Wide Area and Local Area Augmentations: Design Tools and Error Modelling

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The development of augmentation services, such as EGNOS and WAAS, requires careful modelling and simulation before any deployment of equipment takes place. The ideal location of ground stations, and the potential impact of temporary failures of ground equipment, must be assessed in detail, to ensure that proposed service levels of accuracy and integrity are maintained at all times. The correct analysis of these parameters can only be achieved if the various wide area processing models, and their respective error propagation characteristics, are suitably simulated. This paper describes the use of a sophisticated and versatile suite of GNSS analysis tools in recent studies. It describes the incorporation of realistic error budgets for WADGPS and LADGPS corrections, and the potential use of different combinations of GPS, GLONASS, geostationary and other satellites in both GNSS-1 and GNSS-2.

1. INTRODUCTION. The concept of a civil-owned Global Navigation Satellite System (GNSS) has evolved due to the concerns of the civilian navigation community over the current satellite positioning systems, (i) the Global Positioning System (GPS) and (ii) the Russian Global Orbiting Navigation Satellite System (GLONASS). Neither of these provide continuous availability of accuracy and integrity, and both of them have been developed as military systems owned by single nations, with no absolute guarantee of continuity of service. In the case of GPS, the implementation of Selective Availability (SA) to degrade navigation accuracy means that full GPS accuracy is inaccessible to the civilian community.

It is now generally accepted that the task of finding a successor to GPS should follow an evolutionary process, culminating in the deployment of the new GNSS. The approach is, therefore, a gradual one, starting with the current GPS constellation and enhancing its potential, in stages, through augmentation with existing satellites, such as communication satellites in Geostationary Orbits (GEO), GLONASS, and with planned satellite constellations in Low or Medium Earth Orbits (LEO/MEO). Suggestions have also been made involving satellites in Inclined Geosynchronous Orbits (IGSO) and in Highly Elliptical Orbits (HEO).

The process of GNSS constellation design can be divided into two parts. First, it is possible to design a new configuration of satellites, given specific criteria which it must satisfy. Secondly, it is possible to analyse a given constellation, either resulting from the design process, or based on current satellites, to assess the degree to which it meets the specified requirements. A thorough description of the basic theoretical principles of the design of optimal satellite orbits, in terms of satellite availability, coverage, accuracy and integrity, as implemented in the IESSG design software, is given in this paper. As a demonstration of the analysis principles, a number of GNSS constellations have been tested. The scenarios tested include the full GPS constellation, GPS plus four Geostationary (GEO) satellites (the planned geostationary satellites of Inmarsat III), and GPS plus GLONASS.

2. COVERAGE AND ACCURACY. The navigation potential of any satellite constellation may be analysed on the basis of the computation of an indicator of positional accuracy. These quality measures typically express the horizontal or vertical components of accuracy. They are computed from two factors; firstly, the Position Dilution of Precision (PDOP); and secondly, the error budget of the range measurements. This approach enables the purely geometrical aspects (PDOP) to be separated from the accuracy of the measurements. As a result, any improvements in the ranging accuracy of a system, through some augmentation, may be accommodated by simply changing the appropriate error budget value and re-computing the positional accuracy measures. In this paper PDOP and the range error budget will be considered separately.

2.1. *Position dilution of precision*. In this analysis, the 'maximum PDOP' approach is used, where the entire globe is divided into as many grid cells as is practical and PDOP values are computed at every point at regular intervals for a period of 24 hours. In the following analyses, a time interval of 10 minutes is used. This is a compromise between the accuracy of the results, and the time required to compute the results. It is possible that spikes in the PDOP values will be missed by a time interval of 10 minutes. The maximum PDOP value at every point is then recorded to represent the worst case scenario. This technique is superior to the so-called 'snapshot' approach as it takes care of both temporal and spatial characteristics of the system. This approach enables a direct comparison of the navigation potential of any two candidate satellite navigation systems for the entire globe over 24 hours.

