GPS Supplemental Navigation Systems for Use During the Transition to a Sole-Means-GPS National Airspace System

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ABSTRACT

The current Federal Radio Navigation Plan presents a plan that includes phasing out of existing radio-navigation aids as part of the transition to sole-means-GPS navigation in the United States. GPS based systems are also being envisioned as becoming the primary means of air traffic control resulting in the retirement of older primary and secondary surveillance radar (SSR) systems. This paper discusses the use of existing radio-navigation aids to provide a redundant navigation system alongside GPS/WAAS during the transition to a sole means GPS national airspace system. Specifically, the paper examines three such systems based on existing equipment such as Distance Measuring Equipment (DME), the Traffic and Collision Avoidance System (TCAS) and LORAN. The predicted performance of these systems can be used to determine the number of the existing radio-navigation aids that should be left in place to provide adequate navigation services during the transition to sole-means-GPS navigation.

INTRODUCTION

The Federal Radio Navigation Plan (FRP) describes the architecture of the future navigation system in the United States [1]. The architecture presented in the FRP is one where GPS augmented by WAAS and LAAS will be the sole means of navigation in the United States. The FRP also presents a schedule for this transition to GPS as the sole means of navigation. Initially, WAAS will be implemented. This will provide navigation services good from the en-route phase of flight up to Category I precision approaches. The transition to sole-means-GPS navigation will be complete with the implementation of LAAS which will provide Category II and III precision approach services.

The transition to sole means GPS national airspace system will not be instantaneous. During this transition period there will be a strong incentive to reduce the size of the existing radio-navigation system infrastructure. This is because the radio-navigation infrastructure is a large and costly system to maintain. It is estimated that the annual expenditure for upkeep of this system is $80 Million. It is also estimated that $139 Million will have to spent over the next decade to continue providing the same level of navigation service [2]. GPS Supplemental Navigation Systems (GPS-SNS) are systems intended to address the conflicting demands of needing to provide adequate navigation services in an environment where the size of the radio-navigation system infrastructure has been reduced from current levels and GPS is in the process of becoming the sole means of navigation. More specifically, the idea of a GPS Supplemental Navigation System is to provide navigation services when GPS services are temporarily unavailable. Another function of such a system may be to provide an additional means of receiving DGPS messages. The purpose of this paper is to present a brief overview of the architecture of such systems. Three specific implementations of GPS-SNS will be examined. The first system presented will be one based on fusing ranging measurements from a skeletal network of DME stations with sensors used for dead reckoning. The second system is based on TCAS II equipment currently carried onboard many U.S. commercial aircraft. Next, an alternate method of transmitting DGPS correction messages over the Mode S data link (which is part of TCAS II) is discussed. Finally, another method for transmitting DGPS corrections using LORAN will be presented. These systems are demonstrations of possible implementations of GPS-SNS and will illustrate issues and trade-off important to any GPS-SNS architecture.

GPS-SNS DESIGN CONSTRAINTS

In the previous section the purpose of a GPS-SNS was broadly stated as providing navigation services when GPS is temporarily unavailable. A potential scenario of such an unavailability is presented in [3] and is an instance where GPS navigation services are disrupted in the vicinity of an airport due to interference. In this situation a GPS-SNS should be able to provide navigation services to allow aircraft to safely divert to an alternate destination where GPS services are available. In this paper, it is assumed that the minimum navigation performance required to complete such a mission is equivalent to the level of performance provided by the least stringent of currently available non-precision approaches. An example of such a non-precision approach would a VOR approach based on flying from the VOR located 30 nautical miles away from the airport of intended landing [4]. If it is assumed that the VOR bearing measurements can have errors as much as 4 degrees and that low performance aircraft traveling at 60 nautical miles per hour will require 30 minutes to fly from the final approach fix to the Minimum Descent Altitude (MDA) of such an approach, this translates into an accuracy requirement of 2 nautical miles in position after 30 minutes of flying.

Another constraint imposed on the GPS-SNS described in this paper is the capability of area navigation. This is the ability to display position information in terms of latitude and longitude. While GPS presents information in latitude and longitude format, most existing radio-navigation aids do not normally present information in this format This constraint will make switches from navigating on GPS to navigating on the supplemental system as seamless as possible.

A final constraint that needs to be considered when evaluating specific GPS-SNS architectures is cost since it is one basic factor that will determine the adoption of any system. A supplemental navigation system will be cost effective if the need for building a new navigation infrastructure and user equipment base is eliminated. Therefore, a supplemental navigation system that is based on using existing navigation facilities to the maximum extent possible is desirable

1 . GPS SUPPLEMENTAL NAVIGATION USING DME

The first GPS-SNS that will be discussed is aimed at the General Aviation user and is based on combining range measurements from DME (Distance Measuring Equipment) with dead reckoning. To facilitate understanding the detailed architecture of this system, first a brief description of VOR (Very high frequency Omni-Range) and DME—the building blocks of the current radio-navigation system—will be given. The VOR/DME system is the standard short-range radio-navigation aid agreed upon by the International Civil Aviation Organization (ICAO) [5]. The VOR are ground based radio transmitters which provide a relative bearing (with respect to magnetic north) between the VOR and the user location. DME provides is also a ground based transponder which provides the range between the user and the DME transponder. With a few exceptions, the majority of the 932 VOR and DME facilities operated by the FAA are collocated as shown in Figure 1. The VOR/DME network as shown in Figure 1 are the basis of the area navigation method (ρ–θ navigation) scheme used in the current national airspace system of the United States.

