A Local-Area GPS Pseudolite-Based Mars Navigation System

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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 precision Mars navigational capability and presents preliminary results from field trials conducted onboard the K-9 rover at NASA Ames Research Center. These results demonstrate that navigation with cm-level accuracy is feasible.

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.

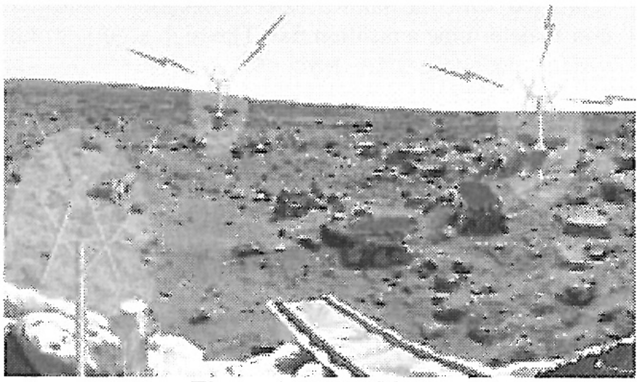

Figure 1: Mars SCPA

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 [2]) is provided by using regularly updated atomic clocks ($\sim 10^{-13}$ stability) on the satellites and by using a redundant range 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 [3].

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 [4]. 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 is 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 short-period averaging. Although uncalibrated line and system biases can degrade the accuracy to within a few 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. This calibration process can also be used to remove unknown biases from the code-range solution.

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 [5].

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 [6]. 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 [7]. The pseudolite is an IntegriNautics IN200C signal generator utilizing a 9% duty cycle RTCM pulsing scheme to help combat the near-far problem associated with near-field operations. The total combined output power of the entire array is less than 1μW.[1] This limits the range of operation of the prototype system to about 20 meters. Higher power levels will enable operation over baselines of kilometers (the only limit being line-of-site restrictions).

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 lack of circular polarization, although this comes at the penalty of losing some multipath rejection.

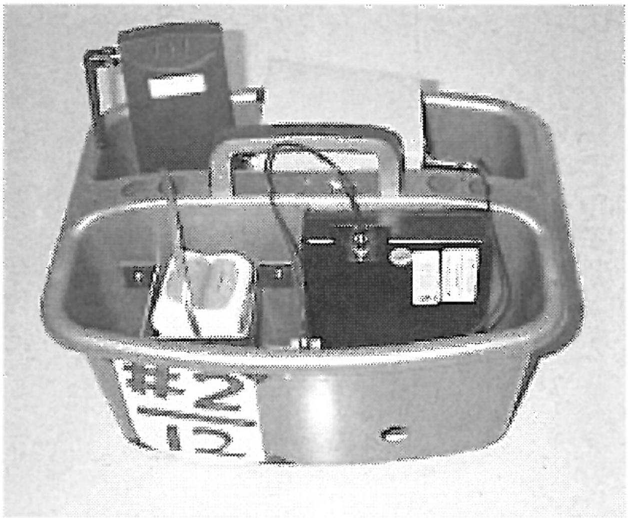

Figure 2: Transceiver Tote

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.

The current system includes four operational transceivers. Three of these transceivers are positioned at fixed locations. The fourth is mounted on the rover. 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.

3.2 K-9 Rover

The rover chosen for these experiments is the NASA Ames K-9 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 blue 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.

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[1] These limits are set by the FCC, which allows users with an experimental license to intentionally broadcast on L1 with a maximum continuous power of 1μW.

