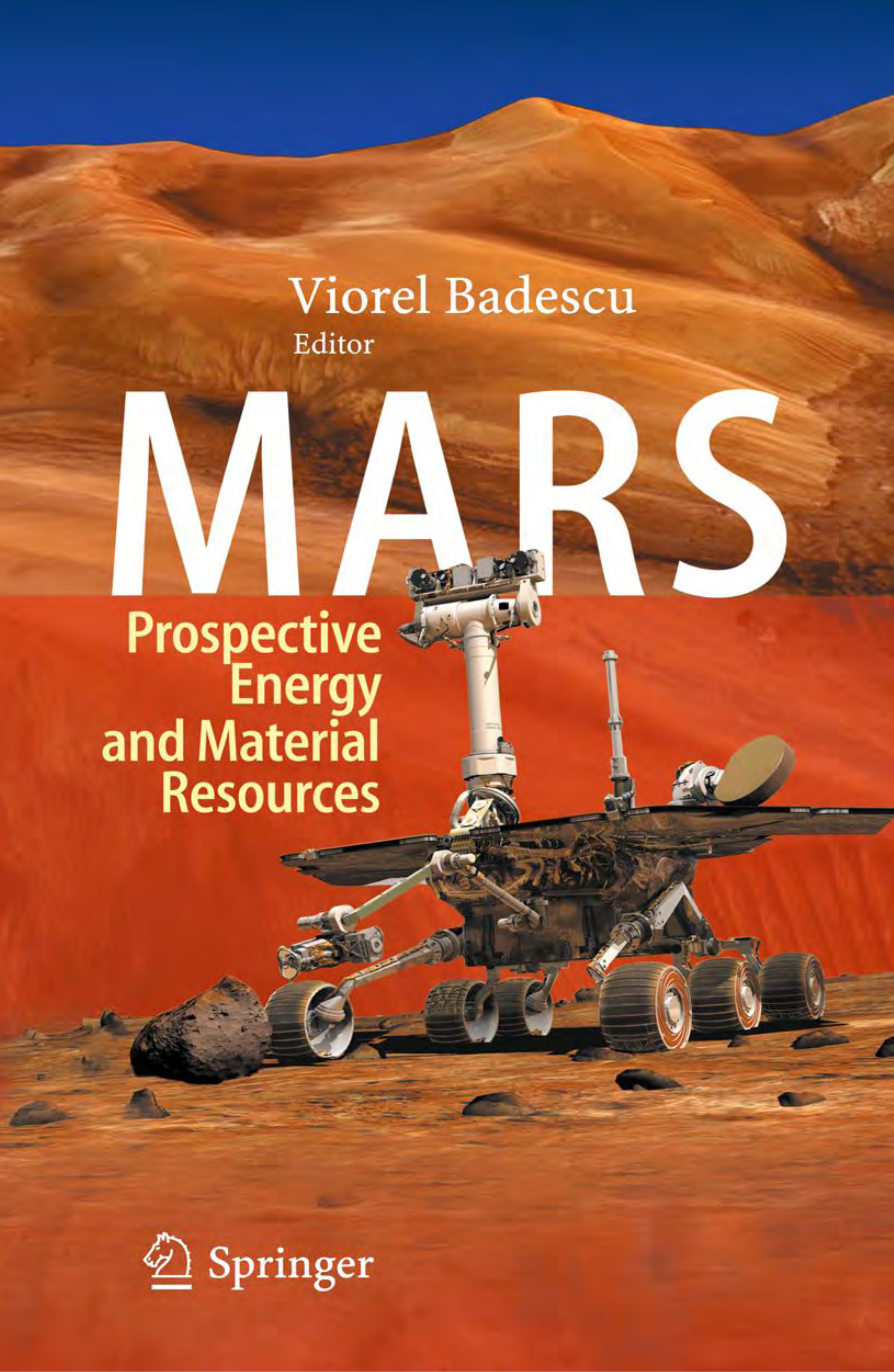
Viorel Badescu
Editor

MARS

Prospective Energy and Material Resources



Springer

Viorel Badescu (Ed.)

Mars

Prospective Energy and Material Resources

Springer

Prof. Viorel Badescu, Candida Oancea Institute
Polytechnic University of Bucharest
Spl. Independentei 313, Bucharest
060042
Romania
E-mail: badescu@theta.termo.pub.ro

ISBN 978-3-642-03628-6 e-ISBN 978-3-642-03629-3

DOI 10.1007/978-3-642-03629-3

Library of Congress Control Number: 2009934313

Typesetting: Data supplied by the authors

Production & Cover Design: Scientific Publishing Services Pvt. Ltd., Chennai, India

Printed in acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Chapter 14
Tumbleweed: A New Paradigm for Surveying the Surface of Mars for In-situ Resources

Kimberly R. Kuhlman[1], Alberto Behar[2], Jack Jones[2], Penelope Boston[3], Jeffrey Antol[4], Gregory Hajos[4], Warren Kelliher[4], Max Coleman[2], Ronald Crawford[5], Lynn Rothschild[6], Martin Buehler[7], Greg Bearman[8], and Daniel W. Wilson[2]

[1] Planetary Science Institute, Tucson
[2] Jet Propulsion Laboratory, Pasadena
[3] Earth & Environmental Science Dept., New Mexico Tech, Socorro, NM
[4] NASA Langley Research Center, Hampton, VA
[5] University of Idaho, Moscow, ID
[6] NASA-Ames Research Center, Moffett Field, CA
[7] Decagon Devices, Pullman, WA
[8] Snapshot Spectra, Pasadena, CA, USA

14.1 Introduction

Mars missions to date have interrogated the planet at very large scales using orbital platforms or at very small scales intensively studying relatively small patches of terrain. In order to facilitate discovery and eventual utilization of Martian resources for future missions, a strategy that will bridge these scales and allow assessment of large areas of Mars in pursuit of a resource base will be essential. Long-range surveys of in-situ resources on the surface of Mars could be readily accomplished with a fleet of Tumbleweeds - vehicles capable of using the readily available Martian wind to traverse the surface of Mars with minimal power, while optimizing their capabilities to perform a variety of measurements over relatively large swaths of terrain. These low-cost vehicles fill the niche between orbital reconnaissance and landed rovers, which are capable of much more localized study. Fleets of Tumbleweed vehicles could be used to conduct long-range, randomized surveys with simple, low-cost instrumentation functionally equivalent to conventional coordinate grid sampling. Gradients of many potential volatile resources (e.g. H_2O, CH_4, etc.) will also tend to follow wind-borne trajectories thus making the mobility mode of the vehicles well matched to the possible target resources. These vehicles can be suitably instrumented for surface and near-surface interrogation and released to roam for the duration of a season or longer, possibly on the residual ice cap or anywhere orbital surveillance indicates that usable resources may exist. Specific instrument selections can service the exact exploration goals of particular survey missions. Many of the desired instruments for resource discovery are currently under development for in-situ applications, but have not yet been miniaturized to the point where they can be integrated into Tumbleweeds. It is anticipated that within a few years, instruments such as gas chromatograph mass spectrometers (GC-MS) and ground-penetrating radar (GPR) will be deployable on Tumbleweed vehicles. The wind-driven strategy conforms to potential natural gradients of moisture and potentially relevant resource gases that also respond to wind vectors. This approach is also useful for characterizing other resources and performing a variety of basic science missions. Inflatable and deployable structure Tumbleweeds are wind-propelled long-range vehicles based on well-developed and field tested technology (Antol et al., 2005; Behar et al., 2004; Carsey et al., 2004; Jones and Yavrouian, 1997; Wilson et al., 2008). Different Tumbleweed configurations can provide the capability to operate in varying terrains and accommodate a wide range of instrument packages making them suitable for autonomous surveys for in-situ natural resources. Tumbleweeds are lightweight and relatively inexpensive, making them very attractive for multiple deployments or piggybacking on larger missions.

14.2 History and Development of Tumbleweed Vehicles

Tumbleweeds are large, lightweight, spherically shaped wind-propelled vehicles that can enable exploration of vast areas of Mars. A variety of vehicles referred to as Tumbleweeds and inspired by the Russian thistle (*Salsola tragus*) have been investigated by numerous groups of investigators. Jacques Blamont of NASA's Jet Propulsion Laboratory (JPL) and the University of Paris originally conceived the first known Mars wind-blown ball in 1977, shortly after the Mars Viking Landers discovered that Mars has a thin CO_2 atmosphere with relatively strong winds (Blamont, 1977). Blamont's "Mars Balls" were conceived as relatively large, 3- to 10-meter diameter inflatable balls that could carry payloads, of 20-30 kg for distances of at least 100 km (Janes, 1989). These proposed balls could be powered either by the wind or powered and steered by an inner drive mechanism.

Fig. 14.1 Original 3-wheeled inflatable rover shown with inventor, Jack Jones, NASA Jet Propulsion Laboratory (Jones et al., 1999).

14.2.1 Inflatable Tumbleweeds

In 2000, Jack Jones of NASA JPL was testing a three-wheeled inflatable rover (Fig. 14.1) in a windy sand dune area in California's Mojave Desert when one of the wheels broke off and took off over the sand dunes, while Jones' crew chased the ball with a dune buggy (Jones, 2001). The renegade 1.5 m diameter ball was able to climb steep slopes, over large boulders, and through the jagged brush without hesitation. This seemingly unlucky incident produced the inspiration for the current Tumbleweed vehicle (Behar et al., 2004). JPL then went on to measure performance of a 1.5 m sphere in the Mojave Desert (Jones, 2001), which was confirmed by theoretical analyses performed by the University of Southern California (Wang et al., 2002). The inflatable Tumbleweed has since successfully been tested in Greenland in 2003 and in Antarctica in 2004 (Fig. 14.2). The latest version of the rover was deployed in Greenland in May 2004, where it autonomously traveled more than 200 km across an ice sheet during a 4-day period. Communicating via the Iridium satellite network, the vehicle successfully and reliably relayed live GPS, temperature, and pressure data to a ground station at JPL.