The following analysis of PDOP is divided into two parts – namely, the current GPS constellation, and the GPS augmentations representing GNSS-1. Analysis has shown that there are four or more satellites visible anywhere on the globe for 100 percent of the time, for the constellations investigated. However, this does not mean that the constellation is 'available' for navigation purposes for 100 percent of the time. To be available for navigation, the constellation must provide sufficient precision (DOP values) and sufficient integrity (capability to perform – Receiver Autonomous Integrity Monitoring (RAIM). The following figures illustrate the global coverage of the tested constellations, based purely on the criterion of PDOP. They are all based on the same grey scale for easy visual comparison.

Figure 1 shows the maximum PDOP value contour plot of the entire globe taken over 24 hours for the 24 GPS satellite constellation. It is evident from the plot that the high latitude regions suffer more than the equatorial and mid-latitude areas. Figures 2 and 3 represent the results of the GPS constellation augmented with four geostationary communications satellites and with 24 GLONASS satellites respectively. The result of augmenting GPS with four

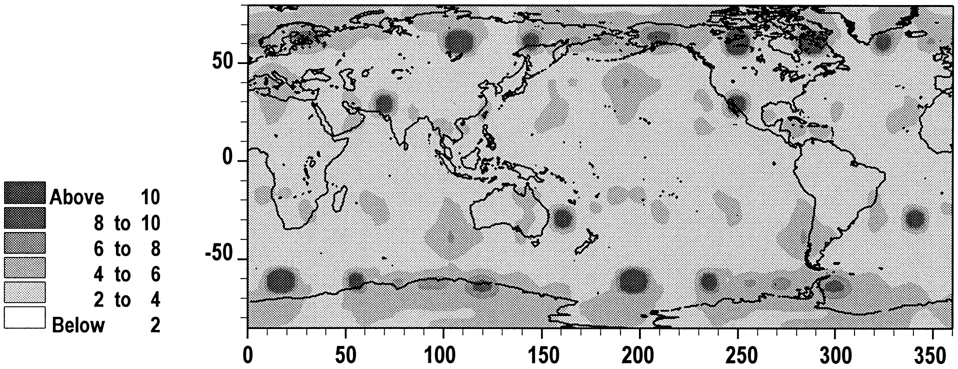

Fig. 1. Maximum PDOP analysis for 24 GPS satellites

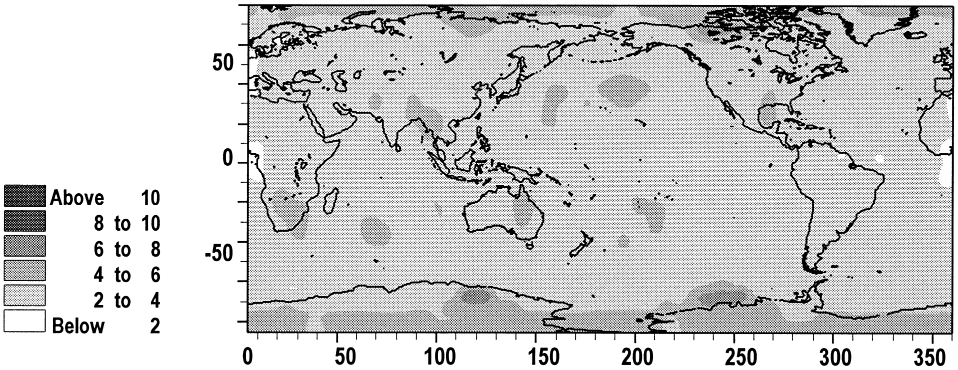

Fig. 2. Maximum PDOP analysis for 24 GPS+4 GEO satellites

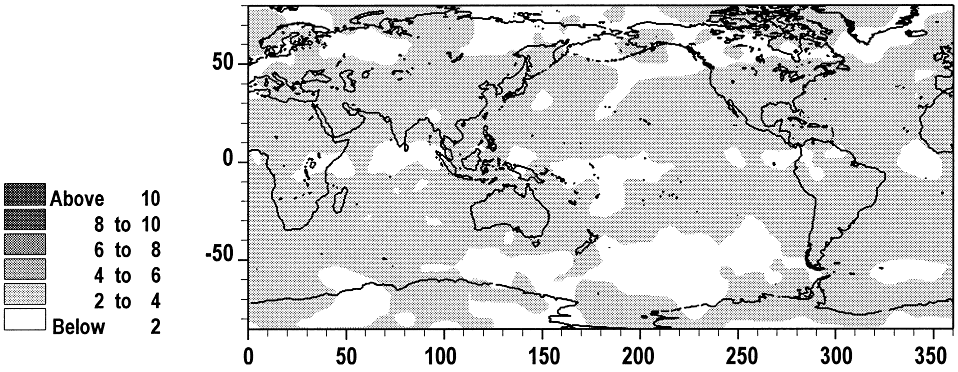

Fig. 3. Maximum PDOP analysis for 24 GPS+24 GLONASS satellites

geostationary communications satellites is the provision of most regions with acceptable PDOP values (6 and below). The augmentation of GPS with GLONASS represents the best possible scenario offering DPOP values of 4 and below, anywhere in the world at any time.

2.2. *The error budget*. The computations of horizontal or vertical positional accuracy, or indeed the availability of RAIM (see Section 3), are based on estimated measurement accuracies, which are derived from strictly defined error budgets. These error budgets will change if it is assumed that wide area differential corrections derived from the stations of a ground based network are available. The Nottingham software has recently been improved to accommodate these variations in the error budget. The ability of differential corrections to account for the various components of the error budget has been carefully modelled. Of particular concern was the need for the software simulator accurately to reflect the degradation in model accuracy at the boundaries of the integrity monitoring network, and for failures in the network to be suitably accounted for.

The error budget was based on the available information regarding the proposed European Geostationary Navigation Overlay Service (EGNOS) wide area modelling approach. However, it should be noted that without a detailed knowledge of the modelling which will be incorporated in EGNOS, it is clearly not possible to provide a definitive description of the errors in that modelling. The Geostationary Broadcast Area (GBA), referred to below, is the area of the Earth's surface within which the transmissions from the geostationary satellite(s) can be received. Clearly, if a user is outside this area, no corrections can be received, so the error budget must assume raw stand-alone accuracies.

