A Local-Area GPS Pseudolite-Based Mars Navigation System

Edward A. LeMaster and Stephen M. Rock
Stanford University
Durand Bldg. Rm. 250, Stanford, CA 94305

Abstract

Tasks envisioned for future generation Mars rovers – sample collection, area survey, resource mining, habitat construction, etc. – will require greatly enhanced navigational capabilities over those possessed by the Mars Pathfinder rover. Many of these tasks will require cooperative efforts by multiple rovers, adding further requirements both for accuracy and commonality between users. This paper presents a new navigation system that can provide centimeter-level, drift-free localization to multiple rovers within a local area by utilizing standard GPS pseudolites and receivers deployed in a ground-based array. This system can replace or augment a system based on orbiting satellite transmitters. However, for successful deployment on Mars, this array must be self-calibrating. This is possible through the use of GPS transceivers and limited rover motion to resolve carrier-cycle ambiguities. This paper describes a prototype system that is being used to develop and demonstrate a SCPA and presents results from field trials conducted onboard the K-9 rover at NASA Ames Research Center. These results demonstrate both navigation and array calibration to cm-level accuracy.

1. Introduction

Mars surface exploration presents many challenges to designers of robotic systems. Long communication time delays (up to 40 minutes round trip) and limited bandwidth dictate high levels of autonomy. The rovers, however, are also operating in a very uncertain and potentially hostile environment. In order for successful autonomy, rovers must be able to sense and make sense of the environment around them. This sensing requirement becomes even more stringent when multiple rovers are attempting to cooperate in a common area to do joint tasks. Such cooperative tasks can include surveying, resource mining and utilization, and habitat construction.

On Earth GPS positioning is an attractive sensing system, especially when attempting to determine the relative locations of multiple users within a relatively small area. Such local-area positioning can be achieved – drift free – to centimeter-level accuracy. Unfortunately the satellite infrastructure necessary for such a system around Mars does not exist. (A more limited communications and navigation constellation of roughly a half-dozen orbiters has been proposed by JPL, and could provide roughly 10 meter positioning on a global scale on a very intermittent basis [1]. Although this would be an important asset, additional capabilities are still needed for more precise continuous-time operations.)

The Aerospace Robotics Laboratory at Stanford University has developed a prototype GPS-based local-area positioning system to help fill this gap. Rather than employing orbiting satellites, small low-power transmitters called pseudolites (short for 'pseudo-satellites') are distributed on the surface. Multiple users operating in the vicinity of the array can then employ GPS-type positioning – to centimeter-level accuracy – as if they had access to a full GPS satellite constellation. This concept is illustrated in Figure 1.

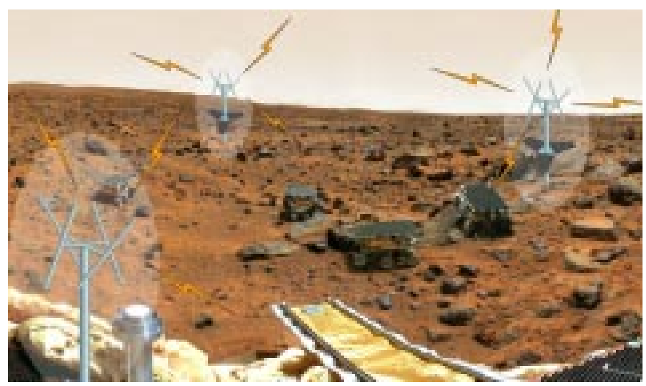

Figure 1: Mars SCPA

One of the main issues that must be overcome to make such a system feasible is how it can be calibrated. That is, the location of the broadcasting pseudolites must be known (to cm-level accuracy if cm-level navigational accuracy is to be achieved). In conventional GPS the satellites broadcast their known positions to the users, enabling localization from the pseudorange measurements. The precise positions of pseudolites deployed in an array on Mars will not be known, however, and performing a survey is problematic.

