Integrity Network Simulator

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Abstract: This paper describes a simulation tool, which will be used to analyze and optimize integrity networks for GPS and Glonass. This simulator includes models for: the signals from the GPS, Glonass and geostationary satellites; the user equipment; the integrity monitors; the integrity network control sites; and the communication links between the monitors and control sites. The paper will describe the simulator and present preliminary results.

1 Introduction

In time, the Global Positioning System (GPS) and Glonass will be used for a wide variety of civilian aircraft applications. Aircraft use of GPS and Glonass raises significant concern with respect to the integrity and availability of these satellite systems. A radionavigation system with integrity notifies its users that position errors are greater than a prespecified level. Clearly, radionavigation systems used by aviators must have integrity, and the integrity requirement depends on whether the system is sole means or supplemental.

A system which is sole means for a particular phase of flight can be used without any backup system during that phase. In contrast, a supplemental system must be backed up by a sole means system. If a radionavigation system is supplemental, then it must detect signal failures with very high reliability. However, the time availability of a position fix is not a critical concern, because a backup system is available. In contrast, a sole means radionavigation system must be able to isolate and replace all faulty signals. Moreover, it must be able to deliver these fault free position fixes with a time availability in excess of 0.99999.

In the summer of 1991, Special Committee 159 of the RTCA finished lengthy consideration of GPS as a supplemental system and approved a Minimum Operational Performance Standard (MOPS) for Airborne Supplemental Navigation Equipment Using the GPS. Late in the same summer, it formed a collection of working groups to develop MOPS for sole means use of GPS. These five working groups focus on various augmentations of GPS, because augmentation of some sort is required to achieve the demanding sole means requirements. Among these, one working group focuses on the GPS Integrity Channel (GIC) and Wide Area Differential GPS (WADGPS). The GIC is the subject of this paper.

The GPS Integrity Channel uses a ground network to identify faults in the satellite ranging signals, and then uplinks warnings to all users [1] [2] [3] [5] [7] [8]. It will be supported by an ultra-reliable network, which includes the following elements:

- multiple remote integrity monitors, to observe the GPS, Glonass and geostationary satellites. The monitors process the ranging signals and navigation messages from the navigation satellites, and send the reduced data to central control stations. They also are capable of making preliminary integrity decisions, which are also forwarded to the control stations.
- communication links from the monitors to the control sites. These can be dedicated land lines or satellite links.
- redundant control sites which collect information from the monitors. The control stations resolve monitor inconsistencies, form the integrity message, and uplink the GIC signal.
- geostationary host spacecraft for the broadcast of the integrity data to the users.

Taken together, the integrity monitors, the higher level sites, the links which connect them, and the broadcast satellites form the integrity network. The integrity data will be used by GPS and Glonass users to insure and improve the accuracy of position fixes derived from GPS and Glonass. First, the data will contain "use/don't use" flags to identify erratic or untrustworthy satellites. Second, the integrity data will contain coarse estimates of the pseudorange error size. The aircraft will use this latter data to determine whether the corresponding position error is too large for its current phase of flight. Integrity networks will be designed to serve specific regions, and they may be combined for global service.

The most advanced GIC concept to date is the geostationary overlay which is being developed by Inmarsat. Inmarsat will include a wideband navigation package on their third generation of satellites (Inmarsat-3) [5] [6] [3] [4]. This package would broadcast a spread spectrum signal very similar to the civilian signals from GPS and Glonass. This signal is called a geostationary overlay and could be received by slightly modified GPS and Glonass receivers. The geostationary overlay would serve two related purposes. First, it would provide an additional pseudorange measurement and would effectively augment the GPS and Glonass constellations. Second, the overlay's data stream would include GPS and Glonass integrity information.

Currently, the GIC and geostationary overlay concepts enjoy widespread acceptance and support. Therefore, critical engineering questions must now be addressed. For example, the monitor and control site algorithms must be designed and extensively tested. In particular, the division of labor between the monitor and control sites must be established. Additionally, the data link between the monitors and control sites must be studied and performance requirements established. The format and data rate of the integrity broadcast itself must be specified. The integrity network as a whole must be designed to provide reliable warnings with a delay which is operationally acceptable.

This paper describes an Integrity Network Simulator, which will help engineer the GIC. The simulator is shown in Figure 1, and consists of an executive program and a collection of separate executable modules. The executive is the primary user interface for setting up and running simulations. Through the executive, the user controls which module to execute, the execution order, and any control parameters. Up to 200 modules may be run from the executive, or any module may be run by itself from the DOS environment.

Each module requires one or more input files and produces one or more output files. The input files may be produced by the current string of module executions as controlled by the executive. Alternatively, the input files may be created by a past module run. This flexibility can greatly reduce execution time. For example, a number of different monitor configurations could be tested and compared based on a single simulation of the GPS and Glonass satellites.

The following sections briefly describe the space segment module, the receiver and trajectory modules, the monitor module, the communication link modules, the control site module, the navigation module, and the error analysis module. In addition, an example of simulation operation is developed throughout this paper. The example simulates an airborne GPS/GIC user near Miami. It places integrity monitors at Miami, Southbury and Frobisher Bay, and it includes a control site which can be colocated with any of the monitors. Throughout the simulation satellites 06, 08, 10, 13, 15, 18 and 21 are visible to the mobile user. All of these satellites are healthy except SV10, which suffers from a very high level of Selective Availability.

