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Space-Based Navigation for RLVs and ELVs

8 February 2006

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VOLPE NATIONAL TRANSPORTATION SYSTEMS CENTER
U.S. DEPARTMENT OF TRANPORTATION
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Space Launch Operations

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16. Abstract

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Abstract

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1. Introduction, Scope, and Focus

1.1 Introduction

Optical tracking for the purpose of reconstructing trajectories of objects traveling in the sky predated Galileo's time; it was practiced even before the laws of mechanics were properly formulated. By 1705 Edmund Halley was able to predict the 76-year return cycle of the comet observed in 1682. Navigation, guidance, and control in aviation and space missions require timely and accurate data. The patient pace of optical trajectory construction cannot guarantee mission success and protect public safety. Since the beginning of the modern space age after World War II, inertial navigation systems (INS) have been used to navigate aircraft, missiles, launch vehicles and satellites, while radars have been used to determine and predict trajectories. At present, there exists a large infrastructure of technology and human resources invested in inertial measurement systems and tracking radars, both in the U.S. and worldwide.

However, INS and tracking radars are well known to be less than completely ideal for their respective tasks. A modern strap-down INS does not measure position or velocity directly, but measures specific forces and rotation rates and depends on the integration of these quantities in a navigation frame of reference to arrive at the navigation state of the vehicle. Early INSs were delicate objects whose calibration, maintenance, and initialization were elaborate, time consuming, and expensive. More recently, these systems have become much more robust and tolerant. Yet modern INSs still lack long-term stability and are subject to accelerometer and gyro drifts. These drifts cause the integrated navigation solution error to grow "unbounded" over time unless external measurements are used to correct and compensate for the integrated navigation solution. Except for missions of short duration, e.g., intercontinental ballistic missile (ICBM) flights, INSs are not truly autonomous instruments.

Tracking radar networks are expensive and their upkeep labor intensive. They restrict vehicle trajectories to the visibility zones of radar sites along prescribed launch corridors, greatly restricting operation and launch options both temporally and geographically. Furthermore, they do not automatically provide navigation solutions onboard the vehicles except through a data uplink, incurring delay and risk of data loss in communication.

The GPS provides a set of tools that perform both navigation and tracking in a manner that is timely, autonomous, and stable. Superficially, the basic GPS measurements are the same as those of ranging radars, i.e., time-of-flight measurement of radio frequency signals, but there is a fundamental difference. The GPS code and carrier phase measurements directly translate into information on position and velocity, and more importantly, these measurements occur in a 4-dimensional space-time framework, presently implemented through the well established World Geodetic System 1984 (WGS84)[*] and the carefully calibrated and maintained GPS system clock. Placing all GPS users in a commonly accessible, precisely defined space-time frame of reference confers on them a great deal of autonomy.

[*] World Geodetic System 1984 is more than a reference frame; it contains a gravity model of the Earth.

It also drastically reduces the need for communication of information and reduces the latency imposed on many operations. This advantage becomes most apparent in operations such as instantaneous impact point (IIP) computation for range safety; launch and landing of vehicles; mutual surveillance and warning [e.g., Automatic Dependent Surveillance-Broadcast (ADS-B)]; environmental monitoring, and natural resource imaging from low Earth orbits (LEOs), etc. GPS measurement quality is relatively stable; unlike INS, it does not degrade with mission duration; and unlike tracking radar, it does not depend critically on visibility from ground-based sites.

In terms of tracking accuracy, GPS outperforms tracking radars. The operating C-band beacon radar has a tracking accuracy of 17–70 m in position and a velocity error of 1.5–5.0 m/s. Civilian GPS position errors can now be bounded at less than 10 m in position and less than 0.3 m/s in velocity. The gain in velocity accuracy is especially important in time-critical operations such as determination of IIP for range safety. Skin-tracking radar is even less accurate than beacon radar.

Single-antenna GPS, unlike INS, does not provide attitude information. In this sense, the ideal, complete navigation system may well be one that integrates a GPS receiver with a small, lightweight, high-performance, inexpensive inertial measurement unit. As discussed below, the synergism between a GPS receiver and INS also provides many advantages other than attitude determination.

Use of GPS on launch and space vehicles requires special care. Most significantly, GPS signals are easily interfered with both intentionally and unintentionally. The system is purposely designed so that its navigation signal, now ubiquitously covering the whole globe, is less conspicuous than (and no more interfering than) background noise, except to GPS receivers. The lower the intensity of the signal, the more it is susceptible to jamming. Furthermore, because GPS is intended for near-Earth missions, its availability for above-LEO altitude operation is limited. Vulnerability to jamming and limited availability spawn problems with security and reliability, especially for time-critical missions. These system-wide questions are being addressed, to a large extent, by the GPS III modernization effort.

Civilian GPS was originally intended for aircraft, land vehicles, and stationary users. The application of GPS to launch and satellite vehicles requires special attention to two areas: the onboard antenna system and receiver design. Multiple antennas are usually required because vehicle configurations and vehicle rotation lead to obscuration and reduction in the number of visible GPS satellites if there is only a single antenna onboard. In early days, this problem was partially addressed by using wraparound antennas on small rockets and launchers, but wraparound antennas are impractical for vehicles with large diameters. To achieve a close-to-hemispherical or omni directional radiation reception pattern, a multiple patch antenna system strategically distributed on the vehicle is the best choice. With such an antenna system, the onboard receiver must implement antenna switching, signal combining, and radiation pattern controlling algorithms. On the other hand, multiple antennas open up the possibility of gaining partial if not total attitude information using GPS signals, as well as achieving some advantage in anti-jamming. GPS is presently at an evolving stage, with new frequencies, new codes, and new wave forms being added onto the existing navigation signals. The popular adoption of GPS has spawned a growing industry, with new products and services for modeling and forecasting the environment. We advocate that future receivers on launch vehicles and spacecraft incorporate built-in flexibility of the type associated with software receivers, to facilitate the ability to be reprogrammed to derive benefits from such advancements.

The next-generation launch and test range architecture is likely to rely on space-based navigation methods. The Range Commanders Council (RCC) invested a significant amount of resources to investigate the use of GPS and inertial measurement as tracking sources for range safety purposes, and have released guidelines[1] and common performance and verification requirements[2] that will assist range safety personnel in safely incorporating GPS into Range Tracking Systems in a way that minimizes the level of risk to life and property.

As will be pointed out below, GPS may be augmented to satisfy civil requirements for accuracy, coverage, availability, continuity, and integrity of signal. The advent of commercial RLVs and ELVs may impose tracking technology requirements that sometimes exceed those for aviation. While RLV guidance and navigation are highly likely to be based on GPS, it may be desirable to augment GPS to meet unique RLV and ELV needs such as higher speeds, increased maneuvering capabilities, and increased communication requirements.

Therefore, evaluating the requirements of the commercial space segment and any deficiencies in the GPS infrastructure serving this segment is appropriate, so that a cost-efficient navigation service may be provided with significant safety, efficiency and capacity benefits.

1.2 Scope

The following issues were considered under this study:

1. Public safety issues or constraints in using GPS.
2. Failure modes and effects considerations of the present GPS system.
3. Reliability and accuracy comparisons of GPS-based navigation to inertial guidance and telemetered inertial guidance (TMIG).
4. Could two independent source requirements be met by GPS receivers from two different manufacturers? Empirical evidence to support this determination.
5. What are the necessary characteristics for high-dynamics receivers, architecture attributes, and the number of frequency channels. Are Doppler shifts resulting from high velocities a factor? What are the feasible operational envelopes and restrictions?
6. GPS hardware availability, selection, and reliability factors.
7. What is the necessary infrastructure for tracking and safety-critical data transport for the Mission Flight Control Officer (MFCO) and Range Safety Officer (RSO) decision process.
8. Vulnerabilities of launch site timing system dependence on GPS and the necessary backup systems.
9. Are supplementary means desirable, e.g., Wide Area Augmentation System (WAAS) or other independent complementary means such as Galileo?
10. Are jamming avoidance features necessary to minimize a vulnerability risk from receiver and antenna perspectives?

11. Development of general guidelines for application of space-based navigation methods to ELVs, RLVs, and commercial space vehicles
12. Recommendations on future tracking and surveillance direction for enhancing the commercial space segment.

Summaries of findings for each of these 12 issues are presented in Section 2.

1.3 Focus of Study

To maximize benefit within the available budget, we chose to focus on two key areas that encompassed the most important aspects of the above 12 topics: (1) Survey of the present and future state of GPS, including GPS III modernization; and (2) Examination of the impact of ionospheric effects along a launch trajectory. These areas of focus are summarized in the following paragraphs and presented in greater detail in Sections 3 and 4.

1.3.1 Current and Future States of GPS

In Section 3, we present a brief survey of the present and future states of GPS, including GPS III modernization and its impact on availability and survivability. GPS is not only a ubiquitous navigation tool but it also allows the buildup of a network of monitor stations that provides close to real-time information of the environment. To be able to exploit the full panoply of tools and information that will become available in the near future, it is imperative that designers of satellite-based navigation systems be familiar with both the future added capabilities of GPS itself and the various environment monitoring and modeling capabilities that are coming online.

1.3.2 Ionospheric Effects Along a Launch Trajectory

Effects of the ionosphere are a large concern when only a single frequency is provided for civilian GPS users. Various elaborate *ad hoc* models have been devised to correct for the ionosphere delay. Now that two, and even three, civilian frequencies have been planned in the present round of GPS modernization, and now that GPS-measurement based ionosphere “nowcasting” models are readily available, the ionosphere question appears to be becoming somewhat moot. However, residual errors (after 2-frequency correction) and fadings (both flat and frequency selective) could remain problems under ionosphere scintillation conditions, and are still worth examining for possible failure modes affecting public safety and mission success. Section 4 discusses an analysis of ionosphere effects along a representative launch trajectory.

2. Summary

This Section briefly addresses each of the twelve issues listed in Subsection 1.2, Scope. Further discussions of these issues are presented in context in Sections 3 and 4.

2.1 Public Safety Issues

Public safety demands a vanishingly small probability of loss of life and property. Estimates of system performance* indicate how well the public safety requirement is met *under normal conditions*. Public safety cannot solely rely on estimates of system performance since such estimates are statistical evaluations and do not preclude the so-called "extreme value cases" from occurring, however small the probability may be. Only multiple layers of integrity monitoring can guarantee public safety. For GPS, this involves two separate activities: (1) monitor the quality of the navigation signals in space (SIS), and (2) monitor the navigation output from the user equipment. The Accuracy Improvement Initiative (AII)[3] has improved SV monitoring by installing 11 additional monitoring stations. Before AII, satellites could be out of view of tracking stations for over two hours at a time. If a satellite's GPS signal starts to diverge from normal operating conditions during this time, the satellite could continue to transmit faulty signals until the condition was detected when the satellite returned into view. With the 11 additional monitoring stations active, all GPS satellites can be monitored continuously without interruption. The time to alert is now completely dependent on the satellite being in view of an uplink station to flag the satellite as unhealthy. Besides the GPS monitoring stations, a growing community of GPS receiver networks operated by commercial, academic, and governmental organizations are distributed internationally. Such networks, cooperating through dedicated communication links or the Internet, have the potential of providing users with early warnings of GPS system anomalies.

