# CHAPTER 3
# GROUND-BASED RF-BEACONS AND GPS

In this chapter we discuss sensors used for active beacon navigation. Active beacons have been used for many centuries as a reliable and accurate means for navigation. Stars can be considered as active beacons with respect to navigation; and lighthouses were early man-made beacon systems. Typical non-robotics applications for active beacon navigation include marine navigation, aircraft navigation, race car performance analysis, range instrumentation, unmanned mobile target control, mine localization, hazardous materials mapping, dredge positioning, geodetic surveys, and most recently, position location and range information for golfers [Purkey, 1994].

Modern technology has vastly enhanced the capabilities of active beacon systems with the introduction of laser, ultrasonic, and radio-frequency (RF) transmitters. It should be noted, though, that according to our conversations with manufacturers, none of the RF systems can be used reliably in indoor environments. Ground-based RF systems will be discussed in Section 3.1.

However, the most revolutionary technology for outdoor navigation is the recently completed *Global Positioning System* (GPS). Because of the rapidly increasing popularity of GPSs we have dedicated a large portion of this chapter to this subject. Section 3.2 explains GPS technology, Section 3.3 includes a major comparative study of five different GPS receivers [Byrne, 1993], and Section 3.4 presents some state-of-the-art commercially available systems.

## 3.1 Ground-Based RF Systems

Ground-based RF position location systems are typically of two types:

- Passive hyperbolic line-of-position phase-measurement systems that compare the time-of-arrival phase differences of incoming signals simultaneously emitted from surveyed transmitter sites.
- Active radar-like trilateration systems that measure the round-trip propagation delays for a number of fixed-reference transponders. Passive systems are generally preferable when a large number of vehicles must operate in the same local area, for obvious reasons.

### 3.1.1 Loran

An early example of the first category is seen in *Loran* (short for long range navigation). Developed at MIT during World War II, such systems compare the time of arrival of two identical signals broadcast simultaneously from high-power transmitters located at surveyed sites with a known separation baseline. For each finite time difference (as measured by the receiver) there is an associated hyperbolic line of position as shown in Figure 3.1. Two or more pairs of master/slave stations are required to get intersecting hyperbolic lines resulting in a two-dimensional (latitude and longitude) fix.

The original implementation (Loran A) was aimed at assisting convoys of liberty ships crossing the North Atlantic in stormy winter weather. Two 100 kW slave transmitters were located about 200 miles on either side of the master station. Non-line-of-sight ground-wave propagation at around 2 MHz was employed, with pulsed as opposed to continuous-wave transmissions to aid in sky-wave

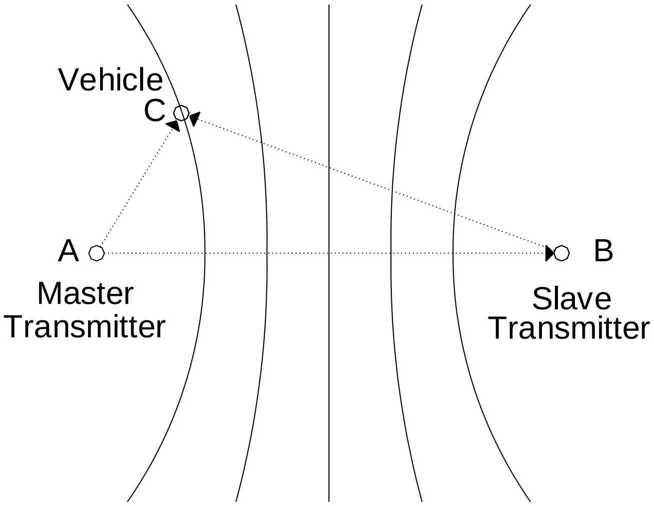


**Figure 3.1:** For each hyperbolic line-of-position, length ABC minus length AC equals some constant K. (Adapted from [Dodington, 1989].)

discrimination. The time-of-arrival difference was simply measured as the lateral separation of the two pulses on an oscilloscope display, with a typical accuracy of around 1 µs. This numerical value was matched to the appropriate line of position on a special Loran chart of the region, and the procedure then repeated for another set of transmitters. For discrimination purposes, four different frequencies were used, 50 kHz apart, with 24 different pulse repetition rates in the neighborhood of 20 to 35 pulses per second [Dodington, 1989]. In situations where the hyperbolic lines intersected more or less at right angles, the resulting (best-case) accuracy was about 1.5 kilometers.

Loran A was phased out in the early '80s in favor of Loran C, which achieves much longer over-the-horizon ranges through use of 5 MW pulses radiated from 400-meter (1300 ft) towers at a lower carrier frequency of 100 kHz. For improved accuracy, the phase differences of the first three cycles of the master and slave pulses are tracked by phase-lock-loops in the receiver and converted to a digital readout, which is again cross-referenced to a preprinted chart. Effective operational range is about 1000 miles, with best-case accuracies in the neighborhood of 100 meters (330 ft). Coverage is provided by about 50 transmitter sites to all U.S. coastal waters and parts of the North Atlantic, North Pacific, and the Mediterranean.

### 3.1.2 Kaman Sciences *Radio Frequency Navigation Grid*

The Unmanned Vehicle Control Systems Group of Kaman Sciences Corporation, Colorado Springs, CO, has developed a scaled-down version of a Loran-type hyperbolic position-location system known as the *Radio Frequency Navigation Grid* (RFNG). The original application in the late 1970s involved autonomous route control of unmanned mobile targets used in live-fire testing of the laser-guided Copperhead artillery round [Stokes, 1989]. The various remote vehicles sense their position by measuring the phase differences in received signals from a master transmitter and two slaves situated at surveyed sites within a 30 km$^2$ (18.75 mi$^2$) area as shown in Figure 3.2. System resolution is 3 centimeters (1.5 in) at a 20 Hz update rate, resulting in a vehicle positioning repeatability of 1 meter (3.3 ft).

Path trajectories are initially taught by driving a vehicle over the desired route and recording the actual phase differences observed. This file is then played back at run time and compared to measured phase difference values, with vehicle steering servoed in an appropriate manner to null any observed error signal. Velocity of advance is directly controlled by the speed of file playback. Vehicle speeds in excess of 50 km/h (30 mph) are supported over path lengths of up to 15 kilometers (9.4 mi) [Stokes, 1989]. Multiple canned paths can be stored and changed remotely, but vehicle travel must always begin from a known start point due to an inherent 6.3 meters (20 ft) phase ambiguity interval associated with the grid [Byrne et al., 1992].

The *Threat Array Control and Tracking Information Center* (TACTIC) is offered by Kaman Sciences to augment the RFNG by tracking and displaying the location and orientation of up to 24 remote vehicles [Kaman, 1991]. Real-time telemetry and recording of vehicle heading, position, velocity, status, and other designated parameters (i.e., fuel level, oil pressure, battery voltage) are supported at a 1 Hz update rate. The TACTIC operator has direct control over engine start, automatic path playback, vehicle pause/resume, and emergency halt functions. Non-line-of-sight operation is supported through use of a 23.825 MHz grid frequency in conjunction with a 72 MHz control and communications channel.

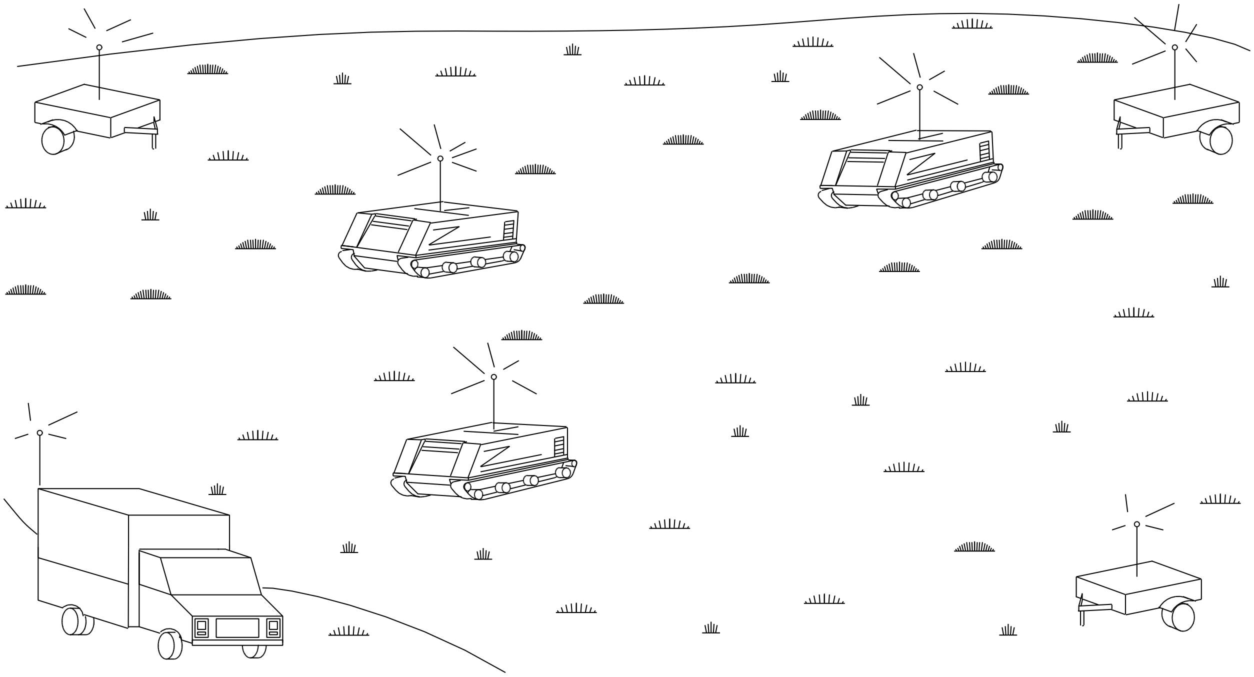


**Figure 3.2:** Kaman Sciences 1500 W navigation grid is a scaled-down version of the LORAN concept, covering an area 8 to 15 km on a side with a position-location repeatability of 1 m. (Courtesy of Kaman Sciences Corporation.)

### 3.1.3 Precision Location Tracking and Telemetry System

Precision Technology, Inc., of Saline, MI, has recently introduced to the automotive racing world an interesting variation of the conventional phase-shift measurement approach (type 1 RF system). The company's *Precision Location* tracking and telemetry system employs a number of receive-only antennae situated at fixed locations around a racetrack to monitor a continuous sine wave transmission from a moving vehicle. By comparing the signals received by the various antennae to a common reference signal of identical frequency generated at the base station, relative changes in vehicle position with respect to each antenna can be inferred from resulting shifts in the respective phase relationships. The 58 MHz VHF signal allows for non-line-of-sight operation, with a resulting precision of approximately 1 to 10 centimeters (0.4 to 4 in) [Duchnowski, 1992]. From a robotics perspective, problems with this approach arise when more than one vehicle must be tracked. The system costs $200,000 to $400,000, depending on the number of receivers used. According to Duchnowski, the system is not suitable for indoor operations.