Modeling and testing have shown that an inflatable 6 meter diameter Tumbleweed is capable of climbing 25° hills, traveling over 1 meter diameter boulders, and ranging over a thousand kilometers of terrain (Wang et al., 2002). Tumbleweeds

Fig. 14.2 NASA JPL Tumbleweed test deployment in Antarctica in 2004. Image courtesy Alberto Behar, NASA JPL.

have a potential payload capability of about 10 kg and could potentially generate 10-20 W of power by means of using an internal kinetic energy production device (Jones, 2009). Stopping for measurements can be accomplished using partial deflation or other braking mechanisms (Fig. 14.3). Carnegie Mellon University (CMU) has also conducted empirical testing of the JPL inflatable concepts (Apostolopoulous et al., 2003). The primary purpose of CMU's test was to

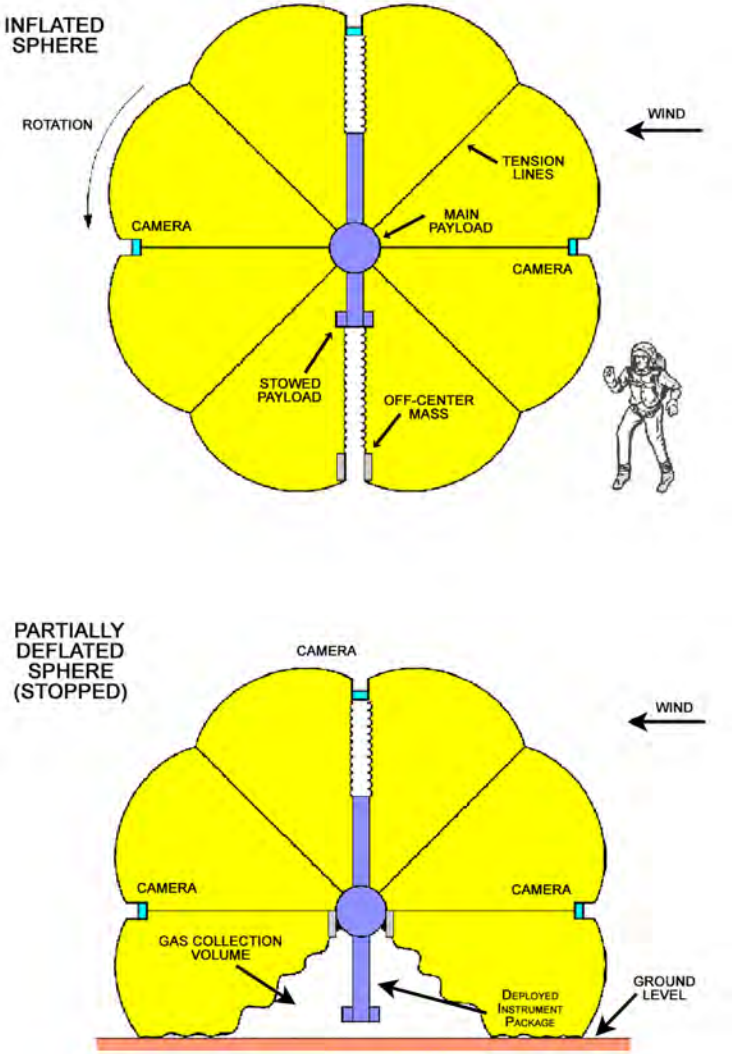


Fig. 14.3 An inflatable Tumbleweed can be stopped by partially deflating the ball and pulling on one of the central payload tension cords to create the “Turtle mode.” This mode of stopping also creates a collection chamber for gas measurements (Jones, 2001).

characterize the rolling resistance, drive torque, drive power and tire wear of a single inflatable sphere, for use on the three-wheeled rover, which utilized the inflatable balls for wheels. A testbed apparatus was developed for these tests that allowed variation of tire design, wheel speed/acceleration, tire pressure, soil/obstacle properties and traverse length.

Inflatable Tumbleweeds have been tested by NASA JPL in Greenland and Antarctica carrying a complete central payload consisting of batteries, inflation/deflation pumps, communications, and a winch (similar to Fig. 14.4). The winch can be used to pull on one or more of the central payload tension lines while the ball deflates. This will create a "turtle" shape and allow the ball to stop, forming a volume underneath that can be used to collect gases emanating from the soil that might indicate hidden subsurface resources (Fig. 14.3). This chamber is very conducive to the collection of gases because its volume to basal area ratio can be very small, providing more rapid feedback to the concentration gradient driving molecular diffusion across the surface (Livingston and Hutchinson, 1995).

14.2.1.1 Example of Tumbleweed Capability: Terrestrial Test Payload

The current terrestrial Tumbleweed payload is suspended at the center of the vehicle (Fig. 14.4). The payload currently consists of a motherboard, a liquid crystal display (LCD), a 900 MHz serial transmitter, an Iridium modem with integrated global positioning system (GPS) receiver, an omni-directional Iridium antenna, an active GPS antenna, a lithium battery pack, a pulse modulated voltage regulator board, a Darlington transistor board, and an air pump. A composite flange with pliable rubber gaskets attaches the air intake to the nylon bag. Similar flanges and gaskets will be implemented on the skin to house the moisture-sensing units.

14.2.1.1.1 Ground Station

To facilitate the field-testing of Tumbleweed, as well as the long-range terrestrial deployments, a highly functional, robust, and user-friendly ground station software has been developed using LabVIEW (Virtual Instrument Engineering Workbench). The LabVIEW ground station software as written, allows for near real-time data processing and distribution via the Internet.

14.2.1.1.2 Electronics Package

The motherboard consists of numerous components that serve to control Tumbleweed, as well as take scientific data. Mounted on the board are two pressure transducers (one for ambient pressure and the other for monitoring the membrane's internal pressure), a thermocouple (for recording ambient temperature), three 2-axis accelerometers (to determine the orientation of the Tumbleweed at the time of acquisition), and a real-time clock (for noting the time at which the readings were made).

The heart of the rover's electronics package is the Basic Stamp microcontroller, which is also mounted on the motherboard. The microcontroller takes temperature, pressure, accelerometer, battery level, time, and position data once every second. Every fifteen minutes, the microcontroller attempts to make a call with the Iridium modem, which includes an integrated GPS receiver. If a connection is

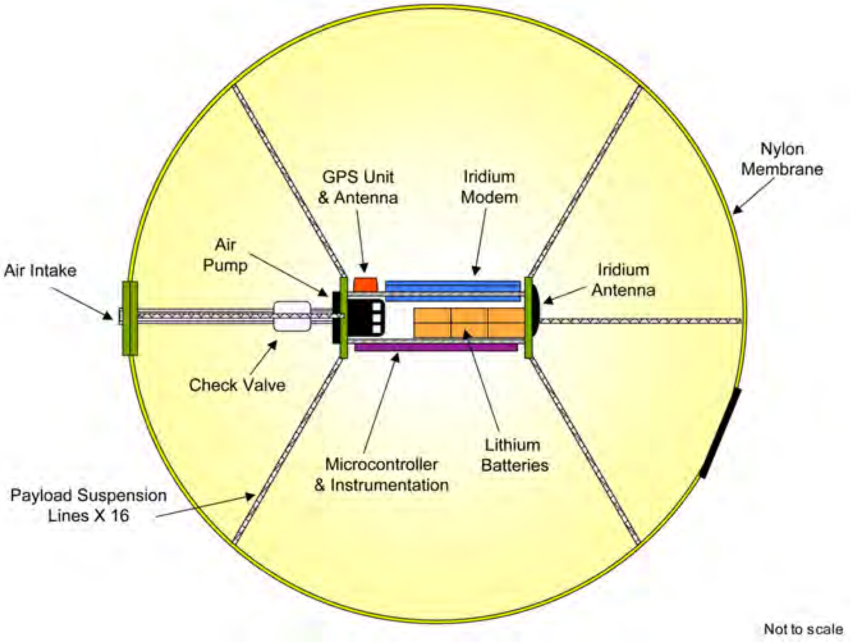


Fig. 14.4 A system diagram showing the inflatable Tumbleweed internal components. Many of these components are part of Tumbleweeds that have been well tested in extreme terrestrial environments by NASA JPL.

made, the Basic Stamp begins sending the stored strings of data. If the connection is unsuccessful, the Stamp will try once more. If the second attempt is unsuccessful, the Stamp will continue taking new data and wait fifteen minutes before making the next attempt.

The power system of the Tumbleweed is designed to satisfy the electrical requirements of six different subsystems currently used for housekeeping and general measurements during polar testing. To handle the various power sources, a pulse modulated voltage regulator is used to knock any voltage from 6 to 16 V down to 5 V.

14.2.1.1.3 Batteries

The factors affecting battery choice are numerous and varied. The weight and number of batteries are given special consideration in order to maintain a balanced load in Tumbleweed such that it rolls along a preferred axis. The maximum weight and number are also affected by the limitation placed on the position of the batteries by the requirement that the modem antenna must remain centrally located to ensure good signal quality. The modem itself experiences current spikes over 4 amps, a level that most batteries are not capable of providing.

Lithium batteries are the clear choice when it comes to power density, weight, and operating temperature, however there are not many lithium batteries available able to handle the current spikes induced by the modem. Although the lithium batteries are the same physical size as Ni-MH, they operate at more than twice the voltage.

14.2.1.1.4 Pumps

In the long-range deployment scenarios planned, Tumbleweed may experience a significant change in altitude. If measures are not taken to counteract the loss of internal pressure occurring from altitude change, not to mention small leaks, the vehicle could deflate to the point that it is no longer possible to roll, well before reaching its final destination. To alleviate this problem, a small pump is included in the central payload to actively inflate Tumbleweed during the course of its journey.

A second pump/valve system has been designed to actively inflate and deflate the Tumbleweed membrane at a relatively high rate as a means of controlling its speed, as well as providing a mechanism for stopping the vehicle. This system is controlled via the onboard Stamp microcontroller and allows the user to command Tumbleweed (via the ground station software) to travel at a certain speed. The microcontroller then compares this desired speed with the actual speed determined by the onboard navigation unit. If the actual speed is not within range of the desired speed, Tumbleweed automatically adjusts its level of inflation (i.e. -- inflate to speed up, deflate to slow down).

14.2.2 Deployable Structure Tumbleweeds

Tumbleweeds utilizing lightweight deployable structures to harness the wind for mobility have been developed by NASA Langley Research Center (LaRC). LaRC engineers were inspired by the Mars Pathfinder airbag landing system, which traveled a significant distance across the surface of Mars (much farther than the wheeled Sojourner rover ultimately would travel) before coming to a rest and deflating. Various methods were considered for maintaining the rolling motion, with the Martian wind appearing to be the most promising (Antol et al., 2003). Leveraging LaRC's expertise in lightweight structures, several notional concepts of Tumbleweeds (Figs. 14.5 and 14.6) were defined with the goal of providing vehicles with superior aerodynamic properties for capturing the wind (Antol, 2005).

The "Box Kite" concept uses fabric sails, similar to a kite, but with the sails attached to spring hoops to provide increased rolling capability. The "Dandelion" concept was biomimetically inspired with the objective of creating a branch structure similar to that of a Tumbleweed plant. However, the configuration evolved into a symmetric array of legs extending from a spherical core and having pads at the ends to prevent sinking into soft surfaces, thus resembling a dandelion more than a Tumbleweed. A variation of the Dandelion that more closely resembles the Tumbleweed plant is the "Eggbeater Dandelion," which replaces the legs with multiple curved struts resembling eggbeaters or whisks. The "Tumble-cup" consists of open-ended cones around a spherical core to maximize aerodynamic surface area while reducing rolling resistance. The open configurations of the deployable structure Tumbleweed concepts have the additional advantage of allowing unobstructed access to the environment for scientific instrumentation.

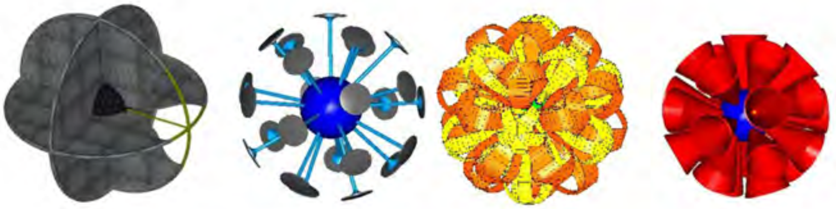


Fig. 14.5 NASA LaRC Tumbleweed Concepts (left to right): Box kite, Dandelion, Egg-beater, and Tumble-cup. Image courtesy NASA/AMA Inc.