2 Space Segment Module

The space segment module generates satellite trajectories and clock offsets for all GPS, Glonass and any geostationary ranging satellites (such as Inmarsat-3). This module takes an almanac data file in the US Coast Guard BBS format as input, and an example entry from such an almanac is shown in Table 1. It produces a true satellite trajectory file from the almanac file. The space segment module also produces a broadcast satellite trajectory file, which differs from the true trajectory. The broadcast trajectory is computed from the almanac plus an ephemeris error file, which defines the error model.

```
****
ID:                           5
Health:                       0
Eccentricity:                 0
Time of Applicability(s):     0
Orbital Inclination(rad):     0.96
Rate of Right Ascen(r/s):     0
SQRT(A)   (m^1/2):            5157.5
Right Ascen at TOA(rad):      0.449
Argument of Perigee(rad):     0
Mean Anom(rad):               6.264
Af0(s):                       0
Af1(s/s):                     0
week:                         516
```

Table 1: An Almanac Entry for the 21 Satellite Optimized Constellation

The space segment module also produces a broadcast SV clock file using data in the almanac file, and it produces a true SV clock which differs

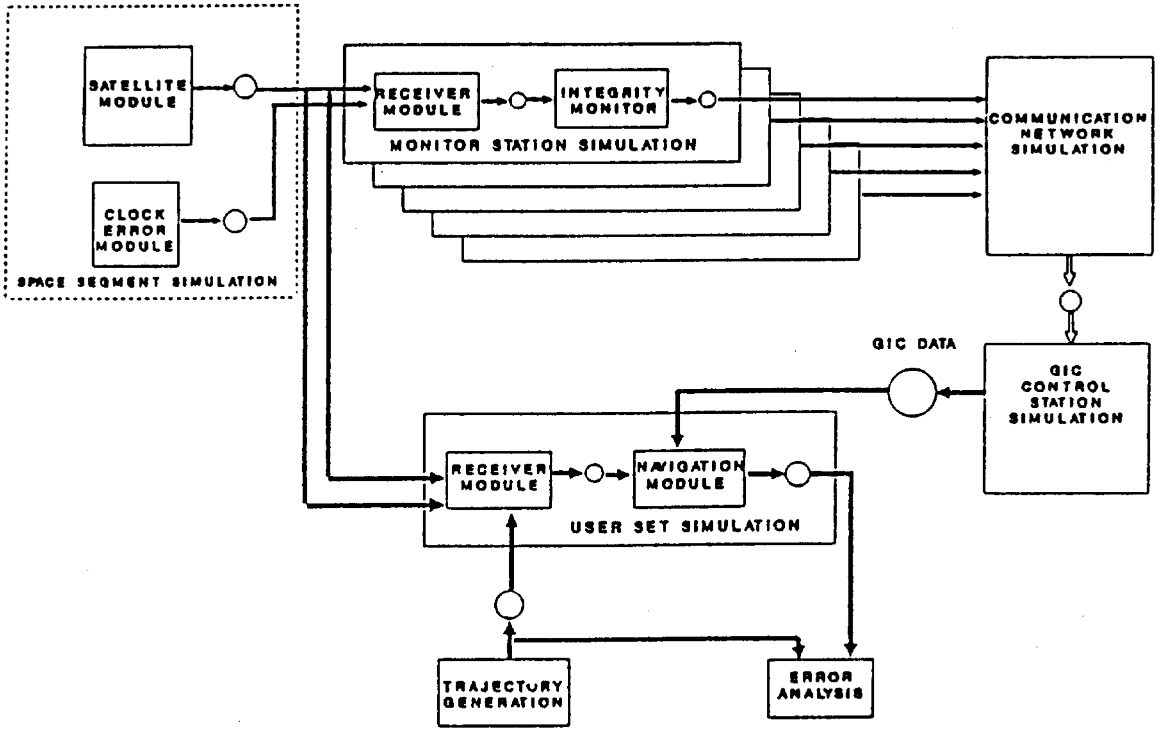

Figure 1: Integrity Network Simulator

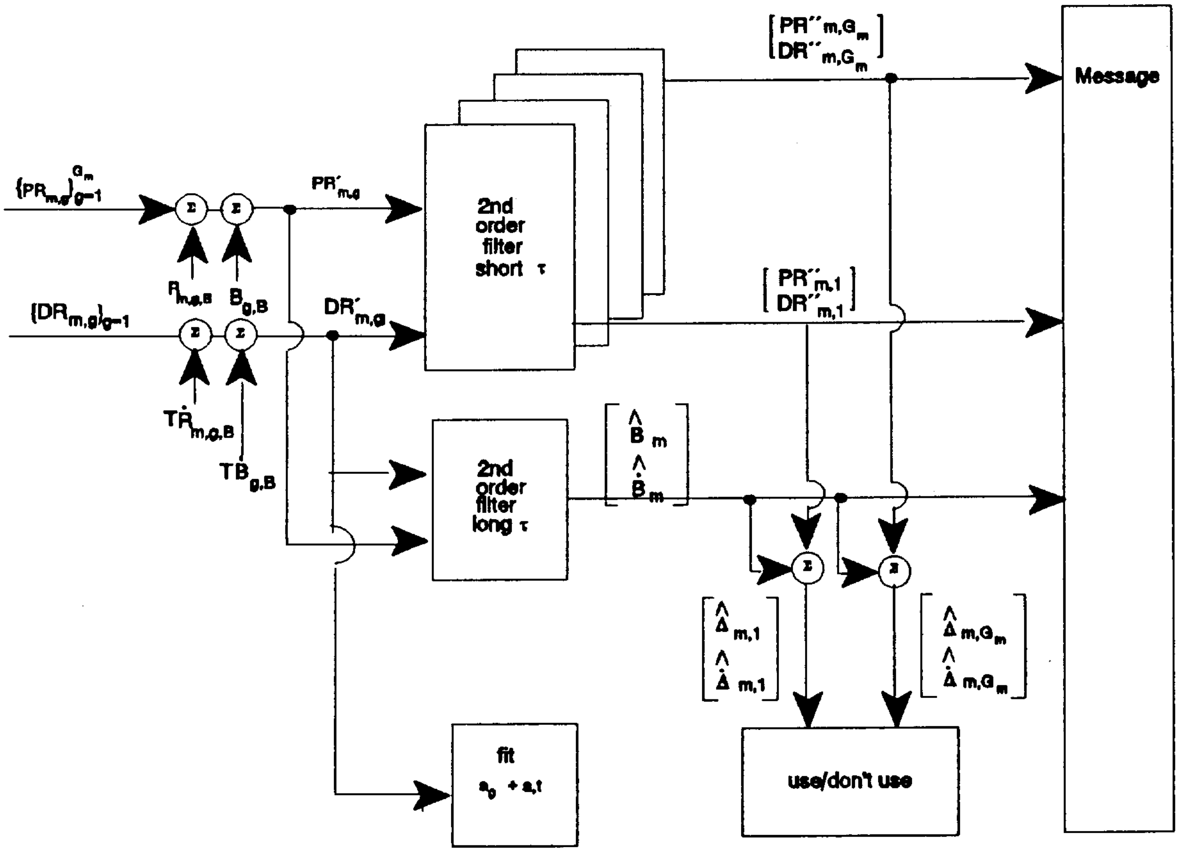

Figure 2: Integrity Monitor Block Diagram

from the broadcast SV clock file. The latter is produced using the almanac data plus a clock error model. A maximum of 64 satellites can be simulated by the space segment module.

3 Receiver and Trajectory Modules

The receiver module generates pseudorange (PR) and deltarange (DR) measurements for all selected satellites. The pseudoranges are equal to the true ranges plus the satellite clock offsets. The measured pseudoranges are equal to the true pseudoranges plus receiver noise, ionospheric errors, and tropospheric errors. The observed delta-ranges are the averaged Doppler frequencies from the receiver's frequency or phase locked loops. As such, they are proportional to the first derivative of the corresponding pseudorange. The delta-range measurements also suffer from observation noise, but the standard deviation of this noise is very small (approximately 1 centimeter per second).