### 3.1.4 Motorola *Mini-Ranger Falcon*

An example of the active transponder category of ground-based RF position-location techniques is seen in the *Mini-Ranger Falcon* series of range positioning systems offered by the Government and Systems Technology Group of Motorola, Inc, Scottsdale, AZ [MOTOROLA]. The *Falcon 484* configuration depicted in Figure 3.3 is capable of measuring line-of-sight distances from 100 meters (328 ft) out to 75 kilometers (47 miles). An initial calibration is performed at a known location to determine the turn-around delay (TAD) for each transponder (i.e., the time required to transmit a response back to the interrogator after receipt of interrogation). The actual distance between the interrogator and a given transponder is found by [Byrne et al., 1992]:

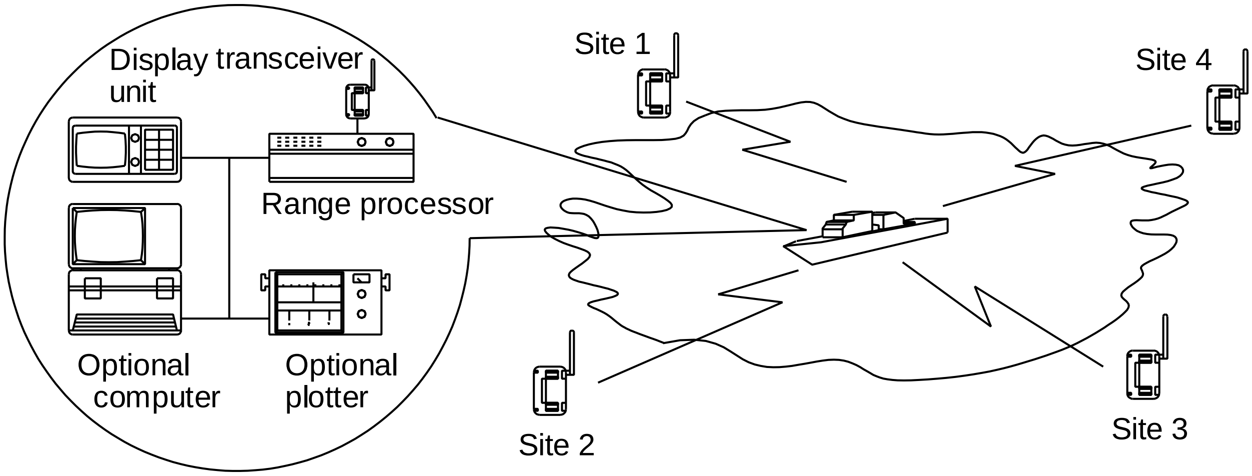


**Figure 3.7:** Motorola's *Mini-Ranger Falcon 484 R* position-location system provides 2 m (6.5 ft) accuracy over ranges of 100 m to 75 km (328 ft to 47 mi). (Courtesy of [MOTOROLA].)

$$D = \frac{(T_e - T_d)c}{2} \qquad (3.1)$$

where
$D$ = separation distance
$T_e$ = total elapsed time
$T_d$ = transponder turn-around delay
$c$ = speed of light.

The MC6809-based range processor performs a least-squares position solution at a 1-Hz update rate, using range inputs from two, three, four, or 16 possible reference transponders. The individual reference stations answer only to uniquely coded interrogations and operate in C-band (5410 to 5890 MHz) to avoid interference from popular X-band marine radars [Motorola, undated]. Up to 20 mobile users can time share the *Falcon 484* system (50 ms per user maximum). System resolution is in tenths of units (m, ft, or yd) with a range accuracy of 2 meters (6.5 ft) probable.

Power requirements for the fixed-location reference stations are 22 to 32 VDC at 13 W nominal, 8.5 W standby, while the mobile range processor and its associated transmitter-receiver and display unit draw 150 W at 22 to 32 VDC. The Falcon system comes in different, customized configurations. Complete system cost is $75,000 to $100,000.

### 3.1.5 Harris *Infogeometric* System

Harris Technologies, Inc., [HTI], Clifton, VA, is developing a ground-based R position location and communications strategy wherein moderately priced *infogeometric* (IG) devices cooperatively form self-organizing instrumentation and communication networks [Harris, 1994]. Each IG device in the network has full awareness of the identity, location, and orientation of all other IG devices and can communicate with other such devices in both party-line and point-to-point communication modes.

The IG devices employ digital code-division-multiple-access (CDMA) spread-spectrum R hardware that provides the following functional capabilities:

- Network level mutual autocalibration.
- Associative location and orientation tracking.
- Party-line and point-to-point data communications (with video and audio options).
- Distributed sensor data fusion.

Precision position location on the move is based on high-speed range trilateration from fixed reference devices, a method commonly employed in many instrumentation test ranges and other tracking system applications. In this approach, each beacon has an extremely accurate internal clock that is carefully synchronized with all other beacon clocks. A time-stamped (coded) R signal is periodically sent by each transmitter. The receiver is also equipped with a precision clock, so that it can compare the timing information and time of arrival of the incoming signals to its internal clock. This way, the system is able to accurately measure the signals' time of flight and thus the distance between the receiver and the three beacons. This method, known as “differential location regression” [Harris, 1994] is essentially the same as the locating method used in global positioning systems (GPS).

To improve accuracy over current range-lateration schemes, the HTI system incorporates mutual data communications, permitting each mobile user access to the time-tagged range measurements made by fixed reference devices and all other mobile users. This additional network-level range and timing information permits more accurate time synchronization among device clocks, and automatic detection and compensation for uncalibrated hardware delays.

Each omnidirectional CDMA spread-spectrum “geometric” transmission uniquely identifies the identity, location, and orientation of the transmitting source. Typically the available geometric measurement update rate is in excess of 1000 kHz. Harris quotes a detection radius of 500 meters (1640 ft) with 100 mW peak power transmitters. Larger ranges can be achieved with stronger transmitters. Harris also reports on “centimeter-class repeatability accuracy” obtained with a modified transmitter called an “Interactive Beacon.” Tracking and communications at operating ranges of up to 20 kilometers (12.5 mi) are also supported by higher transmission power levels of 1 to 3 W. Typical “raw data” measurement resolution and accuracies are cited in Table 3.1.

Enhanced tracking accuracies for selected applications can be provided as cited in Table 3.2. This significant improvement in performance is provided by sensor data fusion algorithms that exploit the high degree of relational redundancy that is characteristic for infogeometric network measurements and communications.

Infogeometric enhancement algorithms also provide the following capabilities:

- Enhanced tracking in multipath and clutter — permits precision robotics tracking even when operating indoors.
- Enhanced near/far interference reduction — permits shared-spectrum operations in potentially large user networks (i.e., hundreds to thousands).

**Table 3.1:** Raw data measurement resolution and accuracy [Everett, 1995].

| Parameter | Resolution | Biasing |
|---|---|---|
| Range | 1<br>3.3 | 5 m<br>16.4 ft |
| Bearing (Az, El) | 2 | 2° |
| Orientation (Az) | 2 | 2° |

**Table 3.2:** Enhanced tracking resolution and accuracies obtained through sensor data fusion [Everett, 1995].

| Parameter | Resolution | Biasing |
|---|---|---|
| Range | 0.1 - 0.3<br>0.3 - 0.9 | 0.1 - 0.3m<br>0.3 - 0.9ft |
| Bearing | 0.5 - 1.0 | 0.5 - 1.0° |
| Orientation | 0.5 - 1.0 | 0.5 - 1.0° |

Operationally, mobile IG networks support precision tracking, communications, and command and control among a wide variety of potential user devices. A complete Infogeometric Positioning System is commercially available from [HTI], at a cost of $30,000 or more (depending on the number of transmitters required). In conversation with HTI we learned that the system requires an almost clear “line of sight” between the transmitters and receivers. In indoor applications, the existence of walls or columns obstructing the path will dramatically reduce the detection range and may result in erroneous measurements, due to multi-path reflections.

## 3.2 Overview of Global Positioning Systems (GPSs)

The recent Navstar Global Positioning System (GPS) developed as a Joint Services Program by the Department of Defense uses a constellation of 24 satellites (including three spares) orbiting the earth every 12 hours at a height of about 10,900 nautical miles. Four satellites are located in each of six planes inclined 55 degrees with respect to the plane of the earth’s equator [Getting, 1993]. The absolute three-dimensional location of any GPS receiver is determined through simple trilateration techniques based on time of flight for uniquely coded spread-spectrum radio signals transmitted by the satellites. Precisely measured signal propagation times are converted to *pseudoranges* representing the line-of-sight distances between the receiver and a number of reference satellites in known orbital positions. The measured distances have to be adjusted for receiver clock offset, as will be discussed later, hence the term pseudoranges. Knowing the exact distance from the ground receiver to three satellites theoretically allows for calculation of receiver latitude, longitude, and altitude.

Although conceptually very simple (see [Hurn, 1993]), this design philosophy introduces at least four obvious technical challenges:

- Time synchronization between individual satellites and GPS receivers.
- Precise real-time location of satellite position.

- Accurate measurement of signal propagation time.
- Sufficient signal-to-noise ratio for reliable operation in the presence of interference and possible jamming.

The first of these problems is addressed through the use of atomic clocks (relying on the vibration period of the cesium atom as a time reference) on each of the satellites to generate time ticks at a frequency of 10.23 MHz. Each satellite transmits a periodic pseudo-random code on two different frequencies (designated L1 and L2) in the internationally assigned navigational frequency band. The L1 and L2 frequencies of 1575.42 and 1227.6 MHz are generated by multiplying the cesium-clock time ticks by 154 and 128, respectively. The individual satellite clocks are monitored by dedicated ground tracking stations operated by the Air Force, and continuously advised of their measured offsets from the ground master station clock. High precision in this regard is critical since electromagnetic radiation propagates at the speed of light, roughly 0.3 meters (1 ft) per nanosecond.

To establish the exact time required for signal propagation, an identical pseudocode sequence is generated in the GPS receiver on the ground and compared to the received code from the satellite. The locally generated code is shifted in time during this comparison process until maximum correlation is observed, at which point the induced delay represents the time of arrival as measured by the receiver's clock. The problem then becomes establishing the relationship between the atomic clock on the satellite and the inexpensive quartz-crystal clock employed in the GPS receiver. This $\Delta T$ is found by measuring the range to a fourth satellite, resulting in four independent trilateration equations with four unknowns. Details of the mathematics involved are presented by Langley [1991].

The precise real-time location of satellite position is determined by a number of widely distributed tracking and telemetry stations at surveyed locations around the world. Referring to Figure 3.4, all measured and received data are forwarded to a master station for analysis and referenced to universal standard time. Change orders and signal-coding corrections are generated by the master station and then sent to the satellite control facilities for uploading [Getting, 1993]. In this fashion the satellites are continuously advised of their current position as perceived by the earth-based tracking stations, and encode this *ephemeris* information into their L1 and L2 transmissions to the GPS receivers. (Ephemeris is the space vehicle orbit characteristics, a set of numbers that precisely describe the vehicle's orbit when entered into a specific group of equations.)

In addition to its own timing offset and orbital information, each satellite transmits data on all other satellites in the constellation to enable any ground receiver to build up an almanac after a "cold start." Diagnostic information with respect to the status of certain onboard systems and expected range-measurement accuracy is also included. This collective "housekeeping" message is superimposed on the pseudo-random code modulation at a very low (50 bits/s) data rate, and requires 12.5 minutes for complete downloading [Ellowitz, 1992]. Timing offset and ephemeris information is repeated at 30 second intervals during this procedure to facilitate initial pseudorange measurements.

To further complicate matters, the sheer length of the unique pseudocode segment assigned to each individual Navstar Satellite (i.e., around 6.2 trillion bits) for repetitive transmission can potentially cause initial synchronization by the ground receiver to take considerable time. For this and other reasons, each satellite broadcasts two different non-interfering pseudocodes. The first of these is called the *coarse acquisition*, or C/A code, and is transmitted on the L1 frequency to assist in acquisition. There are 1023 different C/A codes, each having 1023 chips (code bits) repeated 1000 times a second [Getting, 1993] for an effective chip rate of 1.023 MHz (i.e., one-tenth the cesium clock rate). While the C/A code alone can be employed by civilian users to obtain a fix, the resultant