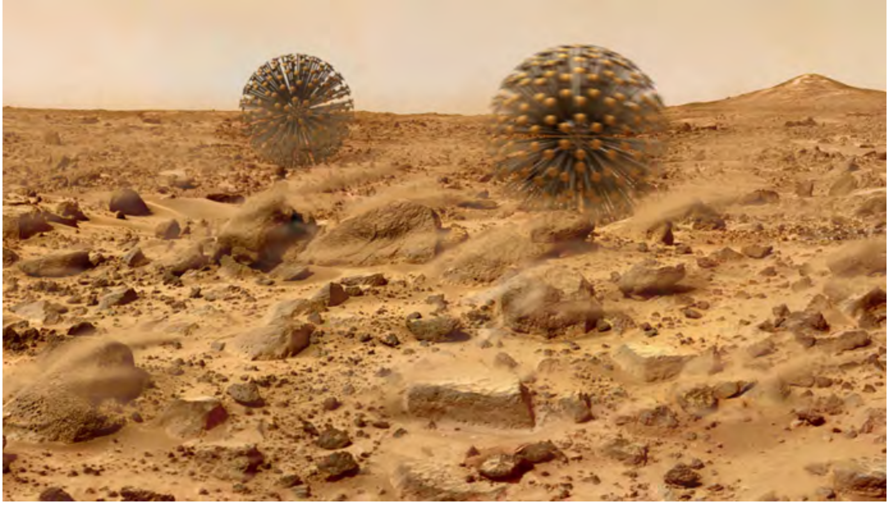


Fig. 14.6 Artist depiction of NASA Langley Research Center Dandelion Tumbleweeds on Mars. Image courtesy NASA/AMA Inc.

Preliminary analysis and wind tunnel testing of the LaRC notional concepts (see Sect. 14.2.2.1) determined that the deployable structure Tumbleweeds require a diameter of approximately 4-6 meters (m) with a mass of no more than 20 kg, including subsystems and instruments, to capture the thin Martian atmosphere and achieve mobility (Antol et al., 2005). The Box Kite Tumbleweed has emerged as the most promising configuration because of its drag properties, packaging efficiency, and open architecture that maximizes access to the environment for sensors and instrumentation.

The first scale prototype of a deployable structure Tumbleweed, based on the Box Kite concept, was developed by students from the North Carolina State University (NCSU) Department of Mechanical and Aerospace Engineering in cooperation with LaRC (Fig. 14.7). Known as the Tumbleweed Earth Demonstrator (TED), the TED includes a central instrument core with temperature/pressure sensors, accelerometers, a Global Positioning System (GPS) package, and a data

Fig. 14.7 Tumbleweed Earth Demonstrator designed and fabricated by North Carolina State University. Image courtesy NCSU.

acquisition/communication system for collecting data during Earth-based field tests of the concept (Hanrahan et al., 2003). NCSU has also developed a second and third generation TED, employing them in field tests on a variety of terrain (Wilson et al., 2008).

Based on preliminary analysis results and leveraging knowledge gained from development of the NCSU TED, NASA LaRC constructed a prototype box kite (Fig. 14.8) for demonstrating mission concepts and science measurement techniques (Antol et al., 2006a). As with the NCSU TED, the LaRC Box Kite prototype has a central core with sensors and a data acquisition/communication system. The primary

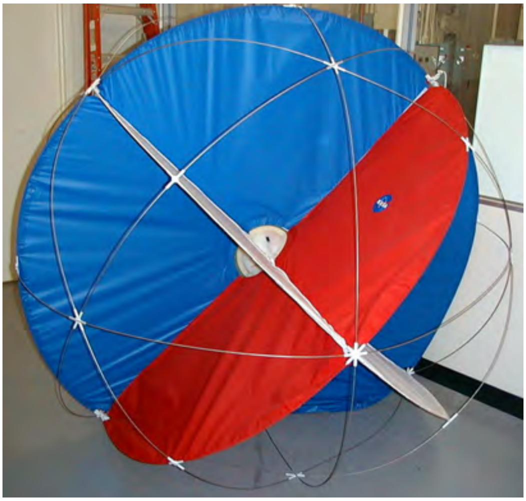


Fig. 14.8 NASA LaRC Box Kite Tumbleweed Prototype.

difference between the NCSU TED and the LaRC prototype is the use of titanium rods in the hoop structures for reduced weight and durability.

The Texas Tech University (TTU) Department of Mechanical Engineering is developing extremely lightweight, miniaturized, deployable structure Tumbleweed concepts, which would permit large numbers to be carried as secondary payloads on Mars missions. The TTU Tumbleweeds, with the configuration of a sector-removed sphere (Fig. 14.9), would be approximately 12 inches in diameter and have a mass less than a kilogram. Constructed of lightweight materials, the TTU Tumbleweed could be covered with solar cells and have electronics and sensors embedded in the structure (Rose et al., 2006).

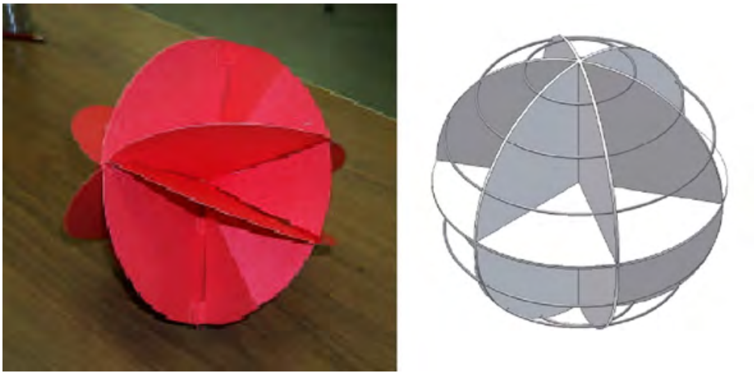


Fig. 14.9 TTU Tumbleweed concept. Image courtesy TTU.

14.2.2.1 Test and Analysis

NASA LaRC, NCSU, TTU, and the Biorobotics Laboratory at Case Western Reserve University (CWRU) have conducted extensive analysis and wind tunnel testing of Tumbleweed concepts. Dynamic simulations have been developed to investigate the potential mobility of Tumbleweed concepts in a Martian environment. Wind tunnel testing was conducted to obtain drag characteristic data on the various Tumbleweed concepts for input to the dynamic simulations. Another objective of the aerodynamics research is to determine which configurations achieve the highest drag coefficient (C_d), using a simple, smooth sphere (~0.5) as the baseline.

LaRC wind tunnel testing was conducted in the Basic Aerodynamics Research Tunnel (BART). Multiple configurations of the Dandelion, Tumble-cup, and Egg-beater Dandelion were tested in a free stream flow at the expected Reynolds numbers for the martian surface (Re = 50,000 – 125,000) (Fig. 14.10).

Analysis of the test data showed the majority of Tumbleweed configurations exceeded the C_d of a sphere. The Box Kite displayed an angle of attack dependency, with the C_d varying from 0.8 up to 1.2 depending on the model orientation. The other concepts, which are symmetric in shape, were consistent across all angles of attack. The C_d for the Tumble-cup and Dandelion models ranged from

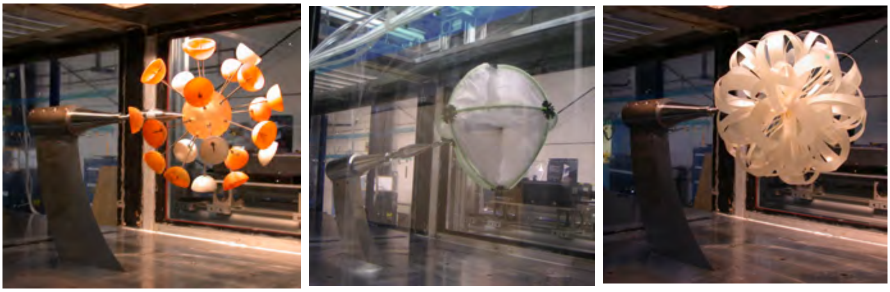


Fig. 14.10 NASA LaRC Dandelion, Box Kite, and Eggbeater Danelion in the Basic Aerodynamics Research Tunnel.

0.8 to 1.0, varying with the number of legs/cups employed, while the C_d for the Eggbeater Dandelion models ranged from 0.6 to 0.85. Several alternative configurations of the Dandelion, equipped with cupped feet, performed no better than a sphere (Antol et al., 2006b).

Testing was also conducted in the TTU Atmospheric Boundary Layer (ABL) Wind Tunnel to study the surface boundary layer effects on the Tumbleweed drag coefficients (Fig. 14.11). Several models, including the NASA LaRC Dandelion and Tumble-cup, were fully submerged in a simulated Martian atmospheric boundary layer based on a theoretical NASA model of a Mars surface wind boundary layer. A comparison of the results with those from testing conducted in the free stream reveals a uniform decrease in the drag coefficients between 6 and 16% in the atmospheric boundary layer testing versus the free stream (Rose et al., 2006).

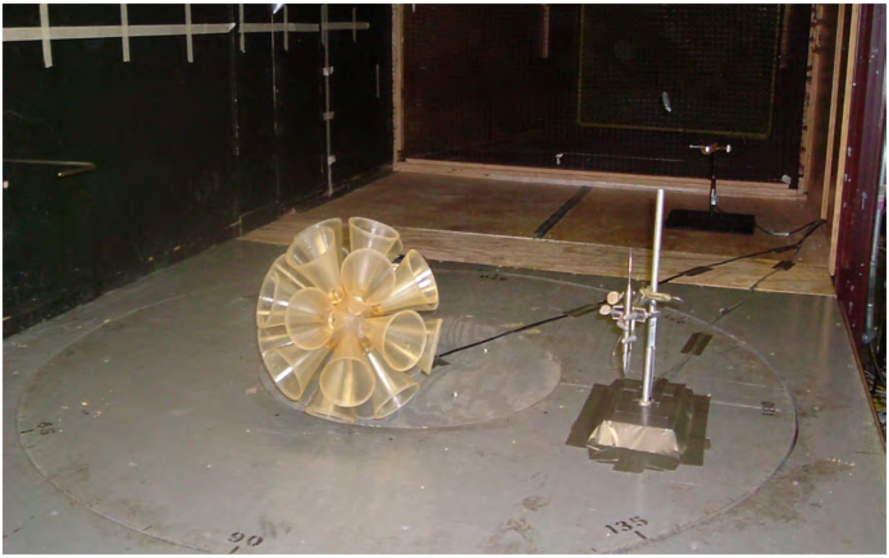


Fig. 14.11 NASA LaRC Tumble-cup model in Texas Tech University Atmospheric Boundary Layer Tunnel. Image courtesy TTU.

14.3 Tumbleweed Deployment

Launch and deployment of Tumbleweed vehicles promises to be simple and relatively low-cost. A small number of Tumbleweeds could piggyback along with other missions, or fleets of Tumbleweeds could be launched together and released at one or multiple locations depending upon the coverage desired. Mobility of a wind driven system is inversely proportional to mass and directly proportional to atmospheric density and drag coefficients. To increase the system mobility, mass should be minimized. Increasing the size of a Tumbleweed will increase the driving force from the wind, but increases the structural mass, which will limit the additional mobility. Communication systems tend to need high levels of electric power. Power systems tend to be heavy to begin with and increase in mass with increased capacity. The preferred approach is to reduce the size and mass of system components such as the structure, power and communication systems.