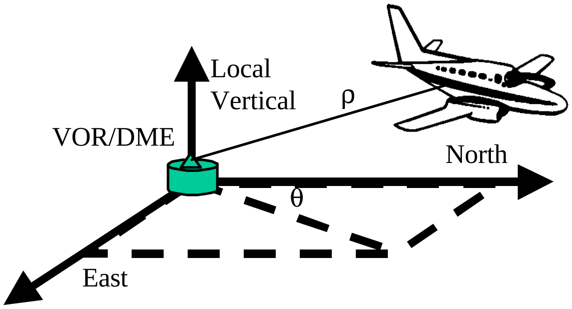


Figure 1. Collocated VOR and DME Stations

As noted earlier, maintaining the network of VOR/DME stations is very costly and, therefore, there is a strong desire to reduce the number of VOR/DME stations in service. One way to reduce the number of these navigation facilities while providing acceptable navigation performance is to eliminate VORs and maintain a system that is based on the ranging signals from DME. Eliminating VORs from the architecture of such a supplemental navigation system has the following advantages: (1) VOR is a system that provides angular measurements and as such positioning accuracy will degrade with distance from the transmitters when used in area navigation system. (2) A usable skeletal network of existing radio-navigation aids *may* require relocating some of these facilities. In comparison to a VOR facility, it’s easier and less costly to install and upkeep a DME facility.

1.1 DME Fundamentals

A brief description of how DMEs operate is given to facilitate understanding of the subsequent analysis. For a more detailed treatment of the subject the reader is referred to [6] and [7]. DME is used to determine the range between a user and a ground-based transponder by measuring the time of flight of a pulse from the user to the transponder and back. Specifically, the airborne DME interrogator emits a pair of pulses which when received by the ground transponder are after a short delay of 50 µseconds retransmitted back to the airborne interrogator. The airborne interrogator then measures the time flight, subtracts the delay in the ground based transponder and computes the distance by multiplying the time of flight by the speed of light. When an airborne transmitter is tuned to a particular ground based transponder frequency for the first time, it emits pulses at an average rate of 135 pulses per second and is said to be in the search mode. Once the airborne interrogator is "locked" on the ground transponder, it reduces its interrogation frequency down to an average of 25 pulse pairs per second and is now in the tracking mode. Each ground transponder is capable of responding to 3000 pulses per second. This translates to roughly 100 airplanes (95 in tracking mode and 5 in search mode) at any instant.

1.2 Positioning using DME

Given three perfect range measurements from three separate DMEs, one can derive latitude, longitude and altitude information. In practice, however, the geometric dilution of precision in the vertical direction is large and will, therefore, require that altitude information be determined using other means. This is not a significant problem, however, since barometeric altimeters are standard equipment on all aircraft. A more difficult problem in practice is obtaining continuous or very frequent range measurements from two or more DME transponders. This is because most aircraft carry DME receivers that are capable of tracking only one DME station at a time. While a specialized airborne DME interrogator called a scanning DME exists which can track multiple stations at a time, it is expensive and used almost exclusively in newest commercial jet liners. One possible solution to this problem is to carry two DME receivers in each aircraft so that, at any instant, two range measurements from two separate DME ground stations will be available. Another solution is to use one DME to acquire the range from multiple DME ground stations intermittently. This scheme is shown in Figure 2.

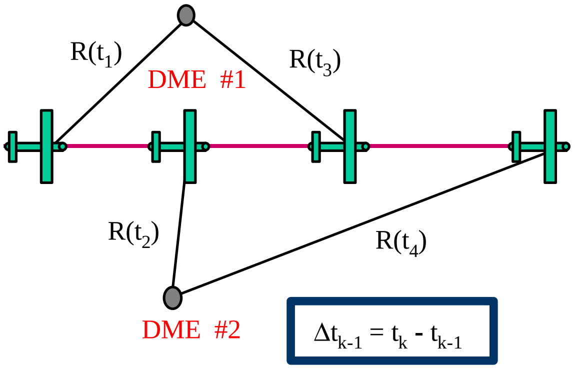
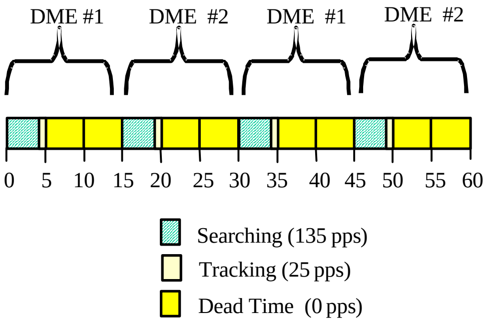


Figure 2. Intermittent DME Interrogation.

