# GPS Pseudolite Transceivers and their Applications

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## BIOGRAPHY

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## ABSTRACT

There are an increasing number of applications requiring precise relative position and clock offset information. The Global Positioning System has demonstrated precise and drift free position and timing information using Code-Division-Multiple-Access (CDMA) spread spectrum technology. This technology is widely used and relatively inexpensive, making it attractive in applications beyond the scope of typical satellite based GPS.

In situations with limited or no visibility of the GPS satellites, ground transmitters that emulate the signal structure of the GPS satellites (pseudolites) can be used as additional or replacement signal sources.

Transceivers (which transmit and receive GPS signals) can be used to improve standard pseudolite positioning systems. If their locations are known, transceivers can be used to remove the need for the reference antenna typically necessary in standard differential systems. By using either the GPS satellite signals or other transceiver signals, a self-surveying transmitter array can be implemented, eliminating the need for a priori knowledge of pseudolite locations. In addition, transceivers mounted on vehicles can allow continuous inter-vehicle positioning without the presence of signals from GPS satellites.

This paper provides an overview of the issues associated with GPS transceiver systems. This includes transceiver architectures, capabilities, and limitations. This paper also discusses several transceiver applications being studied at Stanford University including open pit mining, Mars exploration, and multiple-vehicle space-based interferometry.

## INTRODUCTION

Centimeter level position information is becoming increasingly important for autonomous vehicle control. Carrier-phase Differential GPS (CDGPS) readily provides such information. The feasibility of pseudolites has created interest in using existing GPS technology and equipment in situations not normally feasible for GPS satellite only systems, either by augmenting the existing satellite constellation or by replacing it altogether.

Recently, pseudolites have drawn much attention, but continue to be a cause of confusion. The term "pseudolite" has been used to describe any device that transmits GPS satellite-like signals, most often without mention of the other specific features. With the advent of enhanced signal characteristics, the signals transmitted by

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pseudolites are becoming less like the satellite signals. This paper will not discuss all the variations of GPS signal transmitters, but instead summarize the possible features and implementations when used as a transceiver.

Pseudolite transceivers receive and transmit GPS signals. Transceivers give many benefits beyond those associated with simple pseudolites, and can often enable the use of GPS positioning for applications where pseudolite transmitters alone may be inadequate. As with simple pseudolites, GPS transceivers can have many different features, signal structures, and implementations. This paper summarizes several different implementations and provides three examples of transceiver applications being studied at Stanford University.

## BACKGROUND

GPS signal ground transmitters actually predate the GPS satellite constellation, having been used to test the system at a desert test site in Yuma, AZ [29]. They used similar signal structure to the satellites, but different gold codes and data messages, and were named pseudolites due to their pseudo-satellite signals. Since Klein and Parkinson noted that pseudolites could be used to augment the satellite constellation [13], many pseudolite augmentation systems have been proposed.

The Integrity Beacon Landing System (IBLS) was one of the first projects to use pseudolites experimentally. The system used vehicle motion through two pseudolite "bubbles" to reliably resolve CDGPS integers (thereby increasing system integrity) for auto-landing aircraft [5][15][24]. The project introduced many terms, including: Integrity Beacons, Doppler Marker, and Simple Pseudolite. The project also proposed and experimentally tested a version of a pseudolite transceiver, introducing the synchrolite (originally known as an omni-marker).

As IBLS transitioned to the Local Area Augmentation System (LAAS), the pseudolites were moved onto the airport property and titled Airport Pseudolites or APL's (pronounced "apple"). Stacked APL's and In-Track APL's were introduced to deal with the challenge of less vehicle motion through the pseudolite field. The hyperbolic differential wavefronts from the pseudolites allow sufficient integer observability and additionally allow the approach angle to be determined.

Other projects have also used vehicle motion through a pseudolite field to determine carrier phase integers [6][15][18][20][30]. Others have used indoor simple, independent pseudolite transmitter constellations exclusively for positioning [7][22][30][34]. The measurements are used differentially between two receivers to remove the pseudolite clock errors, requiring an additional datalink between the two receivers. In a similar way, research has shown that pseudolites can be used to augment a GPS satellite system by providing additional differential ranging sources [10][28].

Pseudolite transceivers have been proposed as a ranging source available to orbiting satellites that may not have sufficient ones otherwise [1]. Additionally, the ground based synchronized transmitters may be used by GPS receivers on orbiting satellites to greatly improve the vertical dilution of precision.

Conventionally, receivers are placed on moving vehicles that use surrounding transmitters to determine their location. However, the vehicle itself may carry the transmitter and its location determined by multiple surrounding receive antennas [11]. This provides the advantage of simpler (no) processing on-board the vehicle and no data-link required to or from the vehicle and may be appropriate for some applications.

Other research has introduced the use of pseudolites as a battlefield aid for the military [3]. The research proposes higher power, unique signal structures and pulsing schemes to reduce the effects of enemy jamming.

