# Mars Exploration Using Self-Calibrating Pseudolite Arrays

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## BIOGRAPHY

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## ABSTRACT

Future Mars rover missions will require greatly enhanced navigational capabilities over those possessed by Mars Pathfinder. The centimeter-level accuracy required for these missions makes GPS a natural candidate for any future integrated navigation system. Because there are no GPS satellites around Mars, navigation will require the use of pseudolites.

The Aerospace Robotics Lab at Stanford is developing a new system called a Self-Calibrating Pseudolite Array (SCPA) to solve the problem of autonomously determining the locations of the pseudolites after deployment. This is achieved through the use of GPS transceivers, capable of both sending and receiving GPS signals. Three such devices, together with a technique called Inter-Transceiver Pseudoranging (ITP), allow the rover to navigate across the planetary surface to approximately meter accuracy. Centimeter-level accuracy can be obtained by extending the array to a greater number of devices and using CDGPS techniques.

This paper provides an overview of the capabilities of SCPAs and the challenges associated with pseudolite operation on Mars. The methodology and algorithms associated with ITP are discussed, as well as the expected error sources. Simulation results show the observability of all states of interest for the array self-calibration.

## INTRODUCTION

The recent success of the Mars Pathfinder mission [1] has rekindled interest in the use of rovers for planetary exploration. Rovers with on-board science instruments can greatly extend the range of observation well beyond the vicinity of the lander. Moreover, they allow geologic samples to be retrieved from areas of differing terrain. These benefits have prompted NASA to plan several future Mars missions with rovers, starting with the Mars Surveyor Mission in 2001 and then continuing every two years until 2005.

The Sojourner rover navigated by way of dead reckoning, which was then updated periodically by a stereo vision fix by the lander. A typical task or maneuver would take several Sols (Martian days) to complete, since with its limited navigational capabilities the rover would require corrections from Earth (available once per Sol during the command uplinks) as it approached its target. This worked well for two reasons: (1) Sojourner was always very close to the lander, and (2) it had relatively limited mission objectives, and thus plenty of time to complete them.

Sample collection will be one of the primary tasks of the Athena rover, currently slated for the 2003 mission. The most probable scenario for this task involves the rover making repeated medium-length (< 1 km) traverses away from the lander, returning each time with a sample to be placed in storage bins on the lander for eventual return to Earth during the 2005 mission. An alternative, more ambitious scenario involves extended traverses away from the lander of 100 km or more. In each case the rover might require a lifetime of several months to a year to accomplish its goals.

To accomplish these objectives, the navigational capabilities of the rover must be extended significantly past those of Mars Pathfinder. Longer traverses require a navigation system which functions away from the immediate vicinity of the lander. In order to allow return trips to areas of interest or to the lander, the rover must be able to navigate with an accuracy of roughly better than 10 cm. For extended operations, it must be drift-free. Moreover, because of the finite lifetime of the rover, the navigation system must be autonomous or nearly autonomous. This reduces the risk associated with waiting for corrections or instructions from Earth.

There are many ongoing projects directed at providing these advanced navigation capabilities, including work on vision-based landmark navigation, visual servoing, and improved celestial navigation. A GPS system would provide many important benefits to such an integrated navigation system including centimeter-level accuracy, repeatability, and autonomy.

NASA has no current plans to orbit a constellation of GPS satellites around Mars, and indeed such a system would be extremely expensive. However, GPS navigation can be used in a local area (1 to 2 km across) by using pseudolites. Previous work has successfully demonstrated indoor CDGPS centimeter-level position and degree-level attitude solutions using only a pseudolite array [2]. The use of pseudolites in this manner is limited, though: Just as the GPS satellites must broadcast accurate ephemerides, the locations of the pseudolites within the array must be known very accurately as well. This is infeasible for a robotic mission where the pseudolites would be distributed by methods such as ballistic scattering or by manual placement by the rover, resulting in highly uncertain locations. Experiments in surveying the locations of the pseudolites using GPS signals have relied upon known locations of a moving reference vehicle, again infeasible for a system for planetary exploration [2]. Thus a new method of surveying the pseudolite positions is required.