The potential exists for saturating the DME ground transponder if intermittent interrogations are not done carefully. This is because each time an airborne DME receiver switches from tracking one station to tracking another station, it will interrogate at a rate of approximately 135 pulses per second. This is approximately four times greater than the interrogation rate during normal tracking. If this switching is done too frequently, the number of aircraft that can be serviced by a given ground station will be reduced. This problem can be mitigated by scheduling interrogation in way that ensures that a given DME ground transponder can handle the expected traffic load. Such an interrogation schedule and supporting calculations are shown in Figure 3.



N = Maximum Number of Interrogation Cycles per DME per Minute

$(4 \text{ sec} * 135 \text{ pps} + 1 \text{ sec} * 25 \text{ pps}) * N < 25 \text{ pps} * 60 \text{ sec}$

$N < 2.7$

$\therefore$ N = 2 Cycles per Minute

Figure 3. One Minute DME Interrogation Schedule.

In the schedule shown in Figure 3, it is conservatively assumed that it takes a DME receiver four seconds in the tracking mode before it "locks in." Once the airborne unit is tracking a given DME station, it will obtain range measurements for one second. If we match the number of pulses that would be emitted in a minute in this scheme with the number of pulses that would be emitted if the receiver was in tracking mode continuously, the we see that a given DME station can be interrogated only twice a minute. Another way of interpreting this DME interrogation schedule is that the Δt shown in Figure 2 must be at least 15 seconds. In the following section it will be shown that this scheme produces an acceptable navigation performance.

Referring back to Figure 2, it should be noted that at any instant position is not observable from a single range and altitude measurement. Therefore, a means of obtaining a rough position estimate between subsequent range measurements is required. This can be done by dead reckoning using either inertial sensors or heading information from a fluxgate compass combined with airspeed information from air-data sensors. From the combined intermittent range measurements, altitude information and dead reckoning, position is observable and hence navigation is possible.

1.3 Expected Performance

To assess the performance of a navigator that combines intermittent DME range measurements with dead reckoning based on air speed and heading information, we performed a series of simulations. Dead reckoning based on air speed and heading information was evaluated because it represents the least expensive alternative of such systems. The navigator was implemented as an Extended Kalman Filter with DME range measurements and barometric altitude from an altimeter as the inputs. Figure 4 shows the location of NASA-Ames/Moffet field in Mountain View, California and the VOR/DME stations in the San Francisco Bay area. The input data for the simulations was generated from accurate attitude, velocity and position data that were recorded during a flight test where a series of simulated instrument approaches were flown into Moffet Field. Accurate position and velocity data were generated by GPS augmented with the Stanford University Prototype Wide Area Augmentation System. Accurate attitude information was generated by a navigation grade Honeywell Inertial Reference Unit (IRU).

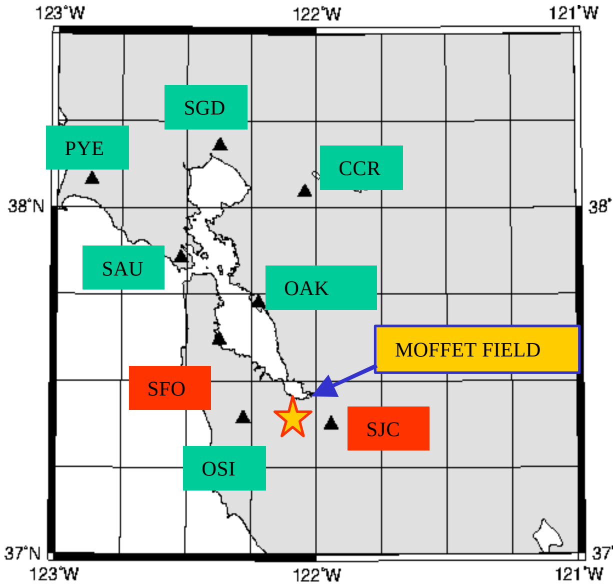


Figure 4. VOR/DME Locations in the San Francisco Bay Area.

Ranges that would be observed along the flight trajectory from only two DMEs (the San Francisco and San Jose International airports) were generated. DME range errors consisting of a bias (which varied in time as a Gauss-Markov process similar to an error model developed in [8]) and sampling noise (white noise) were added to the ranges. The method for generating the DME range data that was used in the simulations is shown schematically in Figure 5.

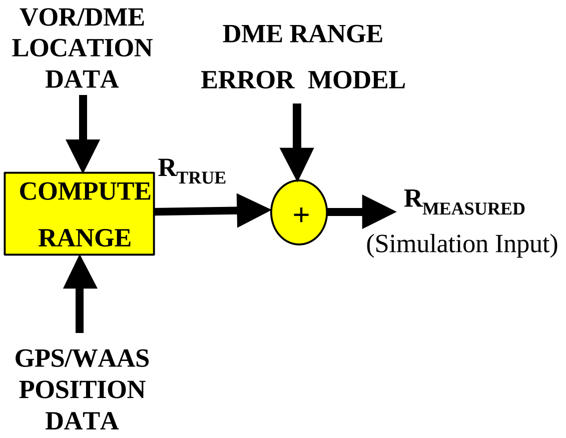


Figure 5. Generating DME Ranges for Simulation Input.

