Experience Using GPS For Orbit Determination of a Geosynchronous Satellite

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BIOGRAPHY

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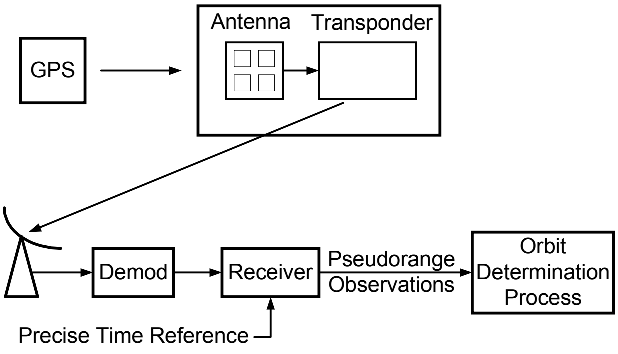
ABSTRACT

There has long been speculation in the GPS user community about the viability of GPS-based satellite navigation from orbits above the GPS constellation. This paper addresses the speculation by describing the experience of a restricted United States satellite program that has routinely been using GPS pseudorange data for orbit determination at geosynchronous altitude for several years. Included is: a discussion of the design issues unique to the geosynchronous application, a description of the implementation, a discussion of the operational results and some observations about accuracy. In addition, actual received signal strength data are presented to illustrate the L_1 transmit antenna pattern difference between the Block II-A and Block II-R GPS vehicles.



Block Diagram of GPS from Geosynchronous Orbit

1.0 INTRODUCTION

There has long been speculation in the GPS community regarding the viability of satellites exploiting the GPS signal for navigation from above the GPS constellation, such as at geosynchronous altitude. Experience gained from the implementation of a transponder-based system has demonstrated that routine, reliable orbit determination is, indeed practical from this orbit altitude. This paper presents the design issues relevant to this application, describes the implementation design of both the space and ground portions and discusses operational experience.

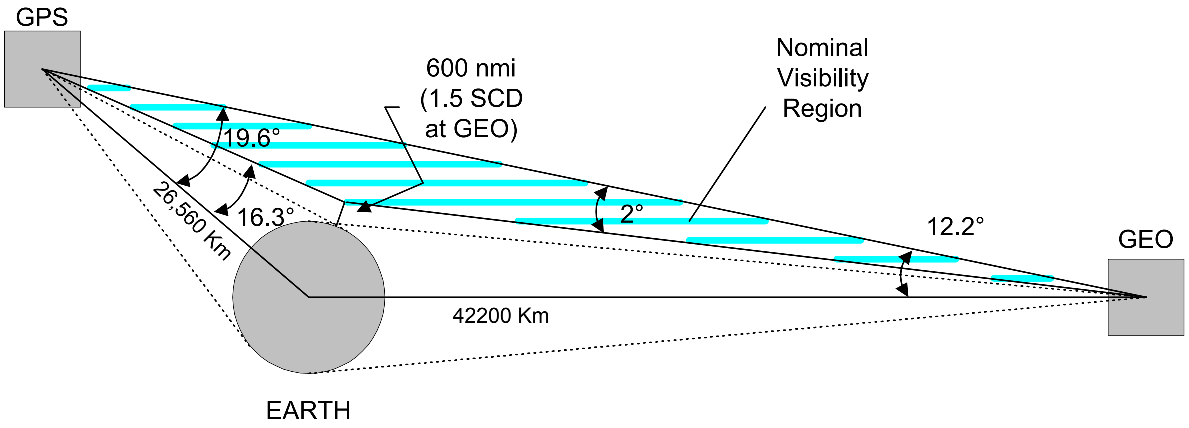
The theoretical bases for this implementation have been presented in numerous papers; this paper does not attempt to repeat those but rather concentrates on the experience of implementation. Several relevant recent papers are listed as References at the conclusion of this paper.[1,2,3,4] Because the spacecraft to which this solution has been applied is one with restricted access, some details of the implementation – especially concerning the spacecraft itself – have of necessity been omitted.

2.0 DESIGN ISSUES

This spacecraft program employed a ground-based receiver, producing two-leg GPS pseudorange data for use in the Orbit Determination process. This section identifies the driving design issues and describes the approach used by this program to address each issue.