## SELF-CALIBRATING PSEUDOLITE ARRAYS

A Self-Calibrating Pseudolite Array (SCPA) is a local-area navigation system which is capable of determining the locations of the pseudolites independent of any external measurements (Figure 1). Each pseudolite is connected to an associated receiver to create a GPS transceiver. These transceivers then exchange GPS signals to self-calibrate their relative positions. Once the locations of the pseudolites are known, any vehicle operating inside the array can determine its location as it would with a standard pseudolite array. In general, such a system can provide full 3-D positioning capability. When distributed on a planetary surface the transceivers will likely be in a nearly planar configuration, giving only 2-D positioning information.

Just as with conventional GPS there are two modes of operation for an SCPA: pseudorange and carrier-phase. Each has distinct advantages in certain situations. Pseudoranging is useful primarily because it requires relatively few transceivers. This could be of critical importance in a natural environment such as the Martian surface, where ridges, rocks, and other obstacles could potentially obstruct line-of-sight. The reduction in the number of required devices would also be useful for longer traverses, where a greatly extended array would be needed. In addition, pseudoranging requires no integer initialization. This lets the rover determine its rough position before it begins moving, a useful feature in robotic exploration. Carrier-phase techniques require more transceivers, but provide greater accuracy. This paper deals primarily with pseudorange calibration.

## INTER-TRANSCEIVER PSEUDORANGING

The pseudorange technique presented here is called Inter-Transceiver Pseudoranging (ITP). In this

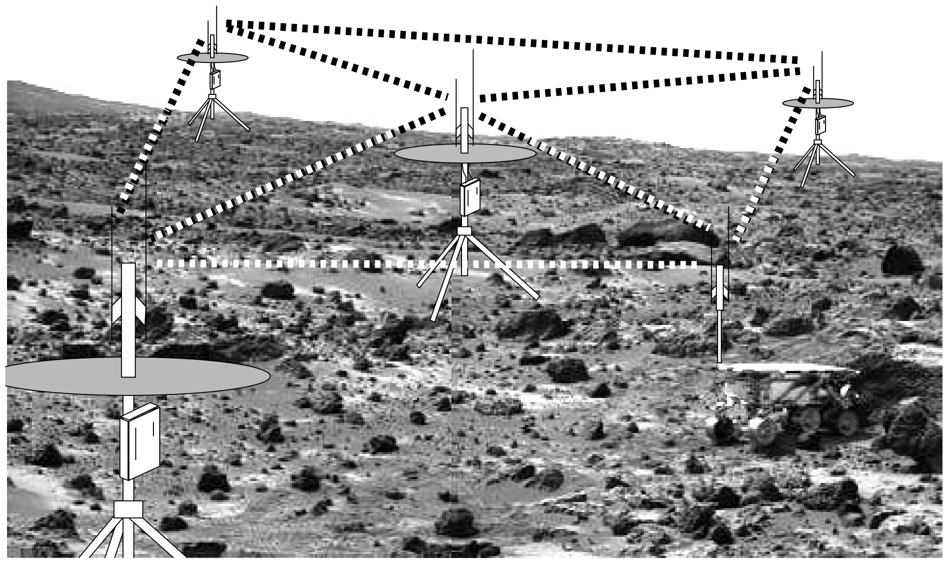

Figure 1: Self-Calibrating Pseudolite Array

method, transceivers are considered on a pairwise basis. Sending two simultaneous GPS signals between the two devices allows them to solve for both their instantaneous relative clock bias and also the range between them, to typical pseudorange accuracy. Thus, two transceivers using ITP effectively define and measure a line in space. Adding a third transceiver extends the array to a plane, while a fourth gives full 3-D navigability. These transceivers can be either fixed or mobile; because pseudoranging is involved no integers need to be determined.