Pulsing has been shown to increase the far to near ratio thereby increasing the functional working area [4][23][31]. Conventional methods using fixed high frequency pulses with low duty cycles are being improved by using spread spectrum pulsing schemes [19]. This allows the use of more pseudolite transmitters than typical fixed duty cycle pulsing schemes provide. More complex pulsing schemes including the Spilker split spectrum pulsing technique [26] may greatly reduce the cross-correlation with the satellite signals, while providing improved protection of the military spectrum.

Recent research has dealt with using pseudolite transceivers for positioning [2][17][7]. This promising research provides a solution with the advantages of pseudolite-based positioning systems while removing some of the disadvantages.

## PSEUDOLITE HARDWARE

The term pseudolite was originally used to refer to any device that transmits GPS satellite-like signals. However, with the advent of new coding methods, pulsing methods, and frequency plans, pseudolite signals are becoming less like the satellite signals. Typically the desired pseudolite signal format is application specific. Table 1 shows an example of the current features that can be incorporated into a typical pseudolite transmitter. Placing the center frequency at a satellite signal spectral null can help reduce cross-correlation with satellite signals, while pulsing is used to reduce the near-far problem [23]. Increasing the data rate can allow the transfer of differential corrections, eliminating the need for additional data links.

If the pseudolite transmitter clock is as stable as the satellite clocks, it may be used as a direct ranging source just like the satellites. However, this option is cost prohibitive and would still require a reference antenna and datalink for differential carrier phase positioning.

Several projects at Stanford University have developed similar inexpensive pseudolite transmitter hardware [4][5][27][28]. The design shown in Figure 1 uses a stable low frequency reference oscillator and a phase-locked-loop to generate the high frequency carrier and a coherent C/A code chipping frequency. The relatively simple design (shown in Figure 2) uses Bi-Phase-Shift-Keying to generate a standard C/A-Code GPS signal. A major design issue is attenuating the extra power effectively so as to not jam the surrounding receivers.

Many manufacturers produce GPS signal simulators intended for lab use and the testing of GPS receivers. It is interesting to note that even though the legal details of broadcasting on L1 has not been finalized, many simulators have ample spare power and may be used with a transmit antenna as a navigational pseudolite. Table 2 lists several manufacturers providing simulators from several thousand dollars to several hundred thousand dollars, depending on the features desired.

**Table 1 – Typical Pseudolite Features**

| Feature | Example Value |
|---|---|
| Output Channels | 1 |
| Center Frequency | 1575.42MHz |
| Coding Method | C/A or P-Code |
| Coding Frequency | 1.023MHz |
| Pulsing Rate/Method | 1KHz with 11% Duty |
| Power Output | -30dbm |
| Stability | Receiver Grade Clock |
| Data Messages | Static/Dynamic |
| Data Rate | 50Hz |
| Synchronization | None |

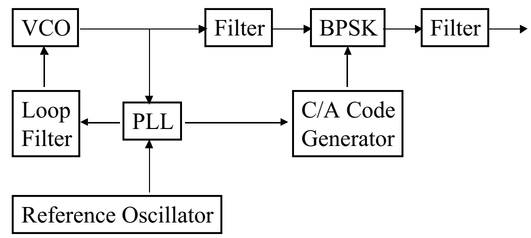


**Figure 1 – Pseudolite Transmitter Block Diagram**

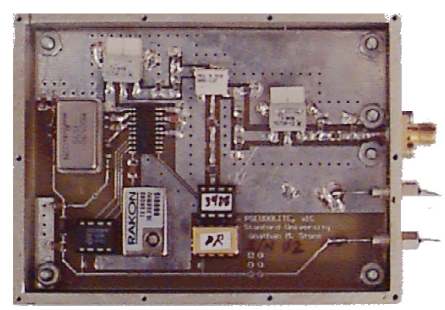


**Figure 2 - Stanford University Single Frequency Pseudolite Picture**

**Table 2 – Pseudolite/Simulator Manufacturers**

| |
|---|
| Global Simulation Systems |
| GPS+ONE Enterprises, LLC. |
| IntegriNautics |
| Rockwell Collins |
| Stanford Telecommunications, Inc |
| WelNavigate |

### PSEUDOLITE TRANSCEIVER IMPLEMENTATIONS

Pseudolite transceivers transmit and receive GPS signals and can be implemented in many different ways. One early implementation of a transceiver simply translates the incoming spectrum to another center frequency [33], commonly called a "bent-pipe". This allows simple transceiver designs by not demodulating and re-modulating the signal but instead requires additional frequency spectrum and more complex user receivers that are capable of receiving several center frequencies. A block diagram is shown in Figure 3.

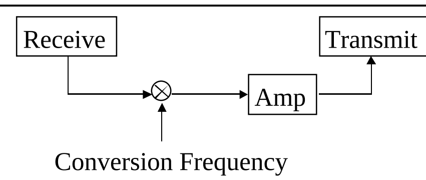


**Figure 3 – Translating Transceiver**

By modulating the transmitted signal with a different code, the signal may be transmitted on the same center frequency, thereby simplifying the user receiver. There are basically two variants of this type of transceiver: those that synchronize their transmitted signal to an incoming one, and those that instead difference the transmitted and received signals and broadcast this difference. Early research on the synchronized pseudolite transceivers introduced the term "synchrolite" [4][5]. We propose the term "differlite" for the second aforementioned category of pseudolite transceivers.

