TRACKING SMALL SATELLITES USING TRANSLATED GPS

Don K. Lefevre, President, and
Daniel J. Mulally, Vice President

Cynetics Corporation
P.O. Box 2422 / 3824 Jet Dr.
Rapid City, SD 57709

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ABSTRACT

This paper discusses using translated GPS for tracking small satellites, the technical trade-offs involved, and the position and timing accuracies which are achievable using translated GPS.

The Global Positioning System (GPS) uses the relative times-of-arrival of multiple spread-spectrum signals at an antenna to determine the position of the antenna. The system can also determine the time the antenna was at that position. The direct-sequence spread spectrum signals are transmitted from GPS satellites whose orbital position and timing (the ephemeris data) are accurately known.

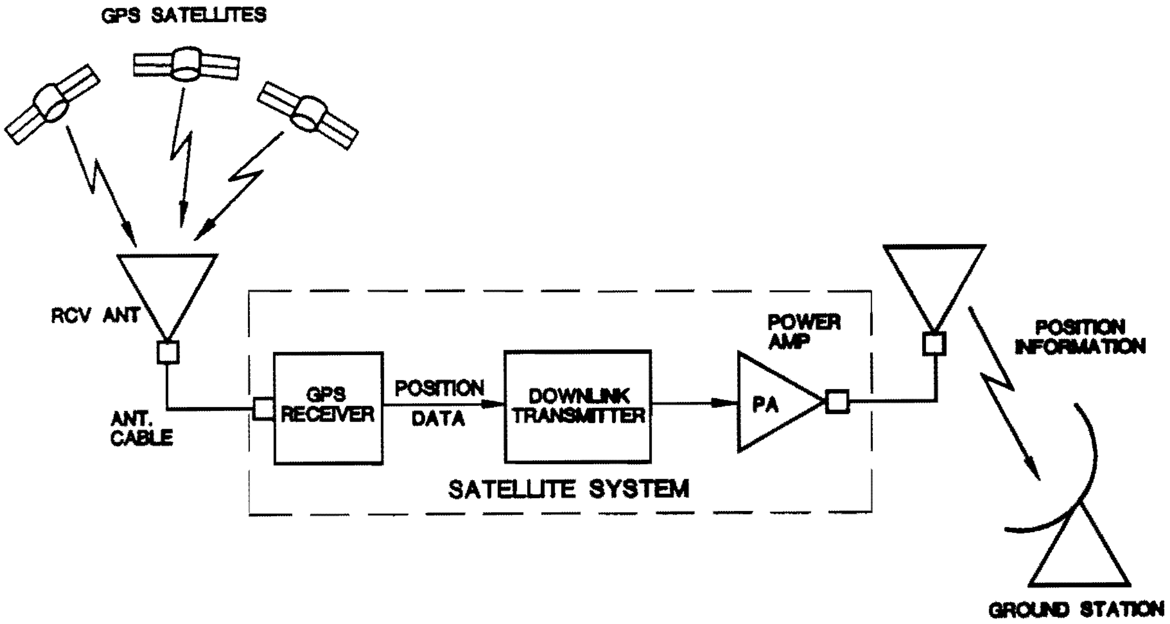
Once the GPS signals are received at the antenna, their relative timings are fixed, and are not changed in subsequent amplifications and signal processing. This fact can be used to track small satellites to a high degree of accuracy without placing a GPS receiver on the satellite. A GPS antenna is placed on the satellite, and the received signals are amplified, converted to a new frequency, and retransmitted to a ground-based GPS receiver. In the most cost-effective arrangement, the ground GPS receiver consists of a low-noise amplifier, a frequency converter to the original GPS frequencies, and an off-the shelf GPS receiver. The off-the-shelf receiver may be coupled to a computer for extensive post-processing. Such post-processing is currently available for IBM PC's.