One method of creating a GPS transceiver is to have pseudolite and receiver capabilities in a single unit, operating with a common clock. To reduce hardware development, however, it is possible to accomplish intra-transceiver clock synchronization through an alternate route. Each receiver has a dual front end, to which separate input lines can be attached. The pseudolite RF output is split, with one line going to the transmit antenna and the other feeding directly into the associated receiver. The receiver then generates pseudorange measurements through single-differencing of the RF inputs from its own and other pseudolites, taking out the receiver clock information but leaving the pseudolite clock information. This effectively uses the receiver's own latching capability to insure that the transceiver components are synchronized. This hardware architecture is presented in Figure 2.

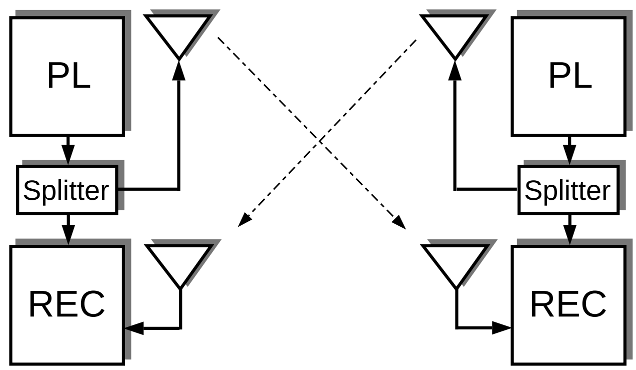


Figure 2: Transceiver Architecture

At a given sample epoch, each receiver measures the code-phase from both pseudolites. If $\psi_i^j$ is receiver $i$'s measurement of pseudolite $j$, then (neglecting biases):

$$\psi_1^1 = t_1 \quad (1)$$
$$\psi_1^2 = t_2 - R \quad (2)$$

where $R$ is the range between the two devices (expressed in units of time) and $t_j$ is the current code-phase of pseudolite $j$. Combining two simultaneous measurements by both receivers, the measurement equations can be written as:

$$\left\{ \begin{array}{c} \rho_1 \\ \rho_2 \end{array} \right\} \triangleq \left\{ \begin{array}{c} \psi_1^2 - \psi_1^1 \\ \psi_2^1 - \psi_2^2 \end{array} \right\} = \left[ \begin{array}{cc} 1 & -1 \\ -1 & -1 \end{array} \right] \left\{ \begin{array}{c} \tau \\ R \end{array} \right\} \quad (3)$$

where $\tau \triangleq t_2 - t_1$ is the time bias of pseudolite 2 with respect to pseudolite 1. Because this pseudolite time bias affects the two pseudoranges in an opposite manner, this linear equation is easily invertible to solve for both $R$ and $\tau$. The range solution can also be used for time-transfer applications, as noted by Lau et al. [3].

If it is assumed that the measurements are corrupted only by gaussian white noise of variance $\sigma^2$, then the resulting range solution has variance $\sigma^2$ as well. For a static configuration, this random error can be reduced to an arbitrarily low level by time averaging. With a moving rover, it can be reduced by carrier smoothing. Note that the accuracy of ITP can be significantly improved by using either P-code or faster chipping rates instead of standard C/A-code for the pseudorange calculations.

Because ITP solutions can be computed on a pairwise basis, it offers several advantages to pseudolite arrays which employ it. First, not all of the pseudolites need to be broadcasting simultaneously. Measurements taken at widely differing times can be combined to survey the array. This can conserve power and also may help to avoid interference problems; although pseudolite pulsing prevents interference for the two transceivers in any given pair, when extended to large numbers of devices it may have limitations. In addition, multiplexing between the transceivers can also reduce the number of separate communications links needed to collect the raw data. Finally, ITP also offers robustness to signal loss. Because of the irregularity of the Martian surface, some of the signal paths will be likely by blocked by boulders, hills, and other obstacles. However, the loss of any single line-of-sight path between transceivers does not affect the operation of the other pairs. Navigational and calibration information is thus available down to a very small number of visible pairs.

