A brief review of Spirit's six years of Mars roving and scientific discoveries

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Abstract: Mars rover Spirit landed in Gusev Crater on January 4, 2004. It became a stationary science platform on 26 January 2010 after NASA's efforts to free it from a sand trap had been unsuccessful. During its six years of exploration of the red planet, Spirit traveled 7.73 km and made significant discoveries, *e.g.* detection of deposits of salts and minerals such as sulfur and opaline silica that only form in the presence of water. This paper presents a brief review of Spirit's six years of Mars roving and major scientific discoveries. In particular, it demonstrates how planetary mapping and remote sensing technologies have been greatly supporting the mission to achieve its science and engineering goals.

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1 INTRODUCTION

Spirit, the first of the two rovers of NASA's Mars Exploration Rover (MER) mission, was launched on 10 June 2003 from Cape Canaveral Air Force Station, Florida, and landed in Gusev Crater on 4 January 2004 UTC. The rover functions as a robot field geologist reading the record that is contained in the rocks and soils at its landing site. The primary scientific objective of the MER mission is to explore the two landing sites on the Martian surface where water may once have been present, and to assess past environmental conditions at those sites and their suitability for life (Squyres, *et al*., 2004). The complete scientific objectives of the mission can be found from NASA's official website (NASA, 2007). The landing site selected for Spirit is Gusev Crater, a flat-floored crater with a diameter of 160 km. The southern rim of Gusev is breached by Ma'adin Vallies, a large branching valley that was likely cut by running water. Thus, exploration of the landing site was anticipated to provide opportunities to study fluvial sediments derived from the southern highlands and deposited in a lacustrine environment (Golombek, *et al*., 2003).

While its nominal mission was designed for 90 sols (a sol is a Martian day, which is 24 h 39 m 35.244 s), the rover functioned effectively over twenty times longer. On 1 May 2009 (sol 1893), Spirit became stuck in soft soil at a location called "Troy". After efforts during the past several months to free it from the sand trap had been unsuccessful, NASA designated the rover a stationary science platform on 26 January 2010. By then, Spirit returned 127000 raw images and 16 color, 360-degree panoramic mosaics (NASA, 2010). The traverse length of the mission was originally planned for 600 m to 1 km. Spirit actually traveled 7.73 km (odometer reading), seven to twelve times longer than the planned traverse. Though Spirit won't be roving Mars anymore, it will continue conducting scientific explorations at its final resting place. For example, by tracking the radio signal from the rover long enough, scientists can get clues about the internal structure of Mars, *i.e.*, to distinguish whether its core is liquid or solid.

The following sections present a brief review of Spirit's six years of Mars roving and major scientific discoveries. In particular, the paper demonstrates how planetary mapping and remote sensing technologies have been greatly supporting the mission to achieve its science and engineering goals.

It should be noted that the current affiliated institutes of the authors are not part of the MER operations. This review is based on the relevant publications of the MER mission and some previous work of the first author performed at the Mapping and GIS Laboratory of The Ohio State University before 2008.

2 INSTRUMENTS AND MISSION OPERATION APPROACH

2.1 Scientific and engineering instruments

Spirit carries an integrated suite of scientific instruments and

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First author biography: DI Kaichang (1967—), male, Ph.D., professor and doctoral advisor. His current research interests include planetary mapping and remote sensing, rover navigation and localization. E-mail: kcdi@irsa.ac.cn tools called the Athena science payload. The payload includes a mast-mounted remote sensing package, an Instrument Deployment Device (IDD)-mounted in-situ package and magnets (see Fig. 1). The remote sensing package consists of the Panoramic Camera (Pancam) and the Miniature Thermal Emission Spectrometer (Mini-TES), both supported by the Pancam Mast Assembly (PMA) (Squyres, *et al*., 2003). Pancam is a high-resolution color stereo pair of CCD cameras used for scientific investigation of the morphology, topography, geology, *etc*., of the landing site. Each of its cameras (left and right) has eight multispectral channels with a 400-1100 nm wavelength range (Bell, *et al*., 2003). Both cameras have an imaging area of 1024 by 1024 pixels and the field of view (FOV) of 16.8 degrees. Pancam has a stereo base of 30 cm, a focal length of 43 mm and effective depth of field (DOF) of 3 m to infinity. Mini-TES is an infrared spectrometer that can determine the mineralogy of rocks and soils from a distance by detecting their patterns of thermal radiation (Squyres, *et al*., 2003). Mini-TES is housed in the body of the rover at the bottom of the PMA, which then acts as a periscope for it. It produces high spectral resolution (10 cm^{-1}) image cubes with a wavelength range of 5—29 μm, and angular resolution modes of 20 and 8 mrad.