Both types may be implemented with one or two antennas, depending on the number of RF inputs on the receiver. The single antenna designs require a passive antenna that is capable of transmitting and receiving, or a more complex antenna that includes the switch and pre-amplifier. Several implementations are shown in Figures 4A-E and will be discussed in detail below. All of the implementations may connect the receiver and transmitter to a common reference oscillator thereby reducing the phase bias variations between the receiver and transmitter. Pulsing is inherent in the designs shown and is necessary for those with separate transmit and receive antennas in close proximity. The switch must be synchronized to the pulsing scheme of the transmitter for efficient operation.

***Synchronized Transceivers***

Pseudolite transmitters that contain an atomic clock synchronized to GPS time may be used as an additional stand-alone ranging source just like the GPS satellites. By using a GPS receiver to solve for the clock offset from GPS time very accurately, this form of a pseudolite transceiver may synchronize its transmitted signal when sufficient GPS satellites are in view. This allows the transmitted signal to be utilized by the user independently of any GPS satellite or reference station. However, very stable clocks and time-synchronization equipment make this option expensive. Additionally a reference antenna must be used for differential positioning.

Synchrolites provide an economical alternative by using a receiver-grade clock. Synchrolites transmit a signal that has the same frequency as an received signal except modulated with a different code. The receiver de-correlates a signal from a master transmitter (the highest elevation satellite, for example) and communicates the carrier frequency and code phase to the transmitter. The transmitter then re-modulates the carrier with another code that is in phase with the received signal. Even though the transmitted signal is phase-synchronous with the received master signal except with a different code, it will most likely have a relatively constant phase bias that is initially calibrated out of the system. Figure 4A shows an example of a synchrolite with a single, combined receive and transmit antenna. A dual antenna version is not shown here.

***Self-Differencing Transceivers***

Transceivers may also make little attempt to synchronize the transmitted signal with the incoming one, but instead measure the difference and broadcast it to the user on a data-link. Similar to a standard DGPS system with a single reference antenna, this effectively provides a distributed multiple reference antenna positioning system.

Figure 4B shows a single antenna implementation that uses a dual input receiver. The transmitted RF signal is split, with one line connected directly into the second receiver front end and the other connected to the transmit antenna. The dual input receiver allows both the received signals from other sources and the transmitter signals to be input. This design may also be implemented with a single input receiver with a more sophisticated switching mechanism as shown in Figure 4C.

Figure 4D shows a two-antenna design where the receiver listens to the transmitter through the same receive antenna. This has the advantage of only requiring one receiver front end and having common line biases for both RF signals, but imposes a line-of-sight requirement between the transmit and receive antennas.

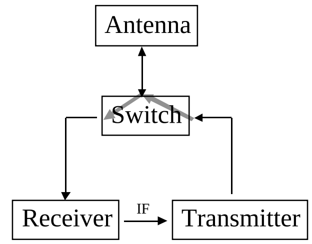


**Figure 4A – Synchronized Transceiver**

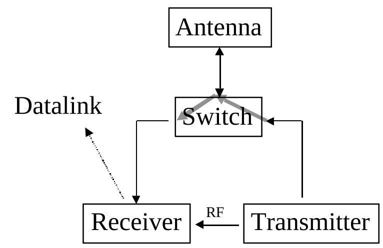


**Figure 4B – Single Antenna, Dual Input Implementation**

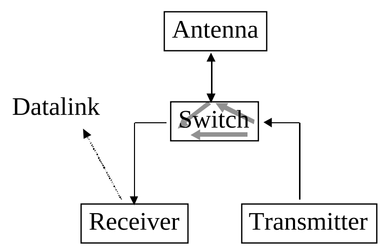


**Figure 4C – Single Antenna, Single Input Implementation**

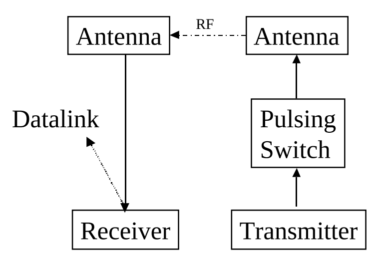


**Figure 4D – Dual Antenna, Single Input Implementation**

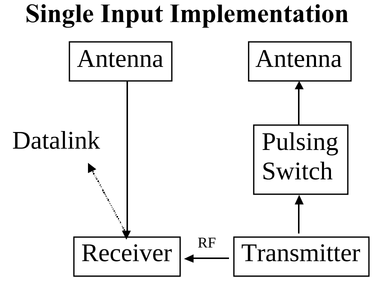


**Figure 4E – Dual Antenna, Dual Input Implementation**

**Table 3 – Summary of Pseudolite Transceiver Implementations**

| Implementation: | Figure 4A | Figure 4B | Figure 4C | Figure 4D | Figure 4E |
|---|---|---|---|---|---|
| | | | | | |
| # of Antennas | 1 | 1 | 1 | 2 | 2 |
| # of Receiver Inputs | 1 | 2 | 1 | 1 | 2 |
| Additional Line-Bias Calibration | Yes | Yes | Yes | No | Yes |
| Synchronized | Yes | No | No | No | No |
| Combined RF design (more complex) | Yes | No | No | No | No |
| Additional Data-link required | No | Yes | Yes | Yes | Yes |
| Antennas must "see" each other | N/A | N/A | N/A | Yes | No |