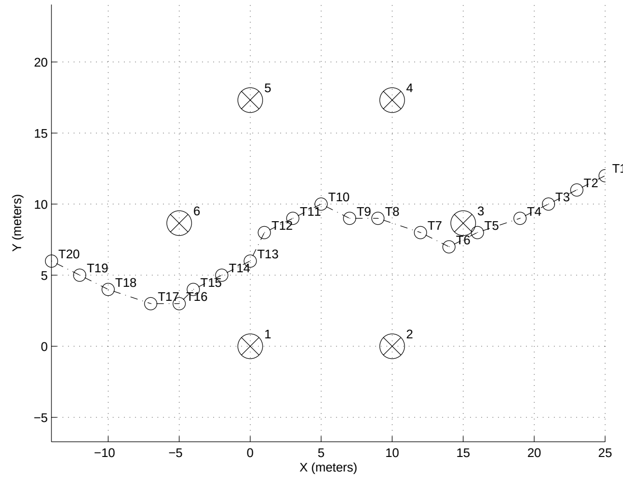


Figure 3: Baseline Simulation Trajectory

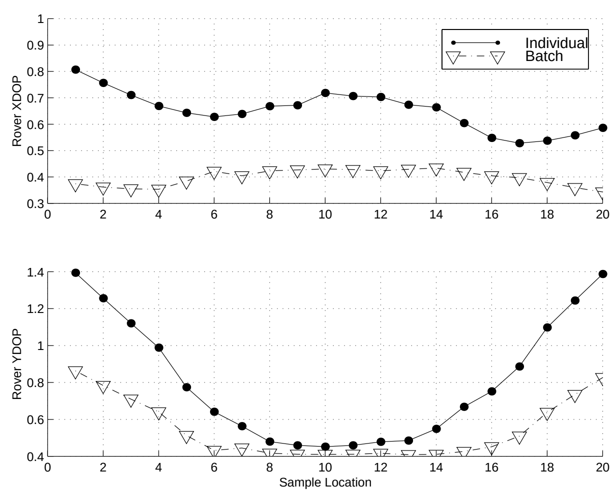


Figure 4: Rover DOP vs. Position (Baseline Case)

## ARRAY SIMULATION

In order to evaluate potential SCPA geometries, we have developed and run several system simulations both with and without a moving rover. The baseline array configuration which resulted is shown in Figure 3. Six stationary transceivers (marked by X's) are arranged in a hexagonal pattern. This configuration supplies a great deal of redundancy in order to improve accuracy and availability, and also includes enough transceivers to allow CDGPS operations. In addition it provides a wide coverage area. For the simulations the rover makes a single traverse from outside of the array on one side, across the middle of the array, to the outside the array on the other side. Data is collected at 20 evenly-distributed sample epochs. In order to make optimal use of the available data, rover position is computed concurrently with the array calibration. All of the simulation results presented here are for ITP positioning.

