A DME Based Area Navigation Systems for GPS/WAAS Interference Mitigation In General Aviation Applications

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Abstract

The Federal Aviation Administration is leading the National Airspace System modernization effort, in part by supplanting traditional air traffic services with GPS aided by the Wide and Local Area Augmentation Systems (WAAS & LAAS). Making GPS the sole-means of navigation will enhance safety, flexibility and efficiency of operations for all aircraft ranging from the single engine general aviation aircraft to the complex commercial jet-liners. This transformation of the National Airspace System will be gradual and the build-up to a sole-means GPS capability is expected to occur concurrently with the de-commissioning of a significant number of existing ground-based navigational facilities. Temporary interruptions of GPS services due to intentional or unintentional interference during this transition period could present significant problems for General Aviation aircraft.

To successfully deal with such outage scenarios, this paper discusses the use of an existing radio-navigation aid, the Distance Measuring Equipment (DME), to provide a redundant navigation system alongside GPS/WAAS during this phase out period. Specifically, a system that fuses a low-end DME receiver with low cost dead-reckoning sensors (inertial, air-data and magnetometers) is shown to provide an affordable area navigation capability for General Aviation users. The justification for choosing DME over other ground based navigational aids is discussed. This back-up system allows reducing the number of operational radio-navigation aids required while still providing adequate coverage for navigation during the transition to a sole-means GPS National Airspace System.

1. Background

In simple terms, the National Airspace System (NAS) is a complex network of ground based facilities that allow safe navigation and traffic separation for aircraft in the United States. The Federal Aviation Administration (FAA) is leading the effort to modernize the NAS. The objectives of this modernization effort are enhanced safety, flexibility and efficiency of flight operations for all aircraft ranging from the single engine general aviation aircraft to the complex commercial jet-liners. The modernization of the NAS entails, in part, supplanting navigation services currently being provided by ground based facilities with the satellite based Global Positioning System (GPS).

There are four primary ground based facilities that currently provide navigation services in the NAS architecture. They are: Non-Directional Beacons (NDB), Very High Frequency Omni-directional Range (VOR), Distance Measuring Equipment (DME) and Instrument Landing System (ILS). A detailed description of these systems can be found in [1, 2]. Of these ground based navigational aids, the 932 VOR and DME facilities operated by the FAA form the backbone of the NAS architecture. VORs are ground based radio transmitters which provide a relative bearing between the VOR and the user location. DME is a ground based transponder which provides the range between the user and the DME transponder. With a few exceptions, VOR transmitters are co-located with a DME transponder and most navigation by General Aviation (GA) aircraft is conducted in a "connect the dots" fashion from one VOR-DME site to the next. The estimated yearly cost for maintaining the VOR-DME infrastructure is around $84 Million [3]. Eliminating or reducing the number of active ground based navigaitonal facilities by transitioning to a GPS based NAS architecture will reduce this cost significantly.

2. Problem Statement

The proposed NAS architecture with sole-means GPS navigation raises several concerns. The primary of these concerns is the susceptibility of GPS to radio-magnetic interference [4]. In an environment of sole-means GPS, unavailability in a large area can be caused by radio-magnetic interference. For most modern commercial jet-liners, however, this does not pose a significant problem. Such aircraft normally have adequate fuel reserves and sophisticated Flight Management Systems. The FMS are coupled to a high accuracy Inertial Navigation Systems (INS) which will allow such aircraft to navigate through temporary GPS outages. GA aircraft are normally not equipped with such instrumentation nor do they carry adequate fuel reserves to navigate out of a large area of interference. A redundant means of navigation, independent of GPS, is required to mitigate the threat of interference. In [5] it is shown that acceptable performance for a such a redundant navigation system would be accuracy on the order of one nautical mile after 30 minutes of use.