Figure 4E shows another example of a two-antenna design with a dual input receiver. The transmitted RF signal is split, with one line connected directly into the receiver front end and the other connected to the transmit antenna. The receive antenna would then ideally be placed in the null of the transmit antenna, reducing the transmission path from transmit to receive antenna that could cause interference.

Table 3 summarizes these different implementations, and lists some of the advantages and disadvantages of each. There is not one particular implementation that is best suited for all applications. For example, one application may be required to use a separate receive and transmit antenna in order to shape the transmitted beam. Additionally, synchronizing the transceiver may be desirable to remove the need of an additional datalink if a more complex RF design is manageable.

By using a receiver with several RF front ends, the AGC does not need to change rapidly to account for a large pseudolite transmitter surge. Figure 5 shows a Mitel (formally GEC Plessey) Orion receiver that has been modified at Stanford University with 2 RF inputs [36] that may be used in the dual input self-differencing transceiver implementations. The 12 channel Mitel correlator allows selection of RF input on a channel-by-channel basis. This allows 11 channels to be used to track received signals from other transmitters, and 1 channel to be used to track the transmitter in the current transceiver. Because the entire board is clocked with a common oscillator, phase variations between the RF inputs are very small, although cable line biases must be initially calibrated.

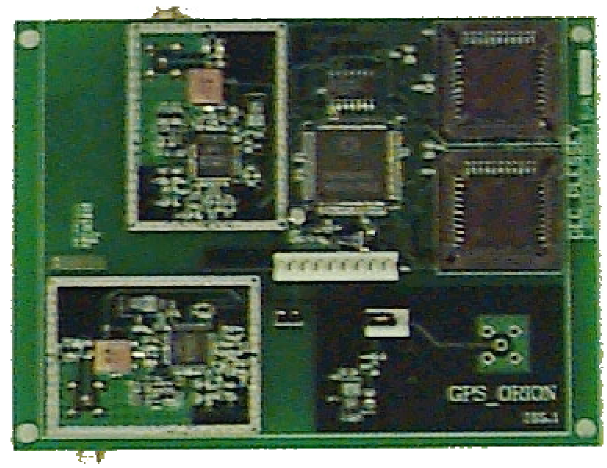


**Figure 5 – Modified Orion Receiver with 2 RF Inputs**

## APPLICATIONS

Traditional differential GPS with independent pseudolites at known locations and a stationary reference station has been fully described in previous papers [10][28][34]. Figure 6 shows an example of this with an open pit mine using satellites and pseudolites with a reference station in view of all the transmitters [28]. Other projects have used similar architectures [10][12][30].

Three applications in which pseudolite transceivers are being investigated at Stanford University are shown in Table 4. They include open pit mining, Mars exploration, and formation flying spacecraft, and will be discussed in detail below.

**Table 4 – Pseudolite Transceiver Applications**

| # | Application Description | Example |
|---|---|---|
| I | Pseudolite Transceivers at known locations used to eliminate the need for reference station. | Open Pit Mining |
| II | Pseudolite Transceivers used to self-calibrate their primarily stationary locations. | Mars Exploration |
| III | Pseudolite Transceivers used to continuously update inter-transceiver range. | Formation Flying Spacecraft |

With all of these applications, measurements can be either code or carrier-phase based with corresponding accuracies. Code phase measurements may be used to reduce the carrier phase integer search volume. In cases with strong multipath, like open pit mining and Mars Exploration, dual frequency wide-laning techniques or motion-based resolution techniques may be required [27]. In addition, each of these applications can use either synchronized or self-differencing transceivers. Currently, self-differencing transceivers are being investigated at Stanford and will therefore require additional data links to broadcast the transceiver signal offsets.