To overcome this difficulty, a new type of pseudolite array that is capable of surveying autonomously the locations of the transmitters on the surface has been developed. The resulting system is called a Self-Calibrating Pseudolite Array (SCPA), and utilizes full GPS transceivers instead of separate receivers and pseudolites to accomplish this task.

This system is described below. First, standard GPS navigation techniques are reviewed briefly to put this new capability into context. An overview of the underlying SCPA approach is then provided. This is followed by a description of a prototype SCPA system that has been developed and deployed on the K-9 rover at NASA Ames Research Center (a derivative of JPL's FIDO rovers). Finally, preliminary field-test results are provided that demonstrate the feasibility of cm-level navigation for future Mars deployment.

2 Navigation Algorithms

2.1 GPS Navigation

In standard GPS navigation, a constellation of orbiting satellites is continually broadcasting a BPSK modulated pseudo-random code on a 1575.42 MHz carrier. Data modulated on top of the code sequence contains information as to the time of broadcast of the signal. User receivers decode that timing information to determine the range to each satellite in view. These ranges, when combined with the known satellite locations, allow the user to determine a position fix. The high accuracy of the system (currently 3-5m RMS [4]) is provided by using regularly updated atomic clocks ($\sim 10^{-13}$ stability) on the satellites and by using a redundant range measurement to cancel out the range errors due to the inexpensive and relatively poor ($\sim 10^{-6}$ stability) oscillator on the receiver.

More accurate positioning can be done by using differential positioning between the user and a reference receiver at a known, nearby location. This approach exploits the fact that many of the error sources such as ionospheric interference are highly correlated with receiver position, and so appear as common-mode to all users. This technique is especially effective when the receivers are configured to track the carrier instead of the modulated code on the GPS signal. This Carrier-phase Differential GPS (CDGPS) can give accuracy on the order of 1 cm, at the expense of adding in an unknown ambiguity in the integer number of wavelengths in the received signals. This ambiguity can be resolved either through a change in system geometry over time or by utilizing multiple frequency signals in a process called wide-laning.

A much more complete overview of GPS fundamentals can be found in [5].

2.2 SCPA Navigation

Navigation using an SCPA follows the same principle as Differential GPS, and can be accomplished at both the code or carrier levels. In order to achieve precise navigation without using atomic clocks, a double-difference ranging solution has been developed between GPS transceivers with both receiving and transmitting elements in a common device. The resulting bidirectional inter-transceiver ranging solution involves exchanging ranging signals (corrupted by clock biases) between device pairs. It then cancels out the clock biases associated with the transmitter oscillators in the same manner one normally does with the receiver oscillator, as is presented in [3]. Note that inter-transceiver ranging at the carrier level still suffers from the integer ambiguity present in standard CDGPS.

Determination of the array geometry and the location of the rover are accomplished by combining the range measurements between transceiver pairs, either using triangulation or standard non-linear optimization techniques. Code-level positioning is available instantaneously, allowing a rough navigation capability to all users within the array. It is also available with range measurements to as few as two static transceivers, allowing operation within sparse arrays. The 2-4 meter precision can be improved by either short- or long-period averaging. Although uncalibrated line and system biases can degrade the accuracy to several meters, code-based ranging is sufficient for many tasks such as general navigation between points and collision avoidance. It may be insufficient, however, for more complex or repetative tasks such as cooperative manipulation or construction. In these cases, it is necessary to have the centimeter-level accuracy associated with carrier-phase operations.

Achieving carrier-phase positioning is only possible after an additional calibration step is used to resolve the associated integer ambiguities. The prototype system calibrates by using the relative motion of a transceiver-bearing rover to alter the array geometry over time. During this motion the unknown integers remain constant. A batch process collects range data during the course of this maneuver, and is subsequently able to determine both the integers and the actual positions of the static transceivers to centimeter-level accuracy via a non-linear iterative optimization process. At least three range measurements from the rover to the static transceivers must be available, and rover motion must be considerable

– but not unreasonably so – for successful convergence. For example, a complete circumnavigation of the array by the rover is sufficient. Note that the rover does not have to drive a tightly defined trajectory in order to calibrate the array, since the algorithm backs out the actual rover trajectory as part of its solution. This calibration process can also be used to remove unknown line biases from the code-range solution.