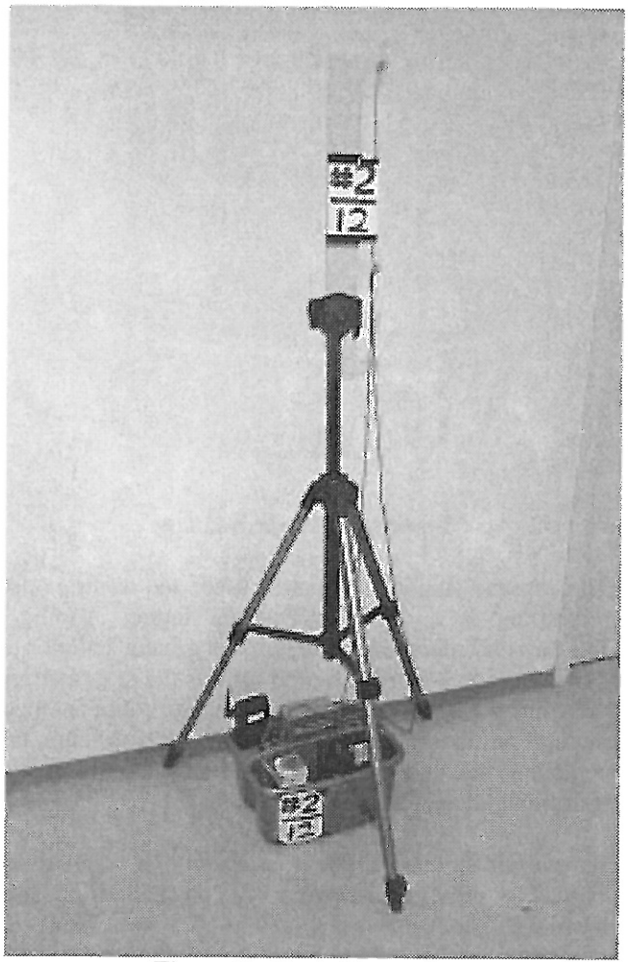

Figure 3: Static Transceiver

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.

Note that the full SCPA algorithm has not been demonstrated in the field-test results reported here. For these tests, convergence of the algorithm to the known correct solution was assumed.

The results demonstrate that navigating with cm-level accuracy is feasible.

4.1 Test Location

Field testing of the SCPA using the K-9 rover was conducted at NASA Ames Research Center at Moffett Field, California. This was done in a large empty lot near the exit diffuser 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 K-9 rover. Other testing without the K-9 rover has also been performed on a large open field at Stanford University, a relatively low-multipath environment. [5]

Figure 4: K-9 Rover

Figure 5: NASA Ames Test Site

4.2 Experimental Results

Static transceiver ranging tests:
Figures 6 and 7 show the accuracy with which the system can position a static transceiver using range measurements from two other transceivers. Figure 6 shows code-range positioning, and Figure 7 shows the corresponding carrier-phase positioning. This data comes from field tests at Stanford and represent what is probably near the best-case accuracy of the system because of the low multipath environment. The non-circular shape of the 2-σ error ellipses shown is because the ranging signals are not orthogonal. (This corresponds to positioning transceiver #3 with respect to transceivers #1 and #2 in the geometry shown in Figure 8. X-DOP = 1.36, Y-DOP = 0.82) Raw ranging accuracies are better than 1.3 meters and 0.8 cm RMS for code-based and carrier-based ranging, respectively.

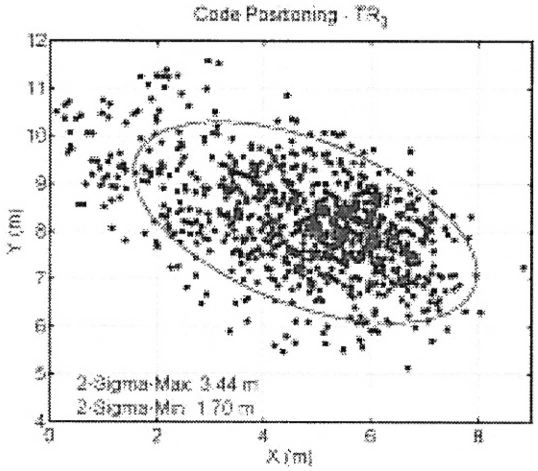

Figure 6: Transceiver 3 Static Code Positioning

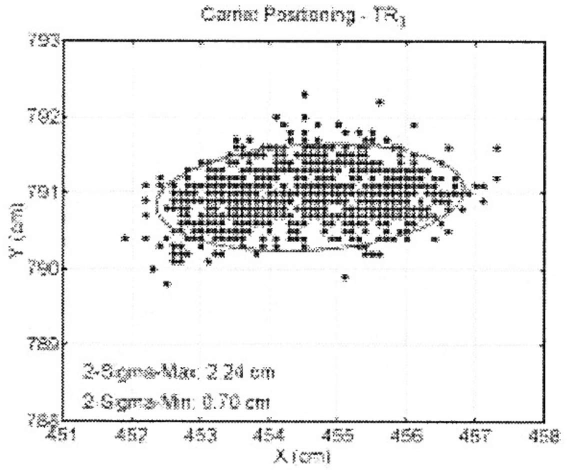

Figure 7: Transceiver 3 Static Carrier Positioning

Static transceiver plus rover ranging tests:
Figure 8 shows a sample trajectory followed by the K-9 rover during one of the field tests at NASA Ames in December 2000. The static transceivers are arranged in an equilateral triangle roughly 9 meters on a side, and their locations are pre-surveyed for truth comparison. The rover starts at a pre-determined reference point in the middle of the array and then makes a pair of loops counterclockwise around transceiver #3 at the top of the figure. Finally the rover is returned to its starting point. These maneuvers are performed open-loop by a human operator, who with practice can control the rover position to about 10 cm.