Receiver output integrity monitoring can also have many layers. A basic layer could be Receiver Autonomous Integrity Monitoring (RAIM), which checks for consistency between GPS pseudorange measurements. Other layers of navigation solution integrity checking could be implemented with the cooperation of ground stations, with other satellite assets, or with other users of the same category operating in the vicinity. Another layer of navigation integrity known as Fault Detection and Isolation (FDI) could be implemented onboard the user vehicle by cross-checking independent INS and GPS solutions. Integrated GPS/INS (IGI), described in Subsection 3.3, blends the GPS and INS measurements to produce a navigation solution that is better than its individual components; however, if there is a fault in either system, the navigation solution performance can be severely degraded. There is advantage in having a flexible receiver architecture, which would routinely maintain the decoupled independent solutions from each subsystem for purposes of cross-checking and redundancy.

* GPS performance, i.e., system accuracy, availability, and security, are discussed in Subsection 3.2.

Range safety is a major concern when dealing with launch vehicles. The Range Commanders Council (RCC) has released two excellent reports that detail guidelines and requirements for utilizing GPS as a tracking source.[1,2] In addition, these reports contain data, surveys, and lessons-learned that were collected from range users over many years. The advent of civilian spacecraft has created additional concerns since these vehicles may be capable of operating from civilian spaceports or even conventional landing strips at civilian airports. The FAA has established a set of CFRs detailing the requirements that must be met in order to launch any commercial or civil launch vehicle within the United States.[4]

2.2 Failure Modes and Effects Considerations

GPS failures can be classified as global and local. Global failures are system-wide and affect one or more satellites. They can be caused by hardware failure or environmental damage, such as a high-energy particle hit that causes an abrupt jump in the satellite clock, or when there is a shift in the bias between different frequencies, or when the satellite database is corrupted so that an erroneous navigation message is broadcast. Local failures occur at the GPS receiver, such as when measurements to one or more satellites signal are corrupted by the environment, by unintentional jamming, by undetected intentional jamming, or by receiver hardware or software faults.

GPS is a quintessential distributed, highly redundant system and affords potential growth for many layers of integrity monitoring. AII and GPS III will strengthen the monitoring capability of the ground-tracking stations. The goal is to detect and identify a malfunctioning satellite as soon as possible and warn users not to depend on its signals. As to local failures, receivers must incorporate as many layers of integrity monitoring as feasible. Thus, a two-frequency receiver is better than a single-frequency receiver, and a three-frequency receiver is even more preferable; a high-data-rate receiver is better than one with a low data rate. The key point, both for system and point designs, is that integrity should be considered up front and not treated as an afterthought.

GPS modernization is discussed in Subsection 3.4, GPS Vulnerabilities are discussed in Subsection 3.5, and possible disruptive effects of the ionosphere are treated in Section 4.

2.3 Comparisons of GPS-based Navigation to Inertial Guidance

The earliest INSs were purely electromechanical devices. Later versions, especially those based on micro-electromechanical systems (MEMS), include measurement methods made possible by advances in modern physics, but the basic principles of inertial navigation belong to the world of Newton and Maxwell. On the other hand, GPS is of the post-Einstein world; proper working of the GPS system clock depends on correctly accounting for the gravitational red shift of a photon under the influence of gravity.

Because of their fundamental differences, INS and GPS as navigation systems are complementary, mutually independent systems. The INS is totally self-contained and not susceptible to external interferences. An INS measures the specific force on the vehicle and its rotation rate in the sensor frame of reference. It must depend on external means to set up and maintain a convenient working navigation frame of reference. This is done through initialization processes (gyrocompassing and/or alignment with some optical device) and periodic updates with star sensors, Earth sensors, Sun sensors, etc., and now even with GPS. INS errors mainly stem from the integration of stochastic error in the gyro and accelerometer outputs and as such are essentially unbounded.

GPS places all users in a common four-dimensional space-time frame of reference. This frame is realized through WGS84 and the GPS system clocks. Its measurements are time-of-flight of RF signals; hence these measurements are subjected to interference and disturbances in the environment.

Because GPS and INS are based on such totally different physical phenomena, they are genuinely independent and afford a very useful synergism between them. INS can help GPS coast through short durations of signal loss due to disturbances or obscuration; GPS can help by bounding INS drift errors.

INS and GPS are not necessarily redundant systems, however. Stand alone GPS does not provide attitude information needed for launch vehicle navigation (unless some type of multiple antenna architecture or other technology is used to derive attitude information from GPS measurements). A redundant IMU integrated with GPS should meet the launch vehicle redundancy requirements and still provide improvements in accuracy. Should a failure occur in the IMU, the backup system of the IMU can continue to operate with GPS. Likewise, should GPS fail, the IMUs can navigate independently.

2.4 GPS Receiver Manufacturer Independence

There is little gain in using redundant copies of GPS receivers as backup except to protect against software or hardware receiver failure. Most failures in the space segment or control segment will affect receivers from different manufacturers identically, unless they employ completely different measurement and processing strategies. In addition, any interference, whether intentional or not, will simultaneously affect both receivers regardless of measurement and processing strategy. Dual-redundant GPS receivers with separate antennas on each system will not protect against these failures.

One example of a "different strategy" is the treatment of ionosphere delay. Nowadays, there are very accurate and up-to-the-moment ionosphere models that can be downloaded from the Internet. Presumably, with appropriate initialization, a single-frequency receiver making very good ionospheric corrections can be realized with the help of these models. On the other hand, a two-frequency receiver can incur large ionosphere error if the bias between the two signals is somehow corrupted. Thus, the single- and two-frequency receivers can monitor each other in this respect and form a useful redundant pair.

These two modes of operation need not be assigned to two separate receivers. The most efficient approach is to have one receiver that performs two-frequency corrections and model-based computations, and from these two sources form an optimal estimate.

This points to the needs for open and flexible system and receiver designs. For example, software receivers can be reprogrammed to exploit new system capabilities and environmental databases as they evolve.

2.5 Necessary Receiver Characteristics

The basic GPS receiver operation can be described by a few parameters: operation frequency or frequencies, number of satellite tracking channels, tracking loop bandwidth, correlator separation, navigation solution output rate, acquisition/reacquisition time, and radiation hardness.

The bandwidth of the receiver and the frequency search window of the Coarse/Acquisition (C/A) algorithm are important for highly dynamic maneuvers. A wide bandwidth-tracking loop allows the receiver to maintain lock throughout these maneuvers.

Most commercial-off-the-shelf (COTS) receivers disable the ability of the receiver to accommodate velocities and altitudes greater than the limits imposed by the International Traffic in Arms Regulations (ITAR),[5] so that the product can be marketed and exported abroad. For a space vehicle designed to operate outside these limits, the chosen receiver must also operate outside the ITAR velocity and altitude limits. Analysis has shown that receivers for commercial RLVs must be able to accommodate a Doppler shift larger than 1.5 km/s.

More recommendations on receivers are presented in Section 5, Conclusions and Recommendations.

2.6 GPS Hardware Availability, Selection, and Reliability Factors

A modern GPS receiver for space use should anticipate future development of the GPS system and reserve the capacity to:

- be capable of acquiring signals with larger Dopplers due to speeds of the ELVs/RLVs being much greater than civilian aircraft
- have a bandwidth large enough to track through the maximum dynamic maneuvers the ELV/RLV will encounter if GPS is not augmented by inertial sensors
- exploit new and additional signals such as civilian L2C, L5, and L1C frequencies (1227.60, 1176.45, and 1575.42 MHz, respectively) when available
- adapt to the rapidly developing GPS-based models of the environment ("nowcasting" troposphere and ionosphere and their scintillation maps) when available
- incorporate interference mitigation techniques for non-environmental interference (anti-jam algorithms)
- incorporate measurements from Galileo satellites when available
- incorporate RAIM
- incorporate FDI if integrated with INS

2.7 Necessary Infrastructure for Tracking and Safety-Critical Data Transport for the Mission Flight Control Officer (MFCO) and Range Safety Officer (RSO) Decision Processes

The primary objective of MFCOs and RSOs is protection of life and property; their secondary objective is assurance of mission success. These officers make decisions based on vehicle Time, Space, Position Information (TSPI) obtained from independent tracking sources and in-flight vehicle performance, health, and status information. In some cases, instantaneous impact point (IIP) computations and/or vehicle attitude, typically available only from on-board inertial units, are used. Tracking sources must provide precisely timed tagged position and velocity information. GPS is capable of meeting these demands and can provide one source of independent measurements for range safety. The infrastructure and decision processes involved with using GPS as a tracking source are beyond the scope of this report and have been thoroughly studied under the above-cited reports published by the RCC.

2.8 Launch Site Timing

Launch ranges use GPS as a timing source. Theoretically, the maintenance of GPS time at a local station depends on tracking at least one GPS satellite, as long as the ephemeris and clock state of that satellite are healthy and the station location is precisely surveyed. Circumstances may arise in which the time signal from GPS is inaccessible or corrupted. A redundant backup timing system at the range will reduce the vulnerability caused by this dependence on GPS for timing. A redundant backup timing system will include clocks that are independent of the GPS time signal. These clocks, once calibrated, could routinely perform comparisons of the precision and accuracy between them and the GPS time signal. If the GPS time signal is lost, the backup clocks will be used to establish the time at the launch range. The necessary accuracy of the range clocks depends on the unique timing requirements of the range and mission. These requirements may include, but not be limited to, collision-avoidance (COLA) timing, countdown and lift-off timing and sequencing, and vehicle telemetry timing. If a range GPS receiver's time signal were to deviate from the range's backup timing system, the multi-segment nature of GPS means that it is possible that a receiver onboard an RLV would experience a similar problem with the GPS time signal. This may affect the accuracy of GPS, and mission planning should include contingencies for this situation should it arise during the launch countdown.

2.9 Supplementary and Complementary Radionavigation

Supplemental radionavigation systems, including differential GPS (DGPS), Wide Area Augmentation System (WAAS), and Local Area Augmentation System (LAAS), have been considered. These augmentations are not well suited to civilian spacecraft. High-gain antenna systems with narrow beams, e.g., controlled reception pattern antennas (CRPAs), would increase the number of visible satellites and improve measurement geometry at medium-Earth orbit (MEO) and geosynchronous Earth orbit (GEO) altitudes slightly. The Galileo satellites will offer additional navigation signals from an independently operated constellation. Future GPS receivers with the capability to use signals from the Galileo constellation in addition to GPS are worth considering. GPS augmentation is addressed in Subection 3.3.

2.10 Jamming Avoidance Features

GPS modernization will reduce as much as possible unintentional interference threats. The higher signal power of modernized GPS means that hostile agents will need to transmit more power at more frequencies in order to effectively jam GPS. Augmenting GPS with INS is an effective backup strategy to protect against interference. Other jamming avoidance techniques are discussed in Subsection 3.5.