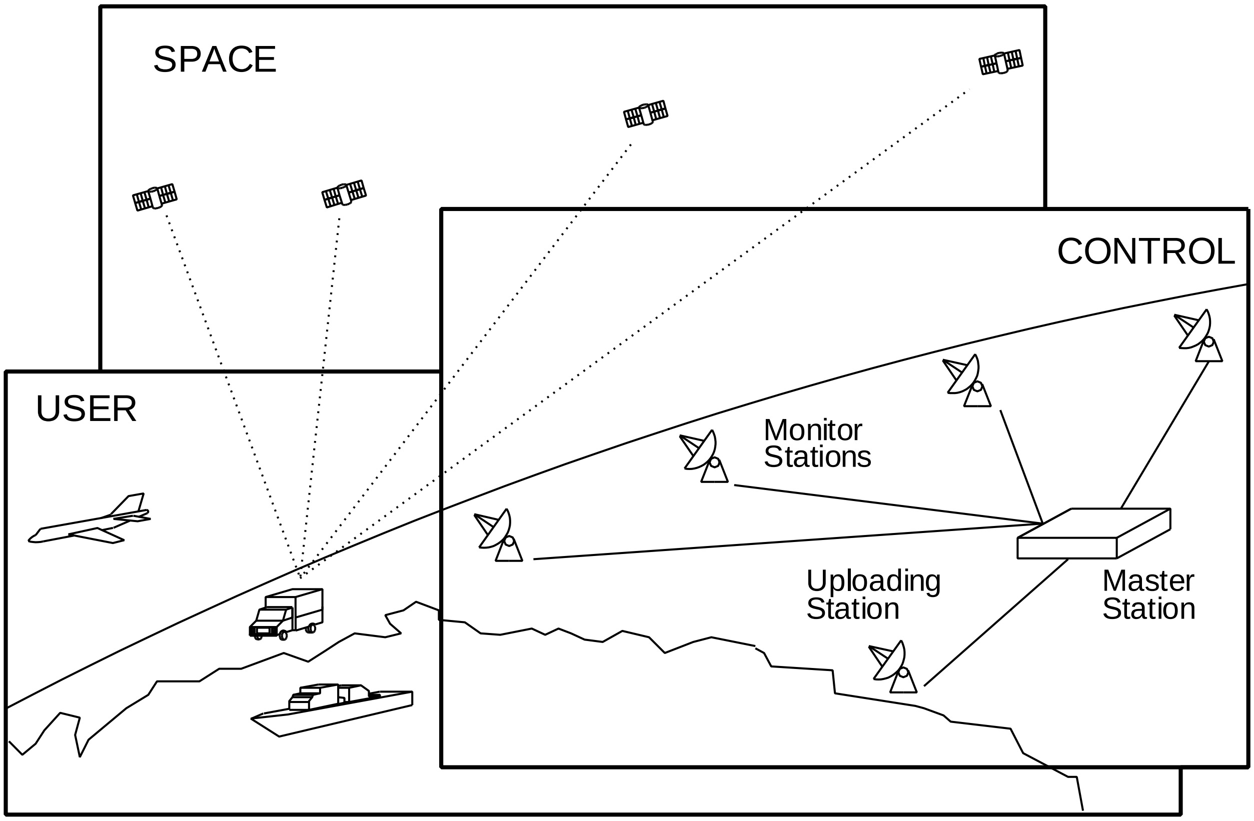


**Figure 3.4:** The Navstar *Global Positioning System* consists of three fundamental segments: Space, Control, and User. (Adapted from [Getting, 1993].)

positional accuracy is understandably somewhat degraded. The Y code (formerly the precision or P code prior to encryption on January 1st, 1994) is transmitted on both the L1 and L2 frequencies and scrambled for reception by authorized military users only with appropriate cryptographic keys and equipment. This encryption also ensures *bona fide* recipients cannot be "spoofed" (i.e., will not inadvertently track false GPS-like signals transmitted by unfriendly forces).

Another major difference between the Y and C/A code is the length of the code segment. While the C/A code is 1023 bits long and repeats every millisecond, the Y code is $2.35\times10^{14}$ bits long and requires 266 days to complete [Ellowitz, 1992]. Each satellite uses a one-week segment of this total code sequence; there are thus 37 unique Y codes (for up to 37 satellites) each consisting of $6.18\times10^{12}$ code bits set to repeat at midnight on Saturday of each week. The higher chip rate of 10.23 MHz (equal to the cesium clock rate) in the precision Y code results in a chip wavelength of 30 meters for the Y code as compared to 300 meters for the C/A code [Ellowitz, 1992], and thus facilitates more precise time-of-arrival measurement for military purposes.

Brown and Hwang [1992] discuss a number of potential pseudorange error sources as summarized below in Table 3.3. Positional uncertainties related to the reference satellites are clearly a factor, introducing as much as 3 meters (9.8 ft) standard deviation in pseudo-range measurement accuracy. As the radiated signal propagates downward toward the earth, atmospheric refraction and multi-path reflections (i.e., from clouds, land masses, water surfaces) can increase the perceived time of flight beyond that associated with the optimal straight-line path (Figure 3.5).

Additional errors can be attributed to group delay uncertainties introduced by the processing and passage of the signal through the satellite electronics. Receiver noise and resolution must also be taken into account. Motazed [1993] reports fairly significant differences of 0.02 to 0.07 arc minutes in calculated latitudes and longitudes for two identical C/A-code receivers placed side by side. And finally, the particular dynamics of the mobile vehicle that hosts the GPS receiver plays a noteworthy role, in that best-case conditions are associated with a static platform, and any substantial velocity and acceleration will adversely affect the solution.

For commercial applications using the C/A code, small errors in timing and satellite position have been deliberately introduced by the master station to prevent a hostile nation from using GPS in support of precision weapons delivery. This intentional degradation in positional accuracy to around 100 meters (328 ft) best case and 200 meters (656 ft) typical spherical error probable (SEP) is termed *selective availability* [Gothard, 1993]. Selective availability has been on continuously (with a few exceptions) since the end of Operation Desert Storm. It was turned off during the war from August 1990 until July 1991 to improve the accuracy of commercial hand-held GPS receivers used by coalition ground forces.

Table 3.3: Summary of potential error sources for measured pseudoranges [Brown and Hwang, 1992].

| Error Source | Standard Deviation [m] | [ft] |
|---|---|---|
| Satellite position | 3 | 29 |
| Ionospheric refraction | 5 | 16.4 |
| Tropospheric refraction | 2 | 6.6 |
| Multipath reflection | 5 | 16.4 |
| Selective availability | 30 | 98.4 |

There are two aspects of selective availability: epsilon and dither. Epsilon is intentional error in the navigation message regarding the location (ephemeris) of the satellite. Dither is error in the timing source (carrier frequency) that creates uncertainty in velocity measurements (Doppler). Some GPS receivers (for example, the Trimble ENSIGN) employ running-average filtering to statistically reduce the epsilon error over time to a reported value of 15 meters SEP [Wormley, 1994].

At another occasion (October 1992) SA was also turned off for a brief period while the Air Force was conducting tests. Byrne [1993] conducted tests at that time to compare the accuracy of GPS with SA turned on and off. The static measurements of the GPS error as a function of time shown in Figure 3.6 were taken before the October 1992 test, i.e., with SA "on" (note the slowly varying error in Figure 3.6, which is caused by SA). By contrast, Figure 3.7 shows measurements from the October 1992 period when SA was briefly "off."

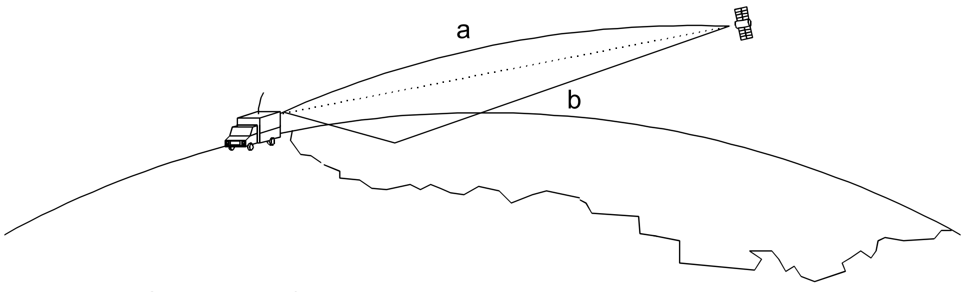


Figure 3.5: Contributing factors to pseudorange measurement errors: a. atmospheric refraction; b. multi-path reflections [Everett, 1995].

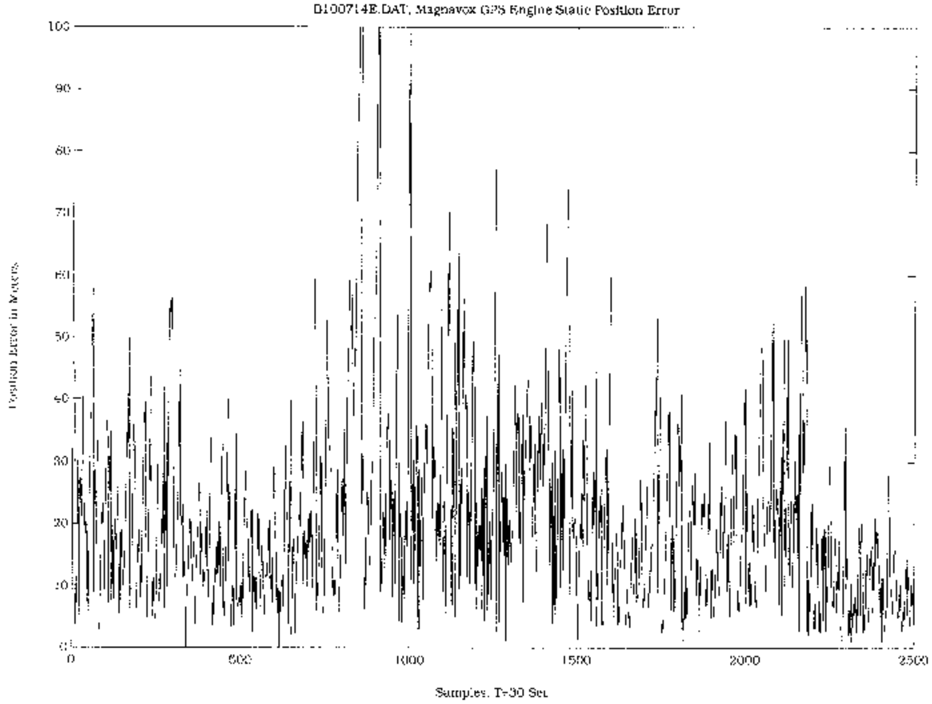


**Figure 3.6:** Typical GPS static position error with SA "On." (Courtesy of [Byrne, 1993].)

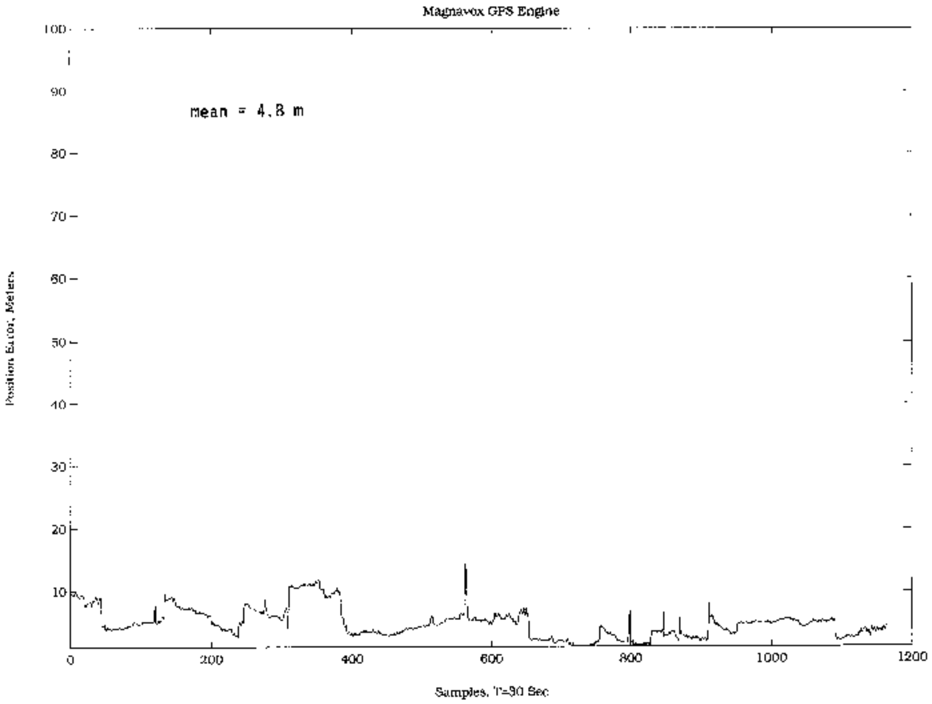


**Figure 3.7:** Typical GPS static position error with SA "Off". (Courtesy of Byrne [1993]).

All of the error sources listed in Table 3.3 are further influenced by the particular geometry of the four reference satellites at time of sighting. Ignoring time synchronization needs for the moment (i.e., so only three satellites are required), the most accurate three-dimensional trilater-ation solutions will result when the bearing or sight lines extending from the receiver to the respective satellites are mutually orthogonal. If the satellites are spaced close together in a tight cluster or otherwise arranged in a more or less collinear fashion with respect to the receiver as shown in Figure 3.8, the desired orthogonality is lost and the solution degrades accordingly.