Once potential science targets are identified using Pancam and Mini-TES, they will be investigated in more detail using the in-situ instruments. The IDD-mounted in-situ instruments include an Alpha Particle-X-Ray Spectrometer (APXS), a Mössbauer Spectrometer (MB), a Microscopic Imager (MI) and a Rock Abrasion Tool (RAT) (see Fig. 1) (Squyres, *et al*., 2003). The APXS determines the elemental abundances of rocks and soils by exposing Martian materials to energetic alpha particles and X-rays from a radioactive ^{244}Cm source and then measuring the energy spectra of backscattered alphas and emitted X-rays. The MB is used to determine the mineralogy and oxidation state of Fe-bearing phases. It measures the resonant absorption of gamma rays produced by a ^{57}Co source to determine splitting of nuclear energy levels in ^{57}Fe atoms. The MI uses the same CCD detectors and electronics as Pancam and can obtain high resolution (30 μm/pixel) images of rock and soil surfaces. The RAT can remove 5 mm of dusty and weathered surface of a rock over a circular area 45 mm in diameter so that the exposed fresh material can be investigated in detail using the in-situ instruments.

Along with Pancam and MI, each MER vehicle includes six engineering cameras (see Fig. 1), all of which share the same electronics design and spacecraft interfaces as the Athena science cameras (Maki, *et al*., 2003). The Navigation Camera (Navcam) is a mast-mounted stereo pair each with a 45 degree FOV and a spectral bandpass of 580—770 nm. Navcam has a stereo base of 20 cm, a focal length of 14.67 mm, and an effective DOF of 0.5 m to infinity. It is primarily used for navigation purposes and general site characterization, capable of providing 360° panoramic image mosaics and targeted images of interest. The Hazard-avoidance Cameras (Hazcams) are mounted in stereo pairs, one pair on the front end of the rovers' warm electronics box (WEB) below the solar panel, and one pair on the rear end of the WEB below the solar panel. Each Hazcam assembly includes two cameras with a 124 degree FOV and 580—770 nm spectral bandpass. Hazcam has a stereo base of 10 cm, a focal length of 5.58 mm, and a DOF of 0.1 m to infinity. The Hazcam are used for onboard hazard detection and for selecting near field target and IDD operations.

Before launching, all of the Athena science instruments had undergone extensive calibration, both individually and using a set of geologic reference materials that were measured with all the instruments (Squyres, *et al*., 2003; Bell, *et al*., 2003). All of the MER engineering cameras had also been calibrated over the flight range of temperatures (Maki, *et al*., 2003). After landing, in-flight calibrations have been performed for the science instruments, for