To generate the PR and DR measurements, the receiver module requires the following files as input: true SV position files, true SV clock offset files, vehicle trajectory file, the receiver error model file, and the receiver parameter file. The receiver error model file contains statistics for the receiver noise, the receiver clock (bias, frequency offset, and white noise), tropospheric noise, and the ionospheric model. The receiver parameter file describes the antenna mask angle as a function of azimuth, the terrain mask as a function of azimuth, the number of satellite channels available, and the SV selection algorithm (maximum HDOP, or all in view).

The receiver module is used to simulate the airborne user receiver as well as the receivers which are colocated with each of the ground monitors. In both cases, the true location of the receiver is required. The true location of the mobile user is generated by the trajectory module and stored in a trajectory file, which is input to the receiver module. The monitor location is fixed and so no trajectory file is required to generate the PR and DR measurements for the monitor.

In addition to the PR and DR measurements, the receiver generates an SV visibility file. The SV visibility file contains the azimuth and elevation angles to all selected SVs, as well as GDOP, PDOP, HDOP, VDOP and TDOP.

4 Integrity Monitors

The integrity monitors process pseudorange and delta-range measurements from a colocated satellite ranging receivers. They then report their findings to the control sites. The monitor module is shown in Figure 1, and receives the following inputs: a receiver measurement file, a broadcast SV position file, and a broadcast SV clock file.

The signal processing performed by the monitors is shown in Figure 2. The monitors use their known location and the broadcast data to compute the nominal SV ranges and SV range rates. Then as shown in Figure 2, the monitors subtract the nominal SV ranges, SV range rates, SV clock offsets and SV clock rates from the PR and DR measurements.

The reduced observations (PR' and DR') are processed by a collection of second order Kalman filters to estimate the pseudorange errors and error rates. The estimated pseudorange error and error rate are denoted $\Delta_{m,g}$ and $\dot{\Delta}_{m,g}$ respectively, where the subscript m denotes the m^{th} monitor and the subscript g denotes the g^{th} satellite.

One second order Kalman filter is used for each satellite to reduce the random observation noise. These filters have short time constants, and as such they do not remove Selective Availability. Instead, they produce smoothed estimates of the pseudoranges ($PR''_{m,g}$) and deltaranges ($DR''_{m,g}$).