Terms used to describe the strength of the position fix based on the geometry include: *Dilution of Precision* (DOP), *Horizontal Dilution of Precision* (HDOP), *Geometric Dilution of Precision* (GDOP), *Position Dilution of Precision* (PDOP), *Time Dilution of Precision* (TDOP), and *Vertical Dilution of Precision* (VDOP). The various DOPs are error multipliers that indicate the accuracy of a particular type of position fix based on a certain pseudo-range error. For instance, if the pseudo-range measurements are accurate to 10 meters (33 ft) and the HDOP is equal to 3.5, the horizontal position accuracy would be 10 × 3.5 = 35 meters (100 ft). A PDOP of 2 or 3 is fairly good, while a PDOP of 10 is not so good. Certain geometries can cause the DOP to become very large (infinite). Two useful DOP identities are shown in Equations (3.2) and (3.3).

$$PDOP^2 = VDOP^2 + HDOP^2 \tag{3.2}$$

$$GDOP^2 = PDOP^2 + TDOP^2 \tag{3.3}$$

Acronyms used in this section

| | |
|---|---|
| DOP | dilution of precision |
| GDOP | geometric dilution of precision |
| HDOP | horizontal dilution of precision |
| PDOP | position dilution of precision |
| TDOP | Time dilution of precision |
| VDOP | vertical dilution of precision |
| SA | selective availability |

Kihara and Okada [1984] show that the minimum achievable (best-case) value for GDOP is 1.5811. This optimal constellation occurs when the four required GPS satellites are symmetrically located with an angle of 109.47 degrees between adjacent bearing lines as shown in Figure 3.9.

With the exception of multi-path effects, all of the error sources listed in Table 3.3 above can be essentially eliminated through use of a practice known as *differential GPS* (DGPS). The concept is based on the premise that a second GPS receiver in fairly close proximity (i.e., within 10 km — 6.2 mi) to the first will experience basically the same error effects when viewing the same reference satellites. If this second receiver is fixed at a precisely

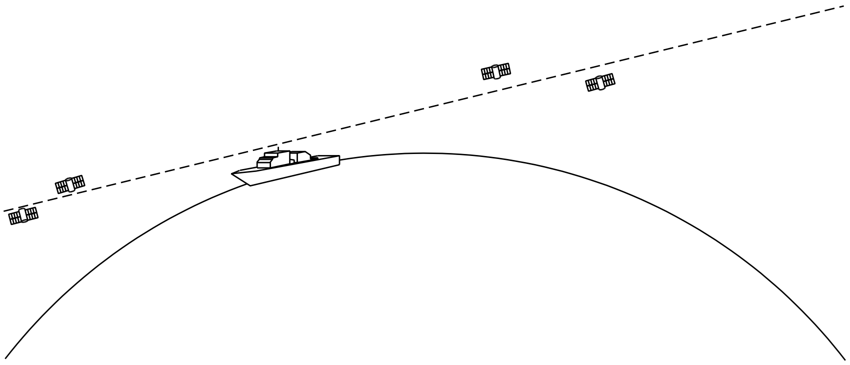


**Figure 3.8:** Worst-case *geometric dilution of precision* (GDOP) errors occur when the receiver and satellites approach a collinear configuration as shown [Everett, 1995].

surveyed location, its calculated solution can be compared to the known position to generate a composite error vector representative of prevailing conditions in that immediate locale. This differential correction can then be passed to the first receiver to null out the unwanted effects, effectively reducing position error for commercial systems to well under 10 meters.

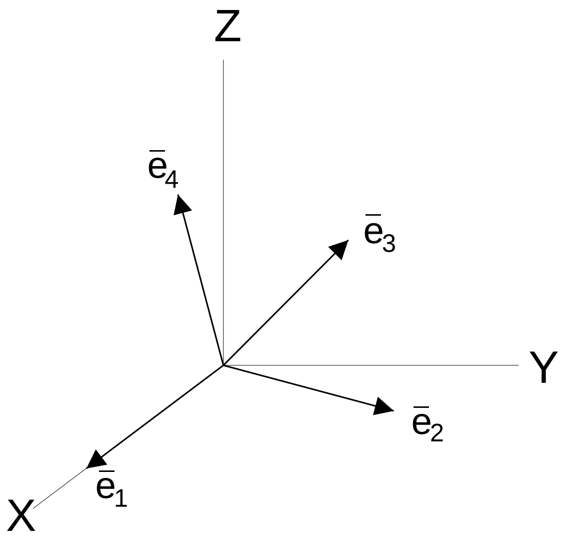


**Figure 3.9:** GDOP error contribution is minimal for four GPS satellites symmetrically situated with respect to the receiver (at origin) along bearing lines 109.47° apart [Kihara and Okada, 1984].

The fixed DGPS reference station transmits these correction signals every two to four minutes to any differential-capable receiver within range. Many commercial GPS receivers are available with differential capability, and most now follow the RTCM-104 standard developed by the Radio Technical Commission for Maritime Services to promote interoperability. Prices for DGPS-capable mobile receivers run about $2K, while the reference stations cost somewhere between $10K and $20K. Magnavox is working with CUE Network Corporation to market a nationwide network to pass differential corrections over an FM link to paid subscribers [GPS Report, 1992].

Typical DGPS accuracies are around 4 to 6 meters (13 to 20 ft) SEP, with better performance seen as the distance between the mobile receivers and the fixed reference station is decreased. For example, the Coast Guard is in the process of implementing *differential GPS* in all major U.S. harbors, with an expected accuracy of around 1 meter (3.3 ft) SEP [Getting, 1993]. A differential GPS system already in operation at O'Hare International Airport in Chicago has demonstrated that aircraft and service vehicles can be located to 1 meter (3.3 ft). Surveyors use differential GPS to achieve centimeter accuracy, but this practice requires significant postprocessing of the collected data [Byrne, 1993].

An interesting variant of conventional DGPS is reported by Motazed [1993] in conjunction with the Non-Line-of-Sight Leader/Follower (NLOSLF) program underway at RedZone Robotics, Inc., Pittsburgh, PA. The NLOSLF operational scenario involves a number of vehicles in a convoy configuration that autonomously follow a lead vehicle driven by a human operator, both on-road and off-road at varying speeds and separation distances. A technique to which Motazed refers as *intermittent stationary base differential GPS* is used to provide global referencing for purposes of bounding the errors of a sophisticated Kalman-filter-based GPS/INS position estimation system.

Under this innovative concept, the lead and final vehicle in the convoy alternate as fixed-reference differential GPS base stations. As the convoy moves out from a known location, the final vehicle remains behind to provide differential corrections to the GPS receivers in the rest of the vehicles. After traversing a predetermined distance in this fashion, the convoy is halted and the lead vehicle assumes the role of a differential reference station, providing enhanced accuracy to the trailing vehicle as it catches up to the pack. During this time, the lead vehicle takes advantage of on-site dwell to further improve the accuracy of its own fix. Once the last vehicle joins up with the rest, the base-station roles are reversed again, and the convoy resumes transit in "inchworm" fashion along its intended route. Disadvantages to this approach include the need for intermittent stops and the accumulating ambiguity in actual location of the appointed reference station.

Recall the Y-code chip rate is directly equal to the satellite cesium clock rate, or 10.23 MHz. Since the L1 carrier frequency of 1575.42 MHz is generated by multiplying the clock output by 154, there are consequently 154 carrier cycles for every Y-code chip. This implies even higher measurement precision is possible if the time of arrival is somehow referenced to the carrier instead of the pseudocode itself. Such codeless interferometric differential GPS schemes measure the phase of the L1 and L2 carrier frequencies to achieve centimeter accuracies, but they must start at a known geodetic location and typically require long dwell times. The Army's Engineer Topographic Laboratories (ETL) is in the process of developing a carrier-phase-differential system of this type that is expected to provide 1 to 3 centimeters (0.4 to 1.2 in) accuracy at a 60-Hz rate when finished sometime in 1996 [McPherson, 1991].

A reasonable extraction from the open literature of achievable position accuracies for the various GPS configurations is presented in Table 3.4. The Y code has dual-frequency estimation for atmospheric refraction and no S/A error component, so accuracies are better than stand-alone single-frequency C/A systems. Commercial DGPS accuracy, however, exceeds stand-alone military Y-code accuracy, particularly for small-area applications such as airports. Differential Y code is currently under consideration and may involve the use of a satellite to disseminate the corrections over a wide area.

**Table 3.4:** Summary of achievable position accuracies for various implementations of GPS.

| GPS Implementation Method | Position Accuracy |
|---|---|
| C/A-code stand alone | 100 m SEP<br>(328 ft) |
| Y-code stand alone | 16 m SEP<br>(52 ft) |
| Differential (C/A-code) | 3 m SEP<br>(10 ft) |
| Differential (Y-code) | unknown (TBD) |
| Phase differential (codeless) | 1 cm SEP<br>(0.4 in) |

A typical non-differential GPS was tested by Cooper and Durrant-White [1994] and yielded an accumulated position error of over 40 meters (131 ft) after extensive filtering.

Systems likely to provide the best accuracy are those that combine GPS with Inertial Navigation Systems (INS), because the INS position drift is bounded by GPS corrections [Motazed, 1993]. Similarly, the combination of GPS with odometry and a compass was proposed by Byrne [1993].

In summary, the fundamental problems associated with using GPS for mobile robot navigation are as follows:

- Periodic signal blockage due to foliage and hilly terrain.
- Multi-path interference.
- Insufficient position accuracy for primary (stand-alone) navigation systems.

Arradondo-Perry [1992] provides a comprehensive listing of GPS receiver equipment, while Byrne [1993] presents a detailed evaluation of performance for five popular models. Parts of Byrne's performance evaluation has been adapted from the original report for inclusion in this survey as Section 3.3.

## 3.3 Evaluation of Five GPS Receivers by Byrne [1993]

In 1992 and 1993 Raymond H. Byrne at the Advanced Vehicle Development Department, Sandia National Laboratories, Albuquerque, New Mexico conducted a series of in-depth comparison tests with five different GPS receivers. His results were originally published in September 1993 as Sandia Report SAND93-0827 UC-515. With permission of the author we have reproduced and adapted parts of that report in this section.

### 3.3.1 Project Goals

The intent of Byrne's study was to compare the performance of a particular two-channel, sequencing GPS receiver (a 10 year old, outdated Magnavox 6400) to that of newer five- and six-channel parallel receivers. The parallel channel receivers used in this study were selected based upon availability, cost, size, and receiver specifications.

The receivers tested are listed in Table 3.5. The "original equipment manufacturer" (OEM) receivers are single board GPS devices that are meant to be integrated into a system or product. The Trimble and Magnavox 6400 receivers are "integrated" commercial products.

**Table 3.5:** GPS receivers tested. (Courtesy of Byrne [1993]).

| Receiver | Description |
|---|---|
| Magnavox 6400 (10-year old system, outdated) | 2-channel, sequencing receiver, receiver in current system, integrated system |
| Magellan OEM GPS Module | 5-channel GPS receiver, OEM type |
| Magnavox GPS Engine | 6-channel GPS receiver, OEM type |
| Rockwell NavCore V | 5-channel GPS receiver, OEM type |
| Trimble Placer | 6-channel receiver, Integrated System |

The performance of the current GPS receiver was tested along with four commercially available receivers. The experiments included static as well as dynamic testing. The results of these tests are presented in the following section.

### 3.3.2 Test Methodology

Many parameters may be measured when comparing GPS receivers. Section 3.3.2.1 discusses the parameters that were chosen to compare the performance of Sandia's old Magnavox 6400 GPS receiver to newer commercial off the-shelf units. Section 3.3.2.2 describes the test fixture hardware developed to gather GPS data from the five different receivers, and the post processing of the gathered data is discussed in Section 3.3.2.3.

### 3.3.2.1 Parameters tested

In the experiments performed at Sandia National Laboratories testing focused on receiver sensitivity, static accuracy, dynamic accuracy, number of satellites tracked, and time-to-first-fix. The tests aimed at evaluating the five different GPS receivers in both static and dynamic environments. This section discusses the parameters tested and the rationalization for choosing these parameters.

For many navigation applications time-to-first-fix is an important parameter. The older Magnavox 6400 receiver can take up to 30 minutes to initialize and lock onto the satellite signals before it starts navigating. However, all of the newer receivers advertise fast position fixes, usually under one minute, if the receiver knows its position to within several hundred miles. This is often referred to as a "warm start." The difference between a 30-second first fix and a 2-minute first fix is not that important for most applications. However, 1 to 2 minutes is a great improvement over 30 minutes. Although this parameter was not explicitly measured, attention was paid to time-to-first-fix to confirm that the newer receivers were meeting the quoted specification.