Clock error is a one-dimensional error, therefore giving an identical accuracy anywhere the correction can be received, namely within the GBA. However, it is not enough for the user simply to be within the GBA. If the integrity monitoring network cannot see the satellite, then no correction can be computed, regardless of the user's position. Furthermore, for integrity purposes, it was assumed that at least two integrity monitoring stations within the network must be able to see the satellite, before a valid correction can be transmitted. Thus, it was necessary to check that not only was the user inside the GBA, but also whether at least two integrity monitoring stations could see the satellite. These requirements also apply to the latency error budget, since latency is only applicable if a clock correction is being transmitted.

Ephemeris error is a three-dimensional error. It depends on the ability of the integrity monitoring network to model the satellite orbit. Since the EGNOS ephemeris computation will use dynamic integration techniques, the ephemeris error was modelled to have a minimum over the integrity monitoring network, and to increase gradually away from the influence of the integrity monitoring network. Once again, for integrity purposes, it must be assumed that at least two integrity monitoring stations within the network must see the satellite, before a valid ephemeris correction can be transmitted.

Ionospheric error is a two-dimensional error. Ionospheric accuracy depends on the ability of the integrity monitoring network to model the effect, using observations of ionospheric effect at a number of discrete 'pierce points'. In a wide area implementation, these pierce point observations will probably be combined into a surface model, or a grid, of ionospheric activity. A user will then evaluate an ionospheric correction for each satellite in his local constellation, based on the coordinates of the pierce point associated with the chosen satellite. Other error sources included in the model, which are not improved by wide area corrections, are tropospheric error, the receiver noise error and the multipath error.

3. INTEGRITY. Integrity is defined by the FRP (Federal Radionavigation Plan) as the ability of a system to provide timely warnings to users when the system should not be used for navigation [DOD/DOT, 1992]. The development of GPS has clearly demonstrated the advantages of GNSS. It has global coverage, 24-hour, all-weather availability, provides a high level of positioning accuracy, and has proven to be cost-effective for a variety of applications, from navigation to high-precision surveying. However, the civil air navigation community has very demanding requirements for the 'integrity' of any systems used in safety-critical operations. A navigation system can be said to have integrity if it never gives a position which is significantly in error, or if it has the ability to inform the user when the position error is out of tolerance. The RTCA, through its Special Committee 159, has defined the integrity requirements which GPS must meet, in terms of four distinct parameters, as follows:

(i) *Alarm limit*. The size of a 'significant' position error, which the user must be informed of. This depends on the proximity of hazards, such as other aircraft (or the ground!), and therefore on the phase of flight.