An additional 2 state Kalman filter is used to estimate the unknown monitor clock offset and clock rate. This single filter has a long time constant to reduce observation noise and Selective Availability. Additionally, it averages together the observations from all of the satellites, because the monitor clock is common to all the measurements from all of the SVs. In this way, this filter is able to further reduce the impact of SA on the accuracy of the monitor clock estimates.

Figures 3 and 4 show $PR''_{m,g}$ and $DR''_{m,g}$ for all satellites in view of the integrity monitor at Miami in our example simulation. The figures show that all satellites except SV10 are healthy. SV10 suffers from a high level of Selective Availability, which as described later, results in a sequence of "don't use" messages. Nonetheless, the clock and clock rate estimates are quite accurate, because of the averaging performed by the monitor clock filter.

As shown in Figure 2, the clock estimates are subtracted from the smoothed pseudrange and deltarange estimates to provide estimates of $\Delta_{m,g}$ and $\dot{\Delta}_{m,g}$. Then, each monitor generates local "don't use" messages for satellites which are behaving erratically. The formation of this emergency

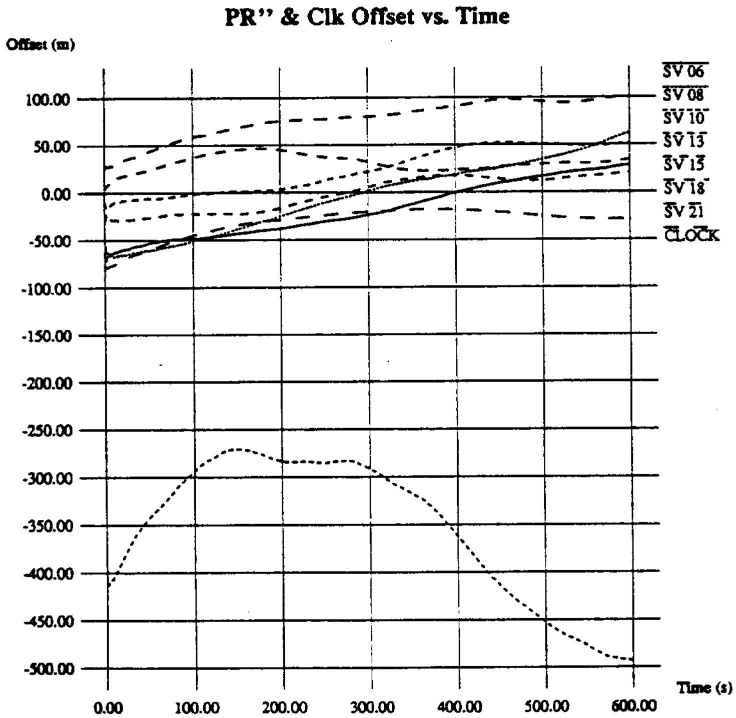

Figure 3: Smoothed Pseudorange and Monitor Clock Estimates at the Miami Monitor

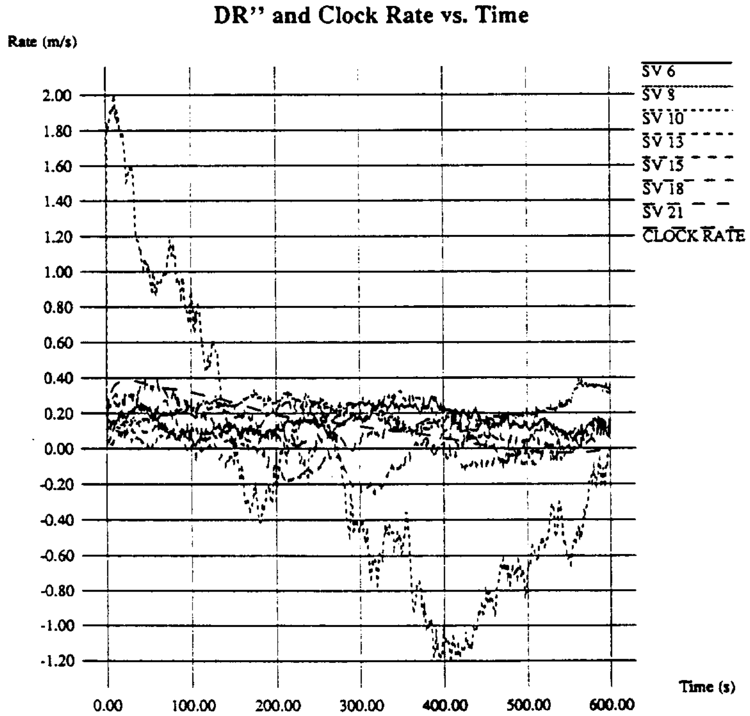

Figure 4: Smoothed Deltarange and Monitor Clock Rate Estimates at the Miami Monitor

message is based on the estimates of $\Delta_{m,g}$ and $\dot{\Delta}_{m,g}$ and possibly $\ddot{\Delta}_{m,g}$. Indeed, an estimate of $\ddot{\Delta}_{m,g}$ comes from fitting the function $a_0 + a_1 t$ to the last 3 to 5 delta-range measurements.