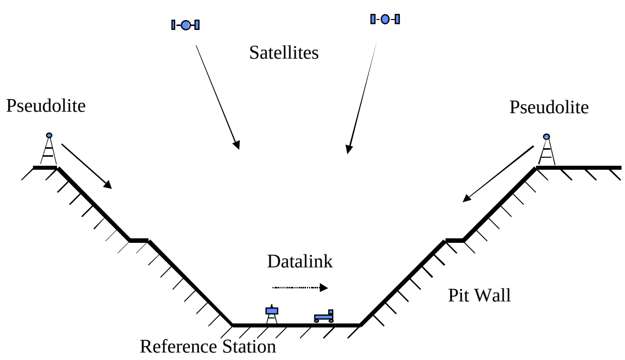


**Figure 6 – Side View of Typical Open Pit Mine Augmented with Pseudolites**

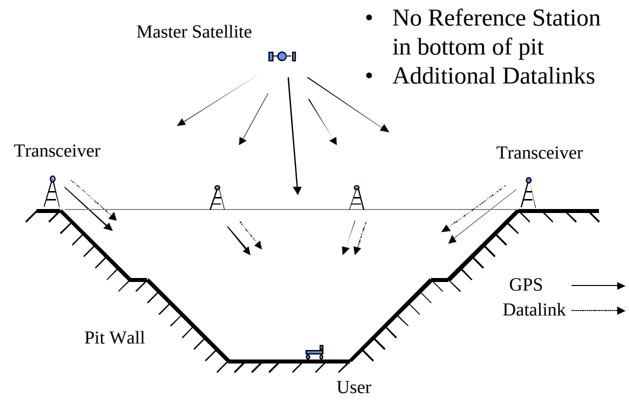


**Figure 7 – Side View of Typical Open Pit Mine Augmented with Transceivers**

### *Open Pit Mining*

The steep pit walls in open pit mining may introduce an obstruction angle up to 45 degrees, thereby reducing the satellite visibility and increasing the Dilution of Precision (DOP). This can reduce the operational time of a satellite only system to 20% of the time [28].

Precise positioning systems have been proposed and experimentally tested using pseudolites along the mine pit rim with a stationary reference station in view of all the transmitters [28]. The traditional system requires that the pseudolites be surveyed relative to a reference station that is in view of all the transmitted signals used by the user vehicle.

Placing a reference station antenna in the center of the working area is undesirable because the mine pit floor is very dynamic and may change daily. Future implementation of the system could employ the use of pseudolite transceivers instead of pseudolite transmitters only, and eliminate the need of the reference station at the bottom of the pit, as shown in Figure 7. The transceiver locations may be determined by initially surveying them with the GPS satellites or traditionally with theodolites.

Figure 8 shows a diagram of how the transceiver measurements may be processed to determine the user position. The pseudolite transceiver location $\overline{P}$ and the satellite location $\overline{S}$ are known, and the user location $\overline{U}$ is to be determined by at least 3 transceiver differential measurements $\Delta\phi$ as shown by the equation below.

$$\Delta\phi = \phi_2 - \phi_1 = \left|\overline{S} - \overline{P}\right| + \left|\overline{U} - \overline{P}\right| - \left|\overline{S} - \overline{U}\right| + \phi_{delay}$$

The transceiver delay $\phi_{delay}$ accounts for the clock offset between the transmitted and received signal within the transceiver. It remains relatively constant for synchronized transceivers and is initially calibrated out of the system. With self-differencing transceivers, it is measured and broadcast to the user. The rate at which the delay is transmitted to the user largely depends on the stability of the transmitter and receiver clocks in the transceiver, and the variations may be reduced by connecting the transmitter and receiver to a common oscillator.

Other issues must also be addressed for open pit mining. For example, conventional methods of attenuating multipath may not be available in an open pit mine. The multipath signals will arrive at the user antenna at significant elevation angles due to the steep pit walls. This suggests alternative integer resolution techniques like dual frequency pseudolite transceivers [27] or vehicle motion. Care must also be taken to ensure elevation angle diversity [28]. Using transceivers with large far/near ratios may allow the transceiver to be placed along the pit walls, and even at the bottom of the pit.

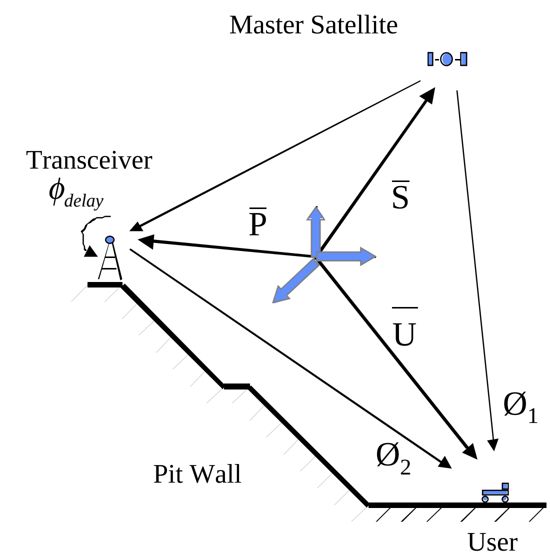


**Figure 8 – Transceiver Positioning in an Open Pit Mine**

### *Mars Exploration*

GPS transceivers may also be used when no GPS satellites are available. One such application is planetary exploration. An array of pseudolites can allow precise local navigation to rovers to aid in surveying and sample collection and retrieval. Unlike conventional pseudolite arrays, however, it is not an easy task to precisely survey the locations of the pseudolites using robots on a foreign planet. Transceivers allow a way around this difficulty by self-surveying their own locations using GPS signals, creating a Self-Calibrating Pseudolite Array (SCPA) [17]. Once the array has self-surveyed, vehicles can move through the area of coverage as if it was a conventional pseudolite array. The array can be either 2-dimensional, only allowing accurate navigation in a plane, or 3-dimensional when suitable geometry is available. Figure 9 shows a conceptual diagram of a planar rover positioning system being developed by Stanford and the NASA Ames Research Center for Mars exploration [17]. Other uses on Mars include assisting in the placement of pre-fabricated habitat modules during the construction of a human-staffed research base.