In order to quantify the potential mobility of deployed Tumbleweed vehicles, NASA LaRC has examined the motion of various Tumbleweed designs over various terrains (sand dunes, rocky desert, glacial ice, etc) to determine the optimal size for instrument suites and anticipated topography (Antol et al., 2005). The *Mars Tumbleweed Monte Carlo Simulator* is software that models the dynamics of a vehicle interacting with the environment of Mars to provide a moderate fidelity, end-to-end mission simulation (Flick and Toniolo, 2005). The software allows users to select value ranges for a series of parameters (e.g., mass properties, wind model parameters, terrain properties, etc.), which define bounds on the simulation environment. Random values are then assigned to each parameter during the simulation for each Monte Carlo iteration based on these user-defined value ranges. The purpose is to analyze closely related scenarios in order to identify common behaviors or trends. Figure 14.12 shows the combined result of 2000 Monte Carlo simulations of dispersing Tumbleweeds 120 seconds after release (assumptions: 5m radius, rigid-body Tumbleweed, constant wind velocity of 7 m/s, 1-2m rocks spaced approximately 10m apart in a randomized distribution based on the Viking 1 landing site data). Approximately 890 Tumbleweeds stuck between two rocks in the first 100m (major groupings of 380 at 0-20m, 280 stuck at 80-100m). The Tumbleweeds would remain stuck until the wind shifts direction or the wind speed increases until the resultant force overcomes the resistance to motion and the Tumbleweed rolls over the obstacles. Mars Pathfinder data show a diurnal wind sweep of at least 180 degrees, so a stuck Tumbleweed can become free within one Sol. Mars Pathfinder data also indicates that wind speed cycles throughout a Sol with an average of approximately 7 m/s and peaks between 10 m/s and 15 m/s (seasonally dependent). The software can be enhanced to use the most recent Mars environment models, including, but not be limited to the Mars terrain (Mars Orbiter Laser Altimeter (MOLA) data), rock distribution (Golombek and Rapp, 1997), wind direction/magnitude, boundary layer effects (ARC Global Circulation Model (GCM)) (Haberle et al., 2003), and MSFC Mars Global Reference Atmospheric Model 2001 (Justus et al., 2006).

LaRC also developed a 3 dimensional (3-D) Matlab/Simulink simulation using a lumped mass dynamics model to study the rolling characteristics of the deployable

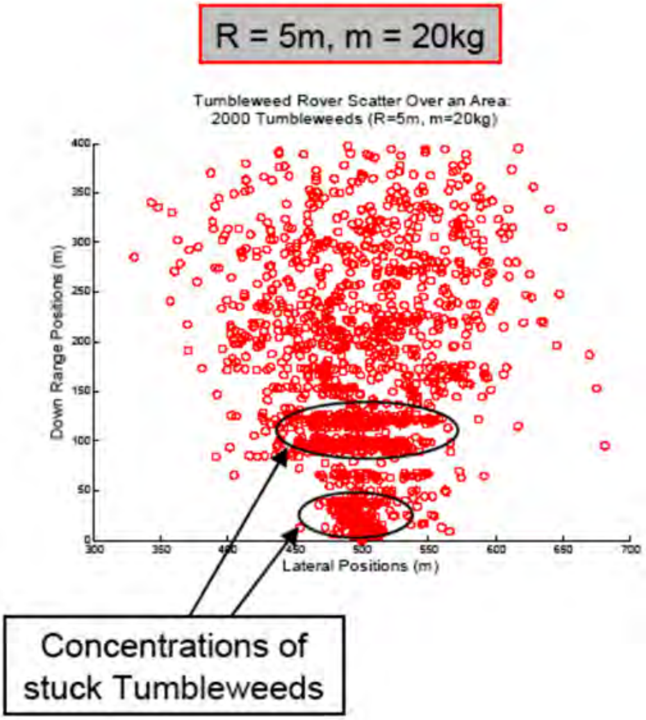


Fig. 14.12 Monte Carlo simulation of Tumbleweed trajectories run for a total of 2000 rovers, with diameter 5 m and mass of 20 kg mass.

structure Tumbleweed concepts. To refine the lumped mass dynamics model approach of the 3-D Simulation and to validate modeling assumptions, a series of empirical tests were conducted at LaRC using photogrammetry techniques. Three Tumbleweed concepts (a simple sphere, a Box Kite, and an Eggbeater Dandelion) were modeled and rolled down a 24-foot plywood ramp and the rolling/bouncing movement recorded using a 6-camera photogrammetry system. Cameras were located to capture 6 degree-of-freedom (DOF) dynamics at start of motion, middle of the ramp, and at the end of the ramp. Three-dimensional motion data was extracted from the test data and used to refine the assumptions and validate the 3-D model.

A stochastic simulation of a group of Tumbleweeds interacting with obstacles was developed by students of the CWRU Biorobotics lab. Mars Orbiter Laser Altimeter (MOLA) mission data was used to create the general topography of the martian surface. Valleys and other geological obstacles were simulated using a Gaussian randomization of the entire surface with a standard deviation of twenty-five degrees. The simulation also employed a group behavior algorithm with Tumbleweed vehicles having limited capability for stopping/starting and steering. A mission scenario to explore Martian gullies, based upon the Dao Vallis topographical data, was analyzed to assess Tumbleweed mobility and group behavior capabilities. An animation of the mission scenario also was created (Fig. 14.13) (Hoeg et al. 2006).

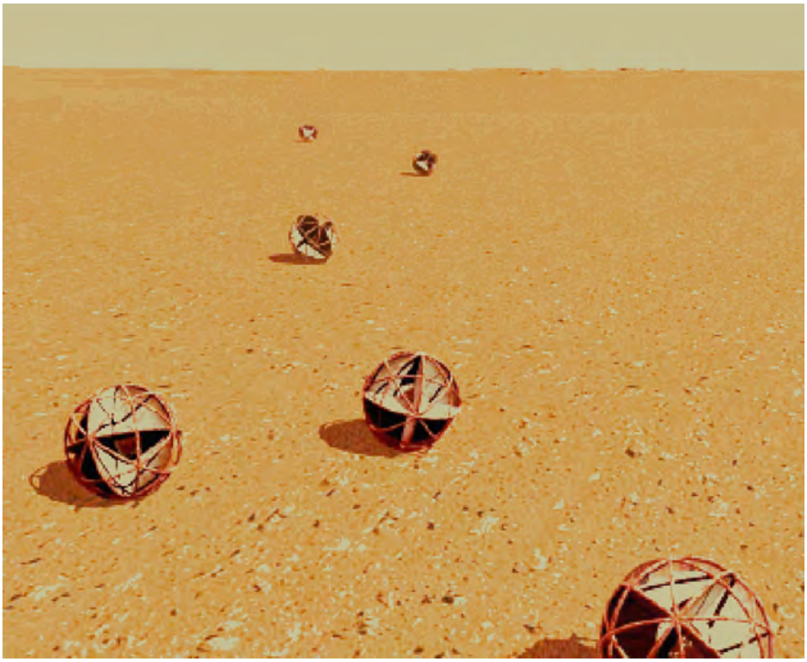


Fig. 14.13 Artist depiction of a group of Box Kite Tumbleweeds crossing a Martian plateau. Image courtesy CWRU.

A preliminary assessment of navigation system options by NASA LaRC identified several possibilities for accurately determining the location of a Tumbleweed rover on Mars, including: Doppler radiometric techniques using existing Mars orbiting assets, odometry using Inertial Measurement Units (IMU), optical terrain mapping, and optical celestial navigation (Antol, 2005). Dead-reckoning using an IMU or optical position updates from terrain mapping could be used for instantaneous navigation, combined with radiometric techniques for regular position updates. The recommended configuration is a Tumbleweed equipped with a Proximity-1 radio with Doppler capability, a roll sensor, Micro-Electro-Mechanical Systems (MEMS) accelerometers, a MEMS IMU (if the technology matures), and 6 MEMS Sun sensors. It is important to note that this recommendation imposes no new Mars infrastructure; however, technology advancements may be needed in the above components to meet Tumbleweed mass and power requirements.

14.4 Target *In situ* Resources

Since the potential resources of Mars have been discussed in detail in other chapters in this book, we will briefly touch upon the resources that can potentially be surveyed using a fleet of Tumbleweed vehicles. It should also be noted that Tumbleweeds and their highly configurable payloads could perform a variety of basic science missions. The most important resource for human habitation is arguably water. A well-defined supply of water is deemed a necessity for a base that is expected to flourish and grow (Taylor, 2001). Tumbleweeds can survey for water in two ways: surface mounted sensors and ground penetrating radar (GPR). Both will be discussed in the following section on instrumentation. GPR in particular will be capable of characterizing the location and abundance of near-surface water, critical for locating a future Martian base (Jakosky and Zent, 1993). In addition to ice and underground aquifers, water may be present in the pore spaces of clays and other hydrated minerals, making these materials potential important water resources on Mars (Baker et al., 1993). Tumbleweeds outfitted as proposed below would be capable of identifying areas of hydrothermal activity and thus deposits of hydrated minerals, such as those found in Nili Fossae by Mars Express (Bibring et al., 2006; Poulet et al., 2005) and Mars Reconnaissance Orbiter (MRO) (Mustard et al., 2008).

Hydrogen and oxygen (both likely derived from water) are key components in the synthesis of fuels and propellants (Stoker et al., 1993), Tumbleweeds would also be useful components in the search for quantities of water that will be needed to fuel a base on Mars and provide transportation off the surface. Tumbleweeds equipped with gas sensors could also be used to locate sources of methane plumes observed on Mars in recent years (Krasnopolsky et al., 2004; Mumma et al., 2009). These sources could be important for production of fuels and propellants.

Another of the future resources that human colonists will need to have on Mars is soil for agricultural activities (McKay et al., 1993; Taylor, 2001). Ever since Viking, there have been indications that the regolith contains montmorillonite (a swelling clay) and other components that may make it difficult to use for agriculture (Bibring et al., 2006; Poulet et al., 2005). Information about pH (seeking the neutral soil), clay types, heavy metal contents, etc. would be target information that would pertain to this goal. Both a multispectral imager and X-ray fluorescence spectrometer would allow Tumbleweeds to survey these properties of the martian regolith (Marshall et al., 1997). These instruments would also be critical to locating sources of nitrates and phosphates, which will be critical to the agricultural enhancement of regolith local to a martian base (Stoker et al., 1993; Taylor, 2001). Tumbleweeds would also be well suited to survey for sulfur compounds, which would be important for a variety of industrial processes that one would assume to be important to a base on Mars.

Conversely, recognition of perchlorate (and possibly chlorate) as discovered recently by the Phoenix mission (Hecht et al., 2008) would be important for two reasons. Natural perchlorate on Earth is thought to be formed by photolytic processes in the atmosphere (Ericksen, 1981). Similar processes produce nitrate. Thus, perchlorate could be a pathfinder for much larger nitrate deposits. Both of these materials are very soluble salts and can accumulate on the Earth's surface in very arid regions, like the Atacama Desert, where the average perchlorate forms less than 0.05% of nitrate deposits (Ericksen, 1983). While nitrate is a valuable fertilizer, perchlorate and, to a much greater extent, chlorate, are herbicides. Concentrations of perchlorate of up to 0.8% have been reported in nitrate fertilizer from Chile (Bohlke et al., 1997). Perchlorate is a powerful oxidant and could be a useful energy source in the same way as it is used in solid fuel rockets.

Tumbleweeds outfitted with similar instruments will also be useful for locating resources of building materials. Aggregates, calcium-sulfates and carbonates are all important materials for building infrastructure (Schmitt, 2004; Taylor, 2001). Calcium-rich sulfates, most likely gypsum, have been observed in several locations on Mars by OMEGA/Mars Express (Gendrin et al., 2005; Langevin et al., 2005). Carbonates have recently been observed at the Phoenix lander site (Boynton et al., 2009; Kounaves et al., 2009; Sutter et al., 2009). Even after a base is established, Tumbleweeds may be used to survey for long-term resources such as ore-bodies, sources of metals, organic compounds and extensive clay deposits. Tumbleweeds will be particularly useful for long-range surveys for resources that require intensive, global geological exploration suggested by Taylor, 2001: sedimentary deposits, hydrothermal deposits, and differentiated igneous provinces. Taylor (2001) suggests that these global searches for resources be started early in the process in order to attract capital for martian investment. Fleets of low-cost Tumbleweeds could play an integral role in such reconnaissance.