2.11 General Guidelines for Space-based Navigation Methods

Because of the rotational maneuvers of RLVs and ELVs, a single GPS antenna cannot provide enough visible satellites to effect a navigation solution. A GPS-based tracking system for RLVs and ELVs should therefore have, as a minimum:

- a set of antennas capable of viewing the entire sky from any feasible vehicle orientation and concomitant multiple-antenna input control software
- a fast acquisition and reacquisition algorithm in case of loss of lock, and
- a commensurably accurate INS to assist reacquisition and bridge gaps of lost GPS data.

In addition, a space-based navigation system should meet the minimum requirements imposed by the FAA on civil aviation navigation systems, which are summarized at the beginning of Subsection 3.2.

2.12 Recommendations on Future Tracking and Surveillance Directions

Tracking and surveillance systems currently allow aircraft to communicate their positions to each other to avoid midair collisions. The Traffic Alert and Collision Avoidance System (TCAS) currently in use and Advanced Dependent Surveillance-Broadcast (ADS-B), which is being developed, are examples of these systems in use or being considered by the FAA. These systems are similar to Blue Force tracking being developed by the military. Tracking and surveillance are complex systems that could not be fully studied under the scope of this report. A full study is recommended to focus on the benefits and technical difficulties associated with incorporating ADS-B into launch vehicles. The primary purpose of this report was to study the benefits and technical difficulties associated with using space-based navigation aboard reusable and expendable launch vehicles.

More recommendations are presented in Subsection 3.6, Findings Regarding GPS Use Aboard Civilian Spacecraft, and Section 5, Conclusions and Recommendations.

3. Current and Future States of GPS

3.1 GPS Description

GPS is a space-based radionavigation system developed to provide accurate position and time information to its users. The Department of Defense (DoD) is responsible for the development and operation of GPS, and is required by law to provide GPS Standard Positioning Service (SPS) to all civil users worldwide free of direct user fees. The DoD and Department of Transportation (DOT) are responsible for publishing performance standards and ensuring that GPS meets defined accuracy, availability, reliability and coverage statistics. A general overview of GPS follows to provide a basic understanding of GPS in the context of this report.

GPS encompasses three segments known as the space, control, and user segments. The space segment consists of a nominal 24-satellite constellation in six orbital planes, although operational spares are proactively added to the constellation augmenting performance. The satellites broadcast a Coarse/Acquisition (C/A) ranging code on the L1 frequency to the surface of the Earth. These signals contain an embedded navigation message that is periodically updated by the master control segment (MCS). The ground stations are part of the Control Segment that includes monitoring stations and dedicated uplink antennas. The navigation message provides the user with accurate positions of each satellite in the constellation. GPS receivers combine these satellite positions with the ranging and timing data to compute the user's position and time. The user segment includes all of the GPS receivers that make use of the broadcast signals.

Augmentations to the base GPS system are available or under development to improve accuracy for the user segment. In addition, there are in place GPS modernization plans that will further improve accuracy and security. At present, the civilian SPS utilizes only one ranging signal broadcast on the L1 frequency (1575.42 MHz). The U.S. Government has determined that additional coded signals on different frequencies are essential to further enhance the use of GPS as a safe civilian radionavigation solution. The new signals will reside on the L2, L5, and L1 GPS frequencies (1227.60, 1176.45, and 1575.42 MHz, respectively) and will be phased in over the next decade.

3.2 GPS Performance

The DoD, DOT, FAA, and various other government organizations have published numerous documents concerning GPS performance. The main publication defining minimum accuracy, availability, coverage, and reliability standards is the *Global Positioning System Standard Positioning Service Performance Standards.*[6] In addition, the FAA sets requirements on the navigation performance of avionics during various phases of flight. In 1996, the FAA planned for GPS to be a sole means navigation system by 2010 as detailed in The *National Airspace System Architecture, Version 2.0*[7] and the *1996 Federal Radionavigation Plan.*[8] The DOT and FAA have since recognized (circa 1996) that "GPS SPS will not meet all the different user performance requirements for navigation, positioning, and timing applications" and that additional vulnerability concerns will keep GPS from meeting the

FAA guidelines for a sole means navigation system. The revised *2001 Federal Radionavigation Plan*[9] and the *2001 Federal Radionavigation Systems*[10] reports establish plans for augmented GPS to become a primary means navigation system by 2009. The systems report specifically declares that "GPS cannot be the only navigation system carried onboard aircraft." Considering the additional complexity and accuracy requirements involved with civilian spacecraft, it is recommended that these rules be carried over to civilian spacecraft navigation systems.

The *2001 Federal Radionavigation Systems*[10] defines the basic requirements for any general aviation navigation system. The important points for this study with respect to launch vehicles are summarized here. The navigation system must:

1. Be safe, reliable, and available over all used airspace regardless of weather, time, terrain, or propagation anomalies.
2. Not limit performance.
3. Have integrity near 100% and provide timely alarms in the event of failure, malfunction, or interruption.
4. Recover from temporary loss of signal without the need for a complete reset.
5. Provide means for the pilot to confirm performance and protect itself from possibility of input blunders.
6. Provide information to the pilot and aircraft systems to determine the position of the aircraft with an accuracy and frequency that will bound the aircraft within an established protected airspace.
7. Compensate for signal fade and propagation anomalies and reduce susceptibility to interference.
8. Be compatible with the overall Air Traffic Control (ATC) system.

The FAA defines phases of flight for civil aviation as en route (including oceanic and remote domains), terminal, approach and landing, and surface. The level of accuracy required for each of these phases is tabulated in the Federal Radionavigation Systems report.

The Federal Radionavigation Systems report defines navigation requirements for civilian and commercial spacecraft vehicles where augmented GPS will be used in near-real-time applications for navigation, attitude, and time determination. The requirements given are three-dimensional position error not to exceed 1 m (1 sigma), three-dimensional velocity error not to exceed 0.1 m/s (1 sigma), attitude error not to exceed 0.01° in each axis (1 sigma), and clock error not to exceed 1 μm (1 sigma). Standard GPS utilizing a single antenna can provide only position and velocity measurements and requires augmentation to measure attitude. The FAA has also published rules in the *Code of Federal Regulations (CFR) Title 14 Chapter III*[4] for licensing and flight safety of commercial space transportation. These guidelines do not address the specific requirements of onboard navigation systems, and only make mention of such systems with respect to performance error parameters used for trajectory analysis. It is recommended that the FAA establish guidelines for accuracy requirements during various stages of flight for civilian spacecraft as they have done for civil aviation. The RTCA requirements for aviation can be used as a guideline for establishing these specifications. These requirements should be a bound on the worst-case accuracy.

GPS performance can be defined in terms of coverage, accuracy, availability, and reliability. The SPS performance standards that the U.S. government is committed to providing are based on signal-in-space (SIS) performance, and therefore do not include error contributions due to ionosphere, troposphere, interference, multipath, and receiver thermal noise.[6] The standards assume the use of a GPS receiver that is designed in accordance with *ICD-GPS-200, Revision C*[11] and is tracking all satellites in view that are 5° above the horizon. Most modern receivers incorporate all-in-view tracking of visible satellites, and the remainder of this report will assume use of such receivers. The coverage of GPS is defined as the volume above the entire surface of the Earth up to an altitude of 3,000 km. It is assumed that 24 satellites are available with 0.95 probability averaged over a single day (and at any given time, a minimum of 22 satellites are available).

Given these assumptions, SPS guarantees a global average SIS positioning accuracy error that is below 13 m (95%) horizontally and 22 m (95%) vertically. That is, the SIS position error averaged over all locations in the service volume has a 95% probability of being less than the given values. The worst case SIS positioning error for a specific location is less than 36 m (95%) horizontally and 77 m (95%) vertically. In terms of the actual ranging errors, SPS provides less than 6 m SIS user range error (URE) averaged for 24 h over the entire constellation from any location in the service volume. The SIS UREs are mainly due to satellite clock error, satellite position or ephemeris error, and phase bias error in the C/A code. Upon completion of the Accuracy Improvement Initiative (AII), the seven-day moving average of the total SIS URE was in the range of 1.1 m. The end user will experience additional range errors due to ionosphere, troposphere, multipath, receiver thermal noise, and interference. The contributions from these additional errors can be estimated and are tabulated in numerous references[6,12,13] assuming that the Klobuchar ionosphere model and the troposphere model given in the Interface Control Document (ICD) are being used. The total range error is found by taking the root mean square (rms) of all error sources.

The number of available satellites greatly influences the average and worst-case global position error (as of July 2005, a 28-satellite constellation is available). In a recent study performed during a period of solar maximum activity, the end user global 50th percentile position error for a single-frequency receiver was determined to be 3.1 m horizontally and 5.8 m vertically.[6] A dual-frequency receiver improves performance by mitigating ionospheric interference. In that same study, a dual-frequency receiver 50th percentile error was 1.6 m horizontally and 3.1 m vertically. The worst site 50th percentile errors were 7.7 m horizontally and 14.0 m vertically for single-frequency receivers, and 2.1 m horizontally and 3.3 m vertically for dual-frequency receivers. This is actual end-user performance as opposed to SIS performance reported earlier. Note that these results are for median 50th percentile performance; the 95th percentile errors are approximately three times as large.

GPS availability is defined as the probability of satellites in the constellation being available in a geometry conducive to maintaining the worst-case accuracy standards given above even in the presence of satellites being offline due to maintenance or malfunction. A minimum of 21 healthy transmitting satellites is assumed. The SPS provides a global average availability of 99% for both horizontal and vertical positioning and a worst-case location availability of 90% for horizontal and vertical positioning. In addition, availability can be defined as the percentage of time the constellation geometry provides a Position Dilution of Precision (PDOP) that is below 6. Dilution of Precision (DOP) is a parameter that characterizes the effect of satellite geometry on position accuracy. For example, if two available satellites are located at the same point in the sky, the second satellite does not provide additional information to the first. Lower values of DOP indicate better satellite geometry. The global average availability under this definition is 98% with a worst-case location availability of 88%. Service availability should meet both of these definitions.

GPS reliability is a measure of how well a GPS maintains SIS URE within a specified tolerance, assuming the satellite is healthy. The global yearly average probability that any satellite will exceed 30 m URE is 99.94%. The worst-case yearly average reliability for a single location is 99.79%.

The GPS SPS global average and worst-case location performance standards found in reference 6 are summarized in Table 1. It is concluded from these standards that GPS SPS alone does not meet the accuracy requirements given by the Federal Radionavigation Systems report for spacecraft or the requirements defined by the FAA for aviation, except for oceanic flight. Please note that the listed values are 95th percentile globally averaged performance limits. Actual performance of GPS receivers will be much better than these limits in most cases; however, such performance cannot be guaranteed. Also note that the accuracies in the table are computed using the minimum constellation of 24 satellites available with 0.95 probability; a user will typically realize horizontal and vertical errors that are smaller than those listed with more available satellites in orbit. The smaller accuracies cannot be guaranteed, so it is useful to understand the sources of errors that degrade accuracy. In addition, knowing the source of the errors may also help to decide the best augmentation or mitigation technique to improve accuracy.