3. A DME Based Solution

NAS architectures that are based on retaining a small subset of the existing radio-navigation aids as a backup while allowing such minimal navigation performance as described above are discussed in [6]. One architecture discussed would retain a skeletal network of DMEs for ρ-ρ navigation capability (i.e., triangulation by multiple range measurements). This architecture can be the basis for a redundant navigation system for all user segments of the aviation community because:

(a) DME triangulation combined with inertial navigation is a scheme of navigation that is currently used by FMS found on complex jet-lines [7]. The availability of inexpensive but high-powered micro-processors along with the recent proliferation of low cost inertial and dead reckoning sensors make construction of similar systems for GA users possible.

(b) VOR and NDB are systems that provide angular measurements and thus have accuracy that degrades with distance when used as part of a navigation system with area navigation capability. Increased accuracy will require a dense network of VOR or NDB sites. This is counter to the philosophy of maintaining as few as possible ground based navigation aids during this period of transition to a sole-means GPS NAS.

(c) A usable skeletal network of ground based facilities may require relocating some radio-navigation aids. In comparison to a VOR facility, it is easier and less costly to install and maintain a DME facility. It is estimated that the cost of installing a DME facility is approximately 25 percent that of a VOR facility.

In this paper, a navigation system that combines DME triangulation with Dead Reckoning (DME-DR navigator) is presented. In section 4, the NAS architecture based on a skeletal network of DME is described. Section 5 presents the DME-DR navigator and the sensors that are part of the system. In section 6, a mathematical formulation and mechanization of the DME-DR navigator are presented. Section 7 presents results which quantify the performance of the DME-DR navigator. Section 8 presents a summary and some conclusions.

4. DME Based NAS Architecture

Figure 1 shows the current distribution of DME transponder sites over the Continental United States (CONUS). Given three range measurements from three separate DMEs, one can derive latitude, longitude and altitude information. In theory, these are the only measurements required to construct an area navigation system. This is not a practical solution since the Geometric Dilution Of Precision (GDOP) in the vertical direction is large and will require that altitude information be determined using other means. A more practical approach is to use two or more DME range measurements and barometric altitude measurements for position fixing. DME is a line-of-site system and from Figure 1 it is readily apparent that there are places in the CONUS airspace where range measurements from two or more separate DMEs (i.e., multiple DME coverage) will not be available at the same time. The DME coverage density shown in Figure 1 does not adequately provide area navigation capabilities everywhere in CONUS airspace; a skeletal network of DME will be even less capable. A solution to this problem is to provide the coverage required in the vicinity of those airports where disruption of GPS navigation services can have a significant effect on the flow of air-traffic in the NAS. Figure 2, based on data in [6], shows the locations of the 200 busiest airports in CONUS. If double DME coverage is provided at these airports, position fixing using DMEs can be accomplished and a redundant means of navigation will have been provided. Figure 3 is a summary of data compiled in [6] and shows the number of existing and new DME sites that will be required to provide double and triple coverage down to altitudes of 500 and 1500 feet AGL at the airport locations depicted in Figure 2. Even though triple coverage down to 500 feet AGL may not be necessary at all airport locations, it should be noted that such coverage will required approximately only 1/2 of the total number of DMEs shown in Figure 1. These results demonstrate the possible reduction in the existing radio-navigation aid infrastructure while providing a redundant means of navigation in the event that GPS services are disrupted.