(ii) *Time to alarm*. The (maximum) time between the cause of the error, and a warning message reaching the user. Again this depends on the phase of flight.

(iii) *Maximum false alarm rate*. The highest rate at which system errors are flagged, without there being a real problem. This is essentialy a 'pilot confidence' factor, since a system which consistently gives false warnings will not be trusted.

(iv) *Minimum detection probability*. The probability that a real error will be detected. This factor is the key to integrity, since safety-critical navigation cannot tolerate system errors which go undetected.

GPS is a complex system, based on data messages transmitted from a constellation of satellites. There is potential for the system to fail at any one of a number of stages, from the production of the data messages and their upload to the GPS satellites, to their transmission, reception and processing within the users' equipment. To counter these possibilities, GPS has a number of built-in checking systems. However, even with these self-checks, GPS cannot meet the integrity requirements set out by the RTCA.

3.1. *Definition and requirements for integrity*. The precision of a position fix represents the position quality, as affected by the random measurement noises through the geometry of the system. In GPS, this geometric factor of the system is described by PDOP. However, if there are systematic errors or outliers in the measurements, the position error could be very large, but not reflected by the PDOP. For GNSS, a user may experience large position errors due to various reasons. These include:

(i) The navigation satellite may transmit incorrect information about its ephemeris and clock.

(ii) Some user related errors (e.g. errors introduced by signal propagation or by the user's receiver), which cannot be monitored by the system itself, may produce large positioning errors.

(iii) When GPS is used as a part of GNSS, the SA error may produce very significant positioning errors on rare occasions.

(iv) Due to the limitation of the GNSS satellite constellation (dependent on the design of the system), the navigation service could be unavailable for users within view of too few satellites in normal operational status. More frequently, the navigation service could be significantly degraded when the satellites have a poor geometric configuration.

Thus, one of the key issues for the GNSS applications is how to monitor the system and position solution, and inform the user when the derived position accuracy does not satisfy the user's requirements. This is the integrity problem. A system can be said to have 'integrity' if:

> With a given probability, either the position error does not exceed a prespecified threshold, or an alarm is raised within a time-to-alarm interval, when the position error exceeds the prespecified threshold.

3.2. *Capability of GNSS to provide RAIM*. The method RAIM is applied by the user to check the consistency of the measurements made from different satellites, to estimate the quality of the resulting position. A number of different algorithms for RAIM have been developed, including position comparison, range comparison, residual analysis, and parity checking methods. With proper selection of the thresholds, it can be shown that all these algorithms are basically equivalent.

The main drawback of RAIM is that it relies on redundancy in the position solution to detect and isolate bad measurements; that is, it requires more than the navigation minimum of four satellites. As a result, it is not always possible to carry out a RAIM computation if, for instance, the user is at a weak point in the coverage of the GNSS constellation, or if satellites are masked or lost during aircraft manoeuvres. The power of the RAIM technique can be improved by adding in measurements from other instruments on board the aircraft. The technique is then no longer 'Receiver Autonomous', but 'Aircraft Autonomous'. AAIM can be applied either by comparing the position solution from GNSS with that obtained by other navigation sensors, such as a barometric altimeter, or an inertial navigation system, or by integrating the raw measurements from each system into a single solution (with appropriate weighting of the various measurements).

The ability of a receiver to perform a RAIM calculation depends on the number and geometry of the satellites in view. Thus, using only the receiver's coordinates and the predicted positions of the GNSS satellites, it is possible to determine whether or not a RAIM calculation can be performed; that is, whether RAIM is 'available' to the user, as an integrity monitoring technique. As described in Section 2.2, the range measurements used in the position solution will have different accuracies, depending on the satellite from which they were made, and the corrections applied by, for instance, a Wide Area Differential network. This must also be modelled when different constellations with different measurement accuracies (GLONASS and Inmarsat, for example, do not have SA) are to be combined.