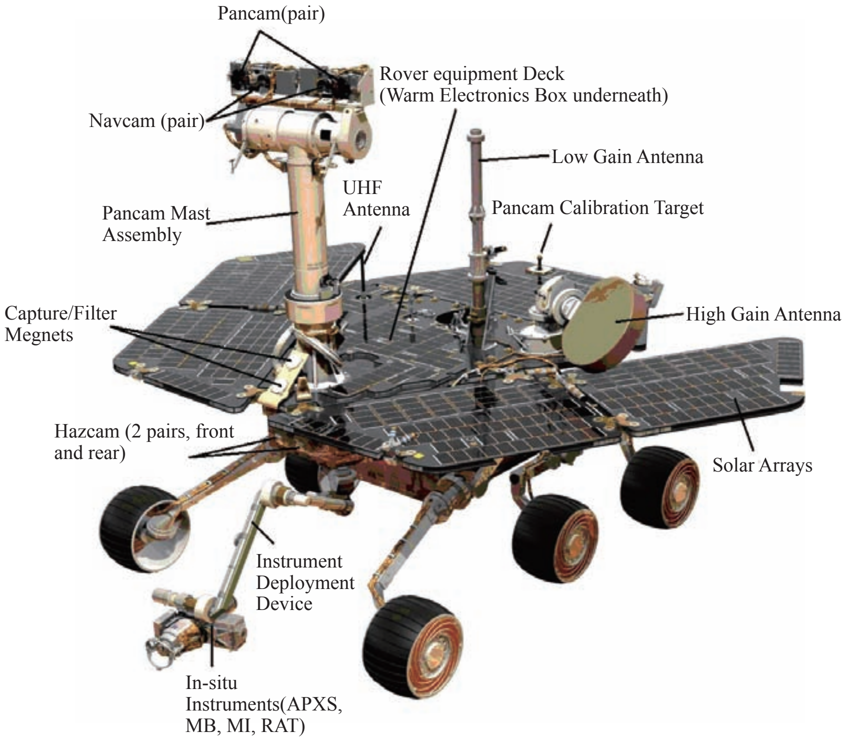

Fig. 1 Spirit rover with scientific and engineering payload (Di and Li, 2007)

example, Pancam has been regularly calibrated using refined preflight-derived calibration coefficients, or radiance factor using near-in-time measurements of the Pancam calibration target and a model of aeolian dust deposition on the target as a function of time (Bell, *et al*., 2006).

2.2 Mission operation approach

The approach for operating both Spirit and Opportunity was based on translating science objectives into specific tasks for the rovers to implement, usually with a cycle of a sol. There are five basic sol types (Squyres, *et al*., 2003; Arvidson, *et al*., 2006) (1) Panorama sol: acquire Pancam or Mini-TES panoramic data for remote sensing of the surface around the rover, which are needed to establish geologic context and to select candidate targets; (2) Drive sol: move tens of meters in the direction of the selected target or area of interest; (3) Approach sol: move close enough to a target that it can be investigated on the next sol with the IDD-mounted in-situ instruments; (4) Spectroscopy sol: deploy the IDD and perform detailed in-situ analyses on a rock or soil target; and (5) ‘‘Scratch and Sniff’’ sol: use the RAT to expose a rock target surface and perform some in-situ analyses on it.

Mission operation planning for a given sol started as soon as the previous sol's data were transmitted to Earth and analyzed. The Spirit Science Operations Working Group (SOWG) considered results from the initial data analysis results and implications of the new findings on both long term strategies and near term objectives (Arvidson, *et al*., 2006). Then, SOWG and the rover mobility team (for traversing and deployment of the IDD) worked cooperatively to develop task sequences that fit power, data volume, and time constraints for the upcoming sol. Finally, the sequences were up-loaded to the rover for execution. This cycle was repeated once each sol.

A typical drive distance within each sol is 20 m to 50 m, occasionally around 100 m. A long drive usually included a blind drive segment and an autonomous navigation segment. The blind drive allowed the rover to drive a distance efficiently to a particular location without hazard avoidance systems activated. The distance for a blind drive was determined offline on Earth by 3D visualization and mapping using Navcam or Pancam stereo images.

3 SIX YEARS OF MARS ROVING

3.1 The rover traverse

Spirit touched down in Gusev Crater about 12 km east of the center of a predefined landing ellipse. The lander location was determined using two-way Doppler radio positioning technology in the inertial reference system and transformed to the Mars Body Fixed frame as (14.571892°S, 175.47848°E). The lander was also localized as (14.5692°S, 175.4729°E) using cartographic triangulation technique through landmarks visible in both orbital and ground images (Li, *et al*., 2005; Li, *et al*., 2006). Comparing with the cartographic location, the inertial location was displaced to the southeast by 370 m at an azimuth of 116° (Li, *et al*., 2006). This systematic offset is consistent with the map tie errors between inertial derived coordinate systems and those derived from imagebased coverage of the planet (Arvidson, *et al*., 2004).