Error sources can be divided according to the three segments that encompass GPS. The space segment is subject to the following errors: clock and navigation system stability, phase uncertainty in the transmitted signal, and predictability of satellite vehicle parameters. Most of the errors associated with the space segment are very small, and each subsequent block of satellites that has entered service reduces the errors associated with these sources through improved hardware. The user can do very little, if anything, to compensate for errors introduced by the space segment. The control segment is subject to errors that arise from ephemeris prediction, clock correction error, and possible human error when updating software. These errors have also been reduced since the introduction of GPS by using better prediction algorithms and error control strategies and the activation of additional tracking stations. The ultimate size of these errors is mostly dependent on the frequency of ephemeris updates to the satellite vehicles by the MCS. Methods to broadcast compensation for these errors will be dis cussed later. Proposed improvements to GPS III satellites include the addition of cross-link receivers to transmit near zero age of data ephemeris and clock corrections as well as perform constellation integrity checks. The improvements can help to further decrease errors in the control segment.

Table 1. GPS SIS Performance Standards

	SPS Accuracy (95 percent) [meters]	**Service Availability**	**Service Reliability**	**Coverage**
Global Average	Horizontal ≤ 13 Vertical ≤ 22	99% and 98% PDOP ≤ 6	99.94%	Global Service Volume up to 3,000 km.
Worst Case Location	Horizontal ≤ 36 Vertical ≤ 77	90% and 88% PDOP ≤ 6	99.79%	

The user segment contains the most error sources, but is also the area where the largest improvements can be gained through augmentation and mitigation techniques, which will be described later in this report. The user segment error sources include ionospheric and tropospheric effects, receiver thermal noise, quantization, multipath, and RF interference (intentional and unintentional). Numerous references report sample error budgets listing the contributions of each of the error sources listed above;[6,12,13,14] however, the errors are dependent on receiver quality characteristics. The Kovach paper[14] provides a baseline for the expected contributions to the User Equivalent Range Error (UERE) due to all segments. These are estimates of the error contributions after the current phase of the GPS modernization effort is complete and are summarized in Table 2. The table also includes Precision Positioning Service (PPS) UERE for those interested in obtaining clearance to use these receivers. The Kovach paper was written in 2000; therefore, spacecraft manufacturers are encouraged to make an individual assessment of error sources present at the time of the mission and for the particular receiver hardware being used. Such an error budget is required to properly complete an application for a license to launch a civilian spacecraft. FAA CFR Title 14 Chapter III requires a launch operator to perform a flight safety analysis that involves computing trajectory dispersions that should make use of the navigation system error budget.

3.3 GPS Augmentation

GPS performance can be improved by various augmentations. Some augmentation techniques include Differential GPS (DGPS), Wide Area Augmentation System (WAAS), Local Area Augmentation System (LAAS), the use of beam-forming and interferometrically processed antenna arrays, and integrating GPS with inertial systems.

Differential GPS (DGPS) uses the assumption that most GPS ranging errors seen by a given user are systematic errors common to all users in the vicinity. For example, all users will be subject to the same errors due to satellite position and timing errors. In addition, all users within a given geographic region will be subject to similar ionosphere and troposphere modeling errors. A ground station with a surveyed location can precisely compute ranging errors to each satellite and transmit the errors to local GPS receivers. Those receivers then subtract the errors from their own pseudorange measurements. For SPS users, DGPS can improve horizontal accuracy to less than 7 m [2-dimension root-mean-square (drms)]. Achievable accuracy degrades as a function of distance from the broadcast site. This is because error corrections due to environmental influences are not valid in the environment far from the broadcast station. For this reason, DGPS has little to no application to space-based operations.

The Wide Area Augmentation System (WAAS) uses assumptions similar to those used for DGPS to generate nationwide corrections for end users. WAAS employs a network of ground stations to measure GPS ranges and local meteorological data. Dual-frequency receivers are used to estimate ionosphere parameters. All the measurements are sent to a master station to generate a nationwide ionosphere and troposphere model as well as accurate ephemeris corrections. This data is uploaded to geostationary satellites and broadcast globally along with an additional ranging signal. Integrity monitoring is performed by the ground stations, and the status is transmitted with the WAAS signal. WAAS is also capable of verifying its own integrity. Currently, GPS does not have an inherent integrity monitoring capability that satisfies the FAA's requirements for aviation. WAAS became operational for the continental United States in 2003. Since then, many problems, including rapid gradients in the ionosphere, have caused WAAS to perform less accurately than standard GPS. In addition, the

Table 2. New UERE Budget for Modernized GPS (Source: [14])

UERE Component Allocations and Sums, meters rms

Allocation	**Dual-Frequency P(Y)-Code Receivers**			**Dual-Frequency C/A-Code Receivers**			**Single-Frequency P(Y)-Code Receivers**			**Single-Frequency C/A-Code Receivers**		
Space Segment												
Clock Stability	0.5			0.5			0.5			0.5		
Group Delay Stability	0.3			1.1			0.5			1.6		
Diff'l Group Delay Stability	1.0			3.3			0.0			0.0		
Selective Availability (SA)	N/A			0.0			N/A			0.0		
Other Satellite Errors	0.3			0.3			0.3			0.3		
Space Subtotal	1.2			3.5			0.8			1.7		
Control Segment	Terrestrial		Space	Terrestrial		Space	Terrestrial		Space	Terrestrial		Space
Clock/Ephemeris Estimation	0.8		0.9	0.8		0.9	0.8		0.9	0.8		0.9
Clock/Ephemeris Prediction	0.5		0.9	0.5		0.9	0.5		0.9	0.5		0.9
Clock/Ephemeris Curve Fit	0.4		0.4	0.4		0.4	0.4		0.4	0.4		0.4
Other Clock/Ephemeris	0.3		0.3	0.3		0.3	0.3		0.3	0.3		0.3
Iono Delay Model Terms	N/A		N/A	N/A		N/A	4.9-9.8		4.9-9.8	4.9-9.8		4.9-9.8
Group Delay Time Estimate	N/A		N/A	N/A		N/A	2.3		2.3	2.3		2.3
Control Subtotal	1.1		1.4	1.1		1.4	5.5-10.1		5.6-10.2	5.5-10.1		5.6-10.2
Subtotal, Space & Control	***1.6***		***1.8***	3.7		3.8	5.6-10.1		5.7-10.2	5.8-10.3		5.8-10.3
Reduction by WAGE*	***1.0***			N/A			1.0			N/A		
Total Signal-in-Space (SIS)	**1.3**		**1.5**	3.7		3.8	5.5-10.1		5.6-10.2	5.8-10.3		5.8-10.3
User Segment**	Air	Surface	Space	Air	Surface	Space	Air	Surface	Space	Air	Surface	Space
Receiver Noise	0.2	0.2	0.4	0.2	0.2	0.4	0.2	0.2	0.4	0.2	0.2	0.4
Multipath	0.1	0.9	0.0	0.1	0.9	0.0	0.1	0.9	0.0	0.1	0.9	0.0
Ionospheric Delay	0.4	1.4	0.6	0.4	1.4	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Tropospheric Delay	0.5	0.5	0.0	0.5	0.5	0.0	0.5	0.5	0.0	0.5	0.5	0.0
Other UE Errors	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
User Subtotal	**0.8**	1.8	**0.8**	0.8	1.8	0.8	0.7	1.1	0.6	0.7	1.1	0.6
Total System UERE	**1.5**	2.2	**1.7**	3.8	4.1	3.9	5.5-10.1	5.6-10.2	5.6-10.2	5.8-10.3	5.9-10.3	5.9-10.3

* Or other means of minimizing effective age of data (AOD) to ≤ 3 hr

** All-in-view receiver; State 5 navigation using carrier-based delta ranges with P(Y)-code, or State 8 navigation using carrier smoothed code with C/A-code signals from the geo-synchronous satellites are weaker than standard GPS signals, making tracking harder. Solutions to these problems are under investigation. The service volume for WAAS is stated to reach a height of 100,000 ft above the Earth's surface, making WAAS of limited use to orbital vehicles or at the apex of flight or for transorbital vehicles even if the current problems are solved.

The Local Area Augmentation System (LAAS) was designed to be a precision navigation GPS augmentation system for approach and landing at airports. LAAS was planned to meet Category II and III requirements for precision approach and autolanding capabilities. Implementation of LAAS at airports is questionable at this time. In addition, the service volume of LAAS is defined as 20 nmi from the runway and below 10,000 ft. This alone rules out the use of LAAS as a feasible GPS augmentation option for civilian spacecraft.

Significant research has been devoted to adaptive antenna arrays, also known as controlled reception pattern antennas (CRPAs). Receivers with this technology can use digital beam-forming algorithms to provide higher gain in the direction of each GPS satellite being tracked. These receivers generally make use of software reprogrammable gains that allow the receiver to be reconfigured and optimized for operating conditions. Beam forming algorithms also greatly mitigate the effects of multipath. The NAVSYS Corporation reported research in digital beam steering for enhanced space vehicle operations.[15,16] In 1997, the "Falcon Gold" spacecraft was flown aboard the Centaur upper stage during a Defense Satellite Communication System (DSCS) launch.[17] The spacecraft was equipped with a high-gain patch antenna to record GPS signals above the GPS constellation. The experiment measured GPS signals up to geostationary orbit and out to 59º with respect to the GPS satellite's broadcast antenna boresight. These results indicate that it is possible to use high-gain antennas to detect sidelobe radiation from the GPS satellite antennas for signal acquisition. The use of high-gain and directional antennas could feasibly increase the number of visible satellites and improve GPS measurement geometry for users with altitudes close to and above the GPS constellation.

GPS can also be integrated with inertial navigation systems (INS) providing many benefits due to the complementary nature of the error sources in each system. Such systems are also called Embedded GPS/Inertial (EGI) or Integrated GPS/Inertial (IGI) systems. The INS is self-contained and immune to external RF interference. GPS provides positioning information with long-term stability because the error is independent of operation time and is always bounded. A calibrated INS has stable measurements and less noise but is subject to drift causing the error to grow without bound over time. The quality of the INS determines this drift rate, for example, a navigation grade INS can provide accurate position for several hours. Combining the long-term stability of GPS with the short-term accuracy of an INS yields a better navigation solution than either system is capable of individually. The magnitude of this improvement is again a function of the quality of the inertial measurement unit (IMU). The accuracy requirements of the final system and a thorough engineering study should be used to define the quality of the IMU needed. IGIs also provide attitude determination, a requirement for space navigation, which is not provided by a stand-alone single antenna GPS receiver.

Different methods of integration can be used to combine GPS with INS. Uncoupled GPS/INS blends the navigation output from these two subsystems into a final position using an external filter, usually by using a low pass filter on the GPS output and a high pass filter on the IMU output. Coupled GPS/INS is categorized based on the complexity of the integration and the data that are shared between the two systems. All coupled systems have in common the fact that they use an integrated navigation filter, usually a Kalman filter of some sort. Loosely coupled systems use the GPS position/velocity solution as measurements to the navigation filter while tightly coupled systems use the raw pseudorange and pseudorange rate measurements directly. It is possible to incorporate feedback from the navigation filter to a GPS receiver with either method. Feedback provides the receiver with a reference navigation solution and inertial aiding. Inertial aiding makes the receiver aware of the vehicle dynamics, allowing narrower bandwidth tracking loops to be used, resulting in improved accuracy. Inertial aiding could also help the receiver maintain satellite lock during high dynamic maneuvers, signal fading, and jamming. The navigation filter can also provide feedback to the INS that, when used, allows in-flight calibration of the INS. The pseudorange and pseudorange rate states available from each satellite in a tightly coupled system provide more information than the computed three-dimensional position and velocity used in loosely coupled systems, allowing the navigation filter to compute a more accurate solution. In addition, a minimum of four satellites is no longer required for tightly coupled systems to compute a navigation solution. Currently, various organizations are researching other advanced coupling schemes, including ultra-tight and deep integration receivers, with the intent of improving jamming tolerance.