In a similar fashion, differentially corrected GPS velocity and aircraft attitude information were used to generate simulated airspeed and heading information. Wind field and heading errors consistent with the error models developed in [9] were added in a fashion similar to that shown in Figure 5. Figure 6 shows the ground track generated by the DME/dead reckoning method (using the interrogation schedule shown in **Figure 3**) superimposed on the ground track that was generated by differentially corrected GPS.

The maximum position error is shown to be less than 0.5 nautical miles. Just as a comparison, the ground track generated by using an interrogation schedule where Δt was 1 second is also shown in Figure 5. Even though an interrogation schedule where Δt was 1 second would not be used with the low-end airborne DME receivers, it can be used in systems with multiple DME receivers or systems that have more costly receivers that use lower DME interrogation rates.

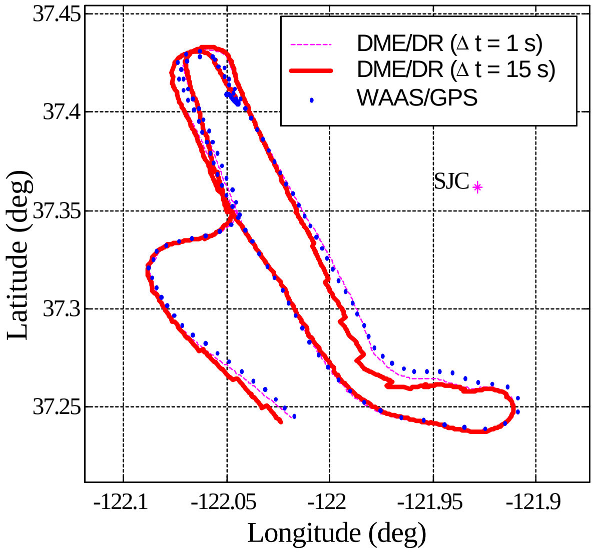


Figure 6. Ground Track of DME/DR System.

1.4 Conclusions on using DME Positioning

The simulations above show that intermittent DME interrogation combined with dead reckoning can produce navigation performance acceptable for a GPS-SNS. The navigation performance is increased if more than two DME ground stations are used. Therefore, if range measurements from three DME can be provided in the vicinity of major airports, an alternate means of navigation to supplement GPS can be provided. This shows that the potential exists for bringing a navigation scheme used by larger and more expensive transport aircraft (i.e., DME-INS navigation) to the general aviation user.

2. GPS SUPPLEMENTAL NAVIGATION USING TCAS

The second GPS-SNS examined in this paper is based on TCAS (Traffic Alert and Collision Avoidance System) II. TCAS II possess many features that can be used to make it a feasible candidate system. A feature of TCAS is its ability to locate nearby aircraft. In principal, the same instruments can find the relative location a known fixed ground transponder. Thus, TCAS positioning can be done by having TCAS perform as a ρ–θ system. In addition, TCAS II equipment on board aircraft includes Mode S (Select) transponders. Mode S transponders enable both ground and air data transmission. The data link can be used to provide WAAS signals to the aircraft.

TCAS has a large installed commercial user base and available commercial equipment because it is required on many passenger carrying civil aircraft [14]. The large user base of TCAS II is a major attribute for considering a TCAS II based GPS-SNS. Another important attribute is that implementation of GPS-SNS on board TCAS II equipped aircraft may only require changes to software thereby eliminating the cost incurred by additional new equipment and its associated maintenance.

2.1 TCAS Fundamentals

TCAS is a system of hardware and software used to detect and alert pilots to the presence of local traffic (traffic advisory). TCAS II has equipment that interrogates secondary surveillance radar (SSR) transponders to detect local traffic. Transponders reply to these interrogations and allowing the interrogating aircraft to locate the replying aircraft. Since nearly all aircraft carry one of these transponders, TCAS can detect most traffic. TCAS interrogates using 1030 MHz channel and replies from the transponder are transmitted on 1090 MHz.

SSR work on the same principal as DME. An interrogator transmits a signal to a desired target. The target's transponder replies upon reception of transmitter's signal. The total time between the issue of the interrogation and the arrival of the reply at the interrogator determines the range. Successive measurements yield the range rate. TCAS II uses directional antennas to get a bearing measurement to the detected aircraft. Newer transponders such as Mode S can transmit barometric altitude information. The information is used by TCAS software to determine which aircraft are threats. More threatening aircraft are interrogated at a higher rate - up to 1 Hz. TCAS transmission power is variable and is decreased in areas of high aircraft density to reduce interference. Its surveillance radius can range from 5 to 30 nautical miles. It is specified to work in areas where the traffic density is up to 0.3 aircraft/nm^2. For a more detailed treatment on how TCAS II operates, the reader is referred to [11], [12], and [13].

Mode S is a surveillance and communications system that operates using a specific data link protocol [15]. Mode S provides a data link by encoding information onto the interrogation and reply signals. All Mode S interrogations are differential phase shift encoded (DPSK) and transmitted on 1030 MHz. The throughput rate is 4 Mb/s. All replies are pulse position modulated and transmitted on 1090 MHz carrier at an effective rate of 1 Mb/s. Mode S formats provide for directed interrogations and replies with the inclusion of a 24 bit unique aircraft identifier.