14.5 Instrumentation for ISRU Surveys

A suite of instrumentation can be envisioned for a fleet of Tumbleweeds for deployment on Mars for *in situ* resource surveys. An example instrument suite could include surface mounted soil moisture sensors (SMSMS), ground penetrating radar to characterize subsurface layering, aquifers and voids, sensors for a variety of useful gases, a miniature X-ray fluorescence spectrometer for elemental analysis of martian regolith and a multispectral imaging system for characterizing grain size and shape distributions as well as surface mineral composition. Other suites of instruments could be envisioned based upon the requirements of specific survey scenarios.

14.5.1 Surface Mounted Soil Moisture Sensors (SMSMS)

During the wind driven phase, surface mounted soil moisture sensors (SMSMS) embedded in the skin of Tumbleweed will measure the soil volumetric water content (VWC) to a depth of 5 cm. Layers of water ice may well exist below 5 cm as buried snow, ice lenses, or ice wedges (Feldman et al., 2008). The SMSMS will be used in combination with real-time ground penetrating radar (GPR) as suggested in the following section. The measurement time for SMSMS is of the order of 10 ms so the results can be used for exception-based monitoring. That is, as Tumbleweed moves along, the VWC will be monitored so that when measurements exceed a threshold value, the motion of Tumbleweed can be stopped. The Tumbleweed will then transform to operate in the Turtle Mode as discussed earlier in the chapter and shown in Fig. 14.3. In this mode, more detailed measurements of the regolith can be acquired using Tumbleweed's suite of analytical instruments.

The SMSMS probes are implemented as nubs on the surface of Tumbleweed between the treads. The probes' electric field will penetrate the soil to a depth of about 5 cm so the instrument will sample the water content of this region. Thus, the sensor design will allow Tumbleweed to measure the soil moisture at a depth well below the surface crust. SMSMS is capable of measuring dielectric permittivity that varies from 1 for air, 3 to 6 for dry soils, 30 to 35 for water saturated soils, and 78 for water. The measurement time is approximately 10ms. Its mass is less than 100 g, and it requires less than 100 mW of power. The instrument has two rugged nubs that are separated by approximately 3 cm. With this spacing, SMSMS is capable of sampling the water content up to a depth of 5 cm (Fig. 14.14).

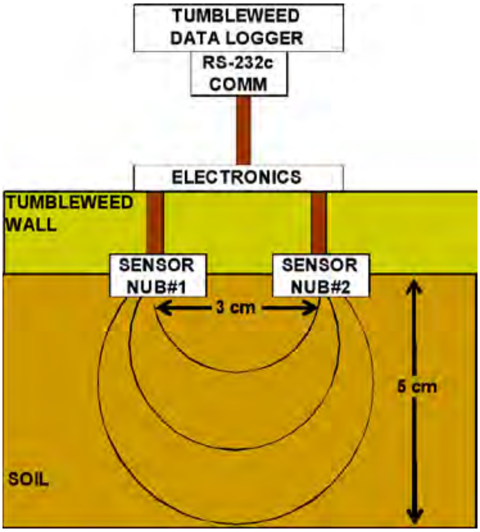


Fig. 14.14 SMSMS embedded in the wall of Tumbleweed showing the nubs separated by 3-cm and the current stream lines penetrating to a depth of 5-cm into the soil.

Operationally, SMSMS can also serve as a tachometer indicating the speed of Tumbleweed. As Tumbleweed rotates, SMSMS will be in air (dielectric permittivity of 1) most of the time and briefly it will be next to the ground (minimum permittivity of 3). Knowing the diameter of Tumbleweed and the time between the ground pulses allows a calculation of Tumbleweed's velocity. Unlike traditional land and Martian rover systems, Tumbleweed allows intelligent sampling through the integration of the SMSMS into its surface. The SMSMS monitors moisture content from 0-5 cm in depth in real time while Tumbleweed is traveling. In turn, anomalous moisture content triggers sampling events. This type of sampling regime, termed "exception-based" sampling, uses real-time information to determine sampling locations rather than site selection based on prior data. The SMSMS system allows Tumbleweed to implement the NASA paradigm, "Follow the Water" in a manner that is *immediately responsive* to its changing surroundings as it travels. We believe this to be a very efficient way of finding and analyzing areas that have the potential for *in situ* resources.

The circuitry for the soil moisture sensors is based on two existing soil moisture sensors; they are the Thermal and Electrical Conductivity Probe (TECP) and ECH_2O Probe. The TECP was built by Decagon Devices, Inc. for the NASA Phoenix Scout Lander, which landed on Mars May 25, 2008 (Cobos et al., 2004). The TECP instrument was designed to measure the dielectric permittivity of the martian regolith, which was assumed to be between 1 and 20; the instrument can resolve the dielectric permittivity to within 0.02. Detecting a dielectric permittivity greater than the anticipated permittivity of 3 to 6 for the regolith is highly suggestive of the detection of liquid water.

The ECH_2O probe, also manufactured by Decagon Devices, Inc measures the dielectric permittivity of the media surrounding two electrodes (Kizito et al., 2008). The soil water content is calculated from the dielectric permittivity measurement of the soil-moisture mixture. The dielectric permittivity of dry soil is between 3 and 4 and the dielectric permittivity of water is 80; so the presence of moisture in the soil is apparent as an increase in the dielectric permittivity. The measurements are comparatively fast, requiring approximately 10 ms for data acquisition.

14.5.2 Ground Penetrating Radar

Ground penetrating radar (GPR) is a non-invasive technique for imaging shallow and midrange subsurface materials and features (Conyers and Goodman, 1997; Doolittle, 1982; Duke, 1990; Huffman III, 1992). Pulses of ultra high frequency microwaves (300 to 1,000 Mhz) are transmitted to the ground through a transducer to ~10 m (high resolution). Deep GPR uses low frequency antennae (25 to 200 Mhz) with poorer resolution. Different materials reflect differently depending upon differing electrical conductivities and dielectric constants (Kolecki and Landis, 1996; Olhoeft, 1979; Wright et al., 1996). Returning waves (received by the same antenna) are compared with two-way travel time, amplified, and plotted. Portable units have been tested with data collection rates of several hundred scans per second with a time resolution of 5 picoseconds (Kathage et al., 2005), which means that GPR can also be used for real-time exception-based monitoring as discussed in the previous section. High conductivity materials (e.g. shales, clay, etc.) can be imaged only to about one meter, which is of limited utility. Depth of imaging ranges from less than one meter in clay soils (Nettwork, 2002) to greater than 5,400 meters in polar ice (Olhoeft, 2000). The depth of investigation that is possible increases with decreasing frequency but with decreasing resolution. Typical depths of useful investigation in clay-free sands saturated with fresh water or low conductivity materials (granites or dry particulates) are about 30 m.

The ability of GPR to reveal the fine structure of layers and small subsurface features has been documented in a wide variety of applications, including the study of centimeter-scale annual layers in a coastal barrier (Moore et al., 2004). Fine structure and layering in soils was an early target of GPR studies (Boll et al., 1996; Kung and Lu, 1993) including measuring the soil water content profile in sandy soil (Lambot et al., 2004). Periglacial terrains have been examined including spatial variability in glaciers (Palli et al., 2002), and in permafrost (Brandt et al., 2007). GPR has successfully resolved layers in sandstone (West and Truss, 2006) and it has been used increasingly in locating karst features like sinkholes and caves (Ezersky et al., 2006). The methodologies of GPR continue to be further refined at a rapid pace including integration with other methods like Resistivity Image Profiling (RIP) (Yang et al., 2006) advanced algorithms for handling multiple modes of GPR data (Stanley et al., 2004), and physical laboratory testing of GPR capabilities (Capizzi and Cosentino, 2008).

Both 2D and 3D imaging of up to hundreds of m^2/day is done with small portable units. Typically, electrical properties are much more important than magnetic properties in controlling propagation speed and amplitudes. Rock or soil density, chemistry, state (liquid/gas/solid), distribution (pore space connectivity) and H_2O content all contribute. Electrical properties of planetary surfaces (Kolecki and Landis, 1999; Olhoeft, 1991) and lunar regolith H_2O (Olhoeft, 1976) are of great interest. GPR use for Mars has been suggested (Olhoeft, 1998). Permafrost (Olhoeft, 1975, 1977), sand dune structures (Schaber et al., 1986; Schenk et al., 1993), organics (Olhoeft, 1986), and oxide minerals critical for human inhabitation (Lindsley, 1991) are all distinctive. Small GPR units (e.g. GeoModel, Inc., GPRS, Inc., GRORADAR™, Enviroprobe Service, Inc., NGPRS Inc., Geophysical Survey Systems, Inc.) are able to test capability of detecting near subsurface structure, composition and inhomogeneities. While present technology is not mountable on prototype Tumbleweeds, future miniaturization may make this a reasonable choice for a Mars-bound Tumbleweed to survey for *in situ* resources (Grant et al., 2003). The smallest currently commercially available system is the RAMAC X3M by Mala Geoscience, which is used for mapping lake sediments, manmade objects, detection of subsurface cavities and for mapping other small-scale features in detail. At a mass of 5 to 7 kg, this unit is approaching the size that could be mounted on a Tumbleweed.

14.5.3 Gas Sensors

Numerous gases will be useful *in situ* resources on Mars as discussed in Chaps. 15, 19 and 20. The handheld VRAE gas surveyor from RAE Systems could be used as the core of an instrument to measure resource relevant gases; oxygen, ammonia and carbon dioxide. A variety of sensor types are used for the various different gases; catalytic sensors for so-called combustible gases (primarily CH_4), thermal conductivity sensors for percentage volume of combustible gas, and electrochemical sensors for oxygen and toxic gases (including H_2S, SO_2, NO, N_2O, NO_2, Cl, HCN, NH_3, and PH_3). The unit is small enough to fit within the central tube of the inflatable Tumbleweed with a flexible probe that will fit alongside an imaging spectrometer. The VRAE weighs slightly more than 0.5 kg and is easily integrated into the data collection system using a USB connection. The measurements can be made while the Tumbleweed is stopped in Turtle Mode and the winches inside have created a gas collection chamber from the skin of the Tumbleweed. The measurements will be made as a function of time in an attempt to determine the concentration of gases in the soil as a function of depth (Livingston and Hutchinson, 1995).

The detection of water vapor in the soil and atmosphere immediately above the soil is desired to extend the range at which ambient water can be measured using Tumbleweed. Methane and hydrogen peroxide are other important resource gases that could be surveyed by Tumbleweeds. The JPL Tunable Laser Spectrometer (TLS) is a component of the Sample Analysis at Mars (SAM) analytical suite scheduled to fly on the Mars Science Laboratory (MSL) mission in 2011 (Tarsitano and Webster, 2007). The TLS uses a multipass Herriot cell and four laser sources -- near-infrared, interband cascade (IC) and quantum cascade (QC) – to measure methane, water, hydrogen peroxide, nitrous oxide and carbon dioxide. The TLS is extremely sensitive. For example, it is capable of measuring methane abundances to 0.01 ppbv (Tarsitano and Webster, 2007).