As shown in the first Pancam panorama (Fig. 2), the landing site, which was named Columbia Memorial Station (CMS), lies in a region of dusty, soil-covered, rock-strewn cratered plains. From this panorama, we can also observe remote mountain peaks, which were used in cartographic triangulation of the lander location. Fig. 3 shows the Spirit rover traverse map from Sol 1 at the landing center to Sol 1457 at Winter Haven on Home Plate plateau.

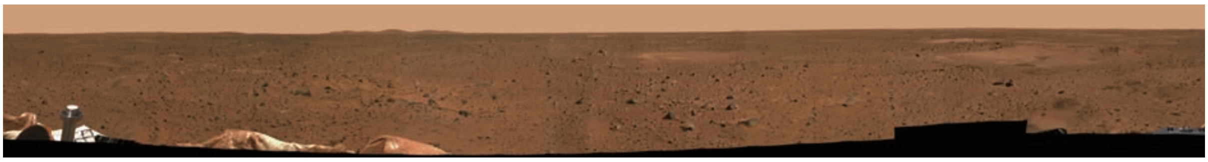

Fig. 2 A mosaic of the first 360 degree Pancam panorama (Image credit: NASA/JPL/Cornell)

Spirit egressed from the lander on Sol 12. Detailed remote sensing and in situ measurements of the rocks Adirondack and Humphrey were performed starting on Sol 15 and Sol 51 respectively, revealing that the rocks were derived from olivine-bearing basaltic rocks (Arvidson, *et al*., 2006). Spirit was then commanded to traverse onto the ejecta deposits of the Bonneville Crater (about 210 m in diameter), hoping to find evidence for preplains aqueous processes by searching for material excavated by the Bonneville event from beneath the basaltic plains rocks. In situ investigation of the Bonneville rim region and remote sensing of the crater floor showed only basaltic rocks similar to those previously found on the plains.

The next phase of the mission was the long drive across the plains to the Columbia Hills, which are clearly embayed by the basaltic plains materials and thus are older than the materials at the landing site. During the traverse to the Columbia Hills, Spirit conducted remote sensing observations for Missoula and Lahontan craters and associated ejecta deposits. The rover reached the West Spur of the Columbia Hills on Sol 157 and the subsequent remote sensing and in situ investigations revealed that Hills rocks have been extensively modified by aqueous processes (Arvidson, *et al*., 2006). Spirit ascended to the summit of Husband Hill on Sol 580 and began a remote sensing campaign of the surrounding terrains from its high vantage point, including looking into the Inner Basin for safe paths to descend to Home Plate. Along the path, a number of rocks, outcrops and deposits were examined in detail.

The next phase of the mission was the descent into the Inner Basin and the drive to Home Plate. Along the path, the rover traversed to the edge of the dark ripple field and conducted remote sensing and in situ measurements of these materials. Fig. 4 shows the detailed rover traverse map at Home Plate and the last position (Sol 1893) at “Troy”. Spirit reached Home Plate on Sol 746. After detailed measurements of some outcrops and a float rock, the rover drove east south through the valley between the eastern edge of Home Plate and the western side of Mitcheltree Ridge. Due to the

