

Space Shuttle Navigation In The GPS Era

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BIOGRAPHY

John L. Goodman is employed by United Space Alliance at the NASA Johnson Space Center, in support of the Mission Operations Directorate. Mr. Goodman graduated from the University of Arizona in 1986 with a B. S. in Aerospace Engineering. His experience includes flight software verification, rendezvous guidance and navigation analysis; and Global Positioning System (GPS) applications for the Space Shuttle, Crew Return Vehicle, and metric tracking.

ABSTRACT

The Space Shuttle navigation architecture was originally designed in the 1970s. A variety of on-board and ground based navigation sensors and computers are used during the ascent, orbit coast, rendezvous, (including proximity operations and docking) and entry flight phases. With the advent of GPS navigation and tightly coupled GPS/INS units employing strapdown sensors, opportunities to improve and streamline the Shuttle navigation process are being pursued. These improvements can potentially result in increased safety, reliability, and cost savings in maintenance through the replacement of older technologies and elimination of ground support systems (such as Tactical Air Control and Navigation (TACAN), Microwave Landing System (MLS) and ground radar). Selection and missionization of "off the shelf" GPS and GPS/INS units pose a unique challenge since the units in question were not originally designed for the Space Shuttle application. Various options for integrating GPS and GPS/INS units with the existing orbiter avionics system were considered in light of budget constraints, software quality concerns, and schedule limitations. An overview of Shuttle navigation methodology from 1981

to the present is given, along with how GPS and GPS/INS technology will change, or not change, the way Space Shuttle navigation is performed in the 21st century.

INTRODUCTION

In the 1970s, the Space Shuttle was designed with three TACAN units for use during the entry phase of flight. By the late 1970s, with the NAVSTAR GPS program promising a revolution in navigation, the use of GPS on the Shuttle orbiters was studied [1]. The orbiters Discovery, Atlantis and Endeavour were all manufactured in the 1980s with GPS antennae and associated wiring. However, due to budget concerns and the developmental nature of GPS, a GPS upgrade to the Shuttle system was not pursued.

In 1990, the introduction of GPS had led the Department of Defense and the Federal Aviation Administration to plan the phase out of TACAN ground stations beginning in the year 2000. GPS promised better performance than TACAN and reduced operating costs. In response, then Shuttle program Manager (and former astronaut) Robert Crippen initiated an effort to study the possibility of replacing the three TACAN units on each orbiter with three GPS receivers.

By 1996, the development of Embedded GPS/INS (or EGI) units employing strapdown inertial sensors [2] motivated the Shuttle program to look at an eventual replacement of the previously mentioned stand alone GPS (the TACAN replacement) and stable member, spinning mass gyro Kearfott High Accuracy Inertial Navigation Systems (HAINS) Inertial Measurement Units (IMUs) with EGIs. The use of strapdown IMUs employing ring laser gyro (RLG) technology was identified as a potential

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source of cost and schedule savings during orbiter processing.

Both the TACAN replacement and GPS/IMU replacement efforts were conducted in parallel. Studies were performed to determine the best integration architecture. Stand alone GPS units and EGIs had to be integrated in a manner that did not compromise the integrity of an operational, certified navigation system. Once it was decided to tailor the GPS receiver requirements to TACAN replacement, studies were conducted to determine if there were other applications for GPS during Shuttle flights.

Changes to the Shuttle General Purpose Computers (GPCs) to support both projects were identified. GPS and EGI hardware was selected; interface, firmware and hardware changes were identified and made. Both the GPS and EGI units were flown on a series of Shuttle missions for test and evaluation. Modifications were made to GPS and EGI firmware based on flight test results.

OVERVIEW OF SPACE SHUTTLE NAVIGATION SYSTEM

Navigation requirements for manned spacecraft are different than those for terrestrial aircraft, unmanned Earth orbiting satellites and interplanetary probes [3, 4]. The guidance, navigation and flight control system had to be designed to ensure safety of flight and mission success for ascent, orbit, rendezvous and gliding entry to a runway landing in the presence of system failures. For ascent and entry, a total of five computers, running in parallel, can control the vehicle. Four of the GPCs run what is known as the Primary Flight Software Sub-System (PASS) software. The fifth runs Backup Flight Software (BFS). PASS and BFS software was coded by different contractors. The BFS contains a subset of the PASS functionality to enable the vehicle to finish nominal ascent, an abort or landing in the event of a generic PASS software failure. While on orbit, only PASS software provides guidance, navigation and flight control functions. Multiple navigation sensors, command paths and power buses within the avionics system ensure redundancy [5, 6].

Navigation sensors used in the "pre GPS era" include:

Ascent

- Three HAINS IMUs
- Ground based C & S Band radar tracking.

Orbit, Rendezvous & Docking

- Three HAINS IMUs
- Two Star Trackers
- One Ku Band Rendezvous Radar
- One Crew Optical Alignment Sight (COAS)
- Trajectory Control Sensor (TCS, a laser)
- Two Hand Held Lasers (HHL)
- Two Payload Bay Television Cameras With Ranging Ruler Overlays
- Ground based C Band radar tracking.
- Tracking And Data Relay Satellite (TDRS) S Band Doppler tracking.

Entry And Landing

- Three HAINS IMUs
- Three TACANs
- Four Barometric Altimeters
- Three Ku Band MLS Receivers
- Two Radar Altimeters
- Ground based C & S Band radar tracking.
- At least two TACAN ground stations.
- MLS ground equipment.

For HAINS IMUs, TACANs, barometric altimeters and MLS units, redundant measurements are passed through Fault Detection, Identification and Reconfiguration (FDIR) algorithms [7]. Selection filters then process data from units deemed to be "good." Selected measurements are then passed to the Shuttle navigation software. HAINS IMU data is used during all flight phases for attitude and sensed velocity determination. During entry, PASS and BFS Kalman filters process selected TACAN, IMU derived altitude and barometric altimeter measurements. Only the PASS Kalman filter processes selected MLS data. Selected radar altimeter data is provided for crew situational awareness, but is not incorporated into the navigation solution.

During rendezvous, a PASS Kalman filter processes on-board radar, star tracker and COAS measurements. TCS and HHL data are processed in Kalman filters residing in a laptop computer for crew situational awareness. Television monitors with ranging ruler overlays provide range information to the crew during docking.

INTEGRATING GPS IN A LOOSELY COUPLED ARCHITECTURE

A loosely coupled architecture using cascaded filters is a common way of upgrading existing navigation systems with GPS. This method of integration has been used on

platforms such as the F-16 [8], F-117 [9], Conventional Air Launched Cruise Missile [10] and B-2 [11].

A cascaded filter approach involves using the position output of the GPS receiver as a measurement for a Kalman filter in the host vehicle navigation system [8]. Position and velocity aiding data from the host vehicle INS are fed back to the GPS receiver to improve signal acquisition and tracking performance. However, the Kalman filter is derived under the assumption that measurements are not time correlated. This assumption is violated by processing the GPS position vector in the host vehicle Kalman filter. Time correlated measurements can lead to filter instability. This problem has been avoided in many applications by processing GPS position vectors at a low rate, such as no higher than every 15 seconds [10].

One option considered was to process GPS position vectors as measurements in the PASS and BFS Kalman filters, as is done in many military applications.

Another option studied was to convert GPS position into a TACAN measurement (known as "TACAN transparency"). This was an attempt to minimize or avoid changes to the PASS and BFS flight software and input/output. This would have resulted in a high rate cascaded filter implementation (TACAN measurements are processed every 3.84 seconds). A "transparent" approach would not have allowed INS aiding to be supplied to the receiver from the GPC. Crew displays required GPS receiver specific controls and quality assessments, and GPS data needed to be sent to Mission Control for the flight controllers. For on-orbit processing, a new Kalman filter would have to be created. On-orbit processing of "pseudo TACAN" measurements could only have been performed within the line-of-sight of the TACAN stations already in the flight software to support landing.

Neither of the loosely coupled, cascaded filter options were acceptable to the Shuttle program. Processing GPS as a TACAN measurement or filtering the GPS position vector could not have been evaluated in flight without actually incorporating the data into the navigation state. Both of these options would have required retuning the entry navigation Kalman filters in the PASS and BFS flight software. A new PASS flight software Kalman filter for the orbital phase of flight would have to be created. Any modifications to the existing filters for entry, or a new Kalman filter for orbit, would result in an extensive flight software development and certification effort.

THE TIGHTLY COUPLED OPTION

In a tightly coupled integration, processing actual GPS measurements (pseudorange, delta range) from a GPS receiver in a host vehicle computer permits the navigation system designer to have more control over the quality of the navigation solution, rather than having to rely on a receiver vendor's proprietary firmware. Processing high rate, unfiltered GPS observables and inertial measurement unit data in a central Kalman filter permits higher accuracy navigation and less vulnerability to GPS outages and jamming. This architecture enables rapid estimation of GPS receiver clock errors and inertial measurement unit errors [8].

Processing of GPS pseudoranges in the PASS and BFS flight software was also considered, but not chosen. Like the cascaded filter options discussed previously, it would have required modifications to baseline entry navigation and a new Kalman filter for the on-orbit phase. Furthermore, there were security concerns with sending "corrected" pseudoranges outside the keyed GPS receiver to the Shuttle GPCs. Uncorrected pseudoranges could be processed in the GPCs, but the entry and new orbit Kalman filters would have to solve for the corruption due to Selective Availability.