The advantages of this translated-GPS tracking are that high-order GPS receivers with large amounts of post-processing can be used for tracking spacecraft, while leaving the spacecraft electronics very simple. This allows highly precise, inexpensive, and power-efficient GPS systems to be used on small satellites without: the risk of non space-qualified GPS receivers; the expense of space-qualified receivers; or the power-consumption of high-order receivers.

1. INTRODUCTION

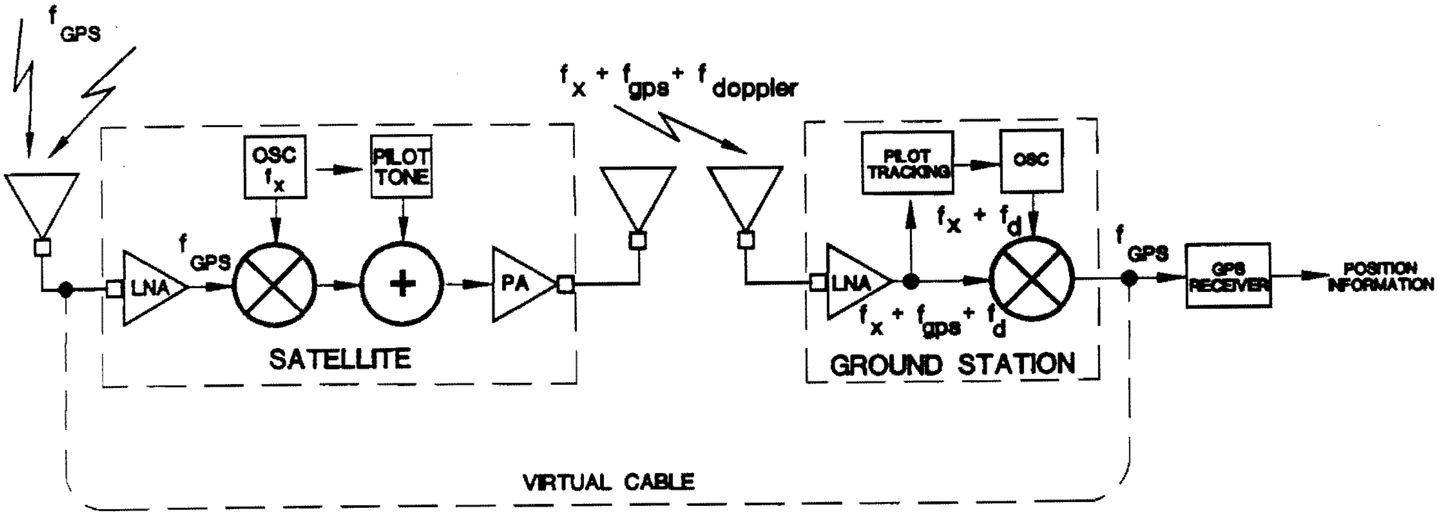
The Global Positioning System, GPS, is an attractive means for determining the position and orbital ephemerides of lightsats. However, the velocities of low-orbiting satellites are high, and simple, cost-effective GPS receivers may not give the desired satellite position accuracies.

Translated GPS tracking can provide highly accurate positioning with extremely simple spacecraft electronics. In a translated GPS system, the GPS signals received at a satellite's GPS antenna are translated in frequency, amplified, and re-transmitted to a ground station. At the ground station, the signals are re-translated to the original frequencies and fed into a conventional GPS receiver. This receiver then calculates the position of the satellite at the time the GPS signals arrived at the satellite's GPS antenna. This has the effect of creating a longer, "virtual" cable between the antenna and the GPS receiver, which is now located on the ground. This is shown in Figure 1.



(a) On-board GPS system

Fig. 1. Comparison of On-Board and Translated GPS Systems for Lightsats.



(b) Translated GPS system.

Fig. 1, cont. Comparison of On-Board and Translated GPS Systems for Lightsats.

2. THE GPS SYSTEM

GPS receivers determine positions by precisely calculating the distances from several GPS satellites to the receiver's antenna. (Actually, differences in distance are used, but once a solution is obtained, the actual distances are available. So, for simplicity, we will discuss the GPS system from the viewpoint of distance measurements, rather than distance-difference measurements.)