A good measure of the observability of the desired

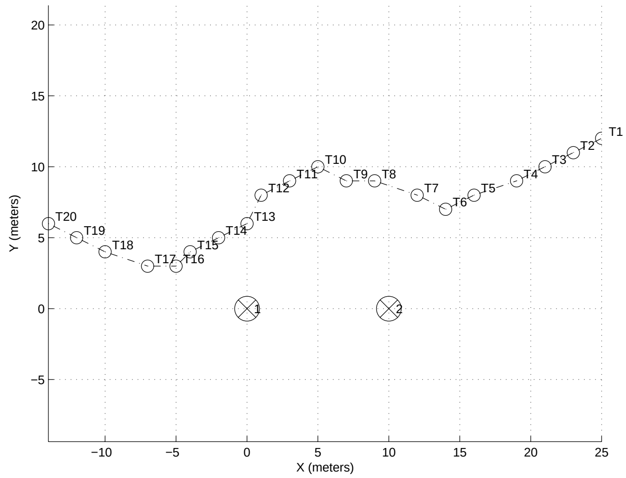


Figure 5: Minimal Simulation Trajectory

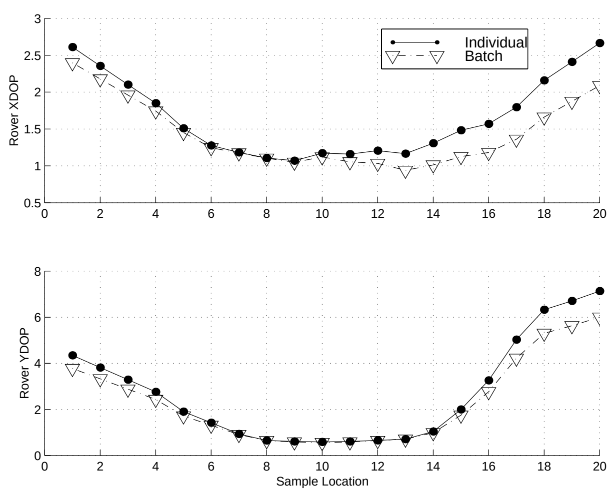


Figure 6: Rover DOP vs. Position (Minimal Case)

states is the Dilution of Precision (DOP), defined as:

$$\text{DOP} = \sqrt{diag((H^T H)^{-1})} \tag{4}$$

where $H$ is the geometry matrix describing the array. For gaussian white noise, the variance in the estimate of position is equal to the raw measurement variance multiplied by the DOP. Thus DOPs much larger than one indicate a poorly observable state.

Figure 4 shows the DOP for the rover position at each

| Processing Mode | TDOP |
|---|---|
| Single Epoch | 0.3780 |
| Rover Batch | 0.2938 |
| Array Batch | 0.0845 |

Table 1: Baseline ITP Simulation TDOP

| Processing Mode | TDOP |
|---|---|
| Single Epoch | 0.5774 |
| Rover Batch | 0.5041 |
| Array Batch | 0.1291 |

Table 2: Minimal ITP Simulation TDOP

sample point in the trajectory. Note that the DOP climbs quite high outside the array, but within the confines of the array tends to fall below one. This is true both when the samples are processed individually and when the entire trajectory is processed in batch form. DOP values for the positions of the static transceivers are not shown, but tend to be equivalent to the values for the rover in the center of the array ($< 1$) for individual samples, and down to roughly 0.1 when the measurements are averaged over the entire trajectory. Taking more samples would of course reduce the DOP for the static transceivers to arbitrarily low levels.

A very quick survey of the observability of all aspects of the array can be obtained by examining the time DOP (TDOP), which for a given sample epoch is common for all elements of the array. These values are given in Table 1 for an individual epoch, for the rover processed in batch form, and for the static transceivers processed in batch form. Note that the rover does gain some benefit from the averaging of the static transceiver locations, but not nearly as great as the transceivers themselves.

In order to examine a worst-case scenario where most of the transceivers were inoperable or blocked by obstacles, we also examined a "minimal" array composed of two static transceivers and one mobile transceiver. This is the minimum number necessary for 2-D positioning. The rover trajectory with respect to the static transceivers is presented in Figure 5, and the rover position DOP is shown in Figure 6. As expected the rover DOP is considerably worse than the baseline case due to loss of measurement redundancy and the degradation of geometry. However, the DOP still drops below one when the rover is close to the static devices, showing that even the minimal configuration may be useful for navigation. TDOPs for the minimal case (Table 2) tend to support this conclusion.