STATE REPLACEMENT CHOSEN

After considering eight integration options, the Shuttle program directed that GPS be integrated "in parallel" with the existing "baseline" navigation on the orbiters. A GPS state (position and velocity) selected by the Shuttle flight software would "overwrite" the Shuttle flight software navigation state. "State replacement" in the Shuttle navigation software was chosen over treating GPS as a sensor and filtering the GPS measurements or state vector. This architecture treats the GPS receiver as a complete navigation system [12]. Any potential problems with cascaded Kalman filters would be avoided. State replacement could be implemented so that the same GPC flight software could be used for GPS processing during both orbit and entry.

Another advantage of state replacement is that it permits flying the GPS receiver in a test mode during flights, without having to use GPS for navigation. This allows operation of a "mixed fleet" of GPS and TACAN hardware configurations with the same version of PASS and BFS flight software. Due to the schedule of orbiter overhaul periods, not all orbiters would be equipped with GPS units at the same time. Supported TACAN/GPS configurations are:

- Three TACANs for operational use and one GPS receiver for data gathering.
- Three GPS units for operational use and no TACANs.
- Three TACANs and no GPS onboard.

It was believed that this approach would also make it easier to upgrade the Shuttle with more advanced receivers, whereas the Kalman filtering of GPS measurements or vectors in the Shuttle GPCs might require retuning the filters in the GPC. Furthermore, if a receiver upgrade occurred, it was believed that this approach would eliminate the need for detailed knowledge of the GPS receiver's firmware.

The GPS receivers are provided with position, velocity and attitude aiding from the Shuttle flight software (PASS, or BFS in the event of a PASS software failure). One aiding state vector is propagated for all three receivers, using selected IMU data from candidates that have been screened by a FDIR algorithm. The single aiding state is periodically reset with the Shuttle navigation state.

The PASS flight software subjects GPS state vectors to three Quality Assurance (QA) checks. The QA tests were designed so that retuning of the receiver Kalman filter, or changes to receiver residual edit tests would not be necessary for the Shuttle missionization.

- A check of several receiver parameters, one of which is the Figure of Merit (FOM).
- The current GPS state is compared with the receiver's previous state propagated to the current time.
- Comparison of the receiver states with each other.

If criteria for any of the QA tests are violated, that receiver's state is not a candidate for selection. State vectors from candidate GPS units are then processed in a selection filter. The BFS flight software uses a simpler QA and selection scheme than PASS. There are crew controls that allow these QA tests to be bypassed, if necessary.

Once the QA checks are complete and a GPS state has been selected, there are two crew commanded methods for incorporating the selected GPS state into navigation. The first involves automatic incorporation at a flight phase dependent rate, if the selected GPS state is within a tolerance of the current navigation state. The second method, called a "force," ignores the comparison test with

the current navigation state and incorporates (forces) the selected GPS state into navigation.

RECEIVER SELECTION

For TACAN replacement, the Shuttle program desired an off the shelf, in production military unit designed for aircraft to take advantage of the existing production line and logistics base. The Shuttle program also desired to be an authorized user of GPS, to take advantage of the jamming and spoofing resistance provided by military GPS units. In addition, the Shuttle program wanted to benefit from firmware that had been "matured" through development and use by the Department of Defense. The Collins Miniaturized Airborne GPS Receiver (MAGR), a 5 channel unit, was selected.

Unlike earlier GPS receivers, the MAGR used digital, rather than analog tracking loops. This permitted space missionization to be performed via firmware, rather than hardware changes. Existing "space rated" GPS receivers were not suitable for the Shuttle (i.e. didn't accept inertial aiding, too big and heavy for the Shuttle, not capable of "authorized" operation). At the time, there was not a military aircraft, all-in-view receiver in production.

INITIAL FLIGHT TESTS AND RECEIVER MISSIONIZATION

The first flight of a GPS receiver on the Shuttle was on mission STS-51 in September of 1993 [13]. A Trimble TANS Quadrex was flown. This experiment was not a part of the TACAN replacement project. The Quadrex was mounted in an overhead window on the flight deck. Signal attenuation from the glass and limited field of view severely impacted receiver performance.

The initial flight test program supporting TACAN replacement involved the 5 channel, Collins 3M receiver. The 3M was a pre-production version of the Collins MAGR. This series of flight tests was intended to prove if a GPS receiver designed for terrestrial aircraft use could function on the Space Shuttle with a minimum number of firmware changes.

INS aiding was supplied to the 3M by the BFS GPC during ascent and entry, while on-orbit the receiver was unaided and operated by a laptop computer. Receiver state vectors and other 3M data were recorded on the laptop. The 3M was not keyed. Since the purpose of the 3M flight tests was purely data gathering, no navigation data was sent from the 3M receiver to the BFS GPC. The Collins 3M unit flew seven times (December, 1993 to

May, 1996) on Endeavor (flights 61, 59, 68, 67, 69, 72 and 77). Modifications were made to the 3M firmware between flights based on flight test results.

Hardware and firmware missionization of the Collins production MAGR for TACAN replacement began in 1995. The version of the MAGR flown on the shuttle is known as the MAGR/S (MAGR/Shuttle). Collins based MAGR/S firmware on military MAGR Link 008, with Link 009 and 010 modifications also included. Lessons learned from the 3M flights were also incorporated into the MAGR/S firmware.

“SINGLE STRING” TACAN REPLACEMENT FLIGHT TESTS

A single MAGR/S unit (the “single string” configuration) is being flown on each orbiter for several years during a test and certification program. The single string MAGR/S flown during the test phase has two antennas, one on the top and one on the bottom of the crew compartment (GPS 2 in Figure 1). Input from the antennas are passed through pre-amplifiers and a signal combiner before reaching the MAGR/S. On many flights, a laptop computer is used to record instrumentation port data. This data proved to be invaluable in resolving MAGR/S performance issues.

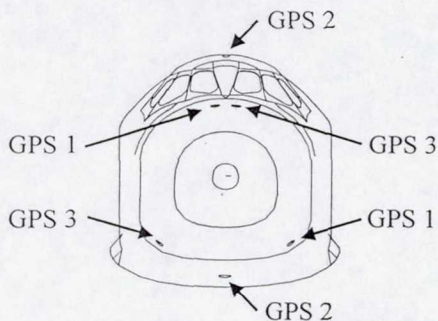


Figure 1: GPS antennae locations.

The first flight of the single string MAGR/S configuration was on STS-79 in September of 1996. MAGR/S data was available in “real time” to Mission Control personnel during ascent and entry. More flights followed as each orbiter in the fleet was equipped with a single MAGR/S receiver. STS-91 in June of 1998 was the first flight during which GPS data was available “in real time” to Mission Control personnel during the orbital phase of flight.

Detailed Test Objectives (DTOs) are being carried out during the single string flights. These tests involve astronaut execution of MAGR/S procedures. Selected MAGR/S state vectors were incorporated into the PASS

and BFS flight software on several occasions while on orbit. On STS-103 (December 1999, before the deactivation of Selective Availability), the MAGR/S was intentionally unkeyed prior to entry. The Shuttle will be certified to land with the MAGR/S unkeyed. Another DTO involved a “late power-on” of the MAGR/S just prior to entry on STS-92 (October 2000). This tested the ability of the MAGR/S to collect ephemerides, download the daily key and establish four satellite navigation during entry.

For most of ascent, the Shuttle is in a “heads down” configuration. The GPS antenna on top of the crew compartment is facing the Earth, while the antenna below the crew compartment is facing the External Tank. In spite of the poor antenna visibility, enough GPS signals “wrap around” the External Tank and orbiter to permit the MAGR/S to track three to four satellites most of the time. However, the Geometric Dilution Of Precision (GDOP) is high, which can result in large state errors. On most flights, a roll to a heads up attitude is performed at about 6 minutes into the flight. This provides excellent GPS satellite visibility to the antenna on top of the crew compartment. Receiver tracking and performance during this phase of ascent is usually exceptional.

Periods of noisy GPS velocity were observed during the orbital phase of flight. Velocity noise was as high as 11 feet/second. Noise periods lasted anywhere from 5 to 20 minutes. Analysis indicated that the MAGR/S was processing noisy delta range measurements due to ionospheric scintillation [14]. This does not pose a constraint to certification of GPS as a TACAN replacement.

Of particular interest is MAGR/S performance during the “plasma” region of re-entry. The term “blackout” is not used, since communication via the TDRS satellites can permit near continuous communication with the orbiter during entry, depending on the orbiter ground track and TDRS satellite visibility.

Flight tests demonstrated that the MAGR/S does not experience a complete “blackout” of GPS signals during entry. Plasma effects begin to degrade lower antenna tracking of GPS satellites as high as 320,000 feet. Upper antenna tracking begins to degrade about the time of the first roll maneuver (typically around 285,000 feet). In spite of the plasma, the MAGR/S still tracks 1 to 4 satellites during the plasma region. Frequent loss of lock occurs, along with a loss of carrier frequency tracking. Code tracking is maintained.

Upper antenna plasma effects begin to subside around 217,000 feet, and continuous carrier frequency tracking

on 4 satellites resumes by 200,000 feet on most missions. Lower antenna tracking can be degraded by plasma until around 185,000 feet.