The monitor uses this data to determine if any of the satellites are too erratic to be used. Most simply, the monitor will send a "don't use" message if any of the following conditions occur:

$$\begin{aligned} |\widehat{\Delta}_{m,g}| &> 250 \text{ to } 300\ m \\ |\widehat{\dot{\Delta}}_{m,g}| &> 1\ m/sec \\ |\widehat{\ddot{\Delta}}_{m,g}| &> 15\ mm/sec^2 \end{aligned}$$

The monitor has a second "don't use" criterion, which is based on the estimated time to threshold. This time ($\tau_{m,g}$) is the estimated time at which the satellite range error will grow to exceed some threshold. The time to threshold can be based on using $\widehat{\Delta}_{m,g}$ and $\widehat{\dot{\Delta}}_{m,g}$ alone or it can include a quadratic term proportional to $\widehat{\ddot{\Delta}}_{m,g}$. In either case, if the time to threshold is less than 20 or 30 seconds then the monitor will issue a "don't use" message.

Each monitor outputs a file which contains the data communicated from the monitor to the control stations. Our simulation assumes that there are three message types. Type 1 messages are emergency messages which are sent when a satellite should not be used. Type 2 messages contain the monitor's estimate of its own clock and clock rate. Type 3 messages contain the smoothed pseudorange and deltarange estimates for a given satellite as well as a health flag for the satellite.

Most of the time, Type 3 messages are sent until data for all satellites in view have been sent to the Control Sites. If a satellite becomes erratic, then a Type 1 message will be sent immediately after the current Type 3 message. In other words, if there is an emergency, then a Type 1 message will interrupt the string of Type 3 messages. If there is no emergency, then a Type 1 and Type 2 message will be sent after data for all satellites has been sent.

As shown in Table 2, a file is created by all the messages flowing from the monitors to the control sites. Each message creates a new line in the file. Every message updates the first column of the file, which gives the time at which the message is complete. This message finish time is equal to the sum of three terms: the maximum of the current time and the finish time of the last message; the transmission time; and the propagation time. The transmission time is equal to the number of bits in the message divided by the bit rate of the link. The bit rate (bps) and the propagation time for each link are user parameters.

The fields which describe the source of the data (Mon), and whether or not a given satellite is erratic are updated by Type 1 messages. The fields for $\widehat{B}_m$, $\widehat{\dot{B}}_m$, and G_m are updated by Type 2 messages only. The fields for satellite PRN (g), $PR''_{m,g}$ and $DR''_{m,g}$ are updated by Type 3 messages only. Fields which are not updated by a given message contain a vertical line.

As shown in Table 2, SV10 is flagged as unhealthy by the monitor at Miami.

5 Communication Module

The communication module simulates the link between the monitors and the control sites, and it simulates the link between the control sites and the mobile user. In both cases, the destination will not receive every message successfully. In fact, the probability of an unsuccessful transmission is modelled as:

$$P_M = 1 - (1 - Pr(\epsilon))^{[\text{numbits}]}$$

In this equation, P_M is the probability of message failure, and [numbits] is the number of bits in the message. $Pr(\epsilon)$ is the probability of bit error, and is a user parameter. The communication module generates a uniform random number ($U[0,1)$) for every message from the monitors. If this number is less than or equal to P_M, then the message cannot be used, and the destination must wait for the next message in the file.

The action of the communication module is shown in the last column of Table 2, where a "yes" is appended if the message can be received, and a "no" is appended if the message is lost.

6 Control Sites

A control site is block diagrammed in Figure 5, and has the following functions:

1. resolve monitor inconsistencies
2. form the integrity message, and uplink the signal to the geostationary satellites.
3. control the time and frequency of the spread spectrum overlay signal

Functions 1 and 2 will be discussed in this section. Function 3 is simulated as part of space segment module.

```
-------------------------------------------------------------------------------
MONITOR #1
-------------------------------------------------------------------------------
Simulation Start Time: 00:30:00.00   Simulation End Time: 00:40:00.00
Simulation Start Date: 09/07/91      Simulation End Date: 09/07/91
Start GPS Time:  455400.00           End GPS Time:  456000.00
Start GPS Week:  604                 End GPS Week:  604
Simulation Step Time: 00:00:01.00    Local UTC difference: 6
Append Flag: 0                       Display Flag: 1

Receiver Measurement File: RCVR1.MSR
Broadcast SV Position File: BRDCST.POS
Broadcast Clock Offset File: BRDCST.CLK
Mon-CS Message File: MON01.CS

Finish       Mon   Bm     BmHat   Gm   PRN   Err1   Err2   PR''m,g   DR''m,g   Comm
Time               m       m/s         g                      m        m/s     Link
00:30:00.37  01    |        |     07   06     no     no       -62      0.00     yes
00:30:00.49  01    |        |     07   08     no     no       -68      0.00     yes
00:30:00.62  01    |        |     07   10     yes    yes     -408      0.00     yes
00:30:00.74  01    |        |     07   13     no     no       -10      0.00     yes
00:30:00.86  01    |        |     07   15     no     no       -24      0.00     yes
00:30:00.98  01    |        |     07   18     no     no         8      0.00     yes
00:30:01.10  01    |        |     07   21     no     no        24      0.00     yes
00:30:01.22  01   -76     0.00    07    |      |      |         |         |      yes
00:30:01.37  01    |        |     07   06     no     no       -56      0.14     yes
```