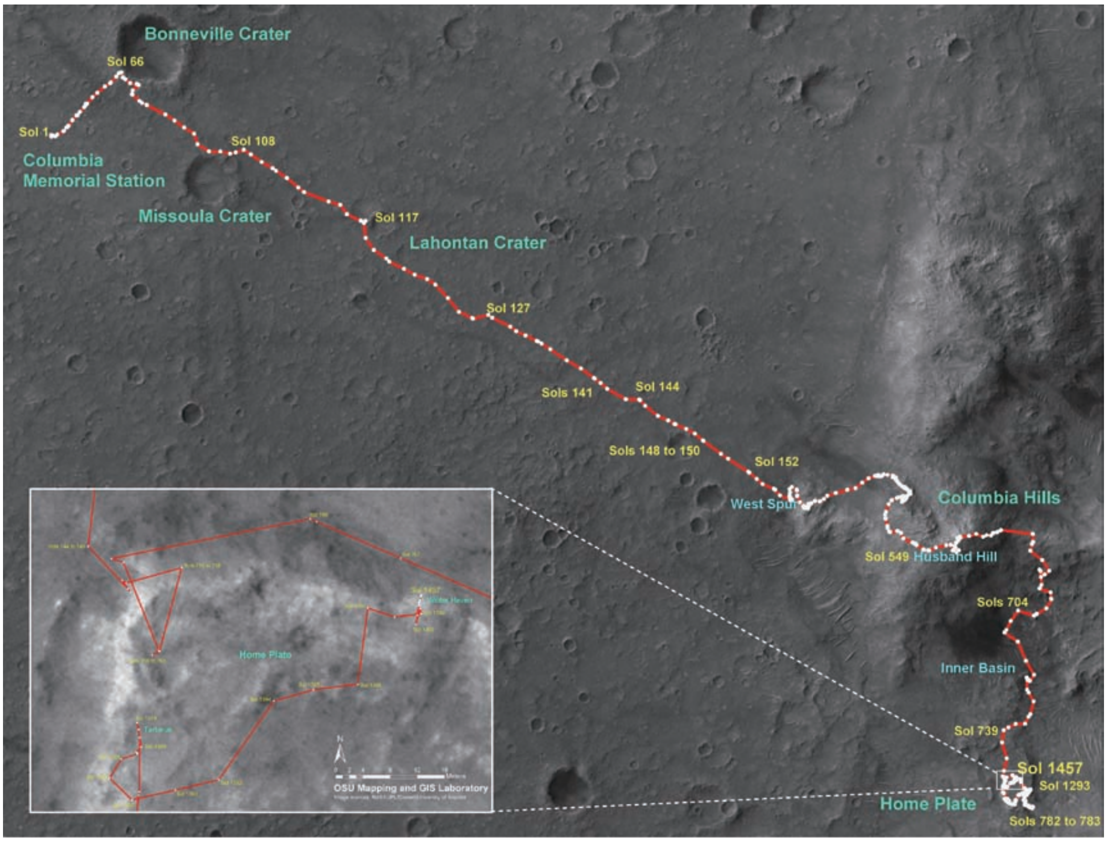

Fig. 3 Spirit traverse map (Sol 1457) (Image credit: NASA/JPL/Cornell/MSSS/OSU)

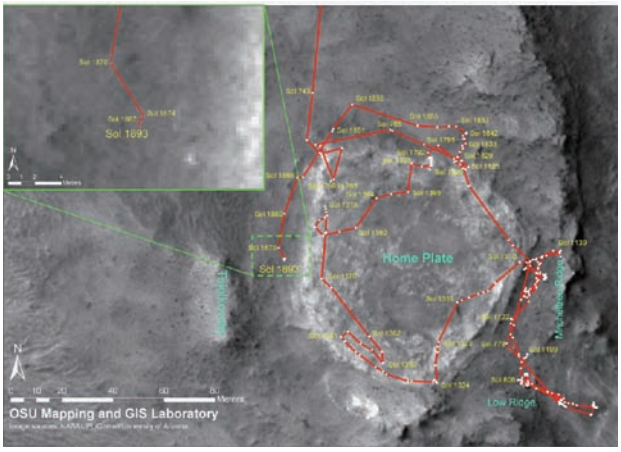

Fig. 4 Spirit traverse map (Sol 1893) (Image credit: NASA/JPL/Cornell/University of Arizona/OSU)

fact that Spirit was located at about 15° S, the rover needed to park on north-facing slopes for the solar panels to get enough sunshine in order to survive the local winter. The intent was to drive to the northern slopes of McCool Hill (over 400 m to the southeast of Home Plate) to find locations for the rover to spend its second Mars winter. However, after the front right wheel drive motor had failed, traversing to McCool Hill became very difficult. Thus, the vehicle was commanded to drive to the northeast slope of Low Ridge, which also provided sufficient north-facing tilt for the rover to survive the winter season.