As part of the suite of GNSS design and analysis software, a program to analyse the RAIM availability for any satellite constellation has been developed at the IESSG. For a given satellite constellation, the RAIM availability is calculated within a certain period, for either a given location (for example, an airport) or a specified flight route. The RAIM availability is calculated with respect to the integrity requirements of a specified flight phase (the alarm limit, false alarm and minimum detection probabilities), and an assumed measurement noise level.

In the following studies, a number of scenarios have been investigated, based on the requirements of an aircraft using GPS. Since the magnitude of a 'significant' positioning error varies according to the required positioning accuracy, a given constellation may provide RAIM for one level of accuracy, while not providing it for a higher accuracy level. The following studies have, therefore, investigated the different phases of flight when using GNSS. The studies have also considered differing numbers of inoperative GPS satellites out of the full constellation. In addition, the augmentation of the GPS solution with additional sources of measurements has also been investigated.

In the following analyses, the availability of RAIM (with an alarm limit of 375 metres horizontally) has been studied for three separate scenarios, consisting of different combinations of navigation satellites (GPS, GLONASS) and geostationary satellites (Inmarsat and others).

Scenario 1: GPS + AOR-E + IOR (Fig. 4);
Scenario 2: GPS + AOR-E + IOR + AOR-W + GEO1 + GEO2 (Fig. 5);
Scenario 3: GPS + AOR-E + IOR + GLONASS (Fig. 6).

The computation of RAIM availability was restricted to the EGNOS coverage area, defined here as from 140 °W to 150 °E and 75 °N to 75 °S (an area encompassing the footprints of the AOR-E and IOR satellites.

A geographical grid of $5° \times 5°$, and a temporal interval of 2·5 min over 24 hours was used. The choice of these values is a compromize between the statistical validity of the results, and the amount of computer time required to produce them. The temporal interval of 2·5 min corresponds to 0·17 percent of 24 hours. Thus, in the computation of RAIM availability, if, for instance, a total of three samples indicated that RAIM was not available, the remaining samples would correspond to 99·48 percent of 24 hours. The geographical grid cell of $5° \times 5°$ gives a total of 1829 samples, so a single grid cell corresponds to 0·06 percent of the area of interest.