These algorithms are described more fully in [3].

3 Experimental System

An SCPA is a distributed system consisting of several GPS transceivers and a common ground station for data processing. The following is a brief summary of the hardware and software involved. A more comprehensive description of the experimental system appears in [2].

3.1 GPS Transceiver Array

Each transceiver consists of a single GPS receiver and a separate pseudolite signal generator. The receiver monitors the pseudolite output signal to form a self-differencing transceiver, as described in [7]. The receiver is a slightly modified Mitel Orion receiver with custom tracking loops for the non-standard pseudolite data message. While the Mitel chipset is not currently space qualified, it has undergone over one year of successful on-orbit operations [6]. The pseudolite is an IntegriNautics IN200C signal generator utilizing a 3% duty cycle RTCM pulsing scheme to help combat the near-far problem associated with near-field operations. The total combined broadcast power of the current experimental system is less than 1μW. (This limit is set by the FCC, which allows users with an experimental license to intentionally broadcast on L1 with a maximum continuous power of 1μW.) The low signal power limits the range of operation of the prototype system to about 30-50 meters. Higher power levels will enable operation over baselines of kilometers, provided that line-of-sight is maintained.

The transceiver is carried in a portable tote-bucket together with a 1.6 Mbps Proxim RangeLan2 wireless link for data collection and a 4.4 A-hr NiCd battery pack, which gives roughly 4 hours of continuous operation. Figure 2 shows one of these ‘transceiver totes’. Broadcast and reception of the pseudolite signals is accomplished through a pair of custom dipole antennas mounted on a tripod near each transceiver, as is shown in Figure 3. Using dipoles instead of commercial GPS patch antennas allows 360° operations around the transceiver because of the omnidirectional pattern and the lack of circular polarization, although this comes at the penalty of losing some multipath rejection.

The ground-station computer used for central data processing is a 133MHz Pentium laptop running a Windows NT operating system. The ground station runs a custom software program that collects the raw data from the transceiver wireless units, combines common-epoch measurements into ranges between transceiver pairs, and computes the array geometry. It also allows remote control and diagnostics of the receivers.

Figure 2: Transceiver Tote

The current system includes four operational transceivers. This is the minimum number needed for both unambiguous dynamic positioning of the rover and for the array refinement algorithm, necessitating nearly constant tracking of all pseudolites on all receiver channels in order to achieve continuous localization. Performance may be improved by adding redundant static transceivers to the array.

Three of these transceivers are positioned at fixed locations. The fourth is mounted on the rover.

3.2 K9 Rover

The rover chosen for these experiments is the NASA Ames K9 rover, shown in Figure 4. This is a variant of the FIDO rover under development at JPL for future Mars missions. It features a rocker-bogie suspension system, 360° variable steering, and an onboard dead-reckoning system. Typical speed of operation is roughly 10 cm/sec. The large sensor mast holds a stereo camera pair used for terrain mapping. A scanning laser rangefinder is mounted on the front of the rover for obstacle detection. The short vertical mast on the far left corner in the photo holds the GPS antennas used for the onboard transceiver.

Figure 3: Static Transceiver

4 Field Tests

The goal of these tests was to determine the level of performance that could be achieved using a SCPA. The first set of results demonstrates the accuracy of the code-based and carrier phase based solutions for a static array in near ideal conditions. The second set of results demonstrates the accuracy with which a rover's position could be calculated as it moves through an array. The final set of results shows the accuracy with which the array can determine the location of the static transceivers during the self-calibration process.

The results demonstrate both navigation and self-calibration with cm-level accuracy.