## MARTIAN ERROR SOURCES

In operation of an SCPA on a foreign planet such as Mars, the error sources are somewhat different than those normally encountered on Earth. The designer of an SCPA controls the pseudolite signal; thus they are not affected by Selective Availability. Moreover the signals do not pass through the ionosphere, so there are no ionospheric delays. Tropospheric delays are negligible for small arrays. This is especially true for Mars because of its thin atmosphere.

Unlike in standard differencing schemes, line and receiver biases caused by small differences in the hardware elements do not cancel because of the different signal paths between the pseudolites and the receivers. They can, however, be reduced to acceptably small values through intelligent design and careful hardware calibration. Clock stability is another concern, as it dictates the maximum range between transceivers as well as the allowable interval between non-simultaneous measurements at the two receivers. If $F$ is the nominal clock frequency and $\Delta f$ is the worst-case error in the frequency estimation during the measurement interval $\Delta T$, then the maximum errors from clock instability are:

$$\text{range:} \quad \frac{\Delta f}{F} \cdot R \tag{5}$$

$$\text{latching offset:} \quad \frac{\Delta f}{F} \cdot \Delta T \cdot c \tag{6}$$

Note that in practice $\Delta f$ is second-order effect, as demonstrated by Zimmerman [2]. For a short-term clock instability of $10^{-9}$ and an allowable error of 1 cm, this translates to a maximum range of 10,000 km or a measurement separation of 33 ms. The measurements can easily be taken much closer to each other than this by using the signal from one of the pseudolites as a latching reference.

Because each transceiver is looking for signals originating close to the ground, multipath is a primary error source. Although experiments to determine the severity of this multipath have not been completed, it could be over a meter for ITP. Since the array is a static entity, this bias does not change with time and cannot be averaged out. It may be somewhat correctable, however, by observing one or more vehicles operating within the array. Ford et al. [4] provide an additional discussion of this pseudolite multipath problem.

Another major error source is geometric in nature. In all previous discussion, it has been assumed that the terrain is relatively flat. This allows one to ignore the fact that there is little observability of height information if all the pseudolites are distributed on the surface. In contrast, actual Martian terrain can be quite rugged, even when landing sites are chosen for their relative flatness. Figure 7 shows the relative error associated with this "flat-Mars" assumption for various baselines and vertical displacements. In a full array, averaging between different pairs will tend to reduce this error.

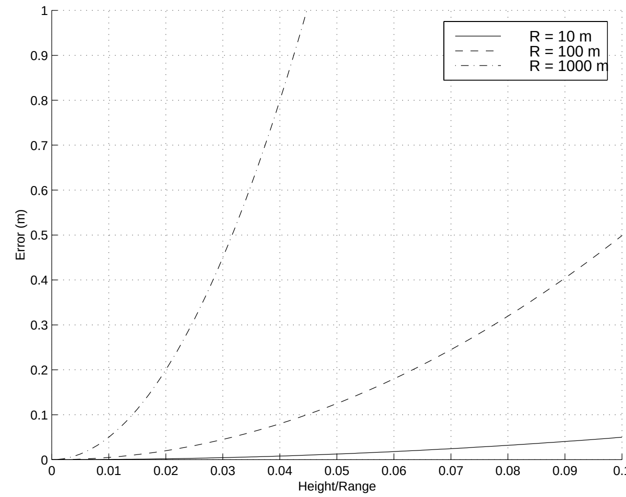


Figure 7: "Flat-Mars" Assumption Errors

It is important to note that these bias error sources, although they do degrade the absolute accuracy of the array, may not necessary harm its ability to provide effective navigation. This is because these errors are highly repeatable with location; ranges and travel times will be distorted, but the rover will still have the ability to reach a specified point.

There is also an associated ambiguity with any SCPA, the so-called "Mirror Ambiguity" (Figure 8). A static array is unable to determine its overall orientation, since the array flipped upside-down would give identical solutions. This can be resolved, however, with a priori knowledge of the basic array pattern or simply by moving the rover in a specified turn and discarding the inconsistent configuration.