Other miniature tunable diode lasers (TDL) are being developed commercially. For instance, Physical Sciences Incorporated fabricates a GasScan™ Miniature Diode Laser-based Ambient Gas Sensor based upon near-IR tunable diode laser absorption spectroscopy (Physical Sciences Incorporation, 2009). This detector can be configured to detect a variety of gases including water and methane with sensitivities of 1.0 ppm.

14.5.4 Miniature X-ray Fluorescence Spectrometer

Tumbleweeds equipped with miniature X-ray fluorescence spectrometers (XRF) will be capable of performing elemental analyses of martian regolith while the Tumbleweed is in the stopped mode. NASA LaRC has been involved in building planetary flight X-ray Fluorescence Spectrometers (XRFS) since its participation in the development and delivery of flight XRFS units for the Mars Viking Project. The XRFS could also be replaced by an XRF coupled with a miniaturized X-ray diffraction (XRD) detector to provide complete mineralogical identification. Examples of potential instruments include the Mineral Identification and Composition Analyzer (MICA) (Martin et al., 2008) and the Chemistry and Mineralogy instrument (CheMin), which is part of the Mars Science Lander (MSL) payload (Blake et al., 2007). An XRFS unit could be mounted inside the central tube of a Tumbleweed such as the inflatable version shown in Fig. 14.3 and could be coupled with a drilling unit. When the Tumbleweed is deflated into a stopped mode, the drill and XRFS unit could be deployed.

Most recently, an XRFS was miniaturized to be able to be inserted into a 27.1mm diameter drilled hole to conduct elemental analysis of Martian regolith strata layers (Elam et al., 2008). The borehole XRFS provides superior performance to the X-ray elemental analyzers on the Mars rovers Spirit and Opportunity in that analysis time has been reduced to 1000 seconds with the borehole instrument versus the 20 hours required by the rover instruments. The analysis time can be further reduced to 100 seconds, making it an ideal instrument for a Tumbleweed science complement in Turtle Mode. Analytical performance of the borehole instrument was determined by checking the lower limits of detection for several elements over a wide range of the periodic table. The performance of the borehole XRFS was tested in a simulated Mars atmosphere using several terrestrial soil Standard Reference Materials (SRM) (Fig. 14.15). Minimum detection limits were below 10 ppm for most elements. No filters or other optics were used in the incident beam, and the detector has an internal collimator to restrict the

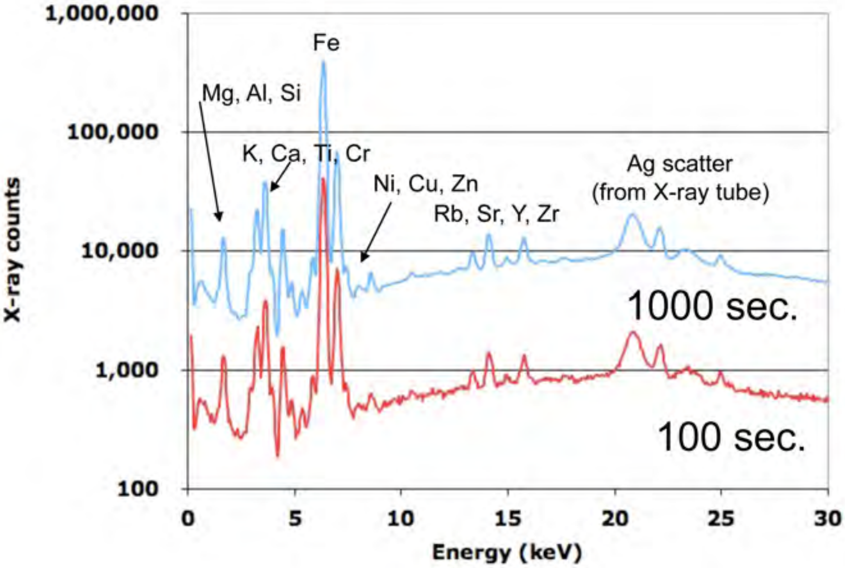


Fig. 14.15 Spectra of SRM 2709 tested using the borehole XRFS in a simulated martian atmosphere. Note that 100 sec spectra provides as much basic info as the 1000 sec does.

beam to the center of the diode. Data collection time was 1000 sec for the upper spectrum and 100 sec for the lower spectrum in Fig. 14.15. Note that the majority of the information is still available even with the 100 sec data collection time. This short data collection will greatly facilitate its use as an instrument on a Tumbleweed vehicle.

14.5.5 Multispectral Imaging

Media for agriculture, aggregates, and structural materials are also subjects for long-range surveys of Mars in preparation for the location of a human outpost. A computed tomography imaging spectrometer (CTIS) designed by NASA JPL will be capable of enabling snapshot spectral imaging by capturing spatial and spectral information in a single frame (Bearman et al., 2007). There are no moving parts or narrow-band filters, and nearly all collected light is passed to the detector at all times. A CTIS captures a scene’s spatial and spectral information by imaging the scene through a two-dimensional grating disperser as in Fig. 14.16. This produces multiple, spectrally dispersed images of the scene that are recorded by a focal plane array (FPA) detector. From the captured intensity pattern, CT algorithms can be used to reconstruct the scene into a cube of spatial (x and y) and spectral (wavelength) information.

Operation of the CTIS is illustrated in Fig. 14.16. With this technique, diffractive optics disperses the spectral and spatial information of each pixel onto an imaging

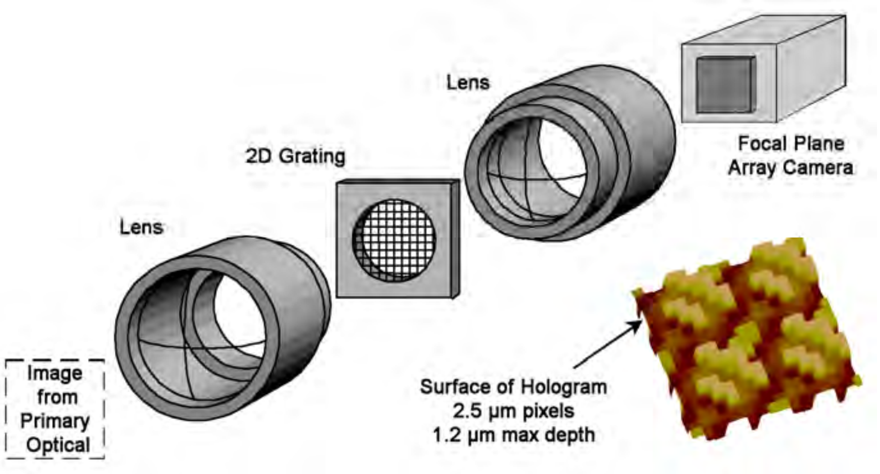
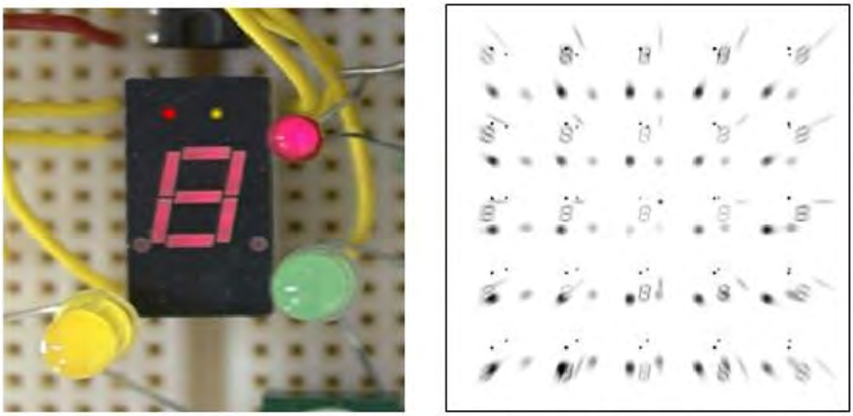


Fig. 14.16 Operation of the computed tomography imaging spectrometer (CTIS).

sensor; an image cube in wavelength space is reconstructed from a *single* image. Note that the CTIS uses just two lenses and a focal plane detector.

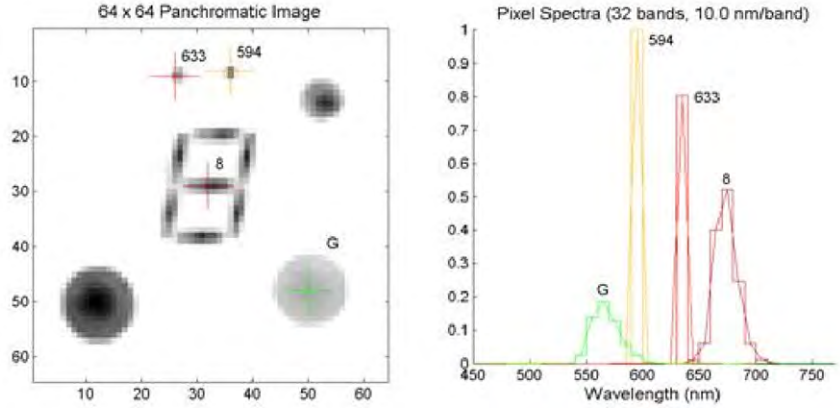
The mathematics of the reconstruction is the same as tomographic imaging. It is important to note that each image is not simply composed of single wavelengths; spatial and spectral information from each object pixel is multiplexed over the entire array – Figure 14.17 shows how the spectrum of a single pixel is distributed by the diffractive disperser. A single image contains all the information required to reconstruct the spectral image cube. A CTIS can operate over a large wavelength range, easily from 400 to 800 nm, and with the proper detector can operate in the IR or UV. The data from a single image can be reconstructed in a variety of ways to adjust image size and wavelength bands. It is also possible to reconstruct the image over a narrow spectral range and place the sampled wavelengths at desired locations.

A CTIS device is ideal for a Tumbleweed platform. The snapshot nature of the device means that object or platform motion is not an issue and that one can obtain spectral scenes from a randomly moving and rotating platform. Camera sensors can trigger the CTIS when appropriately pointed, either down at the contact point or sideways at terrain (not up at sky). For example, a CTIS is being used now for retinal spectral imaging, acquiring a complete image cube in the eye in 3 ms (Johnson et al., 2007). The CTIS easily handles eye saccades and other patient motions. Since the CTIS only requirement is the delivery of an image to an aperture plane that defines the viewed image, the CTIS could even be fiber fed so it does not have to be located on the periphery of the Tumbleweed. Location away from the edge would reduce shock and vibration requirements on the instrument.



(a) Experimental Scene

(b) Intensity on Focal Plane Array (Image taken in dark ambient)



(c) 64 x 64 Panchromatic image

(d) Reconstructed spectra-32 bands @ 10 nm/band

Fig. 14.17 Computed Tomographic Imaging Spectrometer (CTIS). The observed scene is in 2a, consisting of 3-color LEDs, a HeNe laser spot and an 8-segment indicator. 2b shows the resulting image from the monochrome focal plane. There is a zero order image, 2c, which can be used for focusing as well as providing an initial starting point for the reconstruction of the image cube. Recovered spectra are shown in 2d.

14.6 Conclusions

A variety of wind-driven Tumbleweed concepts have been proposed, studied and tested in extreme terrestrial environments as potential scouts for various mission scenarios on Mars. Multiple Tumbleweed rovers could be outfitted to autonomously survey large areas of Mars for *in situ* resources at relatively low cost. Similar missions could also be configured for performing basic science. Communications and navigation would be dependent upon the assets in orbit about Mars at the time of deployment.