3.4 GPS Modernization

GPS modernization efforts are underway to improve the next generation of GPS satellites. Specific purposes of the modernization effort are to improve the accuracy of GPS as well as protect against some of the vulnerabilities of the system. The U.S. government has approved a multi-phased plan for improvements to be implemented over the next decade.[18] The main improvement will be the addition of three new civil signals on the L2, L5, and an additional signal on the L1 GPS frequencies (1227.60, 1176.45, and 1575.42 MHz, respectively) to complement the C/A signal on L1. In addition, all signals will benefit from increased transmission power. The first GPS satellite with L2 capability was launched September 26, 2005. The new L2 signal consists of a set of time-multiplexed codes with the first code containing navigation data and the second code being data-free. In addition, the lengths of the new codes are increased substantially over the current L1 C/A code. The implications of both these improvements will be discussed in the section on the vulnerabilities of GPS. L2 is not located on a protected frequency, as are L1 and L5, and is subject to terrestrial interference. The signal at L5 will provide a phase-multiplexed signal to the civilian population. The in-phase signal will contain navigation data, the quadrature signal will be data-free, and both codes will be substantially longer than the current L1 C/A code. In addition, the new L5 code will be broadcast at 10 times the chipping rate of the current L1 C/A code. The increased chipping rate allows greater resolution and higher bandwidth in the L5 signal, resulting in improved accuracy. L5, like L1, is located on a protected frequency and should be safe from unintentional RF interference. Currently, error due to the ionosphere is the most significant contributor to position error seen by GPS SPS users. Full operational capability of the modernized system is planned for 2014. A large amount of research is currently devoted to learning how to make the best use of the additional signals. Receivers that make use of the new signals are expected to be available soon.

Receivers that make use of additional frequencies provide another benefit by mitigating errors due to the ionosphere. The ionosphere causes phase delays and group delays in the carrier and code signal, respectively, that are opposite in sign, but equal in magnitude, and inversely proportional to the square of the carrier frequency. The error contribution due to the ionosphere can easily be solved given code and carrier measurements at two different frequencies. Multi-channel receivers that intend to use the new civilian GPS signals should perform this estimation. The additional signals can also be used to solve the integer ambiguity problem using a technique known as widelaning.[12,13] The integer ambiguity problem has to do with predicting the integer number of wavelengths between the user and the satellite. The estimation of the integers can take a long time; for example, the GPS receiver on board the International Space Station (ISS) solves for integer ambiguities, but can sometimes take up to an hour to do so. Military receivers can already remove ionospheric error using the P(Y) signal on L2. Users wishing to use this technology must face the additional hurdle of getting approval to use the encrypted PSS signal.

The European Union is developing the Galileo satellite navigation system. Although not technically a modernization of GPS, future GPS receivers will have the option of using satellites from the Galileo constellation in addition to the GPS satellites. The Galileo satellites will provide additional range measurements, improved DOP, and the redundancy of having another independently operated constellation. Space-based operations can benefit from additional satellites, especially above the GPS constellation where the number of visible satellites becomes a concern.

3.5 GPS Vulnerabilities

A study into the infrastructure vulnerabilities of GPS was conducted by the John A. Volpe National Transportation Systems Center, and the findings published in *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System.*[19] This report finds that GPS is vulnerable to unintentional and intentional radio frequency interference. The system is also vulnerable to natural and intentional physical damage, although these scenarios are unlikely. A summary of the vulnerabilities to GPS include ionospheric effects, interference from RF emitters, signal blockage, jamming, and spoofing. All of these vulnerabilities can potentially cause public safety concerns should they result in the malfunction of the navigation system of a spacecraft. Human error can also cause safety concerns. Most aviation accidents to date involving GPS usage have been due to human factors (both in the design and use of GPS). One example is the fact that pilots are likely to take greater poor-weather risks when equipped with GPS.

The primary characteristic that makes GPS vulnerable is the low signal power due to the fact that each satellite is broadcasting continuously to an entire hemisphere of the Earth. The *Report of the Commission to Address United States National Security Space Management and Organization*[20] (the "Rumsfeld report") has recognized the significant potential and ease with which a hostile agent can interfere with GPS signals over a large region. A low-cost 1-W jammer built from readily available commercial components can prevent C/A code acquisition up to 620 mi away. Higher power jammers increase the range for a higher cost. In addition, the study show that receivers subject to jamming may experience large position error (1000 ft or more) with no indication to the user that there is a problem. Two techniques available to detect this interference are Receiver Autonomous Integrity Monitoring (RAIM) and Fault Detection and Isolation (FDI). Additionally, some receivers cannot recover after jamming without a hard reset. Such behavior is undesirable when using the receiver for aviation and space navigation applications. Another form of interference, spoofing, is the use of a transmitter to send signals that appear to be legitimate GPS satellite transmissions. A GPS receiver will lock onto the false signal, resulting in hazardously misleading information (HMI) and large-scale errors. Because the spoofer is imitating a GPS signal, very little power is needed for such a device to affect a very large area, although the complexity needed to build a spoofer is much higher than to build a jammer. Most techniques to defeat jamming do not work against spoofing.

As mentioned above, GPS modernization is aimed at reducing many of these vulnerability threats. Specifically, all unintentional interference threats should be eliminated. The use of multiple frequencies allows significant reduction of ionospheric errors. Additionally, the use of multiple frequencies makes it unlikely that all signals will be jammed by unintentional interference simultaneously. Higher signal power for civilian signals also means that receivers can tolerate higher levels of interference. Multiple frequencies with higher signal power also mean that hostile agents will need to transmit more power at more frequencies in order to effectively jam GPS.

Other mitigation techniques for intentional jamming exist. A costly solution is the use of adaptive antenna arrays that perform beam forming and null steering. These systems are very costly at present and mostly in the experimental phase. Polarization discrimination is a potential technique that promises to offer an inexpensive solution to both broadband and narrowband interference. Practical mitigation techniques for spoofers include multiple-element antenna arrays and possibly integrated GPS/inertial systems.

WAAS and DGPS augmentations are also susceptible to interference as their signals are transmitted. Ground-based DGPS signals will operate at higher power levels and are much harder to jam. WAAS on the other hand will transmit a weaker GPS-like signal from a geostationary satellite; therefore, WAAS signals are more susceptible to the same interference sources that affect normal GPS signals.

Augmenting GPS with INS, as described previously, is an effective backup strategy to protect against most forms of interference. In addition, during periods of GPS outage, it is possible to "coast" on the INS solution until GPS is available again. As stated previously, the performance of the integrated system is predicated on the quality of the INS.

To meet the performance requirements of space radionavigation and to exploit its benefits in mitigating unintentional and intentional interference, the use of an integrated GPS/INS unit is highly recommended. Note that all of these performance enhancements are not mutually exclusive. For example, multiple-element antenna arrays, WAAS, and GPS/INS integration can all be used at the same time. Note that GPS is a multi-segment system; therefore, there is little gain in using redundant GPS systems as backup, except to protect against software or hardware failure. A failure in the space segment or control segment will affect both systems identically. In addition, any interference, whether intentional or not, will simultaneously affect both receivers as well. Dual-redundant GPS receivers with separate antennas on each system will not protect against these failures. In order to be truly redundant, neither system can have common components, including ground or space segments. Integrated GPS/inertial systems, on the other hand, can still navigate when GPS is unavailable. If redundancy is truly important, redundant integrated GPS/inertial systems should be used. Note that attitude information is not available from stand-alone GPS should the INS fail; therefore, it is recommended that redundant IMUs also be used in the INS for launch vehicle applications.

3.6 Findings Regarding GPS Use Aboard Civilian Spacecraft

Special consideration must be given when developing GPS-based navigation systems for civilian spacecraft. There are some practical engineering aspects of incorporating GPS into the flight navigation system, as well as operational capabilities and restrictions of the GPS receiver that are different from those for near-Earth users. In addition to the performance, reliability, coverage, availability, and integrity requirements described in previous sections, there are circumstances unique to spacecraft that must be addressed. For example, a design decision may involve choosing a commercial-off-the-shelf (COTS) GPS receiver for keeping vehicle production costs down. GPS receivers developed for civil aviation were not designed to perform in the environment that a spacecraft will encounter, and a careful engineering study must be performed to evaluate the use of such a system onboard a spacecraft before it is certified. The report, *Spaceborne GPS Current Status and Future Visions,*[21] provides an excellent argument for why the success of GPS in the terrestrial market cannot simply be mapped to the space-based market. A dated survey of receivers designed specifically for space (many of which are still in use) is provided. One simple consideration when using a COTS GPS receiver designed for terrestrial applications is whether the receiver is radiation hardened. Radiation testing on the receivers used for the ISS found that a static random access memory chip needed to be replaced with a radiation-hardened version. The following paragraphs summarize some key considerations analyzed under this study.

GPS receivers are capable of producing accurate and reliable measurements of position, velocity, attitude, and time. For this reason, all GPS receivers must comply with the *International Traffic in Arms Regulation* (ITAR).[5] The ITAR applies to any GPS receiver designed to produce navigation results above 60,000 ft altitude and greater than 1,000 kn velocity and any receiver that uses a null steering antenna. The rational for the regulations is to keep hostile entities outside the U.S. from using the GPS receiver as a navigation instrument for missiles and other weapons. Most COTS receivers disable the ability of the receiver to produce velocities and altitudes greater than the given limits so that the product will not be subject to ITAR. Space vehicles are designed to operate outside these velocity and altitude limits, so receivers chosen for space applications must not be restricted by these limits.

Besides being capable of operating at high velocities, spacecraft might be capable of high dynamic maneuvers. In this case, the bandwidth of the receiver and the frequency sweep of the C/A acquisition algorithm are important. The GPS receiver utilizes a tracking loop to acquire ranging measurements from the GPS signal. A receiver's bandwidth correlates with its ability to track this signal. A narrow (low) bandwidth tracking loop filters out noise at the expense of increased response time, while a wide (high) bandwidth tracking loop has a faster response time, but admits more noise. A wide bandwidth receiver can be fooled into tracking noise instead of the GPS signal. If the receiver is undergoing high dynamics, the range to the satellite will also change rapidly, and a receiver with a narrow bandwidth-tracking loop will lose lock. A wide bandwidth-tracking loop, on the other hand, allows the receiver to maintain lock through high dynamic maneuvers at the expense of accuracy. Designers of spacecraft navigation systems that use stand-alone GPS must ensure that the receiver bandwidth is large enough to handle the vehicle's maximum dynamic maneuvers without losing lock and still meet accuracy requirements. It may be impossible to meet these competing requirements without using integrated GPS/INS in which the INS provides the GPS receiver with information about the vehicle dynamics, allowing the receiver to use narrower bandwidth tracking loops, thus improving accuracy.