## EXPERIMENTAL SYSTEM

The ARL is constructing an experimental testbed in order to further develop and validate this technology. This testbed consists of two parts, the pseudolite array

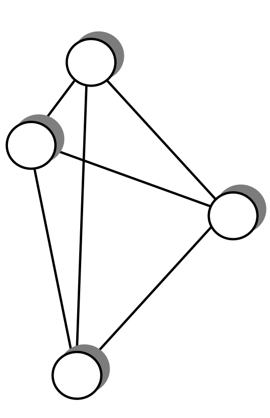

Figure 8: Mirror Ambiguity

Figure 9: Rover Test Platform

and an autonomous rover.

**Pseudolite Array:** The primary component is the pseudolite array, which consists of six transceivers arranged in a rough hexagon to simulate a typical deployment pattern. Each transceiver consists of two devices, an IntegriNautics IN200C pulsed pseudolite and a Mitel Orion receiver, which has been modified to include two RF front ends [5]. These devices have been chosen for their flexibility and programmability. Both receive and transmit antennas are standard hemispherical patches canted in towards the center of the array, although future work will experiment with dipole antennas for more optimal planar operations. Each receiver is equipped with an RS-232 serial link to download raw data to a central ground-station computer for processing.

**Rover Platform:** The rover (Figure 9) serves two purposes, to demonstrate navigational capability once the array is surveyed and to provide motion for integer resolution when using CDGPS. The rover chassis is a 1/10 scale Tamiya RC truck with a modified suspension system to accommodate a payload of 20 lbs. It has an onboard 486 computer to enable autonomous operations. Translation of computer commands to PWM signals for the servos and speed controller is accomplished using a 68HC11 microcontroller. Communication with the reference ground-station is through a wireless Ethernet link. The rover is also equipped with an Orion receiver with two antennas to enable both positioning and heading determination using CDGPS. The rover can also be equipped with an onboard pseudolite to enable it to determine its position using ITP.

## CDGPS

When enough transceivers are available, SCPA accuracy can be improved by using CDGPS. Standard double-differencing techniques - almost directly analogous to ITP methods - allow the survey of transceiver locations by using the rover moving through the array to resolve the integers. The equations can be easily solved by linearizing around previous ITP solutions. A potentially effective surveying technique would be to use dual-frequency wide-laning to resolve the integers without requiring any rover motion. The ITP solution would fix the integers for the 85 cm beat wavelength, and then positioning on this signal would determine the integers for the standard 19 cm carrier wavelength.

CDGPS surveying will likely be required to meet the accuracy requirements of an SCPA for Martian operations, and will be the subject of future experiments.

## CONCLUSIONS

Pseudolites are a useful way of extending GPS navigational capability to areas without coverage by GPS satellites. Self-Calibrating Pseudolite Arrays, by using GPS transceivers to self-survey their own positions, allow the use of pseudolites in areas where accurate surveying by other methods is either impractical or impossible. Using Inter-Transceiver Pseudoranging it is possible to survey the locations of a static pseudolite array to sub-meter accuracy, allowing navigation with similar accuracy within the array. ITP is also usable for dynamic positioning of a moving vehicle within a pseudolite array.

SCPA accuracy on Mars is limited primarily by biases such as multipath and the geometric unobservability of vertical position. These effects can be mitigated through the use of multiple correlators for multipath rejection and possible placement of a transceiver on a mast or other tall structure to provide vertical observability. Other challenges which must be overcome for SCPA use in planetary exploration include long-term power generation (solar cell output drops over time due to dust accumulation) and pseudolite deployment. A communications system for the many array elements must also be developed, possibly by utilizing the pseudolite data message itself.

Other potential uses for SCPAs besides planetary exploration include relative positioning between space vehicles and terrestrial applications such as navigation within factories and warehouses. ITP could also have limited use in time-transfer applications.

## ACKNOWLEDGMENTS

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