Spirit spent sols 805 to 1037 at the Low Ridge site during its winter campaign phase. Next Spirit was directed to drive back north to perform remote sensing and in situ work on the finely layered outcrops on the western side of Mitcheltree Ridge and to the east of Home Plate. After detailed remote sensing and in situ measurements of the strata exposed on the eastern flank of Home Plate on sols 1205 to 1220, an outcrop identified as silica-rich from Mini-TES observations was then examined. Then, after an approximately 60 sol period waiting out the low solar energy conditions associated with a southern hemisphere dust storm, Spirit was commanded to approach and ascend onto Home Plate and obtain measurements designed to characterize the rocks on the top of Home Plate and rocks on the South Promontory. After an evaluation of the possibility and risk for a traverse to Von Braun hill (about 120 m to the south of Home plate), a decision was made to drive to the northern flank of Home Plate to find north-facing slope to survive the third winter season. Spirit reached the site Winter Haven on Sol 1408. After the winter season, Spirit drove down side of Home Plate and drove west then south around Home Plate and performed targeted remote sensing and in situ observations. On Sol 1893 (May 1, 2009) Spirit became stuck in soft soil at “Troy”.

3.2 Rover localization and topographic mapping

Localization of the rover and mapping the landing and traversing areas with high accuracy is of fundamental importance to support science and engineering operations. Rover localization was conducted at several levels with different accuracies (Li , *et al*., 2005, 2006). Within each sol cycle, the onboard dead-reckoning localization (based on IMU and wheel odometry) was regularly performed, supported irregularly by Sun-finding techniques to improve the attitude knowledge (Ali, *et al*., 2005). In areas where the rover experiences slippage caused by traversing loose soil or steep slopes, the onboard visual odometry (VO) technique was applied to reduce position errors accumulated by the dead-reckoning localization (Chen, *et al*., 2006; Maimone, *et al*., 2007). It automatically matches and tracks point features between consecutive stereo images and determines the change in position and attitude. VO was only performed in these difficult areas due to the fact that the onboard VO processing can take two to 3 min per image pair on MER's 20 MHz RAD6000 CPU, which reduces the amount of distance that can be driven each sol when using VO (Cheng , *et al*., 2006). Researchers at The Ohio State University (OSU) performed bundle adjustment (BA)-based rover localization and topographic mapping since the landing of the two rovers in January 2004 (Li, *et al*., 2005, 2006; Di, *et al*., 2008a). Rover traverse maps (see Fig. 3 and 4) were generated wherever the rover stopped and took Navcam or Pancam images. BA was able to correct significant localization errors, *e.g.*, as large as 10.5% at a location along the traverse to the summit of Husband Hill (Di, *et al*., 2008a). BA-based rover localization was performed on Earth. Efforts have been made to integrate VO and BA with the expectation of achieving high efficiency and full automation (Li , *et al*., 2007; Di , *et al*., 2008b).

Once the rover data were transmitted to Earth through the Deep Space Network, the Jet Propulsion Laboratory (JPL) Multi-mission Image Processing Laboratory produced mosaics, linearized (epipolar) images, range maps, and other products within a few hours to support rover navigation and science operations (Alexander, *et al*., 2006). Topographic products, such as DTM, orthophoto, and 3D models, were routinely generated by the OSU team using Pancam and Navcam images along the traverse (Li, *et al*., 2005, 2006; Di, *et al*., 2008a). Special topographic products, such as north-facing slope maps and solar energy maps, were developed to meet the needs of selection of location for the rover to park and survive the Martian winter. Mapping with multi-site panoramas and wide-baseline stereo images based on the bundle adjustment technology were applied and significantly extended the mapping capabilities of single-site panoramas (Di & Li, 2007). High resolution orbital images (*e.g.*, MOC and HiRISE images) had been used for topographic mapping of the Spirit rover landing site (Kirk, *et al*., 2003; Li, *et al*., 2006) and were also as base maps for rover localization during mission operations. The high precision topographic products and rover localization information played significant roles in traverse planning at critical locations, *e.g.*, ascending to the summit of Husband Hill, descending to Inner Basin, driving to Home Plate, and find safe locations for the rover to survive three winter seasons.