Table 2: File Which Contains Messages From the Monitor to the Control Site

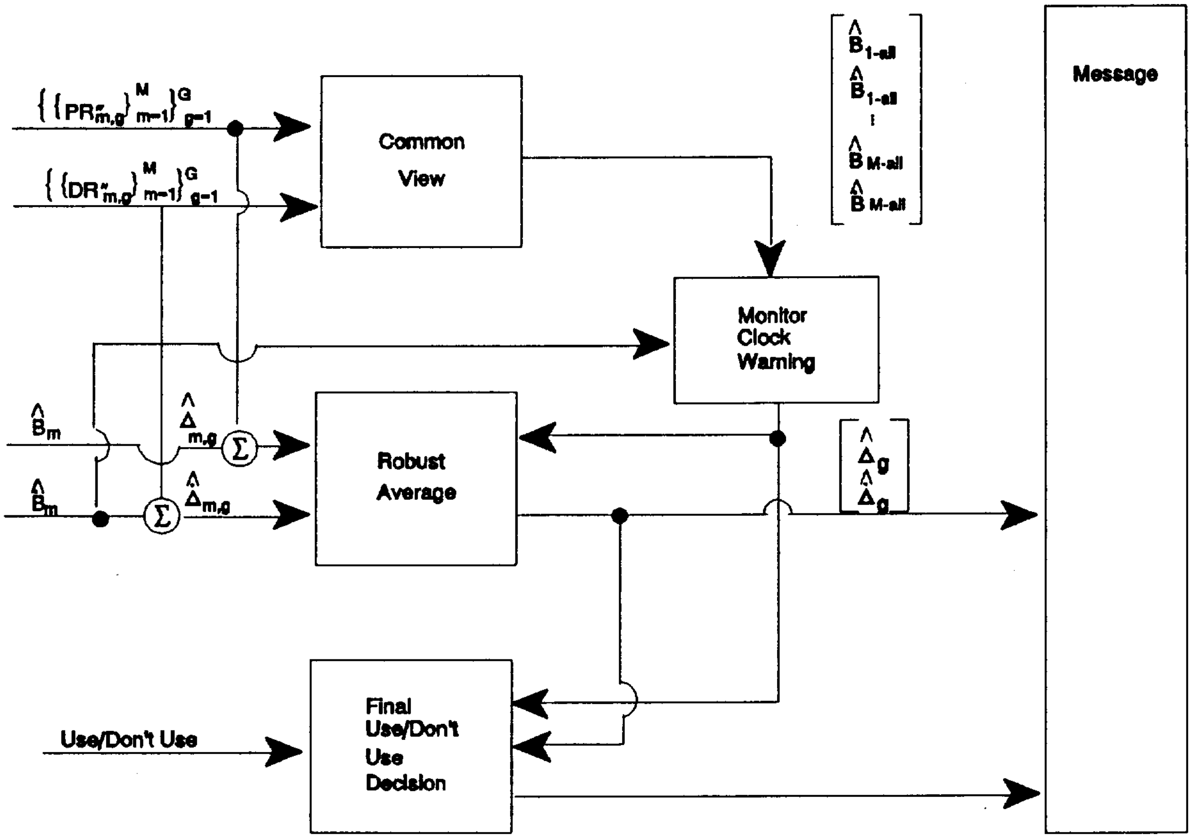

Figure 5: Control Site Block Diagram

As shown in Figure 5, the control station uses common view time transfer techniques to estimate the offset and offset rate of all monitor clocks relative to a set of "paper clocks". The estimated offset rate is used to help resolve inconsistencies between monitors. The control site has a better estimate of the performance of the monitor clocks, because the time constant of the common-view control-site estimates is much smaller than the time constants used at the monitors themselves. This follows because the control sites can use common view to cancel out the effect of satellite ephemeris and clock errors, whereas the monitors must average the data over relatively long periods. Consequently, the control site would be able to pick up monitor clock problems (large accelerations) before the monitors could.

As shown in Figure 5, the control site uses robust averaging to estimate the pseudorange errors and error rates. For each satellite, the control sites will form a simple average as follows:

$$\widehat{\Delta}_g = \frac{1}{M_g} \sum_{m=1}^{M_g} \widehat{\Delta}_{m,g} \qquad (1)$$

$$\widehat{\dot{\Delta}}_g = \frac{1}{M_g} \sum_{m=1}^{M_g} \widehat{\dot{\Delta}}_{m,g} \qquad (2)$$

The control sites will also compute the standard deviations of these estimates (σ_{Δ_g} and $\sigma_{\dot{\Delta}_g}$).

In general, the averages shown in equation 1 are broadcast to the users. However, the data from monitor m is excluded from a second and final computation of the averages if any of the following conditions hold:

- $|(\widehat{\Delta}_{m,g} - \widehat{\Delta}_g)|$ is large relative to σ_{Δ_g}
- $|(\widehat{\dot{\Delta}}_{m,g} - \widehat{\dot{\Delta}}_g)|$ is large relative to $\sigma_{\dot{\Delta}_g}$
- $|\widehat{\dot{B}}_m - \widehat{\dot{B}}_{m-all}|$ is large

In this way, the control site estimates of the pseudorange errors and error rates are "robust".