2.2 Differential GPS Corrections Using TCAS

TCAS provides the data link for differential GPS corrections through the Mode S transponder. Mode S can be used to uplink data. Formats 20 and 21 are 112 bit messages that uses 56 bits for surveillance and 56 bits for data link. It is possible to string up to 4 long interrogations together to generate 224 bits. In addition, Format 24 gives roughly 80 bits of data and it is possible to link up to 16 Format 24s to get 1280 bits of data [15], [23]. Since Mode S interrogations have an effective data rate of 4 Mb/s, the addition of a 250 bps message or even a 1 Kbps (for overhead), should not greatly impact current TCAS operations. The operation of the Mode S datalink only requires a Mode S transponder to receive data. It does not require other TCAS equipment such as the interrogation equipment used for aircraft surveillance.

2.3 Positioning Using TCAS

TCAS II equipment can be used to determine aircraft position several ways. One method is to use knowledge available from ground surveillance. Using the Mode S data link, an aircraft can have its position as determined by ground based surveillance radar transmitted to the aircraft. The concept is like ADS-B (Automatic Dependent Surveillance – Broadcast) with the change that the broadcast is made by the ground rather than each individual aircraft. Another method is to use fixed Mode S ground sites and ground based transponders to provide a reference for TCAS equipped aircraft. TCAS equipment includes transmitting equipment that can interrogate various transponders such as Mode S transponders. This is the method that will be discussed in greater detail.

In areas where ground surveillance and established Mode S sites are unavailable, one can install fixed Mode S ground based transponder units and use them as a ρ–θ positioning system for a TCAS equipped aircraft. The airborne TCAS II unit determines a range and bearing to the ground unit. The ground units only need respond to TCAS II interrogations and to occasionally broadcast its presence. This system will be denoted in the paper as TCAS-N (TCAS – Navigation).

In TCAS-N, aircraft in the area are alerted to the presence of the ground transponder by squitter (spontaneous transmission) from the ground unit. Aircraft that hear the squitter can interrogate the ground unit and receive a directed response. The aircraft then determines range and relative bearing to the ground unit. With these measurements and knowledge of the ground unit's position, the aircraft's absolute position can be determined. If ground units are given unique identifications using the 24 bit unique identifier, the aircraft can use a look up table to obtain the ground site location. Another means is to have the ground station transmit its location. Implicit within the position determination is a knowledge of aircraft heading Aircraft heading errors are normally less than a few degrees and hence the major error source in this positioning scheme is the TCAS II bearing measurement error which is specified to have an rms value of 9 degrees [12].

2.4 Expected Positioning Performance

With TCAS-N, positioning can be obtained with only one ground transmitter. Since bearing errors are large, however, good positioning cannot be expected when using only one station located over 20 nautical miles away due to the 9 degree rms error on bearing. Greater accuracy can be attained with more accurate range and bearing measurements. Increased accuracy in measurements requires new equipment, such as better directional antennas for increased bearing accuracy, and may be not be cost effective. Another alternative is coverage by more than one ground station. The position estimates obtained from a weighted least squares solution using measurements from two or more station can greatly improve accuracy. The analysis results shown in Figure 7 demonstrate this conclusion.

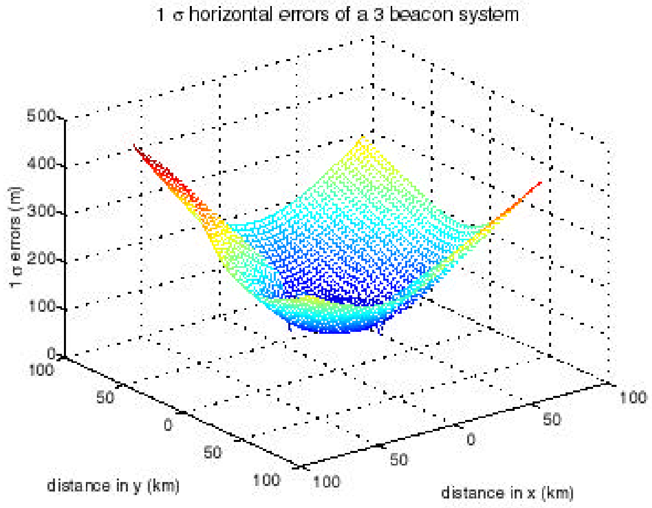


Figure 7. One σ error for Coverage with Three Stations

With measurements from multiple ground stations and good geometry, the weighted least squares solution places less weight on the bearing measurements. This result implies that any aircraft that can obtain range measurements using Mode S transponders can get a similar performance provided the aircraft can interrogate multiple stations and these stations are not co-linear (or nearly co-linear) with the aircraft. This improved accuracy comes at a cost. First, multiple measurements means nearly simultaneous interrogations (~ 1 second) of multiple stations and hence increased communication traffic. Second, multiple station coverage means increasing the number of ground stations or increasing the coverage radius the existing ground stations. The issue of increased coverage is examined in the next section.