4 SCIENTIFIC DISCOVERIES

Previous orbital analyses of Gusev Crater have shown a complex geologic history that includes potential modification by mass wasting, fluvial activity, volcanism, and extensive aeolian (*i.e.*, wind) processes (Golombek, *et al*., 2003). Using Spirit's remote sensing and in situ measurements of rocks and soils, scientists have made numerous new scientific discoveries about the geology, aeolian activity, atmospheric condition and aqueous processes at Gusev Crater (Squyres, *et al*., 2004; Arvidson, *et al*., 2006, 2008; Crumpler, *et al*., 2005; Golombek, *et al*., 2006; Cabrol, *et al*., 2006). This section does not intend to give a complete review of those discoveries. Instead, only some most significant discoveries are introduced below. These discoveries include understanding of the geology, mineralogy, aeolian activity, aqueous activity and atmospheric condition of the landing site. With these discoveries, it has been confirmed that water was long standing on the surface of Mars long ago; this directly contributes to meeting the primary scientific objective of the mission.

Upon entering the West Spur region, the composition of soils and rocks changed dramatically from basaltic plains to heavily degraded rocks. By examining the rocks along the traverse in the Husband Hill region, various evidences of the existence of significant aqueous activity were found, including mineral alterations, salt in the soil in an amount reaching the highest values ever observed on Mars and rocks with significantly elevated sulfur, chlorine, and bromine signatures (Cabrol, *et al*., 2005; Arvidson, *et al*., 2006).

In March 2006, during its drive to McCool Hill, Spirit's wheels unearthed a small patch of light-toned material informally named "Tyrone". Pancam and Mini-TES investigations revealed that the light-toned disturbed soil had a salty chemistry dominated by iron-bearing sulfates, suggesting the past presence of water (Arvidson, *et al*., 2008). This material could be a volcanic deposit formed around ancient gas vents or could have been left behind by water that dissolved these minerals underground and evaporated when they came to the surface and evaporated (NASA, 2005).

During a drive on Sol 1148 (March 27, 2007), Spirit's inoperative right front wheel excavated light-toned soil deposits in Eastern Valley between Home Plate and the Mitcheltree/Low Ridge complex. Fig. 5 shows an approximately true-color image of the soil deposits taken by Pancam on Sol 1158 (NASA Planetary Photojournal ID: PIA09403). Measurements of Mini-TES on Sol 1172 indicated the spectral features of these deposits associated with opaline silica. The rover then drove to the soil and used APXS to further investigate the deposits on Sols 1189 and 1190. APXS observations discovered that these patches of disturbed, bright soil are about 90 weight percent SiO_2 (Squyres, *et al*., 2008). These silica-rich materials were interpreted to have formed under hydrothermal conditions and therefore to be strong indicators of a former aqueous environment. This discovery is important for understanding the past habitability of Mars because hydrothermal environments on Earth support thriving microbial ecosystems.

Fig. 5 Pancam image showing silica-rich soil
(Image credit: NASA/JPL/Cornell)

In December 2005, Spirit examined a strange looking outcrop, called Comanche, along its route down from Husband Hill to the Inner Basin. Fig. 6 is a false-color image taken by Pancam on Sol 689 (December 11, 2005). It took more than four years for a group of scientists to confirm that magnesium iron carbonate makes up about one-fourth of the measured volume in Comanche based on combined analysis of APXS, MB and Mini-TES data (Morris, *et al*., 2010). While previous evidences suggest wet and acidic environments that were less favorable as habitats for life, the substantial carbonate deposit in the outcrop Comanche indicates that a past environment was wet and non-acidic, possibly favorable to life (Morris, *et al*., 2010).

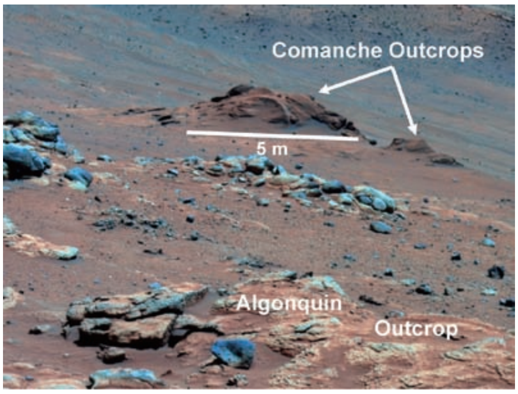

Fig. 6 False-color Pancam image showing carbonate-rich outcrops (Image credit: NASA/JPL/Cornell)