If the GPS receiver is a distance r1 from satellite s1, and a distance r2 from satellite s2, then it must lie on the circle formed by the intersection of the spherical surfaces of radius r_1, and r_2. If the receiver is a distance r_3 from a third satellite, then r_3 will intersect the r_1, r_2 circle at two points as shown in Fig. 2. By determining intersections in this fashion, the position of the receiver's antenna is determined.

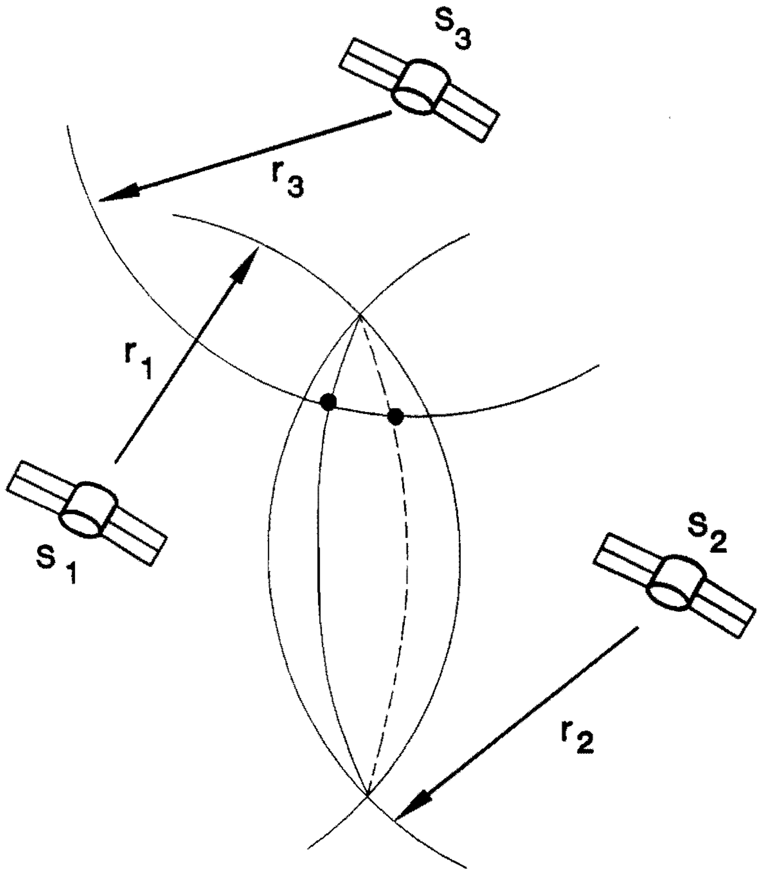


Fig. 2 Position Determination by Intersecting Spherical Surfaces.

The Distance Measurements. The distances from the satellites are found by determining the delays (actually delay differences) in direct-sequence pseudonoise (PN) codes which are transmitted synchronously from the GPS satellites. This signal structure has the advantage of having many transitions, which give high positioning resolution, while maintaining the ability to resolve the ambiguities inherent in carrier-phase positioning systems. The phase-lock loop which tracks the code transitions may have rms tracking jitter on the order of one degree to a few degrees. This gives high resolution which corresponds to the spatial length of the tracking jitter, but it does not distinguish between a one-degree phase difference between, for example, PN chips 23 and 37 (a chip is a "bit" in the PN code) or chips 53 and 213. Without a resolution of this ambiguity, very many position solutions are possible. It is the long length of the code (1023 chips for the C/A Code), relative to one chip, that allows PN ranging systems to achieve high accuracy (from chip-clock phase-locked tracking) and ambiguity resolution (from the chip position within the code.) So, GPS determines position by phase differences on the received pseudonoise (PN) codes, as shown in Fig. 3.