The impacts of the plasma region on the MAGR/S are extended periods of less than four satellite tracking, failed reacquisition attempts, incomplete data collection (i.e. ephemerides) and loss of delta range measurements. Less than optimum number of measurements and poor satellite geometry could result in an increasingly inaccurate GPS state vector. However, navigation errors during the plasma region has so far not been excessive. The orbiter can fly through this region without an update from GPS.

Flight data from the MAGR/S as well as the GPC QA checks are examined both during and after missions. Flight tests and simulation results have driven changes to the MAGR/S firmware and PASS and BFS flight software that processes MAGR/S data.

Flight experience also drove a change to the position and velocity vector aiding scheme used by the PASS flight software. The original design involved propagation of a separate aiding state for each receiver, with each propagator having an independent source of IMU data (i.e. an IMU is assigned to each receiver). Instead, one aiding state vector is propagated for all three receivers, using selected IMU data from candidates that have been screened by a FDIR algorithm. Instead of periodically resetting the aiding states with each receiver's own GPS state, the single aiding state is periodically reset with the Shuttle navigation state. The original design did not perform a "sanity check" on the GPS states used to reset the aiding states in the PASS flight software. Resetting the single aiding state with the Shuttle navigation state takes advantage of protection provided by the GPS QA checks, the GPS state selection process and the comparison of the selected GPS state with the current navigation state before GPS incorporation. The new aiding scheme also permits the ground to have more insight into and control over the position and velocity aiding states sent to the receivers.

Once the MAGR/S units and Shuttle flight software for GPS are certified (anticipated to occur in the spring of 2002), the three TACAN units on each orbiter will be removed and two MAGR/S receivers will be added to each orbiter, for a total of three MAGR/S units per orbiter. TACAN replacement will occur as each orbiter is cycled through a regularly scheduled overhaul. Antennas for the two additional MAGR/S units are on the top and bottom (Figure 1) of the nose in places formerly occupied by TACAN antennas. The first "three string GPS flight" (no TACAN) is expected to occur no earlier than 2003.

MISSION CONTROL AND ON-BOARD, OPERATIONAL USE OF GPS

The following sections give an overview of the current Shuttle navigation methodology. How GPS states will be used by the orbiter navigation system and Mission Control after MAGR/S certification is covered. Range safety is outside the scope of this paper.

PRE GPS GROUND TRACKING

Initially, the Shuttle program required continuous tracking from 2 radars during ascent and entry, so that Mission Control could determine the Shuttle state independently of the on-board navigation system. As confidence was established in the on-board system, the ascent/entry ground tracking requirement was changed from mandatory to highly desirable.

Prior to launch, if there are certain failures on the vehicle, radar tracking to support navigation is required to meet Launch Constraint Criteria. C Band (range and angles) and S Band (range, Doppler, angles) radar data is processed in a Mission Control based Kalman filter. The filter can process data from one S Band and two C Band radars.

If the Shuttle is to rendezvous with a spacecraft already in orbit (a "ground up rendezvous," such as with the International Space Station (ISS) or Hubble Space Telescope), Mission Control checks the cross track velocity error after Main Engine Cut Off. A state vector update may be required prior to the OMS-2 maneuver for cross-track velocity error greater than 6 feet/second. The uplink would be based on ascent ground tracking data processing.

Initially, S Band communication sites provided tracking (range, Doppler, angles) during the orbital phase of flight, when the orbiter was visible. As TDRS satellites were launched, ground S Band use for orbit was reduced. TDRS provides near global communications coverage, but only Doppler measurements due to the type of S Band transponder on the orbiter.

On-orbit, both S Band TDRS Doppler measurements; and C Band radar data (range and angles from a number of tracking stations) are processed to estimate the orbiter's state vector. The on-board navigation state is usually allowed to grow in down-track position error before a new state, based on radar and TDRS tracking, is uplinked. For landing, the maximum allowable downtrack position error at Entry Interface (400,000 feet) is 20 nautical miles.

TDRS S Band Doppler tracking provides a good estimate of the orbital semi-major axis (which reflects both position and velocity). C Band tracking resolves planar errors. Radar geometry plays a large role in determining the accuracy of ground-based navigation. On orbit, a weighted least squares algorithm is used by Mission Control for orbit determination.

Ground-up rendezvous flights require radar tracking of the target spacecraft. Radar tracking begins from 18 to 24 hours prior to Shuttle launch. Ground tracking of the target spacecraft continues through docking (ISS) or grapple (Hubble Space Telescope). If the orbiter deploys a scientific payload that is to be retrieved later in the mission, ground tracking of the deployed spacecraft will be performed to facilitate the rendezvous and grapple.

For entry and landing, radar data is processed by Mission Control in the previously mentioned Kalman filter for independent assessment of onboard navigation systems. Since Shuttle landings are planned for the Kennedy Space Center (KSC), and radars are located there to support the Eastern Test Range, C Band and S Band radar tracking is usually available. C Band tracking is also usually available for landings at Edwards Air Force Base, since NASA has radars at the Dryden facility. However, range scheduling can prevent entry tracking. If there are certain failures in the on-board or ground navigation systems, radar tracking during entry becomes mandatory.

During entry, radar normally becomes available in time for Mission Control to assess the TACAN units and navigation state health prior to TACAN processing in the GPCs. Mission Control can also perform an emergency state uplink to the orbiter if navigation errors are excessive.

POST GPS

Once GPS is certified, the Shuttle program will still consider radar tracking during ascent to be desirable, but not required, unless there are navigation equipment failures on the vehicle.

Radar and TDRS tracking will still be used during the orbital phase to support maneuver planning in Mission Control. The MAGR/S Kalman filter has not been tuned for orbital dynamics, since emphasis was on a TACAN replacement and a Commercial Off The Shelf (COTS) approach that minimized MAGR/S modifications.

The MAGR Kalman filter and navigation algorithms were designed so that the unit could be integrated into a wide variety of platforms, without having to substantially

modify the Kalman filter for each application [15]. Filter tuning assumes a worst case inertial measurement unit and receiver clock. The downside to this approach is that the receiver is not optimized for space navigation. It effectively provides a blended deterministic solution without accurate gravity or drag modeling needed for accurate orbit determination. As a result, MAGR/S velocity errors, and the resulting semi-major axis errors, are not acceptable for orbit maneuver planning and rendezvous. Poor orbital navigation performance of GPS receivers originally designed for terrestrial use and the importance of semi-major axis accuracy is covered by Carpenter and Schiesser [16].

A GPS Ground Filter, for use in Mission Control, has been developed by United Space Alliance to support Shuttle and ISS maneuver planning and collision avoidance with space debris. The accuracy specifications for the ISS GPS receiver were designed to support antenna pointing. Like the MAGR/S, the ISS receiver has not been modified for space dynamics, and is not accurate enough to support maneuver planning. Once certified, the GPS Ground Filter will filter GPS position and velocity to provide Mission Control with more accurate GPS derived state vectors for the Shuttle and ISS.

Near continuous availability of ground filtered GPS state vectors, in conjunction with radar and TDRS tracking, will allow more responsive mission planning. Burns will be confirmed more rapidly than with radar and TDRS data alone. If the orbiter is subjected to perturbations that are not modeled by Mission Control, it can take 2 or 3 revolutions before enough ground tracking data is available to quantify the impact on the orbiter state. The GPS ground filter will permit much more rapid perturbation determination.

Once GPS is certified for operational use, ground radar tracking will be used on the initial "no TACAN" flights as a backup to GPS. After experience is gained with the certified GPS system on the Shuttle, it is expected that ground radar tracking activities will be reduced. TDRS is also used for telemetry and communications, thus the Doppler measurements will always be available for processing. However, radar and TDRS will still be designated as backups to GPS, and Mission Control Center personnel will maintain proficiency in C Band and S Band measurement processing.

ASCENT AND POST INSERTION

Navigation aids (TACANs, barometric altimeters, MLSs, radar altimeters) that would be used for an emergency landing due to an ascent abort are powered on and self

tests are run prior to the day of launch. The three HAINS IMUs are calibrated and aligned prior to liftoff. Only HAINS IMU data (accumulated sensed velocity, gimbal angles) are processed by PASS and BFS navigation during powered flight [17]. No sensor measurements are processed by a Kalman filter.

ASCENT AND POST INSERTION IN THE GPS ERA

There is no change to the Shuttle baseline navigation (use of HAINS IMU data) for powered flight. The MAGR/S units will be turned on approximately 5 hours prior to liftoff. This permits receivers to collect ephemerides of satellites that will be over the Trans Atlantic Landing (TAL) sites at launch. GPS states are not used by the Shuttle navigation software during powered flight, but receiver aiding data is supplied to the MAGR/S units by the GPCs.

After the MAGR/S and the GPS Ground Filter are certified, the GPS Ground Filter could be used as a source of post Main Engine Cut Off state vector uplinks. GPS vectors from the on-board MAGR/S units would not be incorporated directly into navigation.

PRE GPS ORBIT COAST NAVIGATION

During the orbit phase, the on-board navigation state is monitored and maintained by Mission Control via state vector uplinks. A vent force may also be uplinked by Mission Control for use by the GPCs. This takes into account non-propulsive forces acting on the orbiter that cannot be detected by the HAINS IMUs, and reduces error growth in the on-board state. Vent values are based on flight history for specific orbiter attitudes. The orbiter state (and for a rendezvous, the target spacecraft state) determined from C Band and S Band tracking are used by Mission Control for maneuver planning.