The monitors identify erratic satellites and send those determinations to the control sites, but the control sites make the final decision with regard to the useability of a satellite. A number of algorithms are possible. For example, a "Boolean Or" algorithm would be very simple. In this case, if any of the monitors identify a satellite as faulty, then the control site broadcasts a "don't use" message. Alternatively, a "Majority Vote" algorithm would be equally simple.

At this time, our simulator realizes a "Modified Boolean Or" algorithm. The control site broadcasts a "don't use" message, if any of the monitors identify a satellite as erratic, and that monitor is thought to be reliable. The monitor reliability criteria are the same as those listed above for the robust average.

As shown in Table 3, a GIC file is created by all the messages broadcast from the control sites. Each message creates a new line in the file. The Table is based on a modified form of the GIC message design described in [4]. If a satellite should not be used, then the field will contain a "*". Note that SV10 is flagged as unhealthy in our example. If the satellite can be used, then the field will contain $\widehat{\Delta}_g$. In general, a single integrity message can only update a fraction of the satellites, but it can identify any of the satellites as being unhealthy. Fields which are not updated by a given message contain a vertical line.

The finish time field in the GIC file is updated by each message, and this computation is almost identical to the computation for the monitor to control site messsages. However, the transmission time is equal to twice the number of bits in the integrity message divided by the bit rate. This follows, because the frames which bear integrity messages are separated by frames which carry the navigation message for the geostationary satellites.

The GIC file is input to a Communication Module which simulates the link from the Control Sites to the mobile users. The Communication Module is described in Section 5.

7 Navigation and Error Modules

The navigation module computes the navigation solution for the mobile user. As part of this operation, it selects and deselects satellite in view depending on data in the GIC data file. The user module uses the GIC data and two criteria for deselecting satellites. First, it simply deselects satellites with a "don't use" message in the GIC data file. Second, it deselects satellites if their pseudorange error estimate is greater than a specified threshold. In this latter case, the threshold can be fixed, or it can depend on the current horizontal dilution of precision.

Next, the user module computes the navigation solution based on data in the following files: the receiver measurement file (pseudoranges and deltaranges for the selected SVs), the broadcast SV position file, and the broadcast SV clock file. It uses

```
Simulation Start Time: 00:30:00.00   Simulation End Time: 00:40:00.00
Simulation Start Date: 07/09/91      Simulation End Date: 07/09/91
Start GPS Time:   88200.00           End GPS Time:   88800.00
Start GPS Week:  613                 End GPS Week:  613
Simulation Step Time: 00:00:01.00    Local UTC difference: 0
Append Flag: 1                       Display Flag: 1

Mon-CS_MESS_File: MON.CS
CS-User_MESS_File: CS.USR

SV ID             2      5      6      8     10     13     15     18     21      Comm Link
LocalTime/Pseudorange Error (m)
00:00:01.85       0      0      0      0      *      0      0      0      0      yes
00:00:02.85      50    100     25      0   -350     75     50     75    100      yes
00:00:03.85      50     75     25      0      *     75     50     75    100      yes
00:00:04.85      50    100     25     25      *     75     50     75    100      yes
00:00:05.85      50     75     25     25      *     75     50     75    100      yes
00:00:06.85      50    100     25      0      *     75     50     75    100      yes
00:00:07.85      50    100     25      0      *     75     50    100    100      yes
00:00:08.85      50     75     25      0      *     75     50    100    100      yes
00:00:09.85      50    100     25      0      *     75     50    100    100      yes
00:00:10.85      50    100     25      0      *     75     50     75    100      yes
00:00:11.85      50    100     25      0      *     75     50     75    100      yes
00:00:12.85      50    100     25      0      *     75     50     75    100      yes
00:00:13.85      50     75      0      0      *     75     50     75    100      yes
00:00:14.85      50    100     25      0      *     75     50    100    100      yes
00:00:15.85      50    100      0      0      *     50     50    100    100      yes
00:00:16.85      50    100     25      0      *     75     50    100    100      yes
00:00:17.85      50    100     25      0      *     75     50    100    100      yes
00:00:18.85      50    100      0      0      *     50     50    100    100      yes
00:00:19.85      50    100     25      0      *     50     50    100    100      yes
```