2.1 Visibility

GPS visibility at geosynchronous orbit is sparse when compared to low altitude users. Being far above the GPS orbits, the user spacecraft can close the link with the GPS vehicles only when they are on the far side of the earth, illuminating the user spacecraft with spill-over energy in the side of the GPS L_1 transmit beam main lobe.

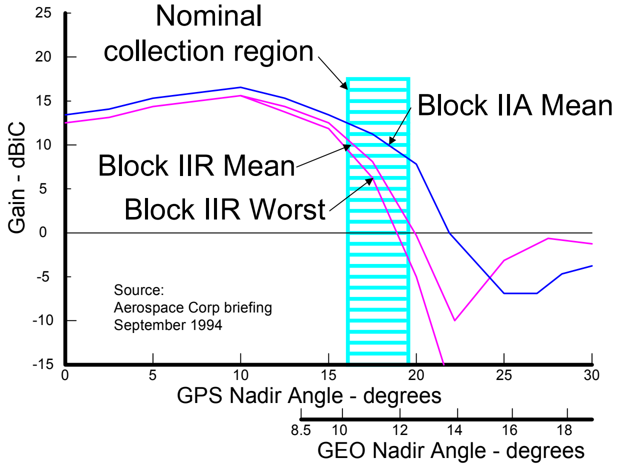


GPS Visibility from Geosynchronous Orbit

Sparse visibility drives an on-board receiver solution to use a very high quality on-board clock; the transponder solution eliminates the need for any knowledge of time onboard the spacecraft.

2.2 Closing the Link

Because the user spacecraft both is seeing the skirt of the main lobe of the GPS transmit beam and is significantly (more than twice) farther away than a terrestrial user, a simple antenna will not suffice to close the link reliably. Fortunately, only modest gain is needed to provide a reliable link; 9dB or more is adequate.



Source:
Aerospace Corp briefing
September 1994

GPS Transmit Antenna Patterns

2.3 Anomalous Doppler

The doppler imposed on the GPS signal as it appears at the ground receiver has two components. One is due to the relative motion between the user spacecraft and the GPS spacecraft and the other is due to the relative motion between the user spacecraft and the receiver on the ground. The ratio of the L_1 carrier to the C/A code frequency, normally an immutable 1540 (1575.42/1.023) for terrestrial direct users, is changed by the two-leg signal path. Specifically, because the GPS signal is frequency translated on the spacecraft, the doppler induced by spacecraft/ground relative motion does not scale to the 1540 ratio. The ground receiver must implement separate carrier and code tracking loops. We call the code doppler discrepancy from a 1540 ratio to the carrier *anomalous doppler*. The magnitude of the doppler anomaly is a function of the user spacecraft orbit dynamics and the IF frequency.

2.4 Dynamics

It is possible for spacecraft orientation and motion to induce errors in the pseudorange measurement if they are not accounted for. This may or may not be a factor in any given application depending upon the size of the spacecraft, the distance from the spacecraft's center of gravity to the GPS antenna and the accuracy required for the mission.

2.5 Signal Path Delay

Ideally, the delay through the entire GPS signal path should be known precisely; the next best – if it is not possible to have this knowledge – is to know that the delay is highly stable. One can solve for a constant bias component of the delay as a part of the orbit determination process.

3.0 ARCHITECTURE

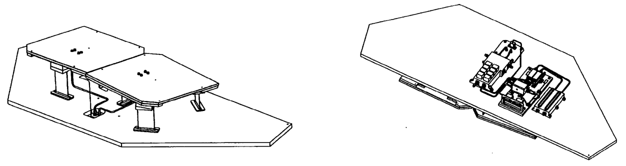
In this section, the specific implementation for this application is described. A transponder architecture was selected because it offered less risk, lower cost and less weight than a receiver in space. Because it is possible to avoid atmospheric effects entirely, a

C/A-only architecture with Selective Availability correction was adopted.