Figure 10 shows the measurements used for the operation of such a system, assuming that each of the devices is a complete transceiver. Looking at a single pair of transceivers for simplicity, each receiver performs a self-differencing operation on its own and the other transmitted signal. Combining these two measurements allows one to solve for both the range between the devices $r_{12}$ and the relative clock offset $\tau$ as shown in the equation below [17].

$$\begin{Bmatrix} \phi_{11} - \phi_{21} \\ \phi_{22} - \phi_{12} \end{Bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{Bmatrix} r_{12} \\ \tau \end{Bmatrix}$$

Once the ranges between all the devices have been calculated, simple geometry will yield the actual relative positions of the devices in the array.

It is important to note that the entire array solution can translate and rotate in space. There can also be multiple solutions, as if the entire array were mirrored about a horizontal plane. In contrast to standalone GPS satellite positioning system, redundant measurements in an SCPA will not eliminate this “mirror ambiguity”.

Similar techniques are useful for both carrier- and code-phase measurements. Motion of one of the devices can be used to resolve the integers when using carrier-phase measurements. With a transceiver located on a rover, measurements are taken as the rover traverses the array and processed to resolve the integer ambiguities. This technique requires an additional transceiver beyond those required for code-phase navigation. Transceiver motion can also be used to resolve the mirror ambiguity mentioned previously.

Using GPS transceivers for navigation on a planetary surface poses several special challenges. The nearly planar configuration makes it difficult to observe out-of-plane displacements. If the array is assumed to be planar when it is not, the position solutions will be slightly in error, yielding an effective "warping" of the navigational area of the array. Another related problem is that of multipath. Since all of the transmitted RF paths are close to the ground, antennas with low gains at low elevations angles cannot be used to suppress multipath. This will result in further biases, which will vary with rover position. However, because the transceivers remain relatively stationary, multiple correlator or other multipath mitigation techniques may be employed. Additionally, because the rover moves very slowly, time averaging can be used to eliminate random errors from the position solutions. This is especially useful for code-phase operation.

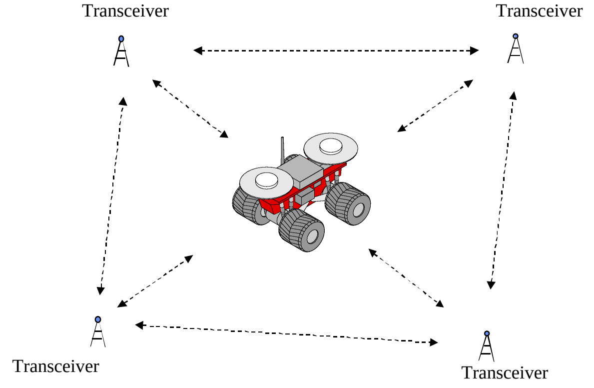


**Figure 9 – Mars Exploration**

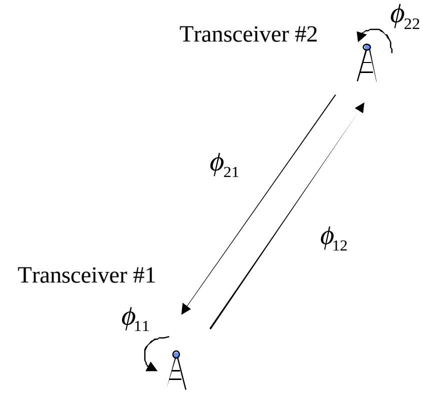


**Figure 10 – Inter-Transceiver Measurements**

### *Formation Flying Spacecraft*

It is sometimes desirable to use GPS to determine the relative positions between vehicles, either for station keeping, formation flying, or collision avoidance. This often occurs in locations where adequate GPS satellite coverage is unavailable. GPS transceivers mounted on the vehicles can allow relative positioning in such cases by augmenting the GPS satellite constellation, and can potentially act as a self-constellation when no GPS satellites are available. Corazzini et.al. at Stanford University are developing such an augmentation system for use in near-earth orbit through formation flying experiments [7][8]. One application where this technology is very useful is in the stellar interferometers for NASA's New Millennium Program. These interferometers are composed of multiple collector spacecraft and a central combiner spacecraft which must maintain nanometer-level relative positioning, most likely by using a combination of GPS positioning and an optical system for the ultra-precise positioning. Some plans for this system call for faster code and carrier frequencies (Ka-band) to improve accuracy [14][25].

Typical measurements consist of single and double differences between GPS satellites or onboard pseudolites and the multiple attitude antennas on a single vehicle, or differences between antennas on different vehicles. The latter measurements are coupled in position and attitude when the signals come from the onboard pseudolites, due to the non-linearities associated with the spherical wavefronts. The equations for formation flying vary depending upon the number of GPS satellites available, and are beyond the scope of this paper. We therefore refer the reader to [7][8], which provides equations for both satellite augmentation and self-constellations.