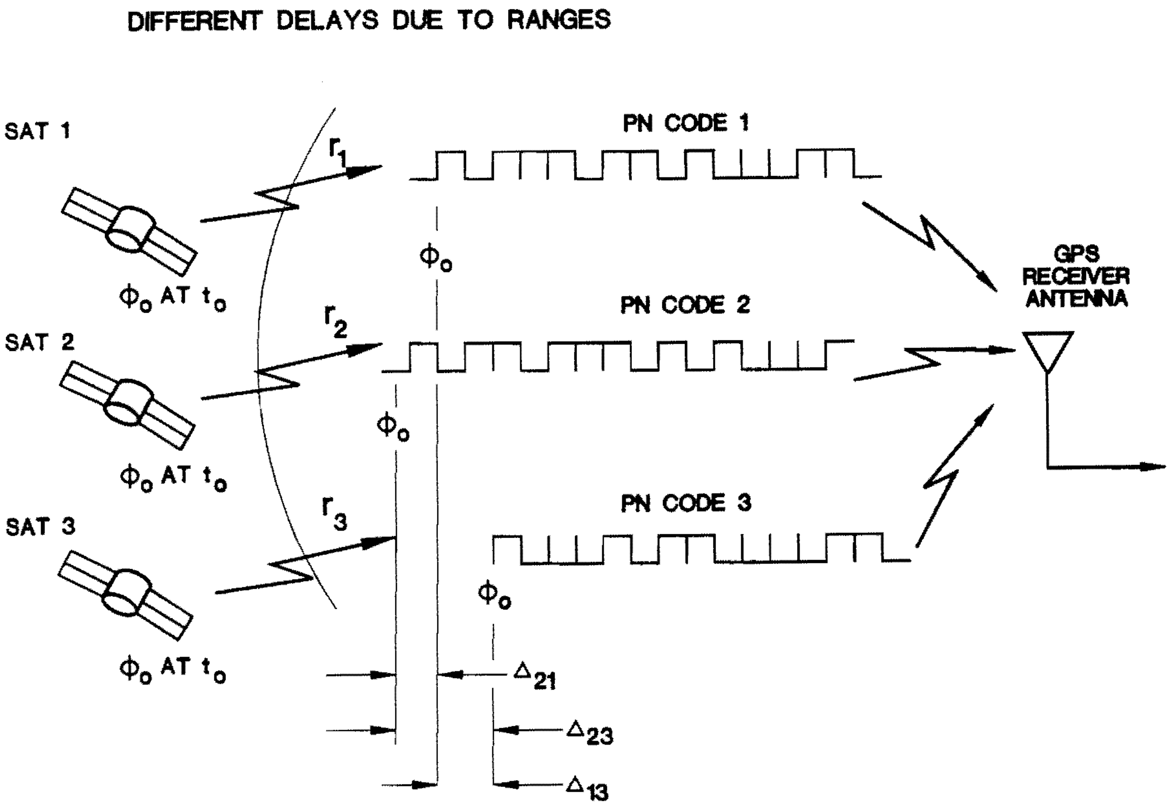


Fig. 3. Position Determination by Phase Differences on PN Codes.

All of the satellite PN codes are received simultaneously, within the same bandwidth. (However, there are <u>two</u> carrier-frequencies, 1575.42 MHz and 1227.60 MHz, which are used to accurately determine velocity of propagation through the atmosphere, so that correct distances can be determined from the time delay information.) The signals are able to occupy the same bandwidth because of the anti-jamming and multiple access properties of spread spectrum signals, as discussed in [1].

The position of the receive antenna (relative to the known positions of the satellites) is determined, as stated previously, from the phase differences between the received codes. However, note that once the codes in Figure 3 have been received at the antenna, their relative phases do not change. This is what allows translated GPS tracking: once the relative code phases are set by reception of the codes at the antenna, the calculation of the corresponding x,y,z, and t can be done at another time and place.

So, in translated GPS tracking, the signals received at the antenna are amplified by a low-noise amplifier (LNA), shifted in frequency, and re-transmitted to a remote GPS receiver. (A pilot-tone is added to aid in tracking out the Doppler shift.) The remote receiver then determines the x,y,z, and t that existed at the moment the signals were initially received. This process was shown in Fig. 1.