Figure 8 shows the results of simulations performed to assess the performance of a TCAS II based positioning system. The input data for these simulations was the same flight test data used to generate Figure 6. Range and bearing measurements were calculated from known Mode S sites at Moffet and San Francisco International (SFO). In a manner similar to that shown in Figure 5, these measurements were corrupted by Gaussian noise on the

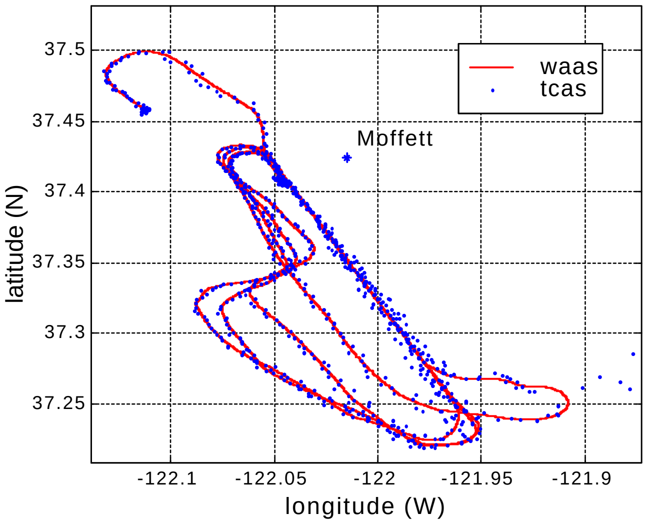


Figure 8. GPS/WAAS vs. TCAS Positioning on Flight Test.

measurements. The measurement noise has σ of 100 m and 9 degrees for range and bearing respectively. In Figure 8 the WAAS derived ground track (solid line) represents our truth measure while the dots are TCAS-N positions. Simultaneous measurements made every five seconds were used to generate the TCAS-N positions. Figure 9 shows positioning errors are generally less than 750 meters which is acceptable. When the plane and stations are nearly co-linear resulting in bad geometry, the errors are around 3500 meters.

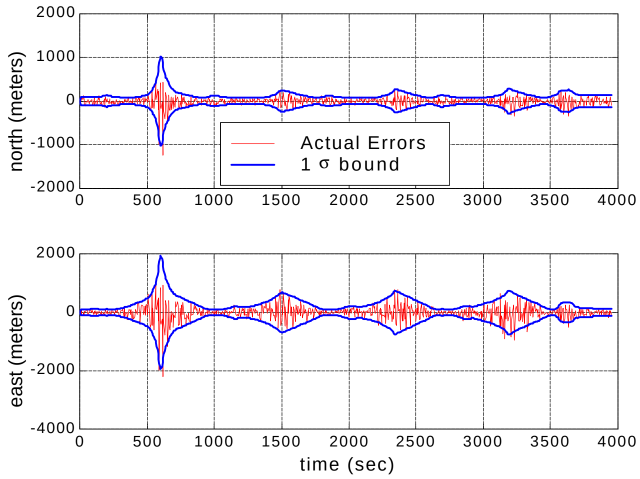


Figure 9. Actual and One σ position error bound on Flight Test

2.5 Coverage

System costs and performance depends on the number of existing ground stations operating in the system. By the end of 1997, there were 88 installed Mode S sites. Eventually, there should be 144 installed Mode S in the United States at locations shown in Figure 10. These Mode S sites are generally located within an airport beacon interrogation system. Using these Mode S sites as part of the TCAS based GPS-SNS chain can provide some limited coverage. It is envisioned that these can also serve as Mode S ground transponder sites. The previous section demonstrated that coverage by multiple ground transponders is preferred.

The number of additional ground stations depends on the coverage radius of each station and the desired positioning performance. One would like as large a radius as possible however as the coverage radius is increased, the ground station will have to serve more traffic thereby increasing the probability of interference. Increased interference results in a lower probability of acquiring a position solution. A starting point is to use the 144 planned and installed Mode S sites. If the Mode S sites are modified to also perform as Mode S transponders with each site providing a coverage radius of 30 nautical miles, Figure 10 shows that CONUS coverage cannot achieved. The same plot could be made for the ground broadcast system with similar results.

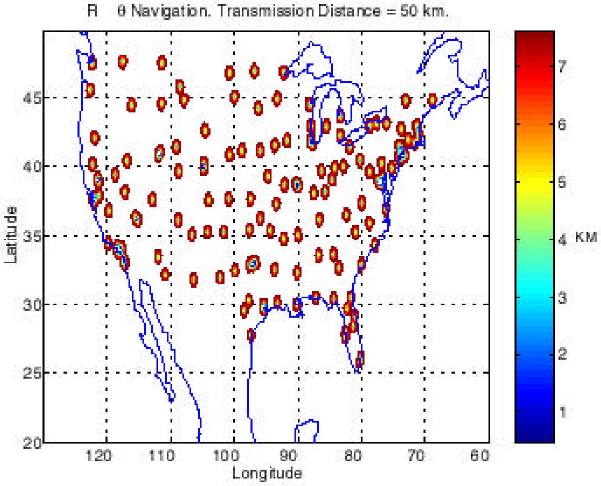


Figure 10. Coverage using 144 established Mode S sites (One σ position error).