The high velocity of the vehicle also poses problems during signal acquisition if the line-of-sight velocity between the vehicle and the satellite is too large. The relative velocity translates into the Doppler, or change in received frequency of the signal. Most receivers are programmed to search for new signals during the acquisition phase within a set range of frequencies that coincide with a reasonable range of Dopplers. If high relative velocity between the vehicle and the satellite causes the frequency to be outside this range, the receiver will not be able to lock onto the satellite signal. This could be a problem for reacquiring a lost satellite signal or acquiring a new satellite that has just become visible.

An Integrated GPS/INS (IGI) solves the problems described above as well as problems related to vulnerability and interference. IGI systems exist in all states of development from production hardware units made by manufacturers for military applications to experimental software programmable receivers. The Space Integrated GPS/INS (SIGI) is an example of a receiver developed for space applications. It is recommended that spacecraft designers do not use production COTS solutions that are not rated for use in space. Using a COTS GPS receiver with an IMU in an uncoupled or loosely couple system might appear simpler and less costly at first, but trying to make the system operate in an environment for which it was not intended could prove more costly in the end. Proprietary firmware in a COTS GPS receiver can hinder resolutions to problems encountered. Software-programmable receivers with a digital front end are available for in-house development of navigation systems. These receivers are highly configurable and have the flexibility to be ported to the latest space-qualified host computer cards. Programmable receivers can also be combined with an IMU in an IGI system. Development with a software-programmable receiver can be extremely complex; therefore, in their reports on lessons learned,[22,23,24] NASA recommends independent validation of the navigation system and very close communication with any contractors.

Spacecraft designers must perform DOP surveys based on the proposed trajectory and launch time, including vehicle attitude, antenna location(s), and masking affects. Some spacecraft designs use a single GPS antenna mounted to the roof of the vehicle. For vehicles that operate in both horizontal and vertical flight orientations, this can pose a significant problem. The vehicle acts as a mask, blocking transmission of satellite signals to the antenna. An antenna on the roof of the vehicle can view all satellites in view in the sky during horizontal flight; however, in vertical flight, the antenna may see less than half the sky. If there were seven satellites visible in a horizontal orientation, this may result in three or less visible satellites in a vertical orientation. In this situation, a stand-alone GPS receiver would no longer be tracking the minimum of four satellites required for operation, and the receiver will stop producing position solutions. An IGI is not subject to this limitation since the internal navigation filter can make use of the pseudorange information even if only one satellite is available. Measurements from additional satellites act to improve the accuracy of the navigation solution. Designers must carefully choose antenna locations and use multiple antennas if required. The positions of the antennas should be chosen to view the entire sky from any vehicle orientation, and the receiver should be capable of handling multiple antennas located at different physical locations. The Space Shuttle is equipped with GPS antennas on the roof and belly of the vehicle for this reason. Even with two antennas, the Space Shuttle cannot utilize GPS during ascent because the external fuel tank blocks the antenna on the belly, and the roof antenna is pointed below the horizon.

Proposed commercial RLVs and ELVs include both suborbital and orbital designs. Orbital vehicles create a new set of problems for GPS acquisition and tracking during reentry. High reentry speeds during return from orbit can cause a plasma layer to form around the vehicle due to friction between the vehicle and the atmosphere. This plasma may interfere with the GPS signals. FAA/AST recently sponsored research at The Aerospace Corporation to investigate this problem.[25] The Space Shuttle has encountered problems with plasma forming on its lower surface during reentry, causing frequent loss of lock and problems with reacquisition, although a "complete blackout" is rare. Orbital spacecraft are usually operated near the equator to take advantage of the additional velocity contribution due to the Earth's rotation. Errors due to the ionosphere are at a maximum near the equator and the poles, and dual-frequency receivers should be used for operation in these locations.

The National Aeronautics and Space Administration (NASA) has been studying the use of GPS on spacecraft for many years, and designers of civilian spacecraft navigation systems could benefit from this experience.[22,23] The Space Shuttle uses a 5-channel aviation GPS receiver, the Miniaturized Airborne GPS Receiver (MAGR)[*], which was modified for space use and initially flown in 1993. The GPS receiver is not integrated with onboard navigation to avoid changes to the proven Kalman filters in the Primary Avionics Software System (PASS). Even with limited integration required, firmware problems prevented the receiver from being certified for operational use until 2002. The Space Integrated GPS/INS (SIGI) was also tested on various Space Shuttle flights, and three are now used on board the ISS. One SIGI is configured to provide attitude determination using multiple antennas, but technical issues with the Kalman filter prevent the use of the IMU. Note that neither the Space Shuttle nor ISS GPS receivers meet the requirements for precise orbit determination, requiring ground station radar tracking to still be used. Many lessons can be learned by studying NASA's efforts to incorporate GPS into their vehicle systems.[24]

These findings regarding GPS use aboard launch vehicles are summarized in Section 5, Conclusions.

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[*] A memorandum of agreement (MOA) with NASA to use PPS has expired. There are no plans to renew the agreement due to the availability of a second GPS civil frequency.

4. Ionospheric Effects Along a Launch Trajectory

The effect of the ionosphere on the various signals was a major concern in the early days of GPS, and the Klobuchar model was suggested for single-frequency users, which presumably corrects for about 60% of the ionospheric delay (magnitude of a few meters), averaged over the northern hemisphere.

The ionosphere causes a code phase delay and a carrier phase advance of the same magnitude. There were attempts to exploit this code-carrier divergence to derive the ionospheric delay, but in the end, these methods turn out to be difficult to implement because of the need to resolve the integer ambiguity of the carrier phase, and this is usually a relatively time-consuming undertaking.* The impression that the 2-frequency method completely corrects for the delay is not true. There is left over a residual uncorrected error, expressed by:

$$\left(\frac{f_1^2}{f_1^2 - f_2^2}\right)\varepsilon \quad \text{for the} \quad f_2 \quad \text{signal,} \quad \left(\frac{f_2^2}{f_1^2 - f_2^2}\right)\varepsilon \quad \text{for the} \quad f_1 \quad \text{signal.}$$

Here ε is the pseudorange measurement error, assumed to be identical for both frequencies, and f_1 and f_2 are the two frequencies. Thus, for L1 and L2 frequencies, and assuming $\varepsilon = 0.1$ m, the residual uncorrected delay can be expected to have magnitudes 25.5 cm for L2 and 15.5 cm for L1.

In reality, the ionosphere can induce three effects on the radio frequency signal: (1) a propagation delay; (2) an apparent velocity, manifested as an equivalent frequency shift, δf; and (3) an apparent acceleration, manifested as a frequency drift rate (df/dt). For normal ionospheres, the 2nd and 3rd effects are very small, and we shall show some estimates of upper bounds on these effects below. Under magnetic storm or scintillation conditions, these effects could be larger since they are dependent on the space and time gradients of the electron density in the ionosphere.

4.1 The Nominal Ionosphere

Figure 1 shows a nominal ionosphere profile, where electron density is plotted against altitude. This is the ionosphere above the geographic point at latitude 35ºN and longitude 245ºW, at 0.00 and 12.00 h local time, on January 1, 2000, as given by the IRI-95† for a "regular" ionosphere day. The maximum electron density peaks at 300 km (the F-layer). The region of major contribution to the total electron content (TEC), where the electron density exceeds $10^5/\text{cm}^3$, lies between 100 and 1000 km during daytime and between 170 and 900 km at nighttime.

* There are more efficient techniques for integer ambiguity resolution, such as 2-frequency and 3-frequency wide laning, but then they require signals on more than a single frequency.

† The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). The IRI master copy is held at the National Space Science Data Center (NSSDC).

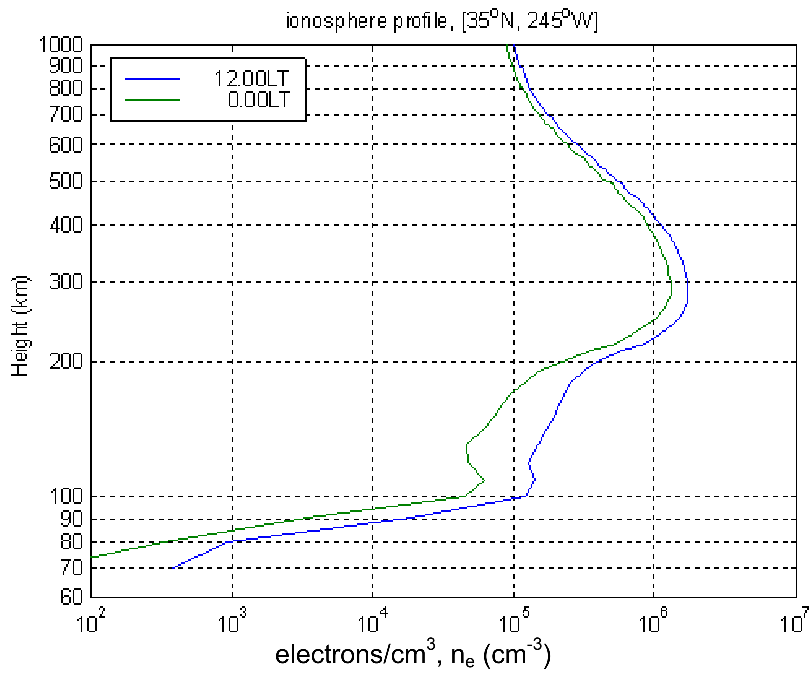

Figure 1. Model normal ionosphere.

Figure 2 Shows the TEC above a given altitude, obtained by integrating the daytime curve in Figure 1 from the top down. Figure 3 is the same plot, but the abscissa now shows the equivalent range delay of an L_1 signal for the given TEC. These curves show that the ionosphere effect for vehicles at altitude below 200 km is similar to that on the ground and that the full ionosphere TEC still lies above it. The noontime ground level vertical TEC for this day is 48.5 TECU.* The nominal ground level TEC varies

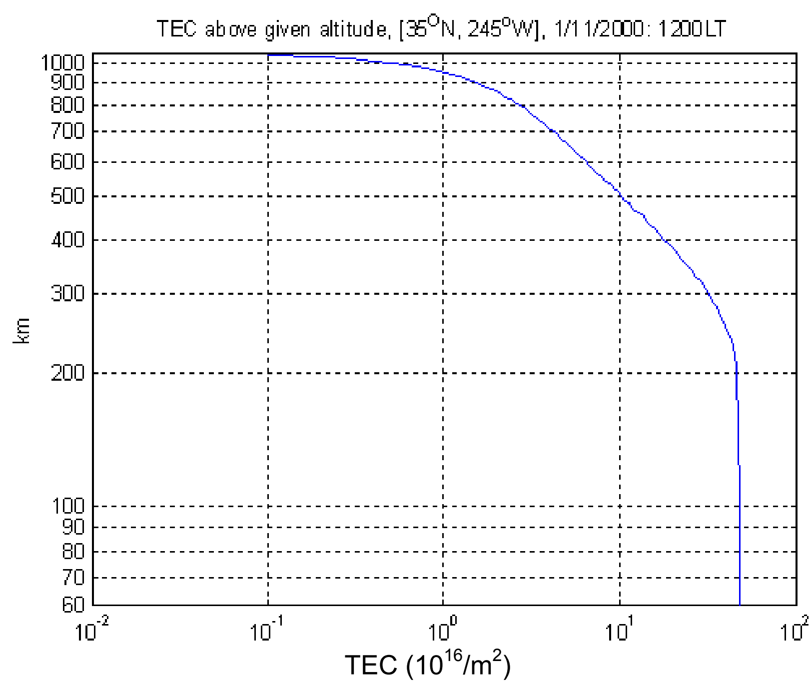

Figure 2. TEC plotted vs. altitude.