The number of satellites tracked and receiver sensitivity are also important parameters. The more satellites tracked, the less likely an obstruction of one or more satellites will result in a loss of navigation. Also, a more sensitive receiver is less likely to be affected by foliage and other obstructions that reduce signal strengths. The receiver sensitivity is affected by the type of antenna used and the type of cabling. Some antennas have higher gains than others, different cables have different attenuation characteristics, and longer cables cause greater signal attenuation. The navigation mode, two-dimensional (2D-mode) or three-dimensional (3D-mode), is affected by the number of satellites visible. Provided that the geometry results in an acceptable DOP, a minimum of four satellites are necessary for three-dimensional navigation. Additional satellites may be used to achieve a more robust position fix. If four satellites are in view, but the DOP is higher than a certain threshold, many receivers will switch to two-dimensional navigation.

Ideally, measuring the signal-to-noise ratio in the receiver and the number of satellites being tracked would yield the most insight into receiver performance. However, this information is usually buried in several different data packets for any given receiver. For some receivers, this information is not always available (the Trimble Placer does not output signal-to-noise ratio or the number of satellites tracked for example). Therefore, a compromise was made and packets were requested that contained the position fix as well as the navigation mode or number of satellites tracked. Usually this data was contained in the same data packet. This reduced the amount of data stored and simplified the data analysis. The information gathered from each receiver is listed in Table 3.6.

Differences in navigation modes can be caused by several factors; these include differences in number of satellites being tracked, differences in the DOP value that cause a switch from 3D-mode to 2D-mode navigation, and differences in satellite mask angles and receiver/antenna sensitivity. The DOP settings and mask angles are known for each receiver, so the navigation mode data will allow comparing the number of satellites tracked and receiver/antenna sensitivity as one performance criterion. Although the navigation mode data lumps several factors together, it does give a comparison of overall receiver/antenna performance.

As mentioned in the previous section, the antenna and cable choice affects the performance of the GPS receiver. The antennas used for the GPS testing were supplied with the receiver or OEM evaluation kit, The cabling was also supplied with the exception of the Magnavox GPS Engine. Therefore, the performance of the antenna and cabling was lumped together with the overall GPS system because each manufacturer recommends (or provides) antennas and cabling.

**Table 3.6:** Summary of data analyzed (Courtesy of [Byrne, 1993].)

| Receiver | Data Gathered |
|---|---|
| Magellan | Latitude, longitude.<br>Number of satellites used - implies navigation mode (none, 2-D, or 3-D). |
| Magnavox GPS Engine | Latitude, longitude.<br>Navigation Mode (none, 2-D, or 3-D). |
| Rockwell NavCore V | Latitude, longitude, navigation mode (none, 2-D, or 3-D).<br>Number of satellites tracked also available from raw data. |
| Magnavox 6400 | Latitude, longitude<br>Number of satellites tracked. |
| Trimble Placer | Latitude, longitude.<br>Navigation Mode (none, 2-D, or 3-D). |

Other performance factors include the amount of filtering in a GPS receiver. Excessive filtering reduces the amount of variance in the position and velocity data, but also slows the response of the receiver. Excessive filtering will cause a receiver to output incorrect positions when starting, stopping, or turning sharply. In applications where the GPS data is processed off board and needs to be transmitted via RF-link to a central computer, this type of error is not very important because the delay introduced by the communication link will probably be much greater than the delay introduced by filtering in the receiver.

Parameters that were not analyzed in the Sandia experiments are velocity and heading accuracy, because in Sandia's application (and many other typical mobile robot navigation tasks) accurate velocity information was already available from odometry. Heading information that would be required for dead reckoning is not needed while GPS is functional.

Another easy-to-measure performance criterion is static position accuracy. This parameter was measured by placing the GPS receivers at a surveyed location and taking data for approximately 24 hours. Although in typical application the receivers are moving most of the time, the static accuracy does give a good idea of the receivers' position accuracy capabilities. The parameters measured and the performance insights gained from these measurements are summarized in Table 3.7.

In summary, the GPS testing performed for this project consisted of storing position and navigation mode data from five different GPS receivers for both static and dynamic tests. The static testing provides information about the static position accuracy as well as the sensitivity of the receiver and antenna if DOP switching is taken into account. The dynamic testing mostly provides information about the receiver/antenna sensitivity and the receiver's ability to recover from temporary obstructions (taking into account DOP switching). The dynamic testing also provides some qualitative information about position accuracy by comparing plots of the data points from the various receivers.

**Table 3.7:** Summary of parameters measured and performance areas evaluated. (Courtesy of [Byrne, 1993].)

| Parameter measured | Performance evaluated by that parameter |
|---|---|
| Time-to-first-fix | How quickly a receiver starts navigating. Not explicitly measured, but qualitatively considered. |
| Static position accuracy | Static accuracy and insight into overall accuracy. |
| Static navigation mode — Number of satellites tracked | Taking into account DOP switching, gives insight into receiver/antenna sensitivity. |
| Dynamic position plots | Some accuracy information is obtained by comparing different data plots taken while driving down the same section of road. Most of this analysis is qualitative though because there is no ground-truth data for comparison. |
| Dynamic navigation mode | Taking DOP switching into account gives insight into the sensitivity of the receiver/antenna and the rate with which the receiver recovers from obstructions. |

### *3.3.2.2 Test hardware*

The GPS receivers tested use a serial interface for communicating position information. The Magnavox 6400 receiver communicates using RS-422 serial communications, while the other four receivers use the RS-232 communications standard. The RS-422 and RS-232 standards for data transmission are compared in Table 3.8.

For the short distances involved in transmitting GPS data from the receiver to a computer, the type of serial communications is not important. In fact, even though RS-232 communications are inferior in some ways to RS422, RS-232 is easier to work with because it is a more common standard (especially for PC-type computers).

A block diagram of the overall GPS test system is shown in Figure 3.10. Figure 3.10 depicts the system used for dynamic testing where power was supplied from a 12-Volt battery. For the static testing, AC power was available with an extension cord. Therefore, the computer supply was connected directly to AC, while the +12 Volts for the GPS receivers was generated using an AC-DC power supply for the static test.

The GPS test fixture was set up in a Chevrolet van with an extended rear for additional room. The GPS antennas were mounted on aluminum plates that where attached to the van with magnets. The Rockwell antenna came with a magnetic mount so it was attached directly to the roof. The five antennas were within one meter of each other near the rear of the van and mounted at the same height so that no antenna obstructed the others.

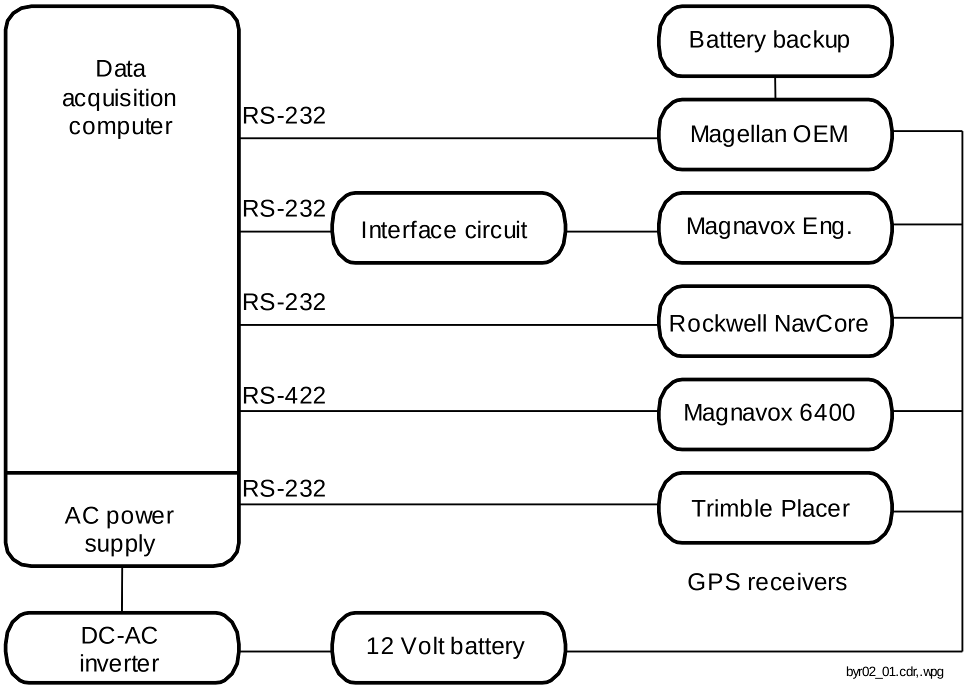


**Figure 3.10:** Block diagram of the GPS test fixture. (Courtesy of [Byrne, 1993].)

For the dynamic testing, power was supplied from a 60 Amp-Hour lead acid battery. The battery was used to power the AC-DC inverter as well as the five receivers. The van's electrical system was tried at first, but noise caused the computer to lock up occasionally. Using an isolated battery solved this problem. An AC-powered computer monitor was used for the static testing because AC power was available. For the dynamic testing, the low power LCD display was used.

### *3.3.2.3 Data post processing*

The GPS data was stored in raw form and post processed to extract position and navigation data. This was done so that the raw data could be analyzed again if there were any questions with the results. Also, storing the data as it came in from the serial ports required less computational effort and reduced the chance of overloading the data acquisition computer. This section describes the software used to post process the data.

Table 3.9 shows the minimum resolution (I..e, the smallest change in measurement the unit can output) of the different GPS receivers. Note, however, that the resolution of all tested receivers is still orders of magnitude smaller than the typical position error of up to 100 meters. Therefore, this parameter will not be an issue in the data analysis.

**Table 3.8:** Comparison of RS-232 and RS-422 serial communications. (Courtesy of [Byrne, 1993].)

| RS-232 Communications | RS-422 Communications |
|---|---|
| Single-ended data transmission | Differential data transmissions |
| Relatively slow data rates (usually < 20 kbs), short distances up to 50 feet, most widely used. | Very high data rates (up to l0 Mbs), long distances (up to 4000 feet at l00 Kbs), good noise immunity. |

Once the raw data was converted to files with latitude, longitude, and navigation mode in columnar form, the data was prepared for analysis. Data manipulations included obtaining the position error from a surveyed location, generating histograms of position error and navigation mode, and plotting dynamic position data. The mean and variance of the position errors were also obtained. Degrees of latitude and longitude were converted to meters using the conversion factors listed below.

| | |
|---|---|
| Latitude Conversion Factor | $11.0988\times10^4$ m/° latitude |
| Longitude Conversion Factor | $9.126\times10^4$ m/° longitude |

### 3.3.3 Test Results

Sections 3.3.3.1 and 3.3.3.2 discuss the test results for the static and dynamic tests, respectively, and a summary of these results is given in Section 3.3.3.3. The results of the static and dynamic tests provide different information about the overall performance of the GPS receivers. The static test compares the accuracy of the different receivers as they navigate at a surveyed location. The static test also provides some information about the receiver/antenna sensitivity by comparing navigation modes (3D-mode, 2D-mode, or not navigating) of the different receivers over the same time period. Differences in navigation mode may be caused by several factors. One is that the receiver/antenna operating in a plane on ground level may not be able to track a satellite close to the horizon. This reflects receiver/antenna sensitivity. Another reason is that different receivers have different DOP limits that cause them to switch to two dimensional navigation when four satellites are in view but the DOP becomes too high. This merely reflects the designer's preference in setting DOP switching masks that are somewhat arbitrary.

Dynamic testing was used to compare relative receiver/antenna sensitivity and to determine the amount of time during which navigation was not possible because of obstructions. By driving over different types of terrain, ranging from normal city driving to deep canyons, the relative sensitivity of the different receivers was observed. The navigation mode (3D-mode, 2D-mode, or not navigating) was used to compare the relative performance of the receivers. In addition, plots of the data taken give some insight into the accuracy by qualitatively observing the scatter of the data.

**Table 3.9:** Accuracy of receiver data formats. (Courtesy of [Byrne, 1993].)

| Receiver | Data format resolution (degrees) | Minimum resolution (meters) |
|---|---:|---:|
| Magellan | $10^{-7}$ | 0.011 |
| Magnavox GPS Engine | $1.7\times\mathrm{l}0^{-6}$ | 0.19 |
| Rockwell NavCore V | $5.73\times\mathrm{l}0^{-10}$ | $6.36\times\mathrm{l}0^{-5}$ |
| Magnavox 6400 | $10^{-8}$ $5.73\times\mathrm{l}0^{-7}$ | $6.36\times\mathrm{l}0^{-2}$ |
| Trimble Placer | $10^{-5}$ | 1.11 |

### *3.3.3.1 Static test results*

Static testing was conducted at a surveyed location at Sandia National Laboratories' Robotic Vehicle Range (RVR). The position of the surveyed location is described in Table 3.10.