The figure of 30 nautical miles as a coverage radius currently is derived from the MOPS [12]. Minimum trigger level (MTL) and TCAS transmitter power limits aircraft transmissions to 30 nautical miles. The conclusion is that the system will need additional ground coverage to provide navigational supplement for CONUS. However, the current ground system does provide coverage around most major airports.

2.6 TCAS-N Availability

A desired feature of the system is the ability to get position solutions at a reasonable rate. We will define this as TCAS-N availability. The availability of TCAS-N is determined by the amount of air traffic in the area and hence aircraft density and coverage area are determinants of TCAS-N availability.

One can get a basic sense of the trade off between coverage area and TCAS-N availability using a 2-D model. Monte Carlo simulations and analytic models were used to develop the coverage radius versus TCAS-N availability curves. The aircraft density is limited to a maximum of 0.3 aircraft/nm^2. Since the number of replies from each aircraft is random, one has to estimate the term. For the analytic model, the estimate was chosen conservatively. Hence it will underestimate the Monte Carlo simulations.

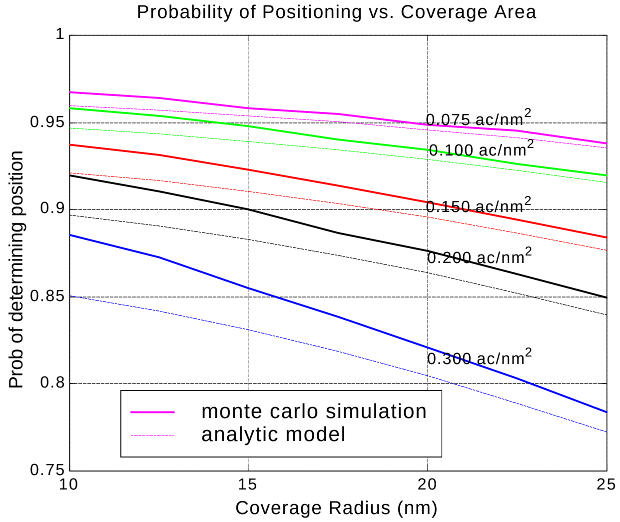


Figure 11. Probability of Obtaining Position with 1 Interrogation.

Figure 11 shows that the analytic model corresponds well with the Monte Carlo simulation. The analytic model can then be used to quickly analyze various traffic situations. Parameters that need to be examined are interrogation rates, positioning interrogation rates, and coverage radius. Figure 11 shows a situation that uses a 100 km by 100 km area (60 nm by 60 nm). All aircraft in the area are TCAS equipped, and that they survey other aircraft to a range of 10 nm. They make twelve Mode S short interrogations per second and if they are within the coverage radius of the ground station, they can make two interrogations of it per second. Replies are transmitted using a short format.

Figure 11 shows the probability as a function of coverage radius, of each position interrogation resulting in position determination. In a worst case aircraft density situation, 0.3 ac/nm^2, the aircraft has a 77% chance of determining its position per ground interrogation. That means that the aircraft has a 99.9999% chance of acquiring a position during a 5 second interval. Simulations and analysis on a couple of different situation demonstrate a high probability (> 75% per interrogation or 99.9% per 5 seconds) that a ground interrogation will result in positioning. The current analysis used TCAS interrogation rates of 10-12 Hz for aircraft. The MOPS imply that for a small survey radius (5 nm), the rate can be as high as 24 Hz. Again, these results are only as good as the assumptions on competing traffic.

The situation is that TCAS surveillance does not have exclusive use of its interrogation and reply channels. The military and air traffic control also use the channels. So the model has to be modified to examine additional transmissions on the interrogation and reply channels.

Another issue is the impact of TCAS-N on normal TCAS operations. TCAS-N will have an effect on normal TCAS and the effect is dependent on coverage radius. Preliminary studies indicate that the impact is small but not always insignificant.

2.7 Conclusions on using TCAS

Analysis and simulations show that TCAS positioning is a feasible concept. Performance is acceptable provided that there is adequate coverage. Coverage does need to be increased to cover CONUS. In addition, Mode S can also provide full WAAS correction signals. With Mode S being proposed as a national aeronautical data link system, the system may be an effective GPS-SNS for a large segment of the aviation community.

3. GPS SUPPLEMENTAL NAVIGATION USING LORAN

LORAN (Long Range Navigation) has long been used for aircraft navigation. It is a hyperbolic ranging system that uses a chain of stations consisting of one master station and at least two secondaries. One chain generally provides navigational coverage over a large region such as the Western United States. LORAN chains operate throughout Western Europe, CONUS, the Middle East, and the Pacific Rim.

Another feature of LORAN is that it can be modified to carry messages. Eurofix modifies the LORAN-C (the current implementation of LORAN) signal and enables the signal to carry data. The University of Delft has shown that the data transmission can achieved with minimal impact to current users [19].