3.1 Space Vehicle

3.1.1 Antenna

Two candidate antenna designs suitable for this application are a horn and a patch array. The choice between the two would probably be made on the basis of spacecraft accommodation. In the case of the implementation being described now, a four-patch array was chosen. A low-noise preamplifier is located adjacent to the patch array. The square array of four 3-inch square patches provides at least 9 dB gain and a half-power beamwidth of 37°. Initially, the design called for two redundant arrays and then an innovative feature was added: the arrays are both used, fed to a combiner circuit to yield roughly semi-conic patterns with approximately 2.5 dB additional gain. One semi-conic covers the northern and the other the southern hemisphere. Should one of the arrays or its associated pre-amplifier fail, the remaining array would revert to a full conic pattern.



GPS Patch Array Antenna and Electronics

3.1.2 Transponder

The transponder provides a simple frequency translation from GPS L_1 to a convenient IF which can either be broadcast directly or applied as modulation to another carrier. For this particular project, the later approach was adopted.

The local oscillator (LO) in the transponder is phase locked to the command uplink which is, in turn, phase locked to a precision frequency source. This serves two purposes: first, it preserves the integrity of the accumulated delta range (ADR) GPS observable and second, it prevents any error in the LO from introducing an apparent tuning error at the ground-based receiver. A coherent LO is optional; without it there is no possibility of obtaining ADR data and one accepts longer signal acquisition times as a consequence of a significantly expanded frequency search window.

3.2 Ground Station

The spacecraft relays the GPS signals to the ground. The burden of all processing falls to the ground station.

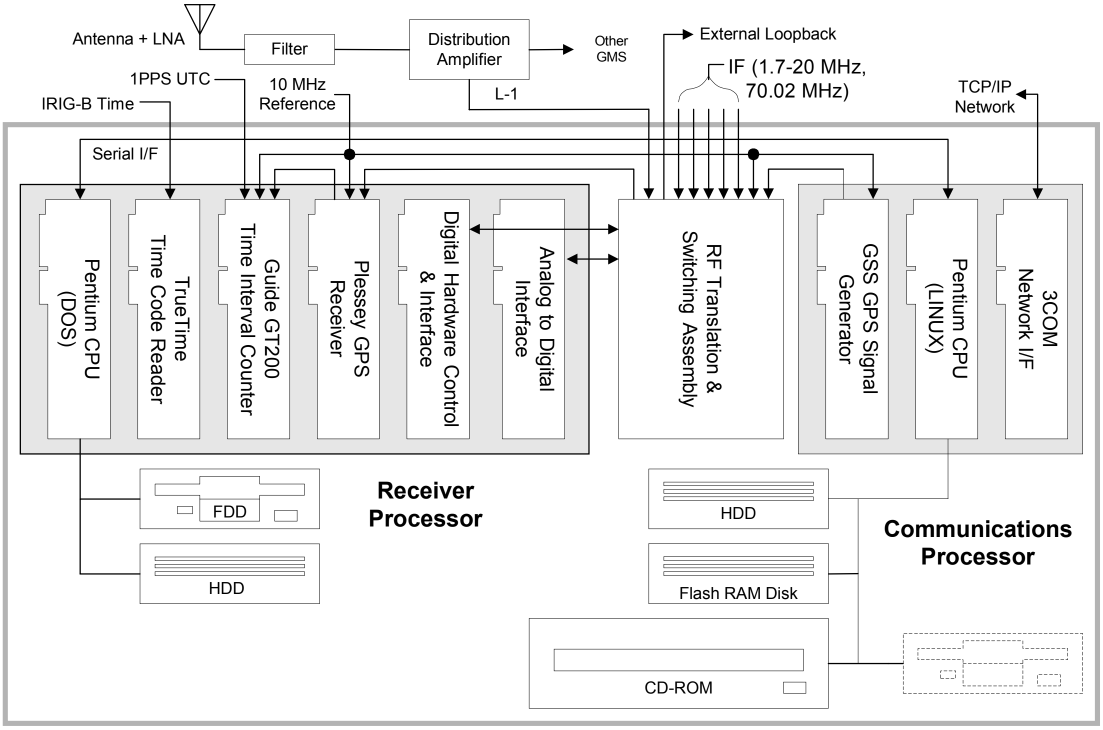
3.2.1 Receiver

An extensive survey of the market led to the conclusion that no commercially available GPS receiver was suitable for this application. Design features unavailable off the shelf include: the ability to navigate off the earth (for acquisition), a second order tracking loop to accommodate anomalous doppler, the ability to accept commands to track specific PRNs, the availability of individual PRN pseudorange data referenced to a precise local time source, S/A correction without P(Y)-code capability. The 1990 solution to these requirements occupied an entire 6-foot cabinet of 19-inch rack panels; the latest receiver, called the GPS Measurement System (GMS) is contained within a single 19-inch rack drawer just 10.5-inches high. All but one of the components in the GMS are commercial off the shelf (COTS) products.