Table 3: File Which Contains Messages From the Control Site to the Mobile User

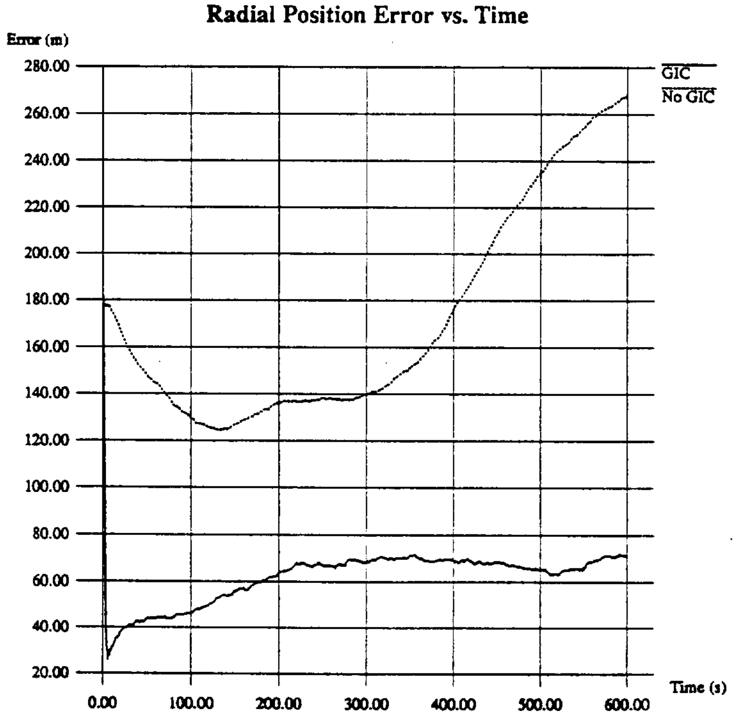

Figure 6: Radial Position Error Versus Time. The monitor uses a pseudorange error threshold of 250 meters and a deltarange threshold of 1 m/sec. However, it does not use a pseudorange acceleration or time to threshold criterion.

a Kalman filter to estimate user position, and the initial Kalman state estimates and covariances are stored in a receiver parameter file.

The Kalman filter includes up to 11 states: three dimensional position, velocity and acceleration, as well as clock offset and rate. If any of the initial covariances are set to zero, then the simulation removes that state from the filter. If clock rate and velocity states are not included, then the filter will not process the *DR* measurements.

The error analysis module analyzes the performance of the integrity channel. The parameters used for evaluation are the position error, the service outage count, the false alarm count and the missed detection count. The position error is the difference between the navigation solution and the true vehicle position from the trajectory module. A service outage occurs when the current HDOP is too large, or the number of satellites in view of the user is too small. A false alarm occurs if there is no large position error, but the GIC deselects a satellite and a service outage or a large position error occurs. A missed detection occurs if a large position error occurs and there is no GIC warning.

8 Simulation Example

The error module produced Figures 6 and 7 for our example simulation. Recall that our example places integrity monitors at Miami, Southbury, and Frobisher Bay, Canada; and a single control site at any of these locations. The mobile user is near Miami, where satellites 6, 8, 10, 13, 15, 18 and 21 were visible throughout the simulation. As shown in Figures 3 and 4, all satellites enjoyed good health except SV10, which was troubled by both overly active Selective Availability.

Figures 6 and 7 show the corresponding radial position error versus time for the aircraft near Miami. In both figures, the dashed plot is the radial error if there is no GPS Integrity Channel, and the solid plot is the error with a GIC. The monitors use a pseudorange error threshold and a deltarange threshold (1 m/s), but do not use a pseudorange acceleration or a time to threshold criterion. In this particular simulation, the GIC data always yields a position error which is smaller or equal to the error without the GIC.

Figures 6 and 7 differ only because they use pseudorange error thresholds of 250 meters and 300 meters respectively. Consequently, SV10 is always flagged as unuseable in Figure 6, but in Figure 7 it is flagged as useable from 50 to 320 seconds. The user in Figure 7 includes SV10 in its navigation solution, because it reduces the HDOP from 1.30 to 1.00, and PDOP from 2.00 to 1.80. However, the pseudorange error is so large that the overall position error increases.

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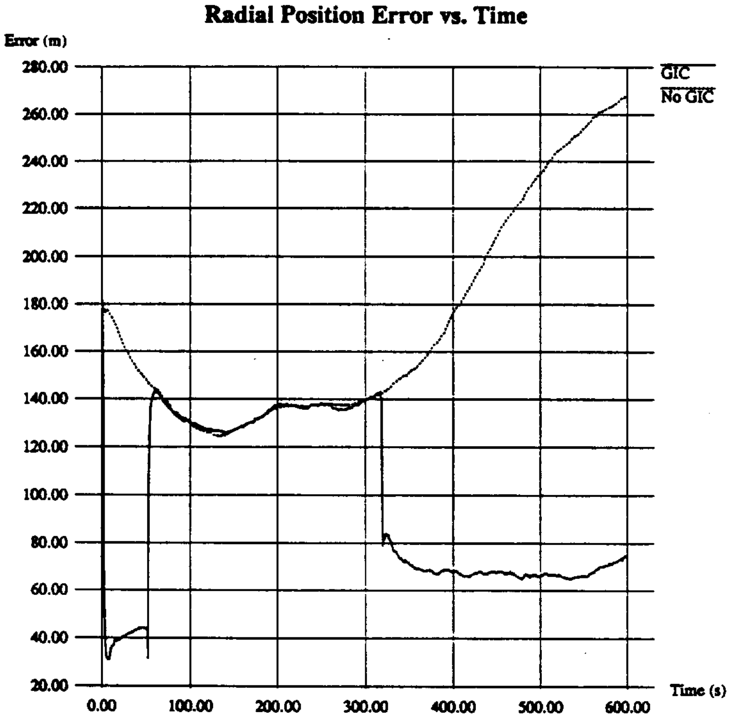

Figure 7: Radial Position Error Versus Time. The monitor uses a pseudorange error threshold of 300 meters and a deltarange threshold of 1 m/sec. However, it does not use a pseudorange acceleration or time to threshold criterion.