The layered plateau “Home Plate” (about 90 m in diameter) was extensively studied by Spirit rover. Textural observations and geochemical considerations suggest that Home Plate is an explosive volcanic deposit. It is composed of clastic rocks of moderately altered alkali basalt composition, enriched in some highly volatile elements (Squyres, *et al*., 2007). As shown in a false-color Pancam image taken on Sol 751 (Fig. 7), the coarse-grained lower unit likely represents accumulation of pyroclastic materials, whereas the finer-grained upper unit may represent eolian reworking of the same pyroclastic materials (Squyres, *et al*., 2007). The presence of bomb sags (white arrow in Fig.7) confirms the hypothesis of Home Plate’s volcanic history.

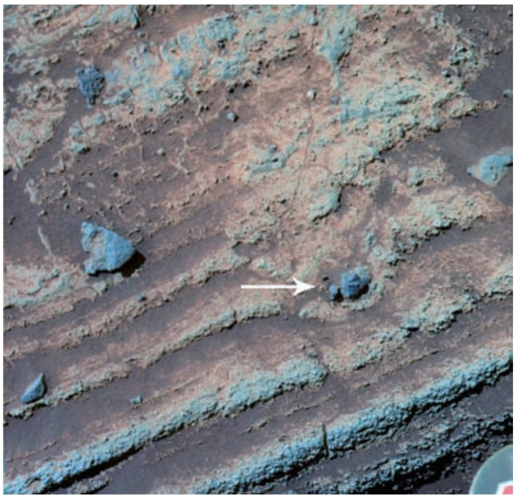

Fig. 7 False-color Pancam image showing a bomb sag (arrow) on Home Plate (Image credit: NASA/JPL/Cornell)

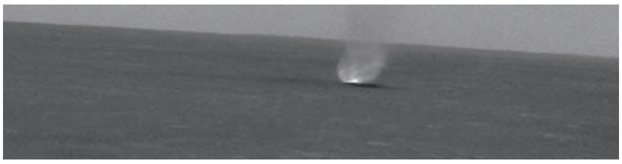

Fig. 8 A frame of a movie of dust devil acquired by Spirit’s Navcam (Image credit: NASA/JPL)

Spirit captured several dust devil events in 2005, providing the best look of the wind effects on the Martian surface as they were happening. As an example, Fig. 8 shows an image of a 21-frame movie of dust devil acquired by Navcam on sol 486 (May 15, 2005) at a location close to the summit of Husband Hill (NASA, 2005). The event occurred during a period of 9 minutes and 35 seconds beginning at 11:48 a.m. local Mars time. By analyzing the images, it was found that dust devil was about 34 meters in diameter and about 1.0 km away from the rover. The dust devil traveled in a northeasterly direction with a speed of about 4.8 m/s and covered a distance of about 1.6 km (NASA, 2005).

5 SUMMARY

This paper presented a brief review of Spirit’s six years of Mars roving and some significant scientific discoveries. Science-driven mission design, powerful scientific instruments, effective mission operation approach, and close cooperation among science and engineering team members have contributed to the unprecedented achievements during rover surface operations. In supporting the mission operations, planetary mapping and remote sensing technologies played a significant role in traverse planning as well as scientific investigations. The experiences of the Spirit rover mission, particularly the mission operation approach and various supporting technologies, are valuable for future Mars or lunar rover missions.

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勇气号火星车六年探测征程及科学发现简述

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摘　要：勇气号火星车2004年1月4日成功着陆古谢夫撞击坑。2009年5月1日，勇气号陷入一个命名为“特洛伊”的松软的沙坑。由于多次尝试从深陷的沙坑中解救勇气号失败，2010年1月26日NASA宣布勇气号不再行使而变成静止科学观测站。 在6年的探测征程中，勇气号行驶了7.73 km并且取得了诸多科学发现，例如发现了只有在水环境才能生成的盐类沉积物以及含有硫和蛋白石的矿物质沉积。本文简要综述勇气号6年漫游火星表面的征程以及重大的科学发现，特别展示了行星制图与遥感技术在实现火星车探测的科学和工程任务中发挥的重要作用。

关键词：勇气号火星车，漫游火星，科学发现，行星制图，遥感

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