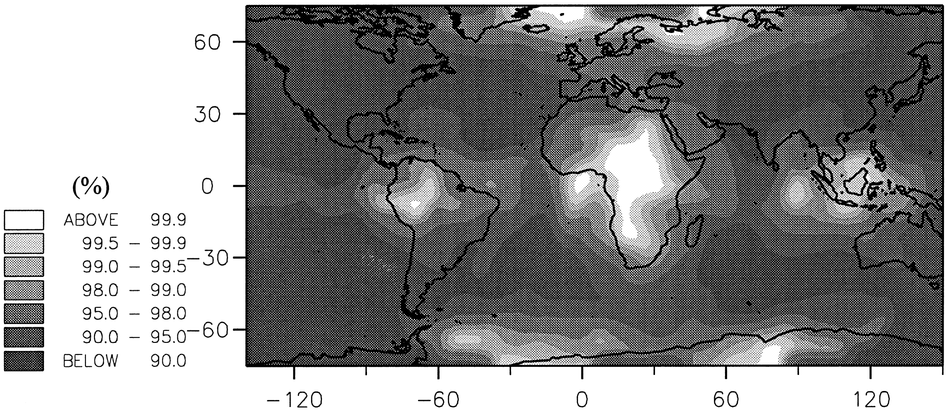

Fig. 4. RAIM availability (375 m horizontal) GPS+AOR-E+IOR

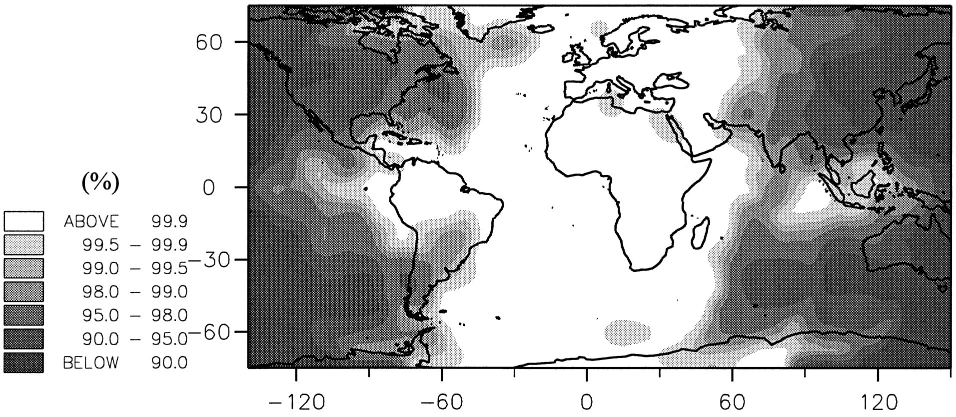

Fig. 5. RAIM availability (375 m horizontal) GPS+AOR-E+IOR+AOR-W+GEO1+GEO2

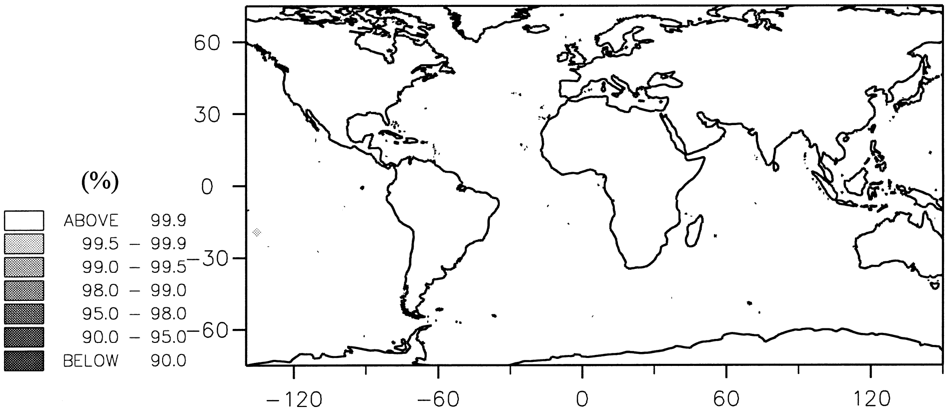

Fig. 6. RAIM availability (375 m horizontal) GPS+AOR-E+IOR+GLONASS.

The plots shown here are contour plots of the percentage of the 24 hour sample for which RAIM, to the specified level, was available. This is simply computed as the percentage of 2·5 min samples, out of the total of 576, for which the specified RAIM was available. In addition to the required protection limit of 375 metres horizontally, the following parameters were also specified:

Probability of False Alarm (P_{FA}) = 10^{-6},
Probability of Missed Detection (P_{MD}) = 10^{-3}.

In Fig. 4, the footprints of the two Inmarsat satellites are evident. Horizontal RAIM availability is improved most at the edges of the footprint. This is clearly due to the fact that the Inmarsat satellites will be at low elevation angles for users in these areas, and therefore the ranges made to these satellites will have a greater effect on horizontal integrity. The improvement due to the addition of the extra geostationary satellites over Europe is evident in Fig. 5. However, with regard to the impact of GLONASS on the availability of RAIM, a comparison of the three figures shows that RAIM availability is significantly improved in the combined GPS/GLONASS case. Within the resolution of these results, the addition of GLONASS provides an availability which matches the best of either of the other scenarios over the whole of the EGNOS coverage area.

4. CONCLUSIONS. This paper has addressed the three major areas of GNSS constellation design - namely, satellite availability, coverage and system integrity. It has been shown that, on its own, GPS has deficiencies in all three categories. The problems of the lack of satellite availability can be overcome to some extent by augmentation with other satellite systems such as Inmarsat geostationary communication satellites. The best situation however, is obtained when GPS is augmented with GLONASS.

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KEY WORDS

1. Satellite navigation. 2. Augmentation. 3. Design tools. 4. Error modelling.