In addition, LORAN has features that are complementary to GPS. It is not affected by interference on L1. Since it is not a line of sight system, it is not affected by some of the phenomena that would obstruct GPS signals from an aircraft. These advantages make LORAN a natural candidate for a GPS-SNS.

3.1 Positioning Using LORAN

With LORAN, a user can determine horizontal location within 460 meters with repeatable accuracy of about 18 to 90 meters (1 σ) [17]. The positioning accuracy of

LORAN can be affected by Precipitation Static (P-static). P-Static mitigation techniques such as using H field antennas have been tried [24]. LORAN augmented with a barometric altimeter can then yield a 3-D position fix. There is much literature about LORAN positioning (including an overview in [6]) and, therefore, it will not be discussed any further in this paper.

3.2 Differential GPS Corrections on LORAN

LORAN-C can be modified to carry data. One system, Eurofix, is being tested. Eurofix is a scheme for encoding LORAN-C with data up to about 70 bits per second (bps) for worst case GRI. The actual data carried is lowered by the overhead required for error correction and error detection. Eurofix is currently used to carry a RTCM Type 9 DGPS correction [19]. There are schemes that are able to increase the raw data rate to about 350 bps. The increased data rate will allow LORAN to carry WAAS signals thereby enhancing LORAN as a GPS-SNS. The enhancement will increase the utility of LORAN within a GPS navigation system. This section will discuss some of the results of research into new LORAN modulation schemes. The details of these schemes will be presented in another paper [18].

One method to increase the data capacity on LORAN signals is to combine a variety of basic modulation schemes. Three basic schemes have been examined. The schemes can coexist and can be combined to from a hybrid signal design. The first scheme is Pulse Position Modulation (PPM) where the LORAN pulse is time advanced/delayed. An example of the scheme is Eurofix. The second scheme is intrapulse frequency modulation (IFM) whereby modulation is encrypted within the pulse by slowly frequency shifting the signal. The third method is Supernumary LORAN whereby additional pulses are generated in between the current pulses [20]. Then the additional pulses can be modulated by both PPM and IFM. So we can create a hybrid scheme that has 16 pulses per GRI. Data is modulated onto the pulses by PPM and IFM. This results in the preferred hybrid scheme seen in Table 1. It is assumed that half of the bits are used for error correction. One cost of employing these schemes is increase noise due to sky wave interference.

Scheme	Data Rate (bps)	Transmitter Costs	Receiver Costs	SNR (for P(error) < 1e-3)
Pulse Position Modulation	35.7	Additional logic	Add'l processing for PPM	17.1 dB
Intrapulse Frequency Modulation	47.5	Additional logic for half cycle generators	3 matched filters and processing	26 dB
Preferred Hybrid (w. Supernumary	171.5	All of the above & 2x Transmission power	All of the above & ability to receive supernumary	26 dB

Table 1. Data Schemes on LORAN [18]

3.3 WAAS Message on LORAN

WAAS messages are 250 bits long and messages arrive at 1 Hz rate. The data rate achieved on LORAN with half the bits dedicated to error correction is 170 bps. The rate is less than the requirement for transmitting WAAS messages. If less bits are used for error correction, the data rate can be increased and the complete WAAS corrections can be transmitted. Less error correction will increase the probability that a message would be corrupted and have to be discarded. Different amounts of bits dedicated to error correction leads to different data rates. These data rates will determine the capability of the differential GPS correction on LORAN. Next, we will examine three other options.

If one uses an error correction scheme that allows a data rate of approximately 200 bps, then an abbreviated set of the WAAS messages could be transmitted. The set would have all WAAS messages except ionospheric messages. The advantage is that the user still receives applicable integrity messages and satellite corrections. Another advantage is that the differential corrections can retain the same format as described by the WAAS MOPS.

For data rates around 150 bps, WAAS corrections can be sent if they are repackaged in a manner that does not follow the MOPS [21]. The ionospheric corrections need not be sent. WAAS MOPS requires the ability to transmit corrections for 51 satellites. A repackaged message may only transmit corrections for currently active satellites. The caveat is that if the constellation increases, the message formats may need to be altered.

At rates down to about 35 bps, a use/don't use message for each satellite could be sent.

The options mentioned do not represent a complete list. More study needs to be conducted on the trade off between error correction and message reception probability. The result will help determine how much of the WAAS message can be sent.

3.4 Conclusions on using LORAN

LORAN has often been presented as a supplement to GPS. Test have shown LORAN communications is possible and our study has shown that transmitting some form of WAAS is theoretically feasible. With LORAN communications, there can be an additional source of user integrity information. While there are still issues with positioning and more testing is needed on LORAN communications, the result is that LORAN is capable of providing both GPS supplemental navigation and differential corrections.

4. FUTURE WORK

The paper examined three potential GPS-SNS. With the DME based system it was shown that adequate navigation performance can be achieved using as few as three DME stations. What the total reduction in the number of VOR/DME sites will be if such a system is implemented is subject currently under study. Another subject under study is the possibility of using DME squitters to transmit WAAS integrity messages. An additional issue that is under study is the effect of TCAS-N on normal TCAS II functions. Further testing needs to be done, especially on placing the WAAS message on LORAN.

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