**Table 3.10**: Location of the surveyed point at the Sandia Robotic Vehicle Range. (Courtesy of [Byrne, 1993].)

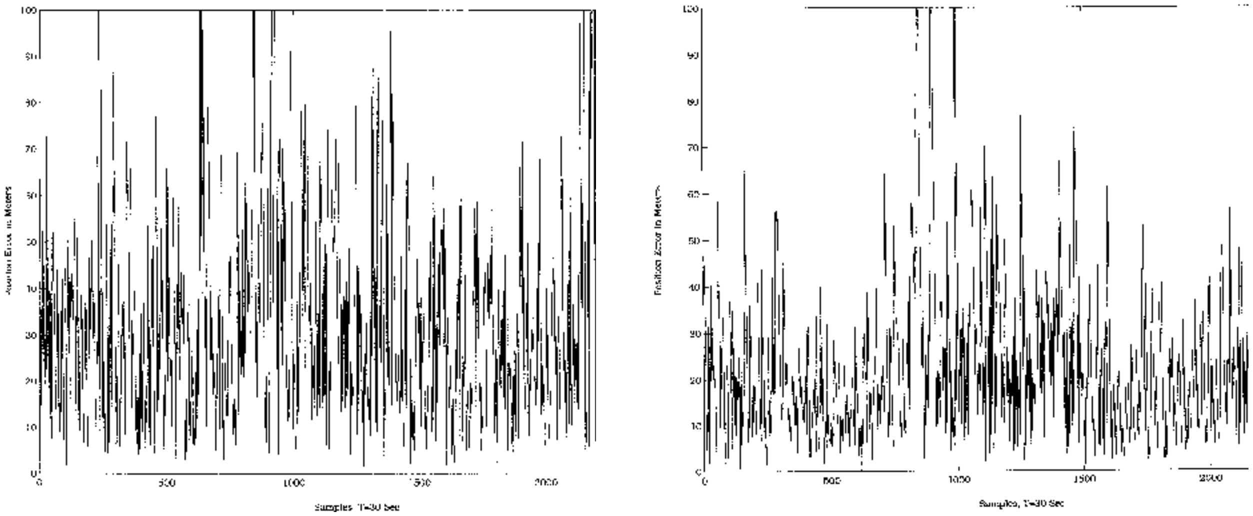
| Surveyed Latitude | Surveyed Longitude |
|---|---|
| 35 02 27.71607 (deg min sec) | 106 31 16.14169 (deg min sec) |
| 35.0410322 (deg) | 106.5211505 (deg) |

The data for the results presented here was gathered on October 7 and 8, 1992, from 2:21 p.m. to 2:04 p.m. Although this is the only static data analyzed in this report, a significant amount of additional data was gathered when all of the receivers were not functioning simultaneously. This previously gathered data supported the trends found in the October 7 and 8 test.The plots of the static position error for each receiver are shown in Figure 3.11. A summary of the mean and standard deviation (σ) of the position error for the different receivers appears in Table 3.11.

**Table 3.11:** Summary of the static position error mean and variance for different receivers. (Courtesy of [Byrne, 1993].)

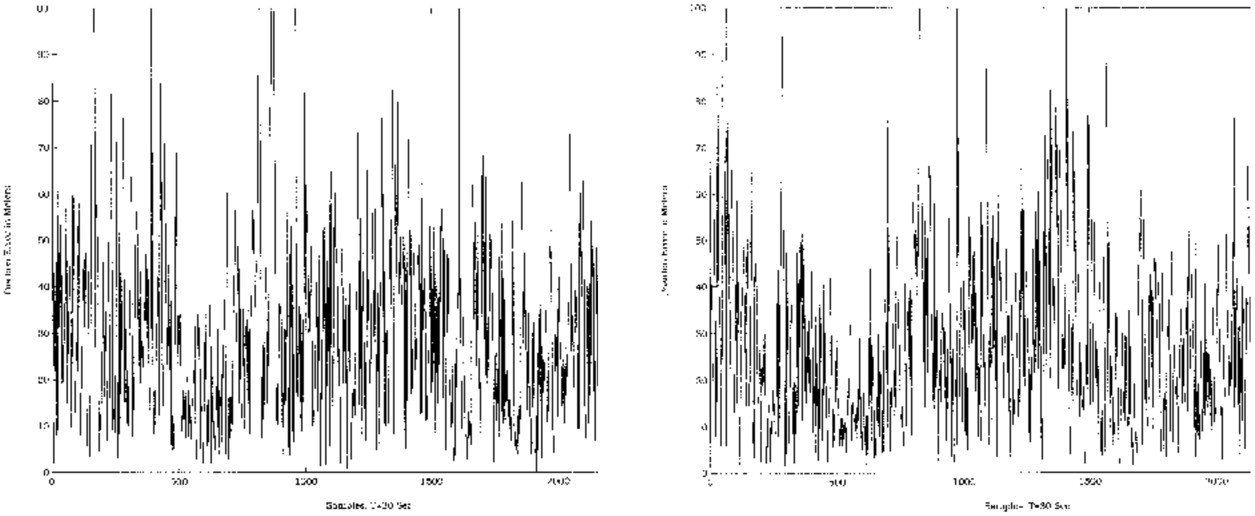
| Receiver | Mean position error | | Position error standard deviation | |
|---|---|---|---|---|
| | (meters) | (feet) | (meters) | (feet) |
| Magellan | 33.48 | 110 | 23.17 | 76 |
| Magnavox GPS Engine | 22.00 | 72 | 16.06 | 53 |
| Rockwell NavCore V | 30.09 | 99 | 20.27 | 67 |
| Magnavox 6400 | 28.01 | 92 | 19.76 | 65 |
| Trimble Placer | 29.97 | 98 | 23.58 | 77 |

It is evident from Table 3.11 that the Magnavox GPS Engine was noticeably more accurate when comparing static position error. The Magellan, Rockwell, Magnavox 6400, and Trimble Placer all exhibit comparable, but larger, average position errors. This trend was also observed when SA was turned off. However, a functioning Rockwell receiver was not available for this test so the data will not be presented. It is interesting to note that the Magnavox 6400 unit compares well with the newer receivers when looking at static accuracy. This is expected: since the receiver only has two channels, it will take longer to reacquire satellites after blockages; one can also expect greater difficulties with dynamic situations. However, in a static test, the weaknesses of a sequencing receiver are less noticeable.



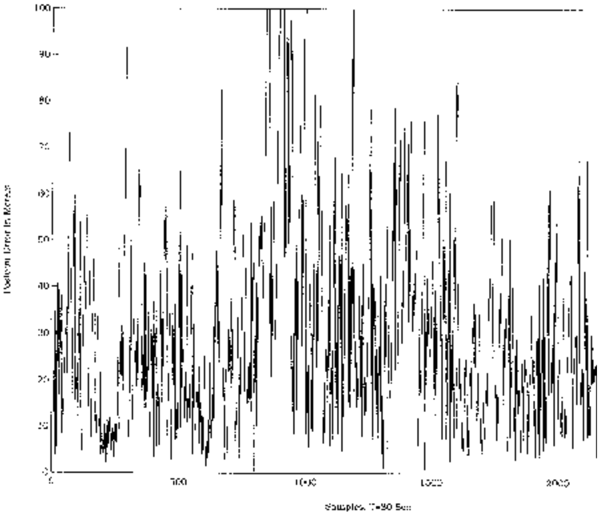
a. Magellan

b. Magnavox GPS Engine.



c. Rockwell NavCore V.

d. Magnavox 6400.



e. Trimble Placer.

**Figure 3.11:** Static position error plots for all five GPS receivers. (Courtesy of Byrne [1993]).

The histogramic error distributions for the data taken during the static test are shown in Figure 3.12. One can see from Fig. 3.12 that the Magnavox GPS Engine has the most data points within 20 meters of the surveyed position. This corresponds with the smallest mean position error exhibited by the Magnavox receiver. The error distributions for the other four receivers are fairly similar. The Magnavox 6400 unit has slightly more data points in the 10 to 20 meter error bin, but otherwise there are no unique features. The Magnavox GPS Engine is the only receiver of the five tested that had a noticeably superior static position error distribution. Navigation mode data for the different receivers is summarized in Figure 3.13 for the static test.

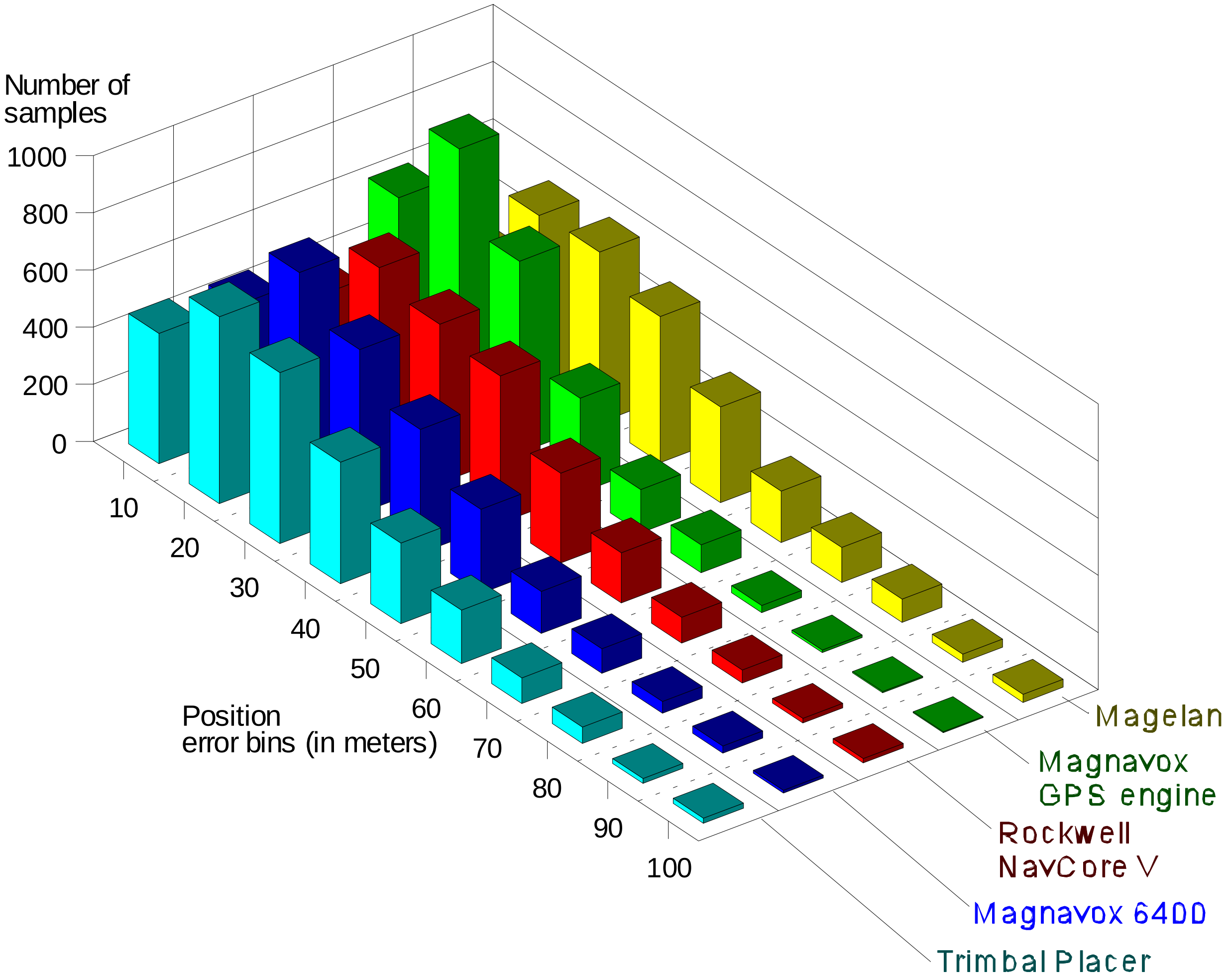


**Figure 3.12:** Histogramic error distributions for the data taken during the static test, for all five tested GPS receivers. (Adapted from [Byrne, 1993].)

In order to analyze the data in Figure 3.13, one needs to take into account the DOP criterion for the different receivers. As mentioned previously, some receivers switch from 3D-mode navigation to 2D-mode navigation if four satellites are visible but the DOP is above a predetermined threshold. The DOP switching criterion for the different receivers are outlined in Table 3.12. As seen in Table 3.12, the different receivers use different DOP criteria. However, by taking advantage of Equations (3.1) and (3.2), the different DOP criteria can be compared.