* One TEC Unit (TECU) = 10^{16} electrons/m^2.

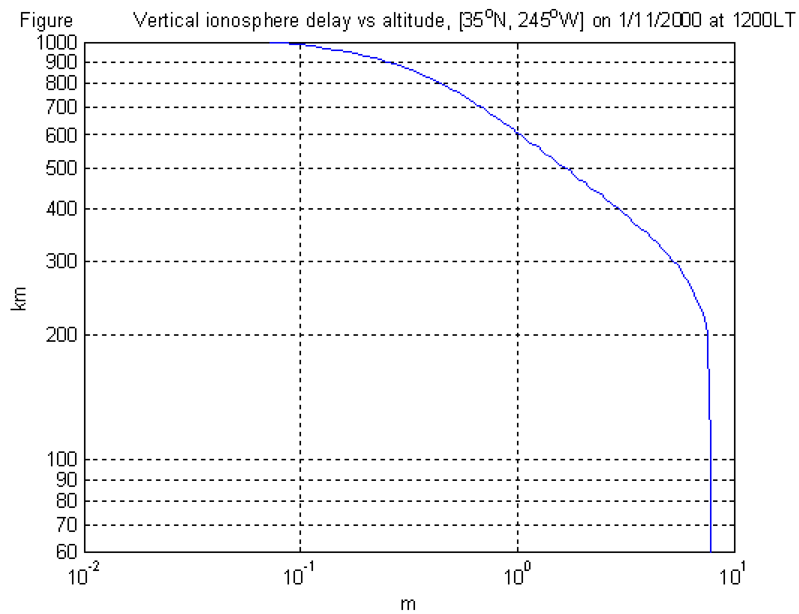

Figure 3. Zenith ionosphere delay at mid latitude plotted vs. altitude.

between 10 TECU for quiet Sun and 100 TECU at solarmax and during solar storms. It is also clear that under nominal condition, there is little ionosphere above 1000 km.

4.2 Ionosphere-induced Pseudorange, Velocity, and Acceleration Errors Along a Delta-II Trajectory

In order to obtain some quantitative results of ionosphere-induced error, we followed the trajectory of a Delta-II launch. Figure 4 shows the altitude of a Delta-II launch as function of time. Note that maximum altitude within the domain of interest for range safety is below 200 km. Figure 5 plots the vehicle absolute velocity as a function of altitude.

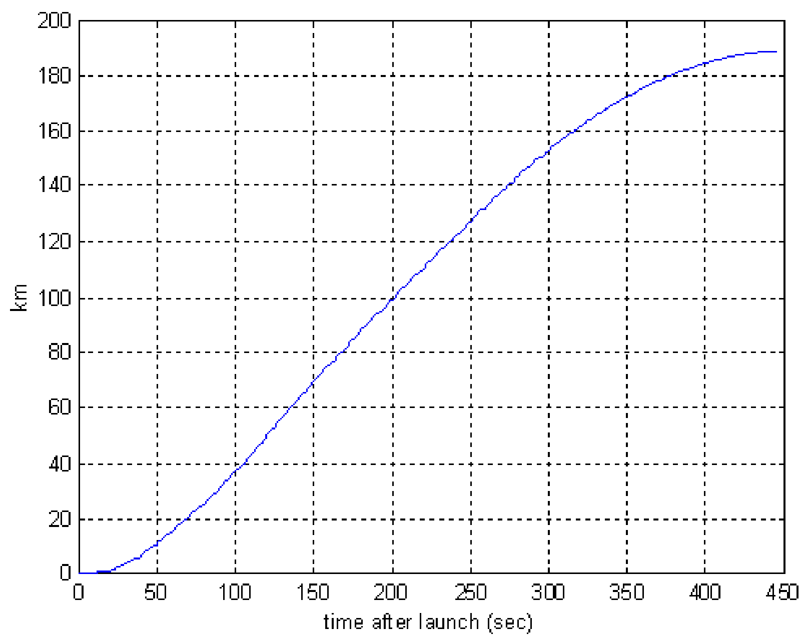

Figure 4. Delta-II altitude time history.

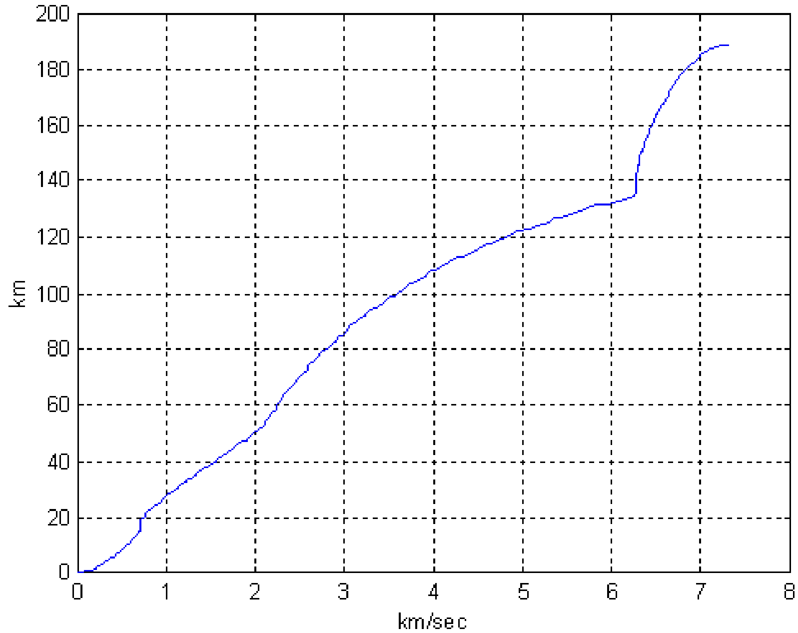

Figure 5. Delta-II velocity plotted vs. altitude.

Figure 6 shows the differential vertical ionosphere delay between ground level and the vehicle. At an altitude of 200 km, this value is 0.5 m. With an (almost extreme) obliquity factor of 10, the line-of-sight (LOS) delay error will be 5 m.

One should note that *the ionosphere induced velocity error is essentially independent of the LOS obliquity factor*. This is because the change in TEC in the direction of vehicle velocity is the dominant factor.

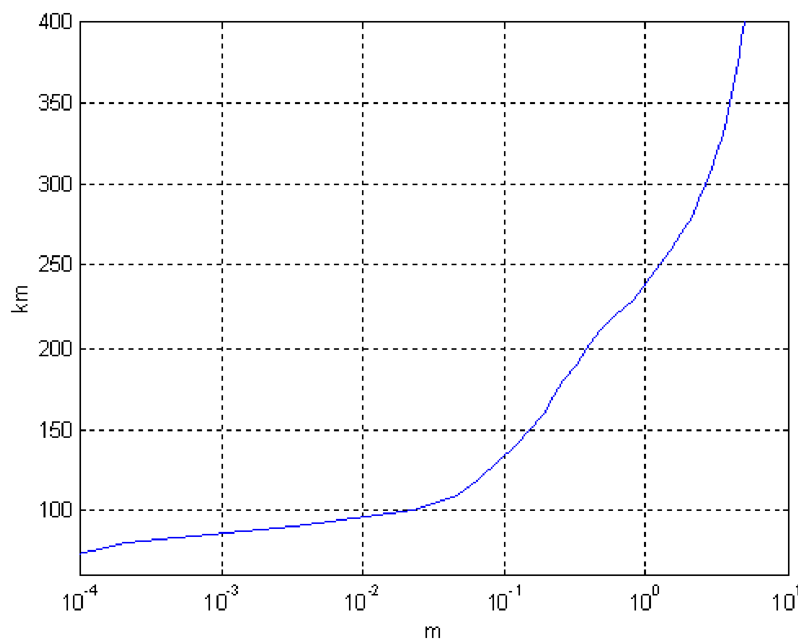

Figure 6. Difference in ionosphere delay between ground level and an altitude.

$$\partial r = \frac{40.3\,N(r)}{f^2}$$

$$N(r) = \int_{LOS} n(r)dr$$

$$\partial v = \frac{d(\partial r)}{dt} = \frac{40.3}{f^2}\frac{dN}{dt} = \frac{40.3}{f^2}\left(\nabla N \bullet V + \frac{\partial N}{\partial t}\right) \le \frac{40.3}{f^2}\left(\frac{\partial N(r)}{\partial h}|V|\right) = \frac{40.3}{f^2} n(h)|V|$$

In the above equations, δr is the ionosphere range delay in meters, δv is the induced velocity error in m/s, N(r) is the TEC in units of electrons/m^2, n(r) is the electron density in units of electrons/m^3, f is frequency in Hz, h is altitude in meters, and V is the vehicle velocity. We have also made the reasonable assumption that ∂N/∂t, the temporal TEC variation is small at the time scale of concern. (This assumption obviously does not hold under scintillation conditions). Similarly, the ionosphere-induced acceleration error is bounded by the following relation:

$$\partial a \le \frac{40.3}{f^2}\frac{\partial n(h)}{\partial h}|V|^2$$

Figures 7 and 8 plot the ionosphere induced velocity and acceleration errors, respectively, as functions of vehicle altitude. The maximum velocity error is 3.5 cm/s, and the maximum acceleration error is less than 7 mm/s^2.

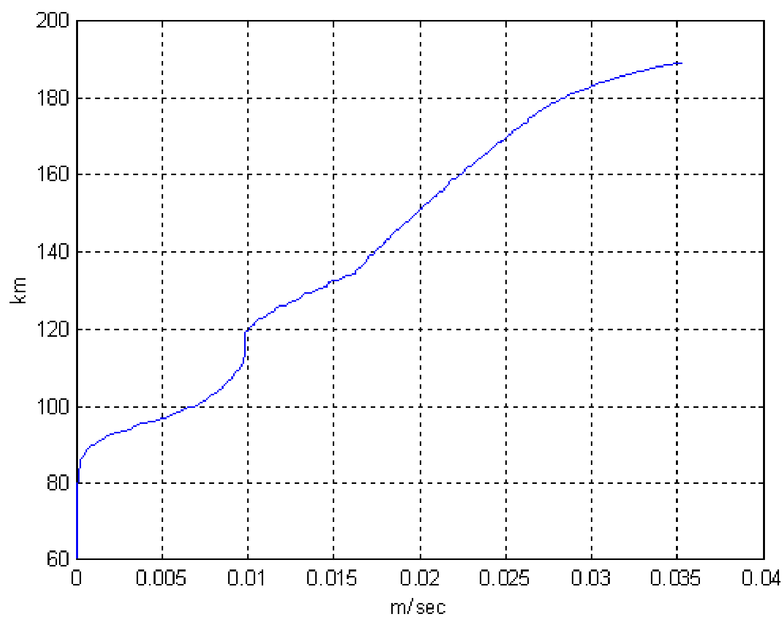

Figure 7. Ionosphere induced apparent velocity.