The GMS contains two Pentium™ computers, the Receiver Processor (RP) and the Communications Processor (CP). The RP, employing the PC-DOS operating system and custom application software, directly controls the GPS receiver hardware and provides precisely time-tagged raw measurement data via a serial interface to the CP. The CP, using the LINUX operating system and custom application software, controls the RP and the internal GPS test signal generator and interfaces with the external controlling software through a network interface using TCP/IP protocol. The CP also hosts GPS Selective Availability (SA) correction software.

The GMS accepts RF input signals at the GPS L_1 frequency (1575.42 MHz), at any intermediate frequency (IF) in the range of 1.7 to 20 MHz or at 70.02 MHz. The L_1 input is connected to a roof-top antenna for the purpose of collecting the GPS Almanac and for self-test. Several IF inputs are provided to allow the GMS to select an input from among several sources. Signal switching, frequency translation and signal level adjustments are accomplished in the RF Translation and Switching Assembly (RFTSA). The heart of the GMS is a Builder-2 GPS receiver board from GEC Plessey (now Mitel). All of the constituent components of the GMS except the RFTSA and miscellaneous mechanical assembly parts are COTS.

The GMS uses an IRIG-B timing signal and a high precision 1 Hz UTC timing signal to accomplish precision time-tagging of the measurement data. All of the critical internal oscillators within the GMS are locked to a 10 MHz signal that is coherent with the 1 Hz timing signal. A Time Interval Counter is used to measure the time interval between the 1Hz timing



GMS Block Diagram

reference and the measurement strobe (also called the “tick”) in the GPS receiver hardware.

3.2.2 Processing

The GPS pseudorange (and, optionally, carrier phase) observables from the receiver are batch processed to produce the spacecraft ephemeris. The OD software uses a differential-corrector algorithm and applies appropriate disturbance models to account for solar radiation forces, gravitational field uncertainties and other phenomenon.

4.0 PERFORMANCE

4.1 Accuracy

It is not possible to discuss the actual accuracy achieved in this specific GPS application; instead, this paper describes the possible error sources.

The primary error contributor in this application is likely to be uncertainty in the hardware path delays both in the spacecraft and in the ground station. Of particular concern are delays that are both unknown and variable, such as a delay that varies over a temperature that is not telemetered on the spacecraft. Another error contributor to be closely controlled is any bias or drift in the ground time reference. Delay knowledge and time tag errors translate directly into pseudorange error.