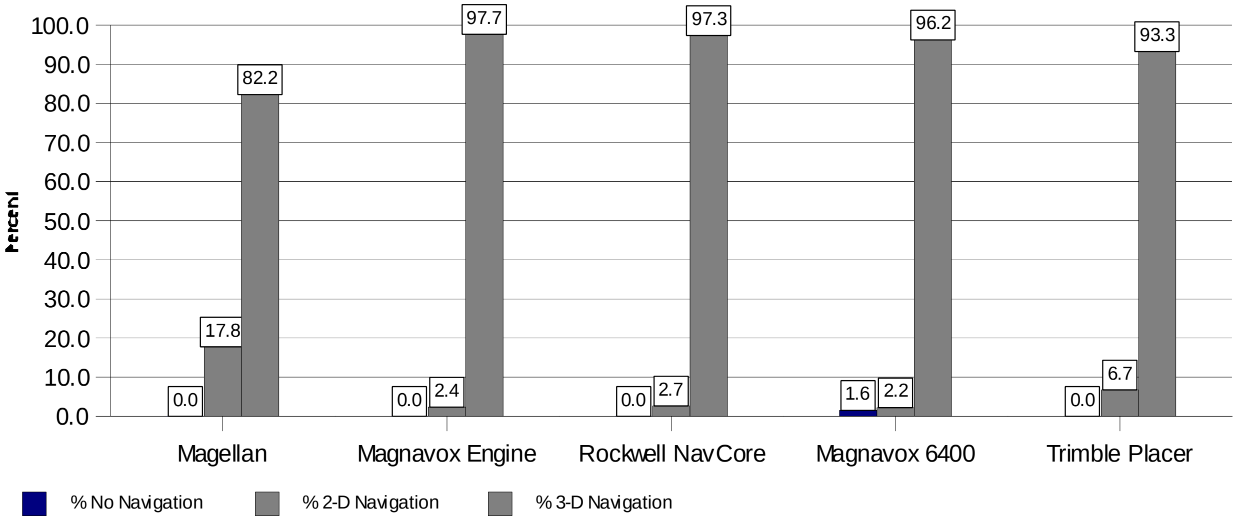


**Figure 3.13:** Navigation mode data for the static test. (Adapted from [Byrne, 1993].)

Table 3.12 relates all of the different DOP criteria to the PDOP. Based on the information in Table 3.12, several comments can be made about the relative stringency of the various DOP criterions. First, the Magnavox GPS Engine VDOP criterion is much less stringent than the Magellan VDOP criterion (these two can be compared directly). The Magellan unit also incorporates hysteresis, which makes the criterion even more stringent. Comparing the Rockwell to the Trimble Placer, the Rockwell criterion is much less stringent. A TDOP of 10.2 would be required to make the two criteria equivalent. The Rockwell and Magnavox GPS Engine have the least stringent DOP requirements.

Taking into account the DOP criterions of the different receivers, the significant amount of two-dimensional navigation exhibited by the Magellan receiver might be attributed to a more stringent DOP criterion. However, this did not improve the horizontal (latitude-longitude) position error. The Magnavox GPS Engine still exhibited the most accurate static position performance. The same can

**Table 3.12:** Summary of DOP - navigation mode switching criteria. (Courtesy of [Byrne, 1993].)

| Receiver | 2-D/3-D DOP criterion | PDOP equivalent |
|---|---|---|
| Magellan | If 4 satellites visible and VDOP >7, will switch to 2-D navigation.<br>Enters 3-D navigation when VDOP<5. | PDOP $\geq$ $(HDOP^2 + 7^2)^{½}$ |
| Magnavox GPS Engine | If 4 satellites visible and VDOP>10, switches to 2-D navigation.<br>If HDOP>10, suspends 2-D navigation | PDOP $\leq$ $(HDOP^2 + 5^2)^{½}$<br>PDOP $\geq$ $(HDOP^2 + 10^2)^{½}$ |
| Rockwell NavCore V | If 4 satellites visible and GDOP>13, switches to 2-D navigation. | PDOP $\geq$ $(13^2 - TDOP^2)^{½}$ |
| Magnavox 6400 | Data Not Available in MX 5400 manual provided | |
| Trimble Placer | If 4 satellites visible and PDOP>8, switches to 2-D navigation. If PDOP>12, receiver stops navigating. | PDOP $\geq$ 8 |

be said for the Trimble Placer unit. Although is has a stricter DOP requirement than the Magnavox Engine, its position location accuracy was not superior. The static navigation mode results don't conclusively show that any receiver has superior sensitivity. However, the static position error results do show that the Magnavox GPS Engine is clearly more accurate than the other receivers tested. The superior accuracy of the Magnavox receiver in the static tests might be attributed to more filtering in the receiver. It should also be noted that the Magnavox 6400 unit was the only receiver that did not navigate for some time period during the static test.

### *3.3.3.2 Dynamic test results*

The dynamic test data was obtained by driving the instrumented van over different types of terrain. The various routes were chosen so that the GPS receivers would be subjected to a wide variety of obstructions. These include buildings, underpasses, signs, and foliage for the city driving. Rock cliffs and foliage were typical for the mountain and canyon driving. Large trucks, underpasses, highway signs, buildings, foliage, as well as small canyons were found on the interstate and rural highway driving routes.

The results of the dynamic testing are presented in Figures 3.14 through 3.18. The dynamic test results as well as a discussion of the results appear on the following pages.

Several noticeable differences exist between Figure 3.13 (static navigation mode) and Figure 3.14. The Magnavox 6400 unit is not navigating a significant portion of the time. This is because sequencing receivers do not perform as well in dynamic environments with periodic obstructions. The Magellan GPS receiver also navigated in 2D-mode a larger percentage of the time compared with the other receivers. The Rockwell unit was able to navigate in 3D-mode the largest percentage of the time. Although this is also a result of the Rockwell DOP setting discussed in the previous section, it does seem to indicate that the Rockwell receiver might have slightly better sensitivity (Rockwell claims this is one of the receiver's selling points). The Magnavox GPS Engine also did not navigate a small percentage of the time. This can be attributed to the small period of time when the receiver was obstructed and the other receivers (which also were obstructed) might not have been outputting data (caused by asynchronous sampling).

The Mountain Driving Test actually yielded less obstructions than the City Driving Test. This might be a result of better satellite geometries during the test period. However, the Magnavox 6400 unit once again did not navigate for a significant portion of the time. The Magellan receiver navigated in 2D-mode a significant portion of the time, but this can be attributed to some degree to the stricter DOP limits. The performance of the Rockwell NavCore V, Trimble Placer, and Magnavox GPS Engine are comparable.