Tumbleweed rovers could also be networked together to provide additional communication and navigational support. Since the Tumbleweed rovers are significantly lower mass and compactable than traditional wheeled robotic rovers, many more of the Tumbleweeds can be deployed on the Mars surface during a single mission. A group of Tumbleweed rovers could survey a particular region of Mars with each Tumbleweed having a unique sensor or long-range communications capabilities. When something interesting is detected by a particular Tumbleweed, it would communicate its findings to the others, activating a swarm intelligence-based algorithm that would direct the others to proceed to the same general area and conduct additional sensing with their unique instruments. Such networking and swarming behavior is currently being studied for robotic systems by several groups (Bae et al., 2005a, b; Baxter et al., 2006; Clark et al., 2003; Hashimoto et al., 2008). An added benefit of a swarm of multiple Tumbleweeds is that a stuck rover would be to act as a fixed facility to gather temporal data while other Tumbleweeds proceed.

Low-mass, highly mobile autonomous vehicles capable of making survey measurements will fill the current void between orbital reconnaissance and landed rovers with limited range. Thus, Tumbleweeds are an attractive option for performing surveys of potential *in situ* resources available on Mars.

References

Antol, J.: A New Vehicle for Planetary Surface Exploration: The Mars Tumbleweed. In: 1st Space Exploration Conference: Continuing the Voyage of Discovery, Orlando, Florida, AIAA-2005-2520 (2005)

Antol, J., Calhoun, P., Flick, J., Hajos, G.A., Kolacinski, R., Minton, D., Owens, R., Parker, J.: Low Cost Mars Surface Exploration: The Mars Tumbleweed, August 2003, NASA/TM-2003-212411 (2003)

Antol, J., Calhoun, P.C., Flick, J.J., Hajos, G.A., Keyes, J.P., Stillwagen, F.H., Krizan, S.A., Strickland, C.V., Owens, R., Wisniewski, M.: Mars Tumblweed: FY 2003 Conceptual Design Assessment. NASA Langley Research Center (2005)

Antol, J., Chattin, R.L., Copeland, B.M., Krizan, S.A.: The NASA Langley Mars Tumbleweed Rover Prototype. In: 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 9-12, AIAA-2006-0064 (2006a)

Antol, J., Harris, S.B., Hajos, G.A., Strickland, C.V.: Wind Tunnel Tests of Evolved Mars Tumbleweed Concepts. In: 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 9-12, AIAA-2006-0069 (2006b)

Apostolopoulous, D., Wagner, M.D., Heys, S., Teza, J.: Results of the Inflatable Robotic Rover Testbed. Carnegie Mellon University (2003)

Bae, J., Lee, S.: IEEE, Active sensing based mobile robot exploration. Monterey, CA, Jul 24-28, pp. 934–939 (2005a)

Bae, J., Lee, S.: IEEE, Exploration algorithm for multiple robots. Seattle, WA, Jul 17-20, pp. 895–900 (2005b)

Baker, V.R., Gulick, V.C., Kargel, J.S.: Water Resources and Hydrogeology of Mars. In: Lewis, J.S., Matthews, M.S., Guerrieri, M.L. (eds.) Resources of Near-Earth Space, pp. 765–797. The University of Arizona Press, Tucson (1993)

Baxter, J.L., Burke, E.K., Garibaldi, J.M., Norman, M.: Multi-robot search and rescue: A potential field based approach, Dec. 11-14, 2006, pp. 9–16. Palmerston, New Zealand (2006)

Bearman, G.H., Johnson, W.R., Fink, W., Wilson, D.W.: An Intelligently Reconfigurable Snapshot Imaging Spectrometer for Planetary Exploration. In: 38th Lunar and Planetary Science Conference, Houston, Texas, Abstract #1103 (2007)

Behar, A., Carsey, F., Matthews, J., Jones, J.: NASA/JPL Tumbleweed Polar Rover. In: IEEE Aerospace Conference, Big Sky, Montana, p. 1003 (2004)

Bibring, J.P., Langevin, Y., Mustard, J.F., Poulet, F., Arvidson, R., Gendrin, A., Gondet, B., Mangold, N., Pinet, P., Forget, F., team O: Global mineralogical and aqueous mars history derived from OMEGA/Mars express data. Science 312, 400–404 (2006)

Blake, D.F., Sarrazin, P., Bish, D.L., Chipera, S.J., Vaniman, D.T., Ming, D., Morris, D., Yen, A.: CHEMIN: A Definitive Mieralogy Instrument on the Mars Science Laboratory (MSL 2009) Rover. In: 7th International Conference on Mars, Pasadena, California, July 9-13 (2007) Abstract #3220

Blamont, J.: Personal Communication, Pasadena (1977)

Bohlke, J.K., Ericksen, G.E., Revesz, K.: Stable isotope evidence for an atmospheric origin of desert nitrate deposits in northern Chile and southern California, USA. Chem. Geol. 136, 135–152 (1997)

Boll, J., van Rijn, R.P.G., Weiler, K.W., Ewen, J.A., Daliparthy, J., Herbert, S.J., Steenhuis, T.S.: Using ground-penetrating radar to detect layers in a sandy field soil. Geoderma 70, 117–132 (1996)

Boynton, W.V., Ming, D.W., Sutter, B., Arvidson, R.E., Hoffman, J., Niles, P.B., Smith, P.: Evidence for Calcium Carbonate at the Phoenix Landing Site. In: 40th Lunar and Planetary Science Conference, Houston, TX (2009) Abstract #2434

Brandt, O., Langley, K., Kohler, J., Hararan, S.E.: Detection of buried ice and sediment layers in permafrost using multi-frequency Ground Penetrating Radar: A case examination on Svalbard. Remote Sensing of Environment 111, 212–227 (2007)

Capizzi, P., Cosentino, P.L.: GPR multi-component data analysis. Near Surface Geophysics 6, 87–95 (2008)

Carsey, F., Boston, P.J., Rothschild, L.J., Coleman, M., Jones, J.A., Behar, A.E., Antol, J., Hajos, G.A., Rudisill, M., Parker, J.R., Kelliher, W.C., Carlberg, I.A.: Tumbleweed: Wind Driven Sampling on the Surface of Mars. International Journal of Astrobiology, 85–86 (2004)

Clark, C.M., Rock, S.M., Latombe, J.C.: Motion planning for multiple mobile robots using dynamic networks. In: Proceedings of 2003 IEEE International Conference on Robotics and Automation, vol. 1-3, pp. 4222–4227 (2003)

Cobos, D., Campbell, G., Campbell, C.: Thermal and Electrical Conductivity Probe (TECP) for Phoenix 2007 Scout. Geophysical Research Abstracts 6 (2004)

Conyers, L.B., Goodman, D.: Ground Penetrating Radar: A Primer for the Archaeologist. AltaMira Press (1997)

Doolittle, J.A.: Characterizing soil map units with the ground-penetrating radar. Soil Survey Horizons 23, 3–10 (1982)

Duke, S.K.: Calibration of ground penetrating radar and calculation of attenuation and dielectric permittivity versus depth. Dept of Geophysics. Colorado School of Mines, Golden, Colorado, 236 (1990)

Elam, W.T., Kelliher, W.C., Carlberg, I.A.: A New X-ray Fluorescence Spectrometer for Planetary Exploration. In: 39th Lunar and Planetary Science Conference, Houston, TX, Abstract #1824 (2008)

Ericksen, G.E.: Geology and origin of the Chilean nitrate deposits. U.S. Geological Survey Professional Paper P 1188 (1981)

Ericksen, G.E.: The Chilean Nitrate Deposits. Am Scientist 71, 366–374 (1983)

Ezersky, M., Bruner, I., Keydar, S., Trachtman, P., Rybakov, M.: Integrated study of the sinkhole development site on the Western shores of the Dead Sea using geophysical methods. Near Surface Geophysics 4, 335–343 (2006)

Feldman, W.C., Mellon, M.T., Gasnault, O., Maurice, S., Prettyman, T.H.: Volatiles on Mars: Scientific Results from the Mars Odyssey Neutron Spectrometer. In: Bell, J.F. (ed.) The Martian Surface, vol. 9, p. 636. Cambridge University Press, Cambridge (2008)

Flick, J.J., Toniolo, M.D.: Preliminary Dynamic Feasibility and Analysis of a Spherical, Wind-Driven (Tumbleweed). In: Martian Rover 43rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, AIAA-2005-0250 (2005)

Gendrin, A., Mangold, N., Bibring, J.P., Langevin, Y., Gondet, B., Poulet, F., Bonello, G., Quantin, C., Mustard, J., Arvidson, R., LeMouelic, S.: Suffates in martian layered terrains: the OMEGA/Mars Express view. Science 307, 1587–1591 (2005)

Golombek, M., Rapp, D.: Size-frequency distributions of rocks on Mars and Earth analog sites: Implications for future landed missions. J. Geophys. Res-Planets 102, 4117–4129 (1997)

Grant, J.A., Schutz, A.E., Campbell, B.A.: Ground-penetrating radar as a tool for probing the shallow subsurface of Mars. J. Geophys Res-Planets 108 (2003); art. no.-8024

Haberle, R.M., Hollingsworth, J.L., Colaprete, A., Bridger, A.F.C., Mckay, C.P., Murphy, J.R., Schaeffer, J., Freedman, R.: The NASA /Ames Mars General Circulation Model: Model Improvements and Comparison with Observations. In: Mars Atmosphere Modelling and Observations, Granada, Spain, January 13-15 (2003)

Hanrahan, H., Minton, D., DeJarnette, F., Camelier, M.: Mars Tumbleweed: A New Way to Explore Mars. In: Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science Workshop, Lisbon, Portugal, October 6-9 (2003)

Hashimoto, H., Aso, S., Yokota, S., Sasaki, A., Ohyama, Y., Kobayashi, H.: Stability of Swarm Robot Based on Local Forces of Local Swarms, Chofu, JAPAN, Aug 20-22, pp. 1201–1204. IEEE, Los Alamitos (2008)

Hecht, M.H., Kounaves, S.P., Quinn, R.C., West, S.J., Young, S.M., Clark, B.C., DeFlores, L.P., Kapit, J.A., Gospodinova, K., Smith, P.H.: Discovery of Perchlorate at the Phoenix Landing Site. Eos Transactions AGU 89 (Fall Meeting Suppl.) (2008) Abstract U14A-04

Hoeg, T., Southard, L., Boxerbaum, A., Reis, L., Antol, J., Heldmann, J., Quinn, R.: Tumbleweed Rover Science Mission to Dao Vallis. In: 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 9-12 (2006) AIAA-2006-0070

Huffman III, A.C.: Characterization of three-dimensional geological heterogeneities using ground penetrating radar. Department of Geophysics. Colorado School of Mines, Golden, Colorado, 189 (1992)

Jakosky, B.M., Zent, A.P.: Water on Mars: Its History and Availability as a Resource. In: Lewis, J.S., Matthews, M.S., Guerrieri, M.L. (eds.) Resources of Near-Earth Space, pp. 737–763. The University of Arizona Press, Tucson (1993)

Janes, D.M.: The Mars Ball: A Prototype Martian Rover. The Case for Mars III, Part II 75, 569–574 (1989)

Johnson, W.R., Wilson, D.W., Fink, W., Humayun, M., Bearman, G.: Snapshot hyperspectral imaging in ophthalmology. Journal of Biomedical Optics 12 (2007)

Jones, J., Yavrouian, A.: JPL New Technology Report (1997)

Jones, J.A.: Inflatable Robotics for Planetary Applications. In: 6th International Symposium on Artificial Intelligence, Robotics and Automation in Space, I-SAIRAS, Montreal, Canada (2001)