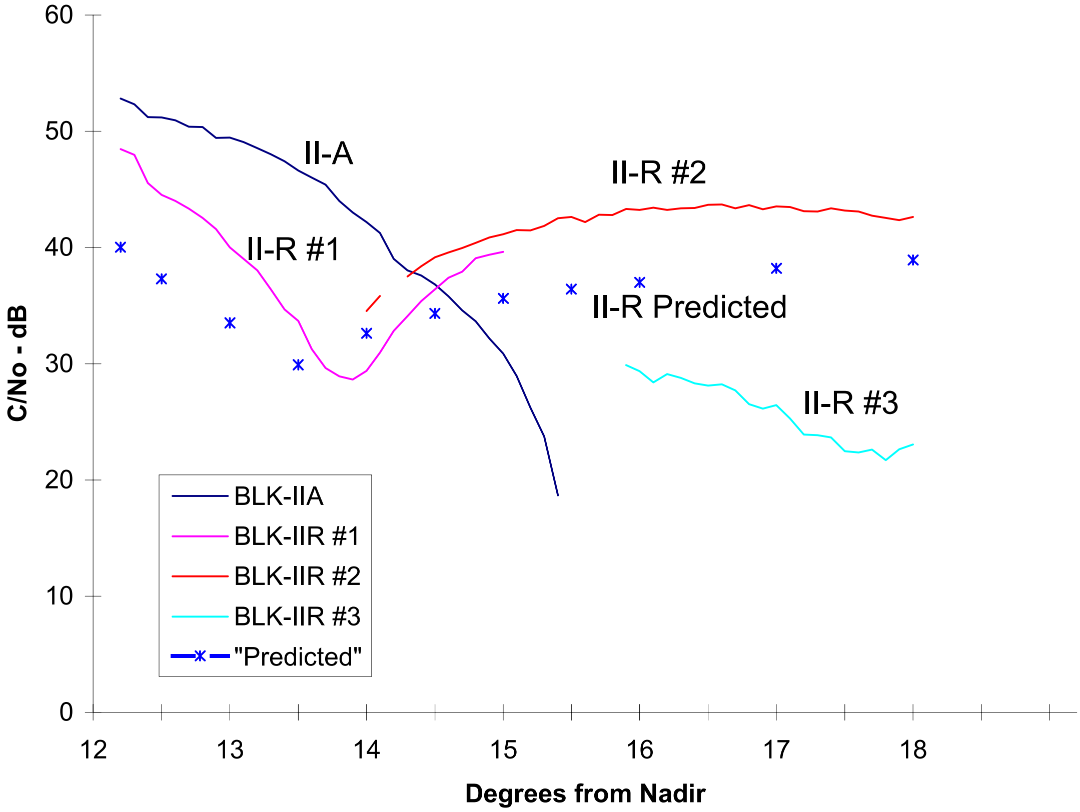
4.2 GPS Visibility and Signal Strength

Actual experience validates the theoretical predictions for GPS visibility. Signal strength has exceeded expectation because the initial link budgets were calculated with specified instead of actual GPS transmit levels. Data are not collected if the GPS vehicle is less than 1.5° from the limb of the earth (as observed from geosynchronous altitude) because of delay uncertainty passing through the atmosphere. The practical outer limit for collection is discussed in the following section.

5.0 COMPARISON OF BLOCK II-A AND II-R ANTENNA PATTERNS

An opportunity presented itself when the spacecraft was positioned such that a Block II-R GPS vehicle appeared to be rising very close to the Earth’s Pole. We took advantage of this opportunity to obtain some rough antenna pattern data.

As can be seen, we obtained two “good” data passes and one that was not useful in a total of three attempts at collecting Block II-R first sidelobe data. A Block II-A pattern is also included for reference. No concrete explanation for the “bad” collect is available but we speculate that it could be caused by the radial variations of the sidelobe radiated pattern. It would appear that there is possible potential for exploiting this first sidelobe of the Block II-R pattern to increase GPS signal availability at geosynchronous altitude.



Signal Strength vs Angle from Nadir (as viewed from geosynchronous orbit)

The Block II-F GPS antenna pattern will revert to approximately the Block II-A, rather than the Block II-R, shape.

This program does not presently collect data from the GPS transmitted sidelobes. It conservatively elects to track GPS vehicles when they are between 1.5° and 3.5° above the earth's limb. This conservatism ensures that there will always be an adequately strong signal not corrupted either by atmospheric delay or a low signal-to-noise ratio. C/N_0 of up to 50dB is not unusual at 1.5° and the signal is almost always in the mid 40 dB range at 3.5°.

As has been suggested by others[2], exploitation of the sidelobe of the GPS broadcast beam appears to hold some promise for either improving accuracy in existing applications or possibly enabling an onboard GPS solution at geosynchronous altitude by dramatically decreasing the gaps where no GPS signals are available.

6.0 CONCLUSIONS

Exploitation of the GPS signal for orbit determination from geosynchronous altitude is not only possible but also practical. The subject spacecraft program routinely meets or exceeds its ephemeris accuracy requirements. From this experience it is reasonable to state that a carefully implemented GPS solution could approach a level of performance where its accuracy is dominated by the GPS system errors.

ACKNOWLEDGEMENTS

Many individuals both within and outside of TRW have made vital contributions to the success of this GPS application over the years.

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