Alignment of the HAINS IMUs is periodically performed using star sightings [18]. Two star trackers with near orthogonal lines of sight are located on the nose of the orbiters. Data from star sightings can also be used by Mission Control to determine IMU gyro biases. The ground determined biases are then uplinked for use in the Shuttle PASS flight software. If the orbiter cannot maneuver to a star sighting attitude due to excessive IMU misalignment, a rough alignment can be executed by a crew member sighting on a star using the Heads Up Display (HUD) or the COAS. This would be followed by a precise star alignment using the star trackers.

ORBIT COAST NAVIGATION IN THE GPS ERA

Current plans call for two of the three MAGR/S receivers to be powered off for most of the orbit period. MAGR/S state vectors will periodically be taken into the PASS flight software to maintain the on-board navigation state accuracy at an acceptable level. Ground and TDRS tracking will remain the primary source of state vectors for maneuver planning in Mission Control, until the GPS Ground Filter is certified.

There is no provision for GPS attitude determination in the MAGR/S. Star sightings will still be used for precise HAINS IMU alignment.

PRE GPS RENDEZVOUS

Successful rendezvous requires an accurate relative state. Relative velocity errors, in particular, are critical. However, ground tracking of the orbiter and the target spacecraft is not accurate enough to guarantee a safe rendezvous within the orbiter's tight propellant budget. An on-board navigation system that provides an accurate relative state is required.

Shuttle rendezvous is divided into two phases, ground targeted and on-board targeted. For the ground-targeted phase, the orbiter navigation state is determined by ground based radar and TDRS tracking as described previously. Burns to be executed by the orbiter are computed by Mission Control (hence the term "ground targeted") and uplinked to the vehicle for execution by the crew. The last ground targeted burn is performed on the day of rendezvous, 40 nautical miles behind the target, at about orbital noon. During the on-board targeted phase (Figure 2), relative sensor measurements are processed in a Kalman filter in the PASS flight software [19]. The PASS software maintains an estimate of the target spacecraft state (initially provided by Mission Control) and the filtered orbiter state. These states are used to compute burn solutions using an onboard Lambert targeting algorithm [20].

The star trackers used for IMU alignments are also used to process angular measurements of the orbiter/target relative state. This permits resolution of navigation errors normal to the star tracker line of sight. The star tracker pass begins shortly after the last ground-targeted maneuver, and will resolve most altitude and out-of-plane position errors. Due to change in relative geometry, some down-track position error will be resolved at the end of the star tracker pass. The end of the pass roughly

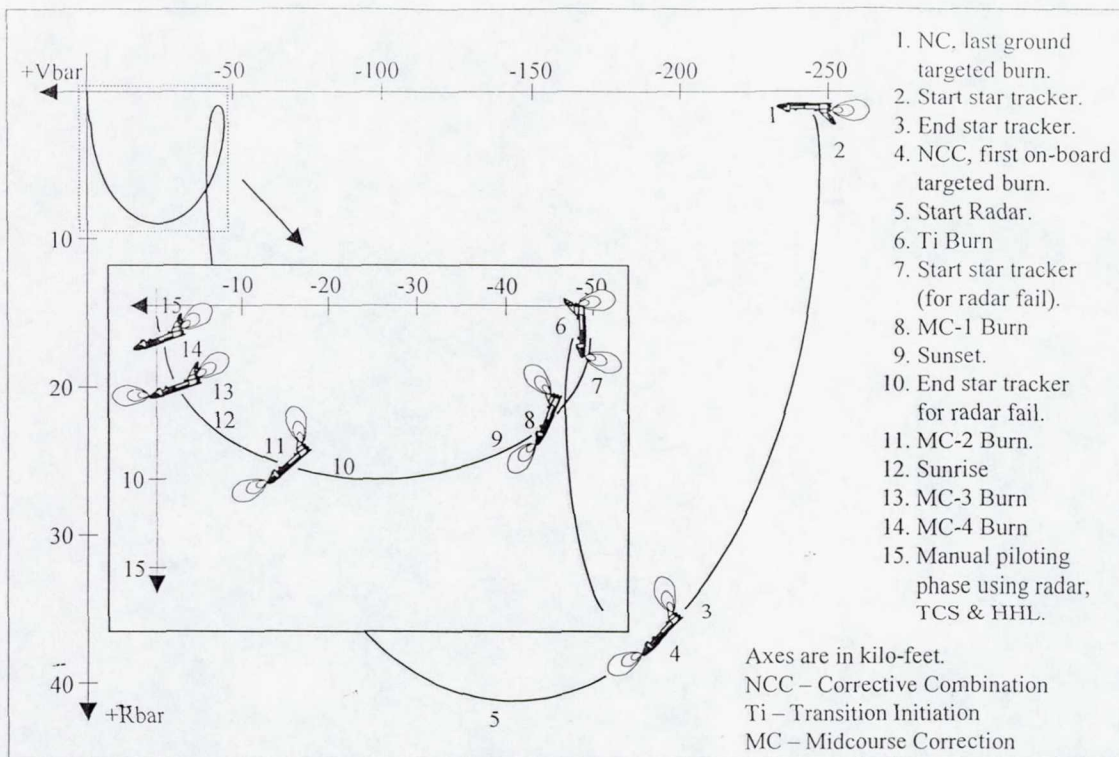


Figure 2: Day of rendezvous profile with burns and navigation activities indicated. Relative coordinate frame centered on the target spacecraft. "Vbar" is in the direction of target motion, "Rbar" is in the direction of the center of the Earth.

coincides with orbital sunset, and is followed by the first on-board targeted maneuver.

Incorporation of Ku Band radar measurements begins at a range of 135,000 feet. Range, range rate and angular data are obtained from this point until a range of about 100 feet. Five more on-board targeted burns are executed to control the orbiter's approach to the target spacecraft.

At a range of approximately 8 nautical miles, there is another opportunity for a daylight star tracker pass, in the event of a radar failure. Due to the size and brightness of the ISS, star tracking during orbital daylight may not be possible for this pass. A tracking light will be on the ISS to facilitate processing of star tracker data at night. The ISS will maneuver to a night star tracker attitude at a predetermined time during the rendezvous. Such a failure occurred on STS-92 (October 2000), forcing execution of an "angles only" rendezvous. The rendezvous and docking was successful, but with slightly higher propellant consumption.

If both the radar and star trackers are failed, the Crew Optical Alignment Sight may be used manually by the crew to obtain relative angular measurements. COAS measurements have never been taken in flight due to a sensor failure. However, after the undocking from Mir on STS-71, COAS data was processed as a test.

After the final on-board targeted burn, at a range of about 2,000 feet, the manual piloting phase begins. Radar data continues to be incorporated into the orbiter navigation state during the manual phase, but the primary source of relative navigation data for piloting comes from the TCS. TCS is a laser system mounted in the payload bay that provides relative range, range rate and angular information. TCS requires retro-reflectors on the target vehicle. Two HHL range finders are also carried. Both TCS and HHL can lock on to the target as far out as 5,000 feet.

A Kalman filter is used in the primary and backup laptop computers to process TCS measurements. HHL measurements are processed in the primary laptop, in a different Kalman filter than TCS. Television cameras in the payload bay, with ranging ruler overlays on the monitors, are used by the crew as an additional range information source from 15 feet to docking. Ku Band radar, TCS and HHL are also used during undocking and fly-around, when the orbiter leaves the ISS.

SHUTTLE RENDEZVOUS IN THE GPS ERA

Even if both spacecraft have GPS units, simple subtraction of state vectors does not provide an accurate enough relative state for use in burn computation. Use of such data could easily result in an unsafe trajectory and an undesirable level of propellant consumption.

Development of the on-board rendezvous navigation system for Apollo [20] (on which the Shuttle system was based) proved that rendezvous could be accomplished with high inertial state errors on both vehicles, but low relative state errors [21]. High accuracy inertial states on both spacecraft are not enough to permit accurate rendezvous navigation.

If GPS relative navigation were to be used for spacecraft rendezvous, identical GPS receivers on the target and chaser vehicles are required. Processing of common satellite measurements from both vehicles in one Kalman filter permits the cancellation of common errors and biases (such as ionospheric error and Selective Availability) [22]. This in turn drives the need for a radio data link between the vehicles.

The Space Shuttle program must preserve the capability to rendezvous with spacecraft that are not equipped with GPS units. The current suite of on board, relative navigation sensors (radar, star trackers, lasers) provide relative states that are just as good as or better than the level of accuracy possible with relative GPS. During the manual piloting phase and docking, there are concerns about GPS satellite visibility and multi-path. The Shuttle program currently has no plans to use relative GPS for rendezvous.

PRE GPS DEORBIT

Currently, a state vector uplink is performed prior to the deorbit burn to both the PASS and BFS flight software. This uplink is based on Mission Control processing of ground radar C Band and TDRS S Band data.

DEORBIT IN THE GPS ERA

The current operations concept calls for the three MAGR/S units to be operating 6 hours prior to the deorbit burn. Selected MAGR/S data will be incorporated into the Shuttle navigation software prior to the burn, replacing the uplink from Mission Control. As with ascent and orbit insertion, MAGR/S data will not be incorporated into navigation during powered flight.

PRE GPS ENTRY NAVIGATION

For most of entry, three independent navigation states are maintained in the PASS [23]. Each uses accumulated, sensed velocity data from a different IMU to protect against IMU failures. A selection filter selects one navigation state (position and velocity) for use in the

Kalman filter. It is also passed on to guidance, flight control and crew display functions.