Using onboard transceivers for relative positioning between vehicles in the absence of GPS satellite signals bears some similarity to the use of SCPAs. There are several notable differences, however. First, the dynamic relative motion requires real-time position updates and also limits the use of time averaging to reduce random errors. Secondly, in many cases the vehicles involved are using GPS to determine attitude or heading as well. This gives multiple baselines between the vehicles, adding robustness and redundancy. Multipath becomes much less of a problem for spacecraft because of the absence of ground reflections, and reflections off the vehicles themselves can be at least partially calibrated for formations controlled to constant relative positions and attitude. Finally, because all of the devices in the system are mobile, vehicle motion becomes a more attractive method for integer determination.

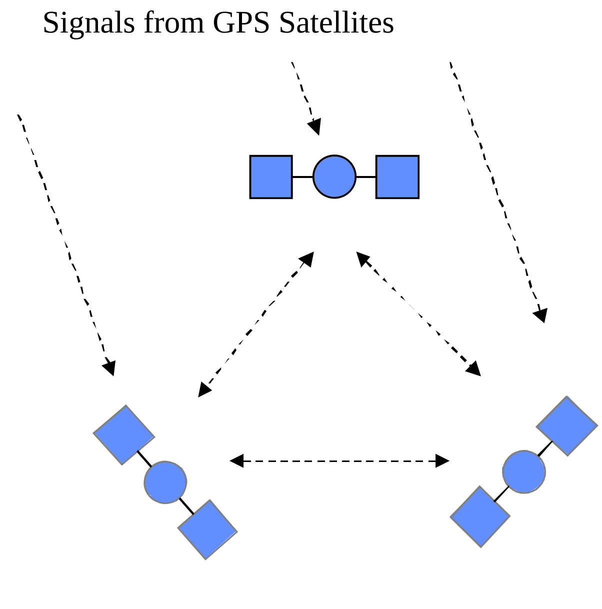


**Figure 8 – Formation Flying Spacecraft**

## CONCLUSIONS

GPS transceivers are an effective way to expand the capability of GPS positioning systems. This can be done by eliminating differential reference stations, allowing pseudolites to self-survey their own locations, or enabling relative positioning between multiple vehicles. Examples of applications employing such advanced capabilities include open-pit mining, rover navigation for Mars exploration, and formation flying for space-based interferometers.

Transceivers themselves can be built in many different fashions. Among those that broadcast at the standard GPS frequencies, they may be implemented in either a synchronous manner by re-modulating a different code onto a received GPS signal (synchrolites) or by measuring the difference between the transmitted and received signal (self-differencing transceivers). Both types can be built with either one or two antennas, and the self-differencing tranceivers can use either a direct line into a second RF front end or rely upon transmission between the transmit and receive antennas. The disadvantage of additional datalinks is eased by the advantage of a simpler RF design.


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## REFERENCES

[1] Altmayer, C., Martin, S., Theil S., "Autonomous Onboard Orbit and Attitude Control of Geostationary Satellites Using Pseudolites", Proceedings of ION-GPS-98, Nashville, TN, Sept. 1998, pp. 1565-1575.

[2] Altmayer, C., "Experiences Using Pseudolites to Augment GNSS in Urban Environments" Proceedings of ION-GPS-98, Nashville, TN, Sept. 1998, pp. 981-991.

[3] Carlson, Stephen G. et. al. "The Expanding Universe of Military Pseudolite Systems", 24th JSDE Symposium, Anaheim, CA, Nov. 16, 1998, Session 6A.

[4] Cobb, H.S., GPS Pseudolites: Theory, Design, and Applications, Ph.D. Thesis, Stanford University, September 1997.

[5] Cobb, H. Stewart et al. "Theory and design of pseudolites" Proceedings of the 1994 National Technical Meeting, San Diego, CA, USA. Navigating the Earth and Beyond, Institute of Navigation 1994, pp. 69-75.

[6] Cohen, Clark E. et al. "Autolanding a 737 using GPS Integrity Beacons" Navigation, Vol. 42, No. 3, Fall 1995.

[7] Corazzini, T., How, J.P., "Onboard GPS Signal Augmentation for Spacecraft Formation Flying", Proceedings of ION-GPS-98, Nashville, TN, Sept. 1998, pp. 1937-1946.

[8] Corazzini, T., Robertson, A., Adams, J.C., Hassibi, A., How, J.P., "GPS Sensing for Spacecraft Formation Flying", Proceedings of ION-GPS-97, Kansas City, MO, Sept. 1997, pp. 735-744.

[9] Elkaim, Gabriel et al. "System identification of a farm vehicle using carrier-phase differential GPS" Proceedings of ION-GPS-96. Part 1 (of 2), Kansas City, MO, USA. v 1 1996, pp. 485-494.

[10] Ford, Tom, et al., "HAPPI - a High Accuracy Pseudolite/GPS Position Integration", Proceedings of ION-GPS-97, Kansas City, MO, Sept. 1997, pp. 1719-1728.