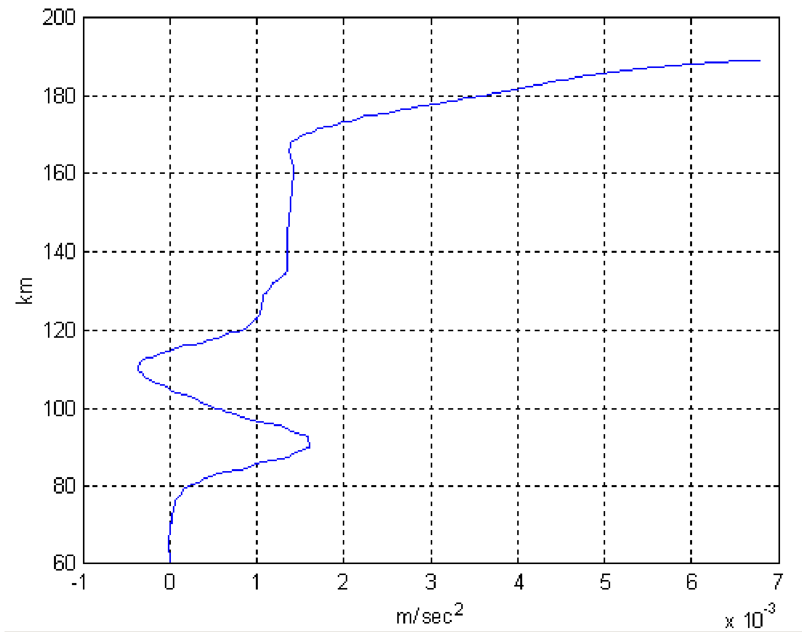

Figure 8. Ionosphere induced apparent acceleration

4.3 Scintillation

We have provided bounds for the ionosphere induced LOS range, velocity, and acceleration errors along a typical Delta-II launch trajectory. The ionosphere delay above 1000 km is small, as are the induced apparent velocity and acceleration due to electron density gradients.

The effect of ionosphere scintillation is a different matter. Scintillation is caused by the formation, disintegration, and migration of high electron density clusters of various sizes, which cause fluctuation in signal power and in the phase of the signal (i.e., flat and frequency selective fadings). Severe scintillation could induce large (order of 100 m) code tracking errors and may knock tracking loops out of lock. The 2-frequency correction residual could increase because now the signal may follow different propagation paths.

Efforts are underway to monitor the ionosphere with networks of GPS receivers,[26] and other efforts attempting to measure the solar wind *in situ* with satellites sent in the Sun's direction to foretell the oncoming of magnetic storms.[27] In the future, incorporation of scintillation model information as part of a renewable database provided to onboard GPS receivers might become a common practice, so that they can selectively exclude measurements from satellites whose line-of-sight is likely to be affected by scintillation effects.

5. Conclusions and Recommendations

Analysis of RLV and ELV flight data shows that the application of off-the-shelf receivers and a casual approach to the integration of such receivers for space flight are unlikely to succeed. J. L. Goodman, who had participated in the integration of GPS on the Shuttle, the International Space Station, and the Crew Return Vehicle, had this to say of that experience:

> "While the basic ability of GPS to perform position, velocity and attitude determination was successfully demonstrated, the effort required to prepare and certify GPS units for operational use far exceeded initial expectations."[23]

Indeed, because of the rotational maneuvers of RLVs and ELVs, a single-antenna stand-alone GPS receiver cannot provide enough visible satellites to effect a navigation solution. The GPS-based tracking system for RLVs and ELVs must as a minimum have (1) a set of two or more antennas capable of viewing the entire sky from any feasible vehicle orientation and the corresponding multiple antenna input control software; (2) a fast acquisition/reacquisition algorithm in case of loss of lock; and (3) a commensurably accurate INS to assist reacquisition and bridge gaps of lost GPS data. A modern space-GPS receiver should also anticipate future development of the GPS system and reserve capacity to exploit new and additional signals such as (1) L2C, L5, and L1C; and (2) the rapidly developing GPS-based models of the environment: "nowcasting" of troposphere and ionosphere and their scintillation maps. The receivers should be capable of acquiring signals with larger Dopplers due to the speed of the ELV/RLV being much greater than civilian aircraft. Also, GPS receivers not augmented by inertial sensors must have a bandwidth large enough to track through the maximum dynamic maneuvers that the ELV/RLV will encounter and still meet navigation accuracy requirements. GPS use as a tracking source for launch ranges has also been thoroughly studied by the RCC, and guidelines and requirements are in place. The FAA has established CFRs that govern commercial and civilian launches but do not specifically address GPS use. GPS availability for altitudes beyond 1.25 Earth radii has been problematic since inception of the system because it was intended for terrestrial applications. The following is a summary of conclusions and recommendations made here and throughout the report.

It is highly recommended that any GPS receivers used for navigation aboard RLVs and ELVs be integrated with an INS and corresponding navigation filter. Otherwise, the GPS receiver must:

- incorporate a set of antennas capable of viewing the entire sky from any feasible vehicle orientation and the associated multiple antenna control software.
- incorporate a fast acquisition/reacquisition algorithm to minimize loss of lock outages and time to acquire new satellites that come into view.
- have a bandwidth wide enough to track through maximum dynamic maneuvers without losing lock, but narrow enough to reject noise to maintain accuracy requirements (Note that it may not be possible to meet these competing requirements.)

Even if an IGI is used, it is still suggested that the GPS receiver adhere to the first two bullets. The optimal bandwidth of the tracking loops in an IGI are tuned by the navigation filter. In addition, both standalone and integrated GPS receivers must:

- be capable of acquiring signals with large Dopplers due to speeds of the ELVs/RLVs being much greater than civilian aircraft.

- not be limited by ITAR restrictions.

It is also suggested that a GPS receiver used for navigation aboard RLVs and ELVs should:

- be adaptable to using additional signals such as civilian L2C, L5, and L1C frequencies (1227.60, 1176.45, and 1575.42 MHz, respectively) when available and use the additional frequencies to mitigate error due to ionospheric interference.

- be adaptable to using the rapidly developing GPS-based models of the environment ("nowcasting" troposphere and ionosphere and their scintillation maps) when available.

- incorporate interference mitigation techniques for non-environmental interference (anti-jam algorithms).

- incorporate measurements from Galileo satellites when available.

- incorporate RAIM.

- incorporate FDI if an integrated GPS/INS is used.

Finally any space-based navigation system used aboard RLVs and ELVs should at least meet the minimum requirements specified by the FAA for civilian aircraft navigation systems:

1. Be safe, reliable, and available over all used airspace regardless of weather, time, terrain, or propagation anomalies.
2. Not limit performance.
3. Have integrity near 100% and provide timely alarms in the event of failure, malfunction, or interruption.
4. Recover from temporary loss of signal without the need for a complete reset.
5. Provide means for the pilot to confirm performance and protect itself from possibility of input blunders.
6. Provide information to the pilot and aircraft systems to determine the position of the aircraft with an accuracy and frequency that will bound the aircraft within an established protected airspace.

7. Compensate for signal fade and propagation anomalies and reduce susceptibility to interference.

8. Be compatible with the overall Air Traffic Control (ATC) system.

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6. Acronyms and Abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast
AII	Accuracy Improvement Initiative
AOD	Age of data
AST	Office of the Associate Administrator for Commercial Space Transportation
ATC	Air Traffic Control
C/A	Coarse/Acquisition code
CFR	Code of Federal Regulations
cm	Centimeter
COLA	Collision Avoidance
COSPAR	Committee on Space Research
COTR	Contracting Officer's Technical Representative
COTS	Commercial-off-the-Shelf
CRPA	Controlled Reception Pattern Antenna
CRV	Crew Return Vehicle
δf	Frequency shift
δr	Ionosphere range delay
δv	Induced velocity error
DGPS	Differential GPS
DoD	Department of Defense
DOP	Dilution of Precision (measurement of goodness of GPS satellite viewing geometry)
DOT	Department of Transportation
drms	dimension root-mean-square
DSCS	Defense Satellite Communication System
ECI	Earth Centered Inertial (a reference frame)
EGI	Embedded GPS/Inertial
ELV	Expendable Launch Vehicle
f	Frequency
FAA	Federal Aviation Administration
FDI	Fault Detection and Isolation
GEO	Geosynchronous Earth Orbit
GPS	Global Positioning System
h	Altitude
HDOP	Horizontal Dilution of Precision
HMI	Hazardously Misleading Information
Hz	Hertz
ICBM	Intercontinental ballistic missile
ICD	Interface Control Document
IGI	Integrated GPS/Inertial
IIP	Instantaneous Impact Point
IMU	Inertial Measurement Unit
INS	Inertial Navigation System

ION	Institute of Navigation
IRI	International Reference Ionosphere
ISS	International Space Station
ITAR	International Traffic in Arms Regulation
JPO	Joint Program Office
km	Kilometer
LAAS	Local Area Augmentation System
LEO	Low Earth Orbit
L1	GPS Frequency, 1575.42 MHz
L2	GPS Frequency, 1227.60 MHz
L5	GPS Frequency, 1176.45 MHz
L1C	New GPS Civil Code Broadcast on L1 Frequency
L1C/A	GPS C/A Code Broadcast on L1 Frequency
L2C	GPS Civil Code Broadcast on L2 Frequency
LOS	Line-of-sight
m	Meter
mm	Millimeter
MAGR	Miniaturized Airborne GPS Receiver
MCS	Master Control Segment
MEMS	Micro-electromechanical systems
MEO	Medium-Earth Orbit
MFCO	Mission Flight Control Officer
MOA	Memorandum of Agreement
NASA	National Aeronautics and Space Administration
NDGPS	Nationwide DGPS
n(r)	Electron density
N(r)	TEC in units of electrons/m^2
NSSDC	National Space Science Data Center
PASS	Primary Avionics Software System
PDOP	Position Dilution of Precision
PPS	Precision Positioning Service
P(Y)	GPS Precision (Y)
P(Y)/M	GPS Precision (Y)/Military Code ("Y" signals encryption)
RAIM	Receiver Autonomous Integrity Monitoring
RCC	Range Commanders Council
RF	Radio Frequency
RLV	Reusable Launch Vehicle
rms	Root Mean Square
RSO	Range Safety Officer
RTCA	formerly Radio Technical Commission for Aeronautics; present designation is RTCA, Inc.
SA	Selective availability
sec	Second
SIGI	Space Integrated GPS/INS
SIS	Signal-in-Space
SPS	Standard Positioning Service
TDRSS	Tracking & Data Relay Satellite System
TEC	Total Electron Content

TMIG	Telemetered Inertial Guidance
TSPI	Time, Space, Position Information
UERE	User Equivalent Range Error
URE	User Range Error
URSI	International Union of Radio Science
U.S.	United States
VDOP	Vertical Dilution of Precision
WAAS	Wide Area Augmentation System

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