4.1 Test Location

Field testing of the SCPA using the K9 rover was conducted at NASA Ames Research Center at Moffett Field, California. This was done in a large empty lot near the inlet of the large 80' by 120' subsonic wind tunnel, yielding a moderately high multipath environment. Figure 5 shows the experimental system in operation, including all three static transceivers (placed in a triangle approximately 10 meters apart) and the K9 rover. Other testing without the K9 rover has been performed on a large open field at Stanford University, a relatively low-multipath environment. [2]

Figure 4: K9 Rover

Figure 5: NASA Ames Test Site

4.2 Experimental Results

Test 1: Static ranging

Several tests were conducted with all the transceivers in known, static locations to evaluate the stability of the static ranging measurements between the transceivers. Accuracies with the pseudolites at full duty cycle (no pulsing) are better than 1.3 meters and 0.8 cm RMS for code-based and carrier-based ranging, respectively. When the pseudolite duty cycle is reduced to 3% via pulsing, the code-based ranging accuracy degrades by approximately a factor of 3 because of the reduced SNR of the tracked signal. Carrier-based ranging accuracy remains largely unaffected.

Test 2: Dynamic ranging

Figure 6 shows a trajectory used to demonstrate the stability of the ranging measurements under dynamic conditions. Three of the transceivers were placed in known, static locations at the vertices of a 10m equilateral triangle. The fourth transceiver was started at a known location and was then carried by hand for 12 consecutive loops around the array, finally returning to its starting location. The transceiver was placed at pre-surveyed reference locations (indicated by squares) during each loop to assess the positioning accuracy.

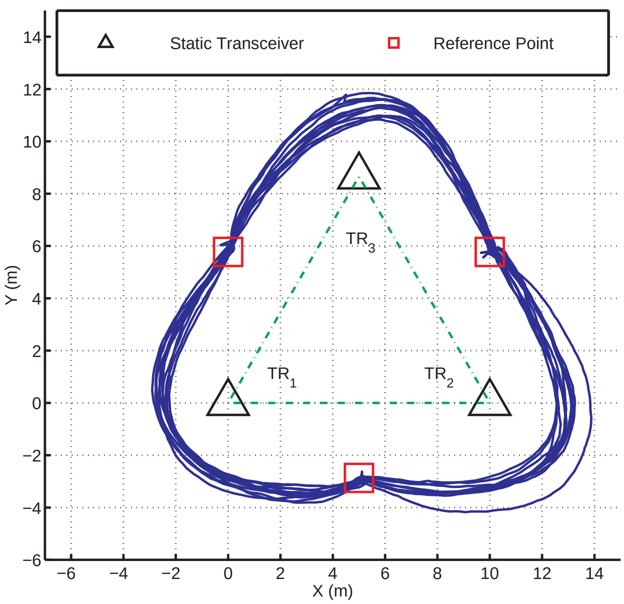

Figure 6: Mobile Transceiver Ground Track

Analysis of the data shows no significant long-term accuracy degradation even with the added dynamic stress caused by the transceiver motion. RMS positioning accuracy at the reference points was 12.4 cm, slightly worse then the technical placement error (the estimated accuracy with which the transceiver tripods can be placed with respect to the reference points) of approximately 10 cm for the mobile transceiver. When the data is corrected to account for a 39.0 cm (~2λ) carrier-phase cycle slip in one of the ranging measurements midway through the experiment, the RMS positioning accuracy improves to 4.5 cm – well below the technical placement error.

Test 3: Array self-calibration:

Figure 7 shows the results of a full array self-calibration performed during a field test at NASA Ames in May 2001. For this experiment the mobile transceiver was placed onboard the K9 rover, which was then driven via teleoperation by a human operator in a single clockwise path around the array and back to its starting location. The trajectory, with a path length of roughly 50 m, took 15 minutes to complete. Because of the slightly rolling terrain (which cants the antennas away from vertical) and the difficulty associated with precisely positioning K9 remotely, the technical placement error for both the mobile and static transceivers is slightly higher than in the previous tests, perhaps as great as 20 cm.