The first navigation filter measurement to be processed is called "drag altitude." Measurement incorporation begins when the IMU sensed deceleration is greater than 11 ft/sec² (Figure 3). Accumulated sensed delta velocity data from the IMUs are used to estimate atmospheric density. A math model of the atmosphere then provides a rough estimate of altitude. Drag altitude measurements are rather inaccurate, but are intended to bound error growth in the event of other navigation system failures

Kalman filter processing of selected TACAN range and bearing measurements begins at a range no greater than 400 nautical miles from the runway and an altitude of roughly 140,000 feet (for a nominal entry and landing). TACAN bearing is not processed when the elevation angle of the slant range is 35 degrees or greater (cone of confusion).

Significant navigation errors during entry can exceed the ability of the guidance and flight control system to fly the orbiter to the landing site. A set of limits, called guidance constraints, defines the maximum allowable state error. In the event of a navigation error that exceeds the constraints, a correction to the state vector can be uplinked directly to the PASS and BFS flight software or voiced to the crew for manual entry. The "delta state update," which is based on radar tracking data, has never been executed in flight.

Barometric altimeter measurements are processed to control navigation errors in the vertical channel. Two barometric altimeter probes are deployed at Mach 5, and data becomes available for Mission Control evaluation at Mach 3.5. Each probe provides two independent measurements. Kalman filter processing begins at Mach 2.5 and an altitude of about 85,000 feet. Drag altitude processing ends once barometric altimeter processing begins. Barometric altimeter processing is inhibited between Mach 1.6 and Mach 1.1 (the Mach jump region).

PASS Kalman filter processing of MLS range, azimuth and elevation data usually begins at about 17,000 feet. Once MLS is acquired, PASS stops processing TACAN and barometric altimeter data and shifts from maintaining three state vectors to one state vector. For a landing site not equipped with MLS, PASS processing of TACAN stops at an altitude of 1,500 feet, and baro processing continues until 500 feet. BFS does not process MLS, and will process TACAN and baro data all the way to landing.

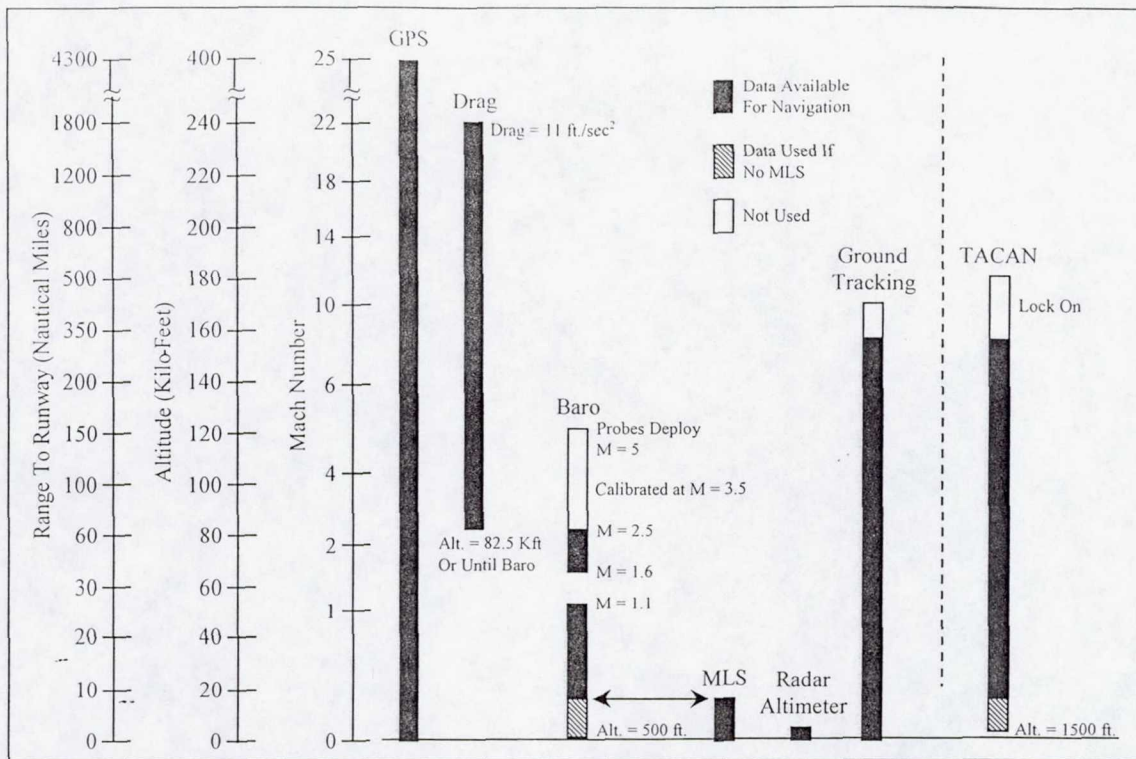


Figure 3: Availability of navigation sensors and systems during entry. BFS does not process MLS, but processes TACAN and Baro all the way to landing. Radar altimeter data is for crew situational awareness only. Ground tracking data is used by Mission Control for independent assessment of onboard navigation systems.

Selected radar altimeter data is available to the crew for situational awareness from 5,000 feet until landing. It is not processed in a Kalman filter, due to a lack of accurate terrain models for Shuttle landing sites.

EMERGENCY USE OF "UNCERTIFIED," SINGLE STRING GPS DURING ENTRY

During the flight test phase (prior to certification, only one MAGR/S on each orbiter), flight rules were developed permitting use of selected MAGR/S state vectors under the following emergency conditions:

- Use in place of a voice delta state uplink during entry. Complexity of the voice delta state uplink makes it more risky than incorporating uncertified GPS data.
- Avoid scenarios (low ceilings at landing, on-board and/or ground station TACAN and MLS failures) that could result in a high risk crew bailout and loss of vehicle.
- Enable Mission Control to resolve dilemmas between redundant navigation sensors (HAINS IMUs, barometric altimeters, TACANs, MLSs). This does not require incorporating GPS states into the Shuttle navigation software.

ENTRY NAVIGATION IN THE GPS ERA

For the first several operational flights, selected MAGR/S data will not be taken into the Shuttle navigation software between the deorbit burn and the acquisition of ground radar tracking (around 140,000 feet, the TACAN acquisition altitude). This will permit a comparison of MAGR/S data with ground tracking before incorporation. Once operational experience with the three string system has been obtained, navigation system updates with GPS will resume after the deorbit burn and continue through MLS acquisition (or landing if MLS is not available). However, selected MAGR/S states do not have to be continuously incorporated into Shuttle navigation to support entry and landing.

Drag altitude measurements will still be processed to bound error growth in the event of GPS outages or IMU failures. It is expected that drag measurements will have little impact on the navigation state when GPS is incorporated in the automatic mode.

Space Shuttle navigation software will continue to process barometric altimeter and MLS data (in the PASS) after TACAN has been replaced by GPS. Whenever selected barometric altimeter measurements are available for processing by the PASS and BFS GPCs, they will also be processed by the MAGR/S Kalman filter. This allows the GPS units to determine the bias on the barometric

measurements during four satellite tracking. In the event of less than four satellite tracking, calibrated barometric altimeter measurements will help maintain accurate MAGR/S states.

GPS states will be an important source of data for Mission Control during emergency landings at sites where there is no ground radar tracking capability.

During entry, Mission Control in Houston will have an open line to the GPS Master Control Station (MCS) at Schriever Air Force Base, Colorado. Mission Control will be informed of any GPS satellite integrity issues that arise. The crew has the ability to command the MAGR/S units not to track specified GPS satellites for measurements.

“SINGLE STRING” GPS USE AFTER CERTIFICATION..

After GPS certification, some orbiters in the fleet will continue to fly with three TACAN units and one MAGR/S, until they receive two more MAGR/S units during regularly scheduled overhauls. Post certification, single string use of GPS during entry has been proposed as follows:

- Those scenarios listed under emergency use of uncertified, single string GPS.
- Use as an extra level of redundancy in case of navigation sensor (TACAN, Air Data Probe, MLS) and/or ground station failures (TACAN, MLS).
- Provide redundancy in the event of ground radar tracking station failures.
- Avoid early mission termination due to TACAN failures while on-orbit.
- Source of vectors to support emergency deorbit.
- On-board navigation updates on-orbit, when not performing translational maneuvers or rendezvous.
- Permit a launch in the event of a navigation aid (TACAN, barometric altimeter, MLS) failure on the pad.

DIFFERENTIAL GPS

Although the MAGR/S does have a differential GPS capability, there are currently no plans to replace MLS with differential GPS. Antennas and cables would have to be added to the Shuttle orbiters to enable reception of differential GPS corrections. There are technical issues with placing omni-directional VHF antennas under the thermal protection tiles in spots formerly occupied by Ku Band MLS antennas. Drilling more holes in the vehicle for antenna placement is not desirable. Studies have shown that differential GPS would provide little accuracy improvement over the current MLS system.

SPACE INTEGRATED GPS/INS (SIGI)

As GPS receivers became smaller, navigation system developers began envisioning the placement of GPS receivers directly inside INS boxes (an “EGI”). This provides cost, size and weight savings. Since GPS data would not have to be sent “outside” a box to be processed, a central Kalman filter could incorporate GPS measurements corrected for S/A effects, as well as other measurements (barometric altimeter, Doppler radar, radar altimeter).