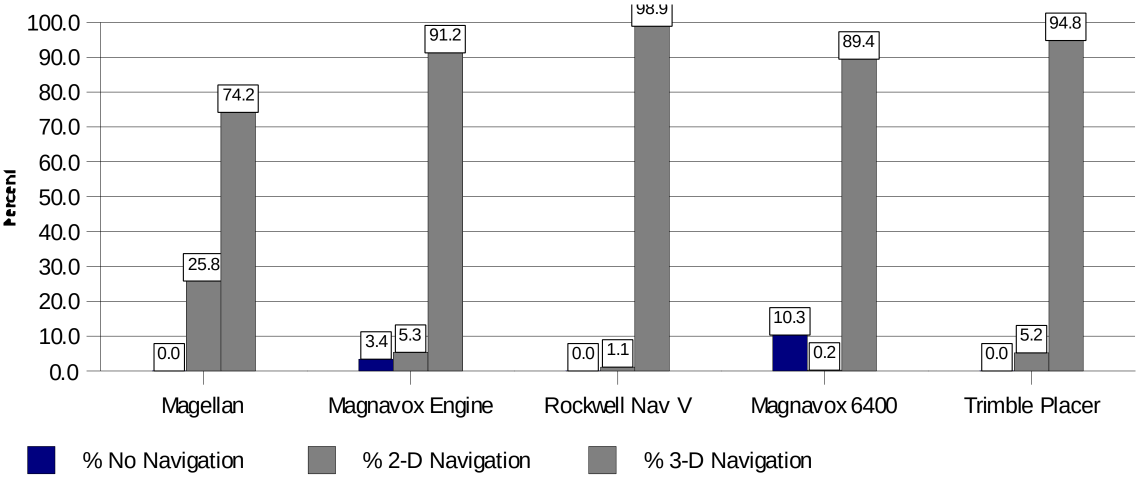


**Figure 3.14:** Summary of City Driving Results. (Adapted from [Byrne, 1993]).

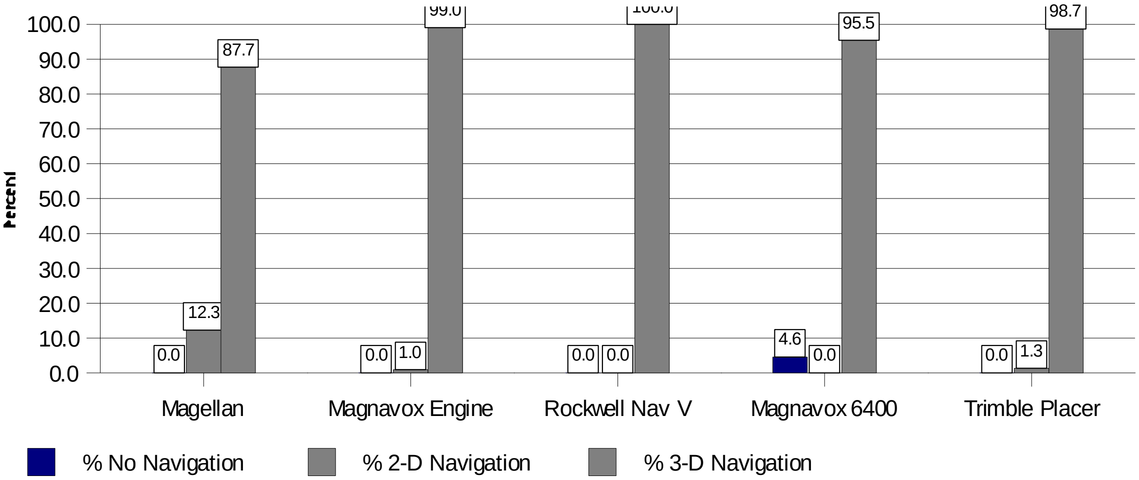


**Figure 3.15:** Summary of mountain driving results. (Adapted from [Byrne, 1993]).

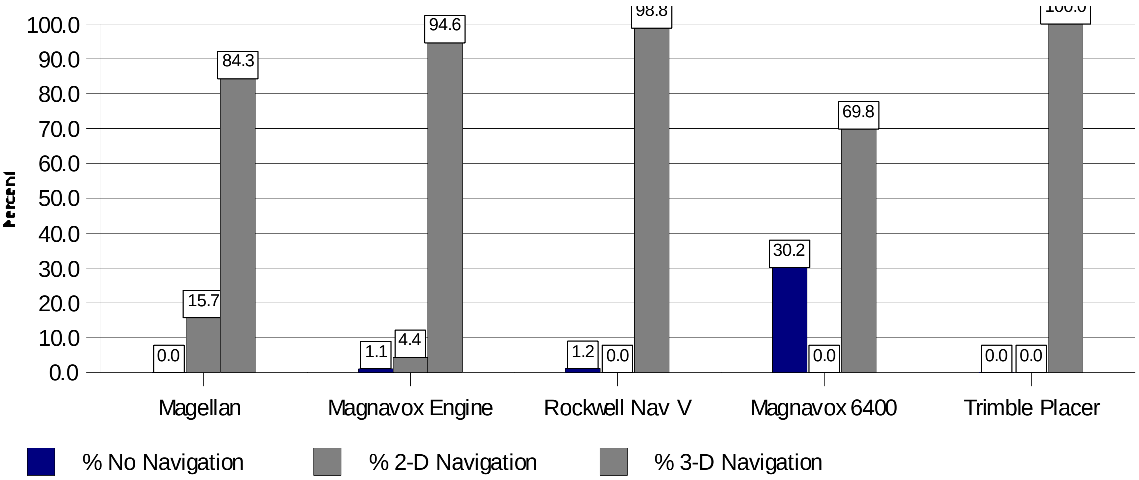


**Figure 3.16:** Summary of Canyon Driving Results. (Adapted from [Byrne, 1993]).

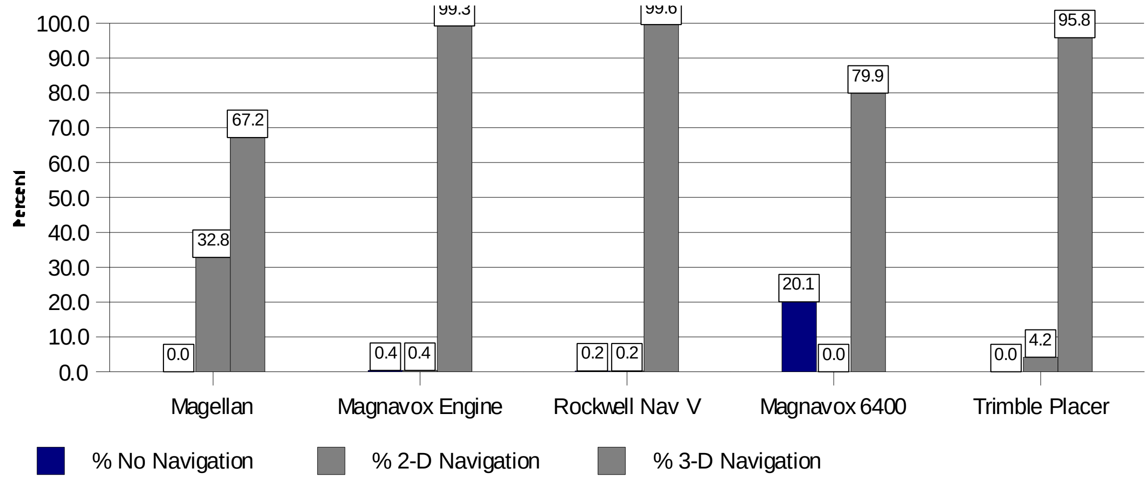


**Figure 3.17:** Summary of Interstate Highway Results. (Adapted from [Byrne, 1993]).

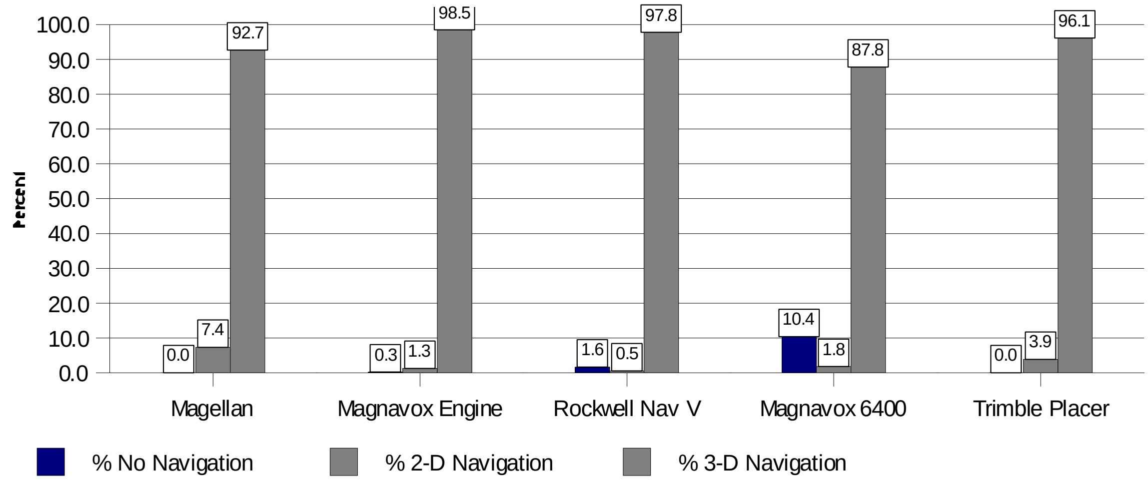


**Figure 3.18**. Summary of Rural Highway Results. (Adapted from [Byrne, 1993]).

The Canyon Driving Test exposed the GPS receivers to the most obstructions. The steep canyon walls and abundant foliage stopped the current receiver from navigating over 30 percent of the time. The Magnavox GPS Engine and Rockwell receiver were also not navigating a small percentage of the time. This particular test clearly shows the superiority of the newer receivers over the older sequencing receiver. Because the newer receivers are able to track extra satellites and recover more quickly from obstructions, they are better suited for operation in dynamic environments with periodic obstructions. The Trimble Placer and Rockwell receiver performed the best in this particular test, followed closely by the Magnavox GPS Engine.

During the Interstate Highway Driving tests, the Magnavox 6400 unit did not navigate over 20 percent of the time. This is consistent with the sometimes poor performance exhibited by the current navigation system. The other newer receivers did quite well, with the Trimble Placer, Magnavox GPS Engine, and Rockwell NavCore V exhibiting similar performance. Once again, the

Magellan unit navigated in 2D-mode a significant portion of the time. This can probably be attributed to the stricter DOP limits.

During the Rural Highway Driving test the Magnavox 6400 unit once again did not navigate a significant portion of the time. All of the newer receivers had similar performance results. The Magellan receiver navigated in 2D-mode considerably less in this test compared to the other dynamic tests.

### 3.3.3.3 Summary of test results

Both static and dynamic tests were used to compare the performance of the five different GPS receivers. The static test results showed that the Magnavox GPS Engine was the most accurate (for static situations). The other four receivers were slightly less accurate and exhibited similar static position error performance. The static navigation mode results did not differentiate the sensitivity of the various receivers significantly. The Magellan unit navigated in 2D-mode much more frequently than the other receivers, but some of this can be attributed to stricter DOP limits. However, the stricter DOP limits of the Magellan receiver and Trimble Placer did not yield better static position accuracies. All four of the newer GPS receivers obtained a first fix under one minute, which verifies the time to first-fix specifications stated by the manufacturers.

The dynamic tests were used to differentiate receiver sensitivity and the ability to recover quickly from periodic obstructions. As expected, the Magnavox 6400 unit did not perform very well in the dynamic testing. The Magnavox 6400 was unable to navigate for some period of each dynamic test. This was most noticeable in the Canyon route, where the receiver did not navigate over 30 percent of the time. The newer receivers performed much better in the dynamic testing, navigating almost all of the time. The Magnavox GPS Engine, Rockwell NavCore V, and Trimble Placer exhibited comparable receiver/antenna sensitivity during the dynamic testing based on the navigation mode data. The Magellan unit navigated in 2D-mode significantly more than the other receivers in the dynamic tests. Most of this can probably be attributed to a more stringent DOP requirement. It should also be noted that the Magellan receiver was the only receiver to navigate in 2D-mode or 3D-mode 100 percent of the time in all of the dynamic tests.

Overall, the four newer receivers performed significantly better than the Magnavox 6400 unit in the dynamic tests. In the static test, all of the receivers performed satisfactorily, but the Magnavox GPS Engine exhibited the most accurate position estimation. Recommendations on choosing a GPS receiver are outlined in the next section.

### 3.3.4 Recommendations

In order to discuss some of the integration issues involved with GPS receivers, a list of the problems encountered with the receivers tested is outlined in Section 3.3.4.1. The problems encountered with the Magnavox 6400 unit (there were several) are not listed because the Magnavox 6400 unit is not comparable to the newer receivers in performance.

Based on the problems experienced testing the GPS receivers as well as the requirements of the current application, a list of critical issues is outlined in Section 3.3.4.2.

One critical integration issue not mentioned in Section 3.3.4.2 is price. Almost any level of performance can be purchased, but at a significantly increased cost. This issue will be addressed further in the next section. Overall, the Magellan OEM Module, the Magnavox GPS Engine, Rockwell NavCore V, and Trimble Placer are good receivers. The Magnavox GPS Engine exhibited superior static position accuracy. During dynamic testing, all of the receivers were able to navigate a large percentage of the time, even in hilly wooded terrain. Based on the experimental results, other integration issues such as price, software flexibility, technical support, size, power, and differential capability are probably the most important factors to consider when choosing a GPS receiver.

### *3.3.4.1 Summary of problems encountered with the tested GPS receivers*

**Magellan OEM Module**

- No problems, unit functioned correctly out of the box. However, the current drain on the battery for the battery backed RAM seemed high. A 1-AmpHour 3.6-Volt Lithium battery only lasted a few months.
- The binary position packet was used because of the increased position resolution. Sometimes the receiver outputs a garbage binary packet (about I percent of the time).

**Magnavox GPS Engine**

- The first unit received was a pre-production unit. It had a difficult time tracking satellites. On one occasion it took over 24 hours to obtain a first fix. This receiver was returned to Magnavox. Magnavox claimed that upgrading the software fixed the problem. However, the EEPROM failed when trying to load the oscillator parameters. A new production board was shipped and it functioned flawlessly out of the box.
- The RF connector for the Magnavox GPS Engine was also difficult to obtain. The suppliers recommended in the back of the GPS Engine Integration Guide have large minimum orders. A sample connector was finally requested. It never arrived and a second sample had to be requested.

**Rockwell NavCore V**

- The first Rockwell receiver functioned for a while, and then began outputting garbage at 600 baud (9600 baud is the only selectable baud rate). Rockwell claims that a Gallium Arsenide IC that counts down a clock signal was failing because of contamination from the plastic package of the IC (suppliers fault). This Rockwell unit was returned for repair under warranty.
- The second Rockwell unit tested output data but did not navigate. Power was applied to the unit with reverse polarity (Sandia's fault) and an internal rectifier bridge allowed the unit to function, but not properly. Applying power in the correct manner (positive on the outside contact) fixed the problem.

**Trimble Placer**

- No problems, unit functioned correctly out of the box.

### *3.3.4.2 Summary of critical integration issues*

**Flexible software interface** Having the flexibility to control the data output by the receiver is important. This includes serial data format (TTL, RS-232, RS-422). baud rates, and packet data rates. It is desirable to have the receiver output position data at fixed data rate, that is user selectable. It is also desirable to be able to request other data packets when needed. All of the receivers with the exception of the Rockwell unit were fairly flexible. The Rockwell unit on the other hand outputs position data at a fixed 1-Hz rate and fixed baud rate of 9600 baud.

The format of the data packets is also important. ASCII formats are easier to work with because the raw data can be stored and then analyzed visually. The Rockwell unit uses an IEEE floating point format. Although Binary data formats and the Rockwell format might be more efficient, it is much easier to troubleshoot a problem when the data docs not have to be post processed just to take a quick look.

**Differential capability** The capability to receive differential corrections is important if increased accuracy is desired. Although a near-term fielded system might not use differential corrections, the availability of subscriber networks that broadcast differential corrections in the future will probably make this a likely upgrade.

**Time to first fix** A fast time-to-first-fix is important. However, all newer receivers usually advertise a first fix in under one minute when the receiver knows its approximate position. The difference between a 30-second first fix and a one-minute first fix is probably not that important. This parameter also affects how quickly the receiver can reacquire satellites after blockages.

**Memory back up** Different manufacturers use different approaches for providing power to back up the static memory (which stores the last location, almanac, ephemeris, and receiver parameters) when the receiver is powered down. These include an internal lithium battery, an external voltage supplied by the integrator, and a large capacitor. The large capacitor has the advantage of never needing replacement. This approach is taken on the Rockwell NavCore V. However, the capacitor charge can only last for several weeks. An internal lithium battery can last for several years, but will eventually need replacement. An external voltage supplied by the integrator can come from a number of sources, but must be taken into account when doing the system design.

**Size, Power, and packaging** Low power consumption and small size are advantageous for vehicular applications. Some manufacturers also offer the antenna and receiver integrated into a single package. This has some advantages, but limits antenna choices.

**Active/passive antenna** Active antennas with built-in amplifiers allow longer cable runs to the receiver. Passive antennas require no power but can not be used with longer cabling because of losses.

**Cable length and number of connectors** The losses in the cabling and connectors must be taken into account when designing the cabling and choosing the appropriate antenna.

**Receiver/antenna sensitivity** Increased receiver/antenna sensitivity will reduce the affects of foliage and other obstructions. The sensitivity is affected by the receiver, the cabling, as well as the antenna used.

**Position accuracy** Both static and dynamic position accuracy are important. However, the effects of SA reduce the accuracy of all receivers significantly. Differential accuracy will become an important parameter in the future.

**Technical Support** Good technical support, including quick turn around times for repairs, is very important. Quick turn around for failed units can also be accomplished by keeping spares in stock.

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