a BS in Aeronautics and Astronautics from Purdue University and a MS from the International Space University. His primary interests are in the design, construction, and testing of planetary mobility system concepts.



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.



Jack A. Jones is a Principal Engineer at Jet Propulsion Laboratory, California Institute of Technology. He has worked in Advanced Thermal and Mobility Technology for twenty four years and has developed several inflatable robotics systems for planetary exploration. He has written over one hundred fifty papers and holds twenty three patents in the area of thermal sciences and mobility systems. He has a BSME from Rutgers University and a MSME from Rice University.



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