The “tightly coupled” integration scheme overcomes data latency issues with previous architectures. Less latency in aiding permits the carrier loops to be aided and speeds up satellite acquisition. The incorporation of all sensor measurements in one filter with high integration rates provides a much more accurate solution than “separate box” architectures. In addition, ground and flight testing has shown that the tightly coupled EGI “blended solution” has far superior performance under less than 4 satellite tracking conditions than a stand alone GPS receiver [8]. Since an aircraft or missile is subjected to continuous specific force (due to thrust, lift and drag), the Kalman filter can obtain estimates of sensor errors as maneuvering makes sensor errors visible to the filter through position and velocity errors. Continuous calibration of the inertial sensors permits an accurate position, velocity and attitude solution during GPS outages (such as jamming). This also allows manufacturers to use lower cost inertial sensors. The Kalman filter also permits alignment of inertial sensors much faster than INS systems without GPS [24].

Three test flights of EGIs were conducted to determine if such a device could be used in space with a minimum number of firmware modifications. The first EGI unit to fly was the Litton LN-100G, with a Collins GEM III five channel SEM-E form factor GPS receiver. The GEM III contained firmware modified for space use, based on

GEM III Link 010, produced by Collins to support the Army Tactical Missile System program. The Litton EGI flew on missions STS-81 and STS-86 to provide data gathering for NASA's X-33 and X-34 programs. A Honeywell H-764G EGI, with the same type of GEM III receiver as was flown in the Litton unit, flew on STS-84.

In September of 1996, Honeywell was awarded a contract by NASA for the Space Integrated GPS/INS, or SIGI. SIGI is a common NASA navigator, based on the H-764G EGI, to be used by both manned and unmanned space vehicles [25]. The Shuttle version of SIGI, intended to replace the MAGR/S and the HAINS IMU, contained the same Collins GEM III GPS receiver that was previously mentioned.

Whereas the MAGR/S was integrated into the Shuttle avionics system as a "navigation system," the Shuttle SIGI was to be integrated as both a sensor and a navigator. The SIGI-blended state vector solution was processed by the Shuttle PASS and BFS flight software using the same software used to process MAGR/S data. GPS receiver data and control commands were kept the same as MAGR/S. This integration concept was known as "MAGR/S transparency," and minimized the amount of changes to the Shuttle flight software.

The Shuttle flight software requires a source of IMU data (integrated attitude rates, change in accumulated sensed velocity). These parameters were taken from the inertial sensors of the SIGI, which are treated as a sensor. The original inertial sensor integration concept was "HAINS IMU transparency," an attempt to avoid changes to the Shuttle flight software. The SIGI strapdown inertial instrument data was to be processed within the SIGI to look like stable member HAINS IMU data, before being passed to the PASS and BFS GPCs. However, the transparency option would have made it impossible for Mission Control to identify and take action on suspect gyros and accelerometers. As a result, the HAINS IMU transparency option was abandoned. More changes were made to the SIGI firmware to support the Shuttle missionization than were expected.

The stable members of the three HAINS IMUs are skewed with respect to each other, so that Mission Control personnel can identify suspect gyros and accelerometers if only two HAINS IMUs are operating. With the strapdown configuration of the SIGIs, the axes of the inertial instruments in all three SIGI units would be parallel, making it difficult for Mission Control to identify suspect inertial sensors if only two SIGIs were operating. As a result, plans were made to carry four SIGIs on the orbiters, rather than three. The SIGI DTO flew on Shuttle missions 86, 89, 91, 95, 88, 96 and 103.

A laptop computer was used by the crew to operate the SIGI and record data. Changes were made to SIGI firmware based on flight test results.

In order to get into a precise orbit the IMUs must be accurately aligned. Stable member HAINS IMUs are aligned by using the sensed Earth rotation and gravity direction. The platform is oriented in various directions so that each of the accelerometers can calibrate against the gravity vector and the gyros can calibrate against Earth rotation. With all of the advantages of a space missionized EGI, preflight strapdown system alignment presents a challenge. There are three opportunities at the Kennedy Space Center to make observations when the vehicle is at different orientations: the Orbiter Processing Facility, the Vehicle Assembly Building, and the launch pad. The difference in orientation at the three locations is not adequate to get a good separation of the alignment variables. During frequent flights of military aircraft the maneuvering, continuous specific force (engine thrust, lift and drag) and processing of GPS measurements permits the EGI Kalman filter to accurately calibrate the gyros and accelerometers. For the Shuttle, however, the short periods of specific force and maneuvering (ascent and entry) coupled with the long time periods between flights (months) makes the reliability of Kalman filter inertial sensor error estimates questionable.

Since the HAINS IMUs are projected to be operational through 2010, replacement of the HAINS IMUs and MAGR/S units by SIGIs has been deferred. Laboratory evaluation of the Shuttle SIGI unit is continuing, along with the GPC flight software modified to support it.

LESSONS LEARNED FROM THE MAGR/S AND SIGI TEST FLIGHTS

Over the last 40 years, the U.S. manned space program has had a long and successful history of incorporating "off the shelf" hardware into spacecraft and ground support systems. Both navigation upgrade projects used COTS products that met the requirements of the original customers. It was assumed that off the shelf military units with proven design and performance would significantly reduce acquisition costs, and require minimal adaptation for the Shuttle and minimal testing. The ground and flight test philosophy was that the units "worked" until proven to be broken.

However, the time and effort need to test, resolve firmware issues and certify the MAGR/S for TACAN replacement exceeded initial projections. A number of important lessons were learned, which are detailed below:

Military and civilian GPS units undergo a less rigorous firmware requirements definition, firmware design, development and testing process than those used in the Shuttle program [26]. Furthermore, development of terrestrial, "non-safety of flight" navigation units entail less detailed analysis of flight data than the Shuttle program. The Shuttle program also processes avionics units in a more thorough and disciplined manner than terrestrial users. This includes strict adherence to work instructions, maintenance of a parts history, thoroughly documented investigation of problems and their resolution, and more rigorous test requirements.

It is difficult to leverage off of another program's firmware verification efforts. Firmware development schedules driven by "time to market" pressures and a desire to lower overhead costs (a small group of programmers, short development and test cycles) result in a higher probability of code with bugs. Some firmware issues resulted from the use of terrestrial GPS receiver algorithms at orbital altitude. However, many of the firmware issues that surfaced during the MAGR/S and SIGI flight tests were due to basic computer science issues, as opposed to problems arising from use of a terrestrial box in an environment for which it was not designed (space). Firmware issues that don't manifest in terrestrial applications due to a flight time of minutes or hours can manifest during a much longer space flight. Shuttle program ground and flight testing of GPS receivers has uncovered many firmware issues that will aid the maintenance and development of terrestrial GPS receivers. Deep integration of systems makes them more vulnerable to software issues. As navigation systems become more complex and more deeply integrated, software quality and verification becomes more important. The test approach must prove that the box will meet requirements, rather than having to prove that the box is broken.

Some firmware modifications made to the MAGR/S during the flight test program were the result of issues discovered by military users. The information that was found to be the most useful was from the vendor, after an investigation of anomalous behavior was complete. Reports of problems from military users received by the Shuttle program were difficult to judge in terms of potential impact to the Shuttle application. User reports tended to be anecdotal in nature, with little or no supporting data. Field reports of receiver problems could be traced to a variety of causes: user errors, lab set up errors, receiver hardware or firmware issues, radio frequency interference, an antenna problem, or a GPS satellite problem [27].

The trend to use Non-Developmental Item (NDI) avionics containing proprietary software may prevent independent validation and verification of firmware. The NASA Independent Verification And Validation (IV&V) contractor played a significant and valuable role in the MAGR/S project, as detailed in [28].

Both the MAGR/S and SIGI projects demonstrated the need for a close working relationship between users and vendors. The navigation vendor needs to be involved in early decisions on architecture and integration. Frequent and open communication between technical personnel should be encouraged. This lesson is best summed up as "communicate early, communicate often." Outside consultants, who do not have a vested interest in the choice of a particular unit, should be used. Such consultants have "hands on experience" with COTS boxes and can be an important information source concerning their design, integration and use.

The Shuttle MAGR/S and SIGI projects reaffirmed the need for rigorous and thorough flight and ground testing. When planning a COTS product missionization and integration, adequate time and personnel must be set aside to analyze flight and ground test data. If data is not thoroughly analyzed in a timely manner, firmware issues will go unnoticed. Performance issues arising late in the development and certification cycle can negatively impact cost and schedule.

COTS projects often do not take into account the complexity of software. Most of the focus in costing COTS projects has traditionally been on hardware. It is easier to "missionize" the hardware of a COTS product than the firmware. Experience has shown that firmware modifications will often result in more delays and cost increases than hardware missionization. The one exception to this is radiation hardening of electronics for the space environment [29].

For a flight critical application (i.e. the box is required to safely conclude the mission), a COTS box will undergo more modification than in other applications. The user will also require more detailed knowledge of navigation unit design and operation than users of non-flight critical COTS boxes. The Shuttle program considers a box to be failed more quickly than a terrestrial user. Engineering and Mission Control personnel must have a thorough understanding of receiver operation and data. For manned space flight, lack of design insight is a safety issue. The assumption that state replacement (treating GPS as a navigation system, rather than a sensor) eliminated the need for detailed knowledge of the GPS receiver firmware was found to be false.