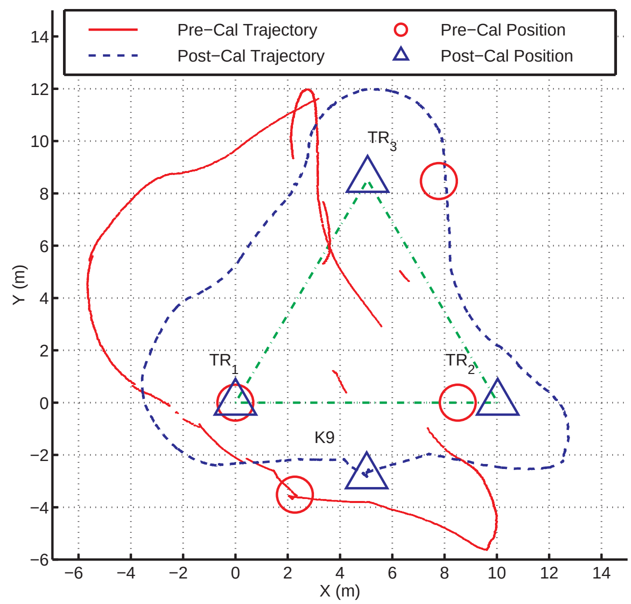

Figure 7: K9 Ground Track

Figure 7 shows the same positioning data from the SCPA under two different operating conditions – pre-calibration and post-calibration. In the pre-calibration stage the array was initially set up in an equilateral formation with K9 outside the array between static transceivers #1 and #2, and the carrier-cycle integers were set using these known locations. Then arbitrary biases of 1.5 m magnitude (15% of the size of the array) and random sign were added to each of the six carrier-range measurements, and new locations (in error by up to 3 m) were calculated. These new starting locations are indicated by the circles in the plot, and simulate the positioning errors associated with a rough deployment of the system using either code-based ranging, dead-reckoning, or other navigational means. This is the starting state for the centimeter-level array self-calibration.

The rover was then driven around the array and data collected along its trajectory, until it returned to its starting location. The return to the starting location is performed to provide an additional truth reference for the experiment, and is not necessary for algorithm convergence. Rover motion can be largely arbitrary, as long as it travels a sufficient distance for geometric observability.

The path followed by K9 as calculated using the corrupted ranging measurements from the GPS system is shown with the solid line. Note the severe warping of the navigation space, taking the estimated path inside the array itself, and the many gaps in the position solution. These gaps occur when the warping is so severe that the range measurements cannot be cleanly and effectively combined to form any position estimate for the rover. This warping and solution incoherence is what one would see if one were to attempt to use a pseudolite array for navigation without proper calibration.

Following the trajectory, the collected data was batch processed to determine the actual locations of the static transceiver, the actual rover trajectory, and the value of the induced ranging biases. The resulting positions are shown in Figure 7 with the triangles and the dashed line. Localization of the static transceivers was performed to 9.6 cm RMS and the difference between the rover starting and finishing locations as measured by the GPS system was 15.1 cm, all within the estimated technical system placement error.

It should be noted that the biases induced in this test were somewhat conservative. Extensive Monte-Carlo simulations (over 40,000 runs) of the self-calibration algorithm show successful convergence and array self-calibration more than 70% of the time even with initial range biases equal to 40% of the size of the array. For biases less than 20% of the array size, the convergence rate is greater than 95%.

5 Conclusions

GPS pseudolites constitute a useful and viable method to achieve CDGPS-type precise positioning for Mars rovers. One of the primary challenges with using pseudolite arrays – that of surveying in the locations of the pseudolites – can be overcome by using a special variant called a Self-Calibrating Pseudolite Array. In an SCPA each device is a full transceiver, and they exchange signals to compute their relative ranges and hence the array geometry.

Field tests of the prototype system have successfully achieved both code- and carrier-level positioning of the NASA Ames K-9 Mars rover prototype, with corresponding static accuracies (with pseudolite pulsing) of less than 3.7 meters and 0.8 cm, respectively. Dynamic positioning has been experimentally demonstrated to similar levels of accuracy. Self-calibration of the locations of the static transceivers in the array has also been successfully demonstrated to accuracies of better than 10 cm RMS.

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