[11] Holden, Tom, et al., "Development and Testing of a Mobile Pseudolite Concept for Precise Positioning", Proceedings of ION-GPS-95, Palm Springs, CA, Sept. 1995, pp. 817-826.

[12] Holden, T. and Morley, T. "Pseudolite Augmented DGPS for Land Applications", Proceedings of ION-GPS-97, Kansas City, MO, Sep. 1997, pp. 1397-1404.

[13] Klein, D., Parkinson, B.W., "The Use of Pseudolites for Improving GPS Performance", Global Positioning System, Vol. 1, Institute of Navigation, Washington, DC, 1980.

[14] Lau, Kenneth, et al., "An Innovative Deep Space Application of GPS Technology for Formation Flying Spacecraft", Proceedings of the AIAA GNC, San Diego, CA, July 1996.

[15] Lawrence, D.G., Aircraft Landing Using GPS - Development and Evaluation of a Real Time System for Kinematic Positioning Using the Global Positioning System, Ph.D. Thesis, Stanford University, 1996.

[16] Lawrence, David et. al. "Augmenting kinematic GPS with a pulsed pseudolite to improve navigation performance" Proceedings of the 1996 National Technical Meeting, Santa Monica, CA, USA., Institute of Navigation 1996, pp. 537-545.

[17] LeMaster, E.A., Rock, S.M., "Mars Exploration Using Self-Calibrating Pseudolite Arrays", Proceedings of ION-GPS-98, Nashville, TN, Sept. 1998, pp. 1967-1974.

[18] Montgomery, P.Y., Carrier Differential GPS as a Sensor for Automatic Control, Ph.D.. Thesis, Stanford University, 1996.

[19] Ndili, A. "”GPS Pseudolite Signal Design", Proceedings of ION-GPS-94, Salt Lake City, UT.

[20] O'Connor, M.L., Carrier Phase Differential GPS for Automatic Control of Land Vehicles, Ph.D.. Thesis, Stanford University, December 1997.

[21] O'Connor, Michael et al. "Kinematic GPS for closed-loop control of farm and construction vehicles" Proceedings of ION-GPS-95, Palm Springs, CA, v 2 1995, pp. 1261-1268.

[22] Olsen, E. "3D Formation Flight using Differential Carrier-phase GPS Sensors" Proceedings of ION-GPS-98, Nashville, TN, Sept. 1998, pp. 1947-1956.

[23] Parkinson, B. et al, ed., Global Positioning System: Theory and Applications, Vols. II, Chapter 2. Pseudolites, Elrod, B.D et al, American Institute of Aeronautics and Astronautics, 1996.

[24] Pervan, B., Navigation Integrity for Aircraft Precision Landing Using the Global Positioning System, Ph.D. Thesis, Stanford University, March 1996.

[25] Purcell, G. et al, "Autonomous Formation Flyer (AFF) Sensor Technology Development", 21st Annual AAS Guidance and Control Conference, American Astronautical Society, Breckenridge, CO, Feb. 1998. (AAS 98-062)

[26] Spilker, J., "A Family of Split Spectrum GPS Civil Signals" Proceedings of ION-GPS-98, Nashville, TN, Sept. 17, 1998, pp. 1905-1914.

[27] Stone, J.M., Powell, J.D., “Carrier Phase Integer Ambiguity Resolution Using Dual Frequency Pseudolites”, Proceedings of ION-GPS-98, Nashville, TN, Sept. 17, 1998, pp. 961-968.

[28] Stone, J.M., Powell, J.D., "Precise Positioning with GPS near Obstructions by Augmentation with Pseudolites", Proceedings of IEEE PLANS 1998, Palm Springs, CA, pp. 562-569.

[29] Strada, J.A., Henderson, D.W., "Navstar Field Test Results", Global Positioning System, Vol. 1, Institute of Navigation, Washington, DC, 1980.

[30] Teague, E.H., Flexible Structure Estimation and Control Using the Global Positioning System, Ph.D. Thesis, Stanford University, May 1997.

[31] Van Dierendonck, A.J., Fenton, P., Hegarty, C., "Proposed Airport Pseudolite Signal Specification for GPS Precision Approach Local Area Augmentation Systems", Proceedings of ION-GPS-97, Kansas City, MO, Sept. 1997, pp. 1603-1612.

[32] Weiser, Martin, “Development of a Carrier and C/A-Code Based Pseudolite System” Proceedings of ION-GPS-98, Nashville, TN, Sept. 1998, pp. 1465-1475.

[33] Wells, Lawrence L., “New Translated GPS Range System”, Proceedings of ION-GPS-97, Kansas City, MO, Sept. 1997, pp. 1705-1709.

[34] Zimmerman, Kurt et al. "Experimental demonstration of GPS for rendezvous between two prototype space vehicles" Proceedings of ION-GPS-95, Palm Springs, CA, v 2 1995, pp. 1905-1913.

[35] Zimmerman, K., Experiments in the Use of the Global Positioning System for Space Vehicle Rendezvous, Ph.D. Thesis, Stanford University, 1996.

[36] Receiver dual front-end modification by Eric Olsen, Stanford University, 1997.