Lessons learned from using COTS software for space applications can also be found in references [30] (Ariane 5), [31] (Lewis spacecraft) and [32] (Multi-Service Launch System).

Perhaps the most important lesson is that modifying a terrestrial navigation unit for use on a spacecraft should be treated as a research and development project. Although GPS shows great promise for improving Earth orbit navigation, the assumption that GPS technology has reached maturity in "all applications" is a common misconception [33, 34].

SUMMARY

Integration of COTS navigation units into the Shuttle avionics system was performed in a manner that attempted to minimize cost, schedule, and modifications to a certified, flight proven navigation system. Proven terrestrial navigation units that were in mass production were selected. The state replacement architecture, which treats the GPS receivers as navigation systems, permitted the flight test of GPS receivers and Shuttle flight software without introducing GPS states into baseline entry and orbit navigation. GPS will provide a more accurate navigation solution than TACAN. Cost and navigation performance considerations have led the Shuttle program to retain other entry and rendezvous navigation sensors. It is expected that GPS will result in a reduction of Shuttle ground tracking, but it will remain as a backup to GPS. A Mission Control based GPS Ground Filter, which filters GPS position and velocity to make up for the lack of space dynamics missionization in the MAGR/S, will provide accurate states for on-orbit maneuver planning. The Shuttle GPS capability will enhance safety during emergency landings at locations where ground radar tracking is not available. The first "three string" GPS, no TACAN flight will occur no earlier than 2003. Eventual replacement of the HAINS IMU and MAGR/S units with an EGI has been deferred.

It was prudent for the Shuttle program to take advantage of existing, in production technology for navigation system upgrades. However, changes to both the MAGR/S firmware and Shuttle flight software were more extensive than anticipated. Modification of aircraft navigation units for space flight should be considered a research and development project, rather than a simple modification of an "off the shelf" box. As digital computers have proliferated and become more complex, the difficulty of integrating "off the shelf" units has increased. It is not safe to assume that COTS avionics are simple and inexpensive to integrate just because thousands of units have been built. This is particularly

true for critical, "safety of flight" applications such as the Space Shuttle. Independent verification and validation of firmware is critical, and played an important role in the Shuttle GPS project. The difference in verification and certification requirements between terrestrial navigation users and the Shuttle program makes it difficult to leverage off of firmware verification efforts of other programs. There is a need for frequent and open communication between participants, at both the management and technical levels, throughout a COTS device missionization and test program. Use of COTS avionics in mission critical, safety of flight applications that differ from the original mission for which the unit was designed require more modification and design insight than is often anticipated.

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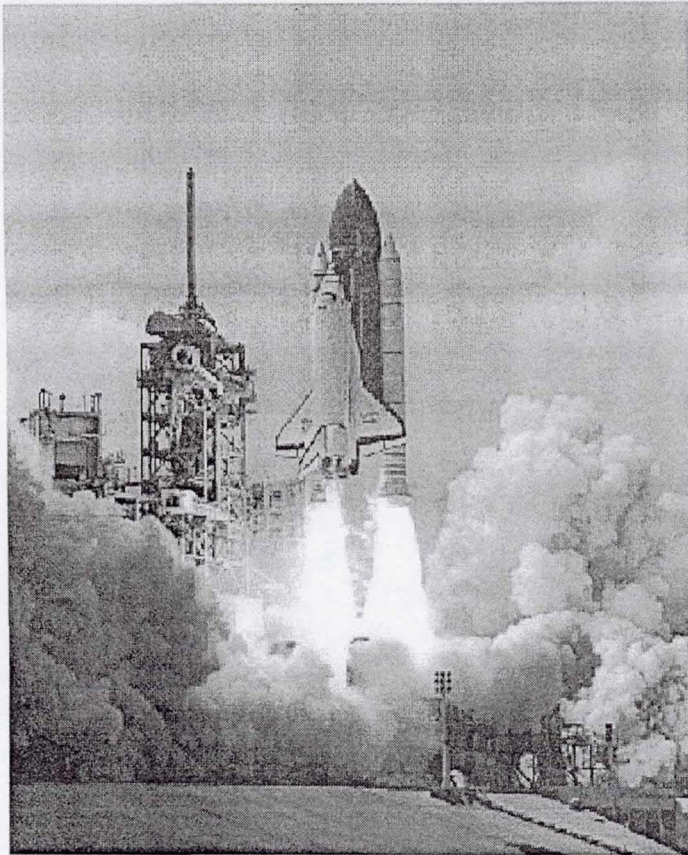
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Space Shuttle Navigation In The GPS Era



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Agenda

- Space Shuttle Navigation
- GPS Integration Architecture
- Ascent
- Orbit and Rendezvous
- Entry
- Lessons Learned
- Navigation Improvements Due To GPS

Redundancy Emphasized In Shuttle Design

- During ascent/entry, 4 primary computers and one backup. Primaries and backup run different software.
- Pre-GPS Ascent/Entry navigation sensors:

Ascent

- Three IMUs
- Ground C & S Band Radar

Entry And Landing

- Three IMUs
- Three TACANs
- Four Barometric Altimeters
- Three MLS Units
- Two Radar Altimeters
- Ground C & S Band Radar
- At least two TACAN ground stations.
- At least two MLS ground stations.

Navigation Sensors For Orbit, Rendezvous & Docking

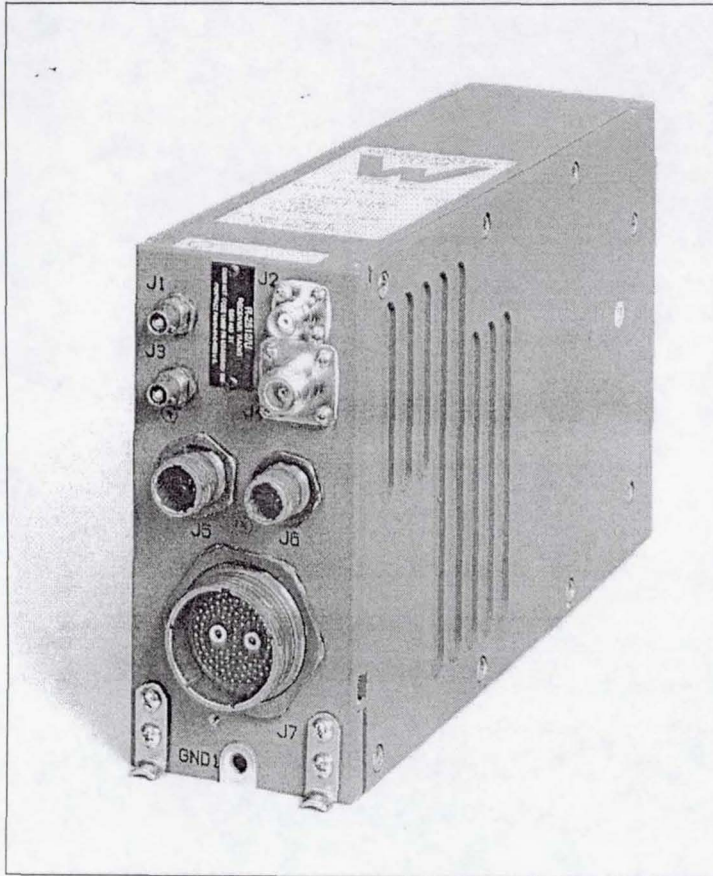
- Three IMUs
- Two Star Trackers
- One Ku Band Rendezvous Radar
- One Crew Optical Alignment Sight (COAS)
- Trajectory Control Sensor (TCS, a laser)
- Two Hand Held Lasers (HHL)
- Two Payload Bay Television Cameras
With Ranging Ruler Overlays

Redundancy Emphasized In Shuttle Design

- Processing of redundant measurements from IMUs, TACANs, Baros and MLSs:
 - Fault Detection and Exclusion algorithms.
 - Selection filters process data from units deemed to be “good.”
 - Selected measurements are then passed to the Shuttle navigation software.

- Ground radar (ascent, orbit, entry) and Tracking and Data Relay Satellite data (orbit) processed by Mission Control to independently determine Shuttle position & velocity.

Space Shuttle Program Is Certifying GPS To Replace TACAN



- A keyed, 5 channel Collins Miniaturized Airborne GPS Receiver was chosen as a Commercial Off The Shelf (COTS) item.
- “Single string” MAGR test flights began with STS-79 in September of 1996.
- Once the MAGR is certified for TACAN replacement, 3 MAGRs will replace 3 TACANs on each orbiter. First flight without TACAN expected no earlier than 2003.

State Replacement Architecture Chosen

- MAGR integrated as a navigation system, not as a sensor.
- Allows data collection during flight tests from both the MAGR and Shuttle flight software while still using TACAN.
- Minimized changes to the proven, navigation flight software.
- Three configurations supported by the same version of Shuttle flight software: 3 TACANs and no GPS units, 3 TACANs and 1 GPS unit, 3 GPS units and no TACANs.
- GPS vectors subjected to quality assurance checks & a selection filter.