3. ADVANTAGES AND DISADVANTAGES OF TRANSLATED GPS

Advantages

The primary advantages of translated GPS are from simplification of the circuitry required on the spacecraft in order to achieve highly accurate spacecraft positioning. The position information is not immediately available to the satellite, but very accurate ephemeris (orbit geometry) data can be uplinked to the spacecraft, which can then extrapolate over a short period of time to predict its present position. Or, payload data and the translated GPS signals can be simultaneously "time-tagged" so that the exact satellite position at the time the data was taken can be determined.

Placing a simple GPS translator in the spacecraft can significantly improve size, weight, and power consumption when compared to many high-order multi-channel GPS receivers capable of handling handle the high velocities of low-orbit satellites. Relay of the actual GPS signals to a ground station allows for extensive post-processing for improvement of ephemeris data. This post-processing can be done with existing software on simple platforms, such as personal computers. Indeed, with this software post-processing approach, very high-order Kalman filters with multiple received channels can be implemented without hardware risk (and particularly without spacecraft hardware risk). These high-order algorithms can track <u>very</u> high dynamics. They have been used extensively by the Range Applications Joint Programs Office (RAJPO) and the Western Space and Missile Center for tracking high-dynamic ballistic missile tests [2],[3].

Translated GPS allows the user to continue to upgrade his tracking algorithms by making changes at the ground station. This is done with ground hardware that does not require space qualification.

Translated GPS can gain a 6-dB theoretical advantage over on-board GPS (temporarily ignoring translator oscillator phase noise) when the direct-path GPS signals (those which go directly from the satellite to the ground station) are used to remove the data modulation from the translated signal. The translated signal is then tracked by the code-lock loop in the GPS receiver [2]. This allows tracking the translated signal with the data removed, so that noisy, data-removing squaring loops are not required.

Disadvantages

Translated GPS requires a large bandwidth (2 - 2.5 MHZ or more, depending on Doppler shifts) for relaying the signals to ground. Real-time positioning at the satellite must be obtained from extrapolating the uplinked ephemeris data by the round-trip-plus-calculation delay from the satellite to the ground and back.

Representative Performances

Consistent, absolute position accuracies of 20 meters have been achieved in real-time (i.e., at the ground station) in U.S. Navy Trident missile tests using translated GPS [2]. Post-processed accuracies of 8m have also been shown.

Tests of the "TPS" translated GPS missile-tracking system on an Apache sounding rocket in March 1990 [4] achieved 15 - 20 m rms position accuracies with velocity errors of roughly 0.1 m/s. The Apache vehicle accelerates at nearly 40 g's for five seconds, but special tracking loops can enable the TPS translated-GPS system to handle up to 50g accelerations and 50g/sec jerk [3].

CONCLUSIONS

Translated GPS is a simple, reliable, low-risk and low-cost means of providing high-order tracking of small satellites. Receivers and algorithms can be readily updated since a virtual cable (the translator system) connects the antenna on the spacecraft to the GPS receiver, which remains at the ground station.

Some degradation in performance may occur due to phase noise (jitter) on the oscillators used in the translators. However, it is also possible to achieve a significant (6 dB) improvement in signal-to-noise ratio by using a second ground-based GPS receiver to remove data modulation before tracking the GPS signals. (This allows tracking without the added noise of squaring loops.) Also, most translated GPS systems inject a pilot tone derived from the translator oscillator into the downlink signal. This allows prereceiver Doppler tracking and removal. It also provides reference information of the translator oscillator frequency offsets.

The same GPS receiver that was being considered for space qualification for a given lightsat can now be used in the ground station with complete accessibility for hardware upgrades and extensive post processing.

In those applications requiring position information at the satellite, short extrapolations of accurate ephemerides can provide this information. Alternately, in many applications, downlink data can be time-tagged for determining position and time from translated calculations.

Translated GPS tracking is a navigation system which should be considered for many lightsat systems.

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