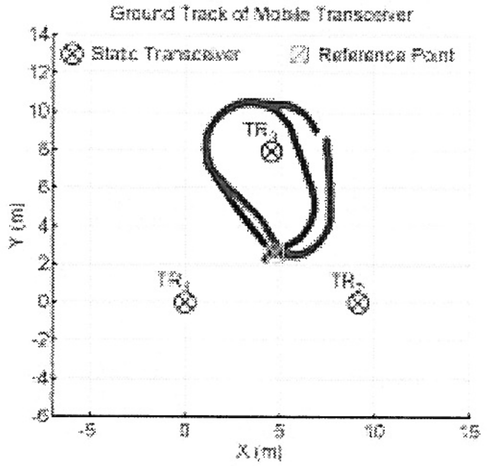

Figure 8: K-9 Ground Track

The position data shown in Figure 8 is derived from inter-transceiver ranging measurements between the transceiver on K-9 and static transceivers #1 and #2 via direct triangulation. The signal from transceiver #3 was not used during this test, showing the ability of the rover to determine its location from only two ranging signals. Additional signal sources would enhance reliability via added redundancy and would help reduce the affect of bias errors. Because of the small size of the array only the position derived from carrier-phase ranging is presented. For this test the carrier-phase integers are assumed known. While the noise in code-phase measurements approaches half the size of this array, code-phase ranging can be successfully used even in small arrays such as this by either time averaging (requiring slow rover motion) or by combining it with carrier-phase ranging in a complementary filter. In that case the carrier-range provides the epoch to epoch changes, while the code-range provides a rough estimate of the carrier-cycle ambiguities.

The small jump in the curve (Figure 8) is caused by a momentary loss of lock between one of the transceiver pairs. Such losses occur somewhat infrequently, but can be overcome in a couple of ways. First, a denser array of transceivers gives redundant range measurements so that continuous positioning is not dependant on any particular signal. Second, other sensors can be used to supplement the array. For example, an IMU or dead-reckoning system generally gives good enough short-period stability to allow the combined system to coast through brief periods of signal loss.

Figure 9 shows the raw range data that corresponds to the test from Figure 8 above. Because the rover begins the trajectory at a pre-surveyed location the integers are known, so the carrier-based ranging is nearly exact. Carrier-range dynamic errors are only slightly higher than those exhibited by static ranging in Figure 7. The offset between beginning and ending position in Figure 8 is due to the brief signal outage described previously.

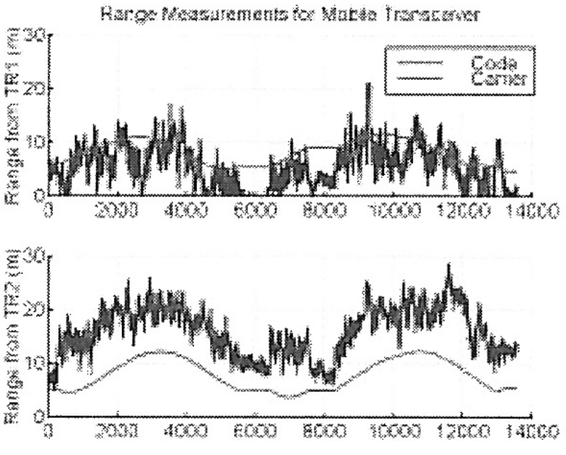

Figure 9: Inter-Transceiver Range Measurements

The code-based dynamic ranging also exhibits similar noise levels as in the static tests of Figure 6. Although there are bias offsets due to uncalibrated factors such line biases, the code-range does in general follow the carrier-range, as expected. The size of these bias offsets can be greatly reduced through more extensive calibration procedures. The code-range solution from transceiver #2 between epochs 6500 and 7500 exhibits an interesting property, in that it moves in the opposite direction from the carrier-range solution. This is most likely a multipath effect, which affects code-phase measurements to a much higher degree than carrier-phase measurements. Multipath therefore presents a limiting factor in the ranging accuracy for a pure code-based SCPA.

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 of less than 1.5 meters and 1 cm, respectively. Dynamic positioning has been experimentally demonstrated to similar levels of accuracy.

Acknowledgements

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