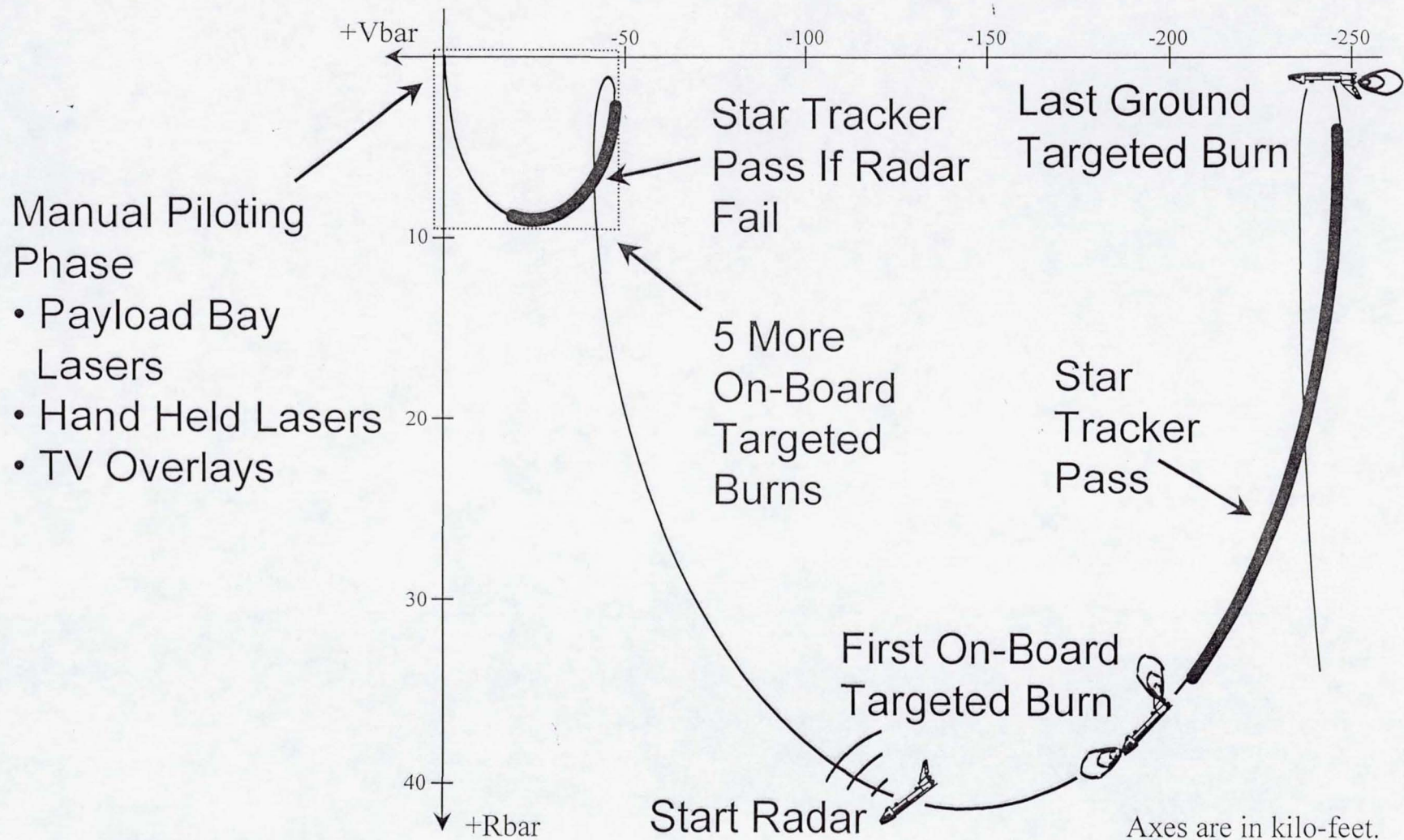
GPS Not Used For Ascent

- IMUs aligned and calibrated before liftoff, used as a source of accumulated sensed velocity and attitude data.
- Navigation aids (GPS, TACAN, Baro, MLS, radar altimeter) that would be used for an emergency landing are powered on prior to launch.
- No on-board sensor measurements are processed by a Kalman filter during powered flight.
- Ground radar tracking not required by Mission Control, is but highly desirable.

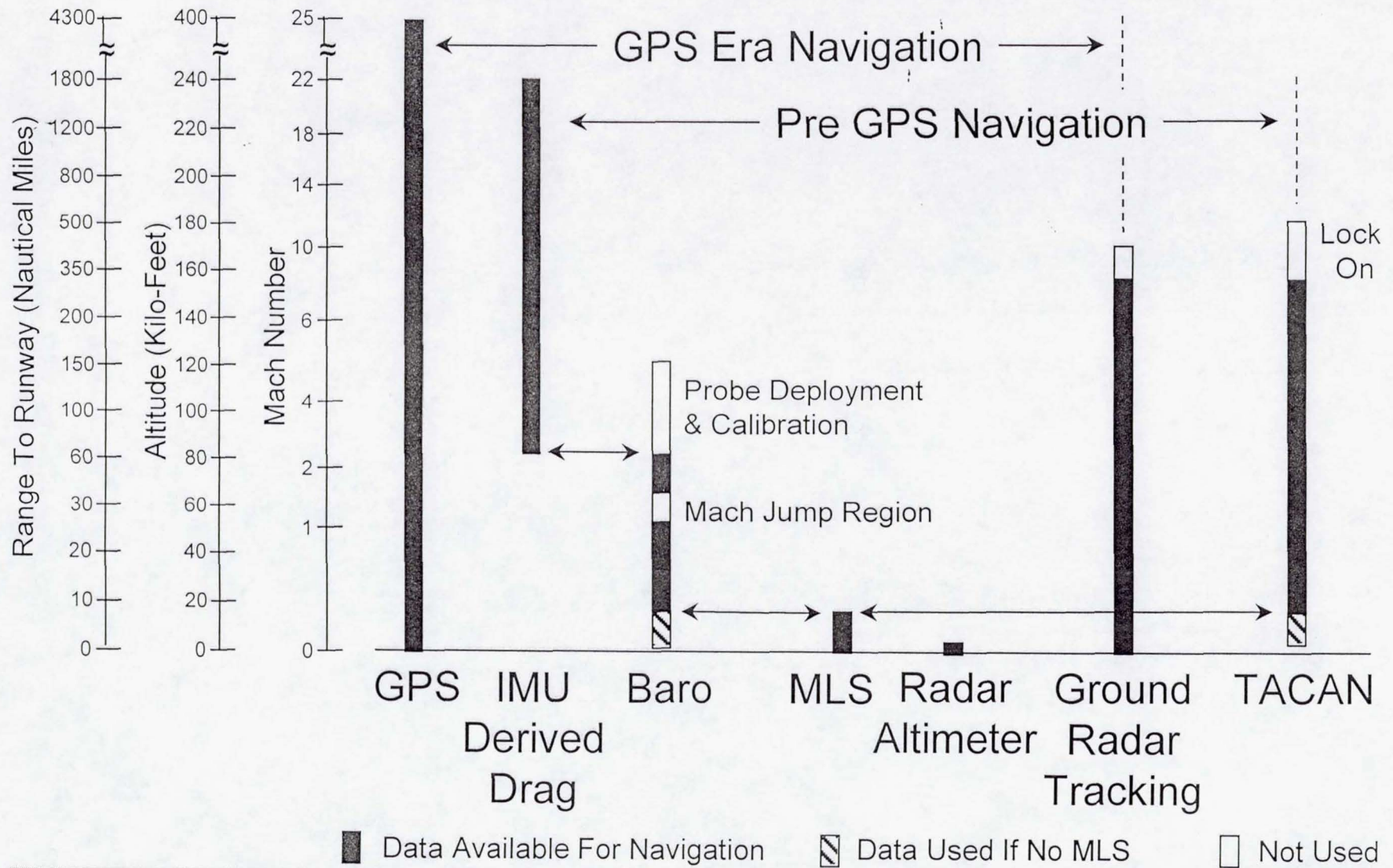
Limited Use Of GPS For Orbital Operations

- On-orbit maneuver planning currently supported by ground based C Band radar tracking and S Band Doppler tracking using the Tracking and Data Relay Satellites (TDRS).
- MAGR firmware has not been modified to meet accuracy requirements to support orbit maneuver planning (TACAN replacement only).
- Mission control based ground filter in development to process MAGR states to support maneuver planning.
- Mission Control personnel will maintain ground radar and TDRS data processing skills.

GPS Will Not Be Used For Rendezvous



Most Entry Navigation Sensors Will Be Retained



“Easy COTS Integration” Was An Unrealistic Assumption

- Scope of modifications and testing required to certify MAGR as a TACAN replacement significantly exceeded expectations.
- As digital computers have proliferated and become more complex, the difficulty of integrating COTS units has increased.
- Integrators tend to focus more on hardware issues, rather than software.
- For a flight critical application, high quality software is essential.

“Communicate Early, Communicate Often”

- Close relationship with the vendor is required. Vendor must be involved in integration architecture decision.
- The NASA Independent Verification And Validation (IV&V) contractor played a significant and valuable role in the project.
- In flight critical applications that differ significantly from the original application that a COTS product was designed for, design insight is essential.

The Most Important Lessons

- Modifying a terrestrial navigation unit for use on a spacecraft should be treated as a research and development project.

- Assumption that GPS technology has reached maturity in “all applications” is a common misconception.

GPS Will Enhance Shuttle Navigation

- Provides more accurate entry navigation than TACAN.
- Improves safety for emergency landing sites where ground radar tracking is not available.
- Near continuous availability of ground filtered GPS states, in conjunction with ground tracking, allows more responsive mission planning.
- On-orbit, GPS is a near continuous source of state vectors for emergency deorbit.