Jones, J.A.: Personal Communication, JPL, Pasadena, CA (2009)

Jones, J.A., Saunders, S., Blamont, J., Yavrouian, A.: Balloons for controlled roving/landing on Mars. Acta Astronaut 45, 293–300 (1999)

Justus, C.G., Duvall, A., Keller, V.W.: Validation of Mars Global Reference Atmospheric Model (Mars-GRAM 2001) and planned new features. Middle and Upper Atmospheres, Active Experiments, and Dusty Plasmas 38, 2633–2638 (2006)

Kathage, A., Niessen, J., White, G., Bell, N.: Fast Inspection of Railway Ballast By Means of Impulse GPR Equipped with Horn Antennas. In: Railway Engineering 2005, Edinburgh, Scotland, June 29-30, 2005, vol. 10(9) (2005), http://www.ndt.net/article/v10n09/kathage/kathage.htm

Kizito, F., Campbell, C.S., Campbell, G.S., Cobos, D.R., Teare, B.L., Carter, B., Hopmans, J.W.: Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor. Journal of Hydrology 352, 367–378 (2008)

Kolecki, J.C., Landis, G.: Electrostatic Charging of the Mars Pathfinder Rover and Electrical Charge Phenomena on Mars. In: 37th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada (1999) AIAA-99-0377

Kolecki, J.C., Landis, G.P.: Electrical Discharge on The Martian Surface. NASA Lewis Research Center, Cleveland, Ohio (1996)

Kounaves, S.P., Catling, D., Clark, B.C., DeFlores, L.P., Gospodinova, K., Hecht, M.H., Kapit, J.A., Ming, D.W., Quinn, R.C.: Aqueous Carbonate Chemistry of the Martian Soil at the Phoenix Landing Site. In: 40th Lunar and Planetary Science Conference, Houston, TX, Abstract #2489 (2009)

Krasnopolsky, V.A., Maillard, J.P., Owen, T.C.: Detection of methane in the martian atmosphere: evidence for life? Icarus 172, 537–547 (2004)

Kung, K.J.S., Lu, Z.B.: Using Ground-Penetrating Radar To Detect Layers Of Discontinuous Dielectric-Constant. Soil Science Society of America Journal 57, 335–340 (1993)

Lambot, S., Rhebergen, J., van den Bosch, I., Slob, E.C., Vanclooster, M.: Measuring the soil water content profile of a sandy soil with an off-ground monostatic ground penetrating radar. Vadose Zone Journal 3, 1063–1071 (2004)

Langevin, Y., Poulet, F., Bibring, J.P., Gondet, B.: Sulfates in the north polar region of Mars detected by OMEGA/Mars express. Science 307, 1584–1586 (2005)

Lindsley, D.H. (ed.): Oxide minerals: petrologic and magnetic significance. Minerological Society of America (1991)

Livingston, G.P., Hutchinson, G.L.: Enclosure-based measurement of trace gas exchange: applications and sources of error. In: Biogenic Trace Gases: Measuring Emissions from Soil and Water, Oxford, Great Britain, pp. 14–51 (1995)

Marshall, J., Koppel, L., Bratton, C., Metzger, E., Hecht, M.: In: Situ Identification of Mineral Resources with an X-ray Optical "Hand-Lens" Instrument. ISRU II Technical Interchange Meeting, Houston, TX, November 18-19, Abstract Number 9028 (1997) http://www.lpi.usra.edu/meetings/ISRU-II-97/ISRU-II-97.3rd.html

Martin, J.P., Marshall, J.R., Mason, L.W., Scheld, D.: In-Situ Geologic Analyzer for Lunar and Martian Surfaces. In: Earth & Space 2008: Engineering, Science, Construction, and Operations in Challenging Environments, Long Beach, California, March 3-5 (2008) doi:10.1061/40988(323)100

McKay, C.P., Meyer, T.R., Boston, P.J., Nelson, M., MacCallum, T., Gwynne, O.: Water Resources and Hydrogeology of Mars. In: Lewis, J.S., Matthews, M.S., Guerrieri, M.L. (eds.) Resources of Near-Earth Space, pp. 819–843. The University of Arizona Press, Tucson (1993)

Moore, L.J., Jol, H.M., Kruse, S., Vanderburgh, S., Kaminsky, G.M.: Annual layers revealed by GPR in the subsurface of a prograding coastal barrier, southwest Washington, USA. Journal of Sedimentary Research 74, 690–696 (2004)

Mumma, M.J., Villanueva, G.L., Novak, R.E., Hewagama, T., Bonev, B.P., DiSanti, M.A., Mandell, A.M., Smith, M.D.: Strong Release of Methane on Mars in Northern Summer 2003. Science 323, 1041–1045 (2009)

Mustard, J.F., Murchie, S.L., Pelkey, S.M., Ehlmann, B.L., Milliken, R.E., Grant, J.A., Bibring, J.P., Poulet, F., Bishop, J., Dobrea, E.N., Roach, L., Seelos, F., Arvidson, R.E., Wiseman, S., Green, R., Hash, C., Humm, D., Malaret, E., McGovern, J.A., Seelos, K., Clancy, T., Clark, R., Des Marais, D., Izenberg, N., Knudson, A., Langevin, Y., Martin, T., McGuire, P., Morris, R., Robinson, M., Roush, T., Smith, M., Swayze, G., Taylor, H., Titus, T., Wolff, M.: Hydrated silicate minerals on mars observed by the Mars reconnaissance orbiter CRISM instrument. Nature 454, 305–309 (2008)

Nettwork, Underground mapping, pipeline location technology, and condition assessment. Univ. Birmingham Infrastructure Engineering & Management Research Centre, Civil Engineering, School of Engineering, Edgbaston, Birmingham, UK (2002)

Olhoeft, G.R.: The electrical properties of permafrost. Department of Physics. University of Toronto, Toronto, Canada. 172 (1975)

Olhoeft, G.R.: Effects of water on the electrical properties of planetary regoliths. In: Colloquium on Water in Planetary Regoliths, Hanover, NH, Dartmouth College, pp. 139–142 (1976)

Olhoeft, G.R.: Electrical properties of natural clay permafrost. Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre 14, 16–24 (1977)

Olhoeft, G.R.: Impulse radar studies of near surface geological structure. In: Lunar and Planetary Science Conference X, Houston, Texas, pp. 943–945 (1979)

Olhoeft, G.R.: Direct detection of hydrocarbon and organic chemicals with ground penetrating radar and complex resistivity. In: NWWA/API Conference on Petroleum Hydrocarbons and organic chemicals in ground water – prevention, detection and restoration, Dublin, OH, November 12-14, 1986, pp. 284–305 (1986)

Olhoeft, G.R.: Magnetic and electrical properties of martian particles. In: Sand and Dust on Mars, NASA Conf. Publ. 10074, Greenbelt, Maryland, pp. 44–46 (1991)

Olhoeft, G.R.: Ground penetrating radar on Mars. In: Proc. of GPR 1998, 7th Int'l. Conf. On Ground Penetrating Radar, May 27-30, 1998, pp. 387–392. The Univ. of Kansas, Lawrence, KS, USA (1998)

Olhoeft, G.R.: Maximizing the information return from ground penetrating radar. Journal Of Applied Geophysics 43, 175–187 (2000)

Palli, A., Kohler, J.C., Isaksson, E., Moore, J.C., Pinglot, J.F., Pohjola, V.A., Samuelsson, H.: Spatial and temporal variability of snow accumulation using ground-penetrating radar and ice cores on a Svalbard glacier. J. Glaciol. 48, 417–424 (2002)

Physical Sciences Incorporation, PSI: Products, vol. 2009 (2009)

Poulet, F., Bibring, J.P., Mustard, J.F., Gendrin, A., Mangold, N., Langevin, Y., Arvidson, R.E., Gondet, B., Gomez, C., Omega, T.: Phyllosilicates on Mars and implications for early martian climate. Nature 438, 623–627 (2005)

Rose, S.E., Moody, C.B., James, D.L., Barhorst, A.A.: Drag measurement and dynamic simulation of Martian wind-driven sensor platform concepts. Journal of Fluids and Structures 22, 21–43 (2006)

Schaber, G.G., McCauley, J.F., Breed, C.S., Olhoeft, G.R.: Shuttle imaging radar: physical controls on signal penetration and subsurface scattering in the eastern Sahara. Institute of Electrical and Electronic Engineers Trans Geoscience and Remote Sensing GE-24, 603–623 (1986)

Schenk, C.J., Gautier, D.L., Olhoeft, G.R., Lucius, J.E.: Internal structure of an aeolian dune using ground penetrating radar. In: Lancaster, N., Rye, K. (eds.) Aeolian Sediments: Ancient and Modern, vol. 16, pp. 61–69. Blackwell Publishing, Malden (1993)

Schmitt, H.H.: Potential Resources of Mars (2004)

Stanley, R.J., Ho, D.K.C., Gader, P.D., Wilson, J.N., Devaney, J.B.: Advances in EMI and GPR algorithms in discrimination mode processing for handheld landmine detectors. In: Proceedings of the SPIE, vol. 5415, pp. 874–882 (2004)

Stoker, C.R., Gooding, J.L., Roush, T., Banin, A., Burt, D., Clark, B.C., Flynn, G.J., Gwynne, O.: The Physical and Chemical Properties and Resource Potential of Martian Surface Soils. In: Lewis, J.S., Matthews, M.S., Guerrieri, M.L. (eds.) Resources of Near-Earth Space, pp. 659–707. The University of Arizona Press, Tucson (1993)

Sutter, B., Lauer, H.V., Golden, D.C., Boynton, W.V., Morris, R.V., Niles, P.B., Ming, D.W.: Thermal and Evolved Gas Behavior of Calcite under Mars Phoenix TEGA Operating Conditions. In: 40th Lunar and Planetary Science Conference, Houston, TX (2009) Abstract #1843

Tarsitano, C.G., Webster, C.R.: Multilaser Herriott cell for planetary tunable laser spectrometers. Applied Optics 46, 6923–6935 (2007)

Taylor, G.J.: Human Exploration for Resources on Mars. Science and the Human Exploration of Mars, Greenbelt, Maryland (2001), http://www.lpi.usra.edu/publications/reports/CB-1089/taylor.pdf

Wang, H., Yang, B., Jones, J.: Mobility Analysis of an Inflated Tumbleweed Ball under Wind Loads. In: 3rd AIAA Gossamer Spacecraft Forum, Denver, Colorado, April 22-25, AIAA-2002-1556 (2002)

West, L.J., Truss, S.W.: Borehole time domain reflectometry in layered sandstone: Impact of measurement technique on vadose zone process identification. Journal of Hydrology 319, 143–162 (2006)

Wilson, J.L., Mazzoleni, A.P., DeJarnette, F.R., Antol, J., Hajos, G.A., Strickland, C.V.: Design, analysis, and testing of Mars Tumbleweed rover concepts. Journal of Spacecraft and Rockets 45, 370–382 (2008)

Wright, D.L., Olhoeft, G.R., Grover, T.P.: Velocity, attenuation and dispersion electromagnetic tomography in fractured rock. In: U S Geological Survey Toxic Substances Hydrology Program Review, Colorado Springs, CO, September 20-23, 1993, pp. 111–118 (1996) USGS WRI Report 94-4015

Yang, C.H., Tong, L.T., Yu, C.Y.: Integrating GPR and RIP methods for water surface detection of geological structures. Terrestrial Atmospheric and Oceanic Sciences 17, 391–404 (2006)