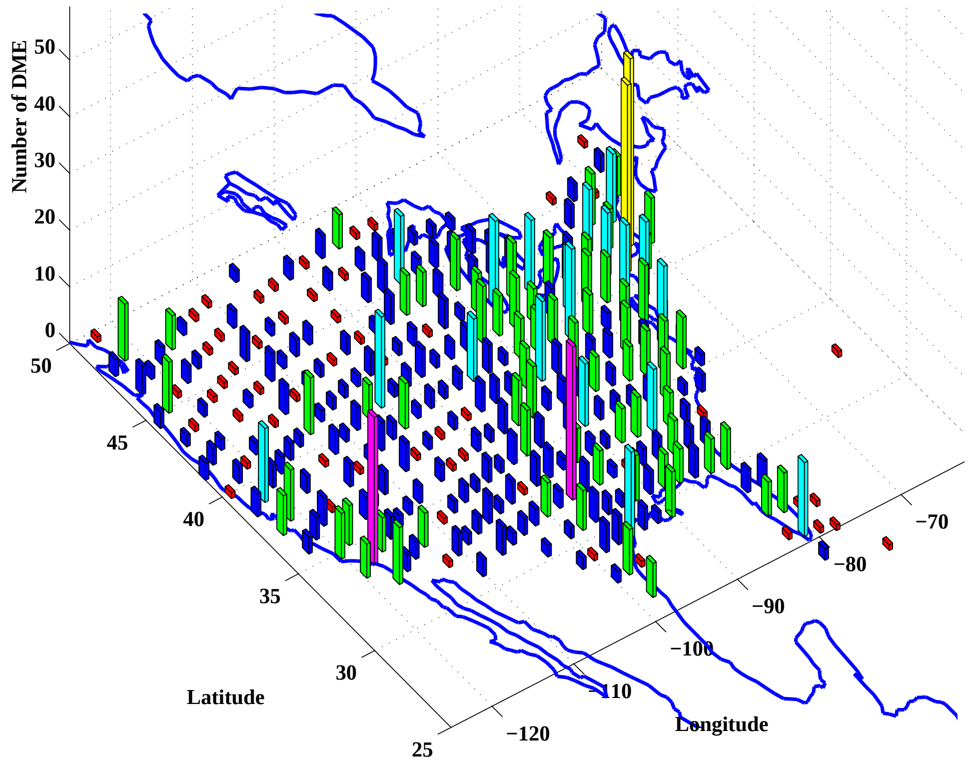

Figure 1: VOR/DME Distribution (Bins = 100 miles^2 Area)

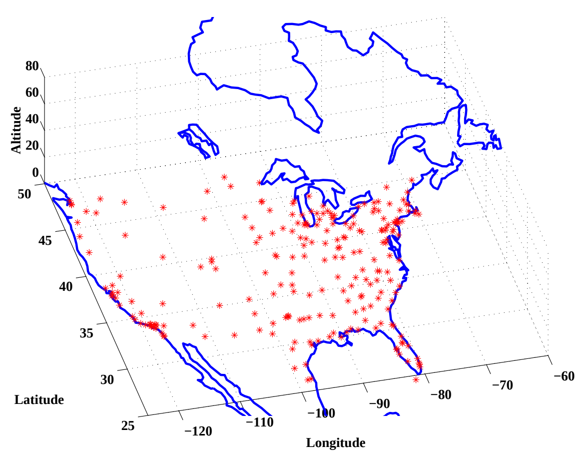

Figure 2: Location of 200 Busiest Airports.

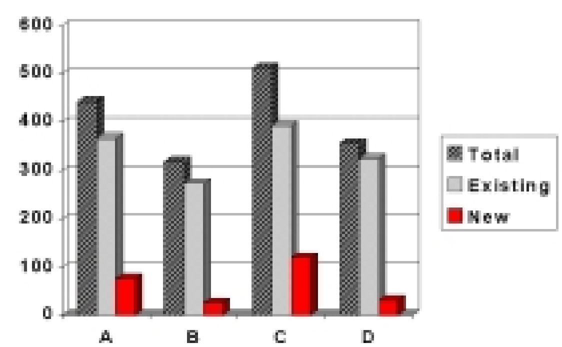

Figure 3: Number of DME Required for Triple and Double Coverage. (A) Triple Coverage to 1500 ft AGL (B) Double Coverage to 1500 ft AGL (C) Triple Coverage to 500 ft AGL (D) Double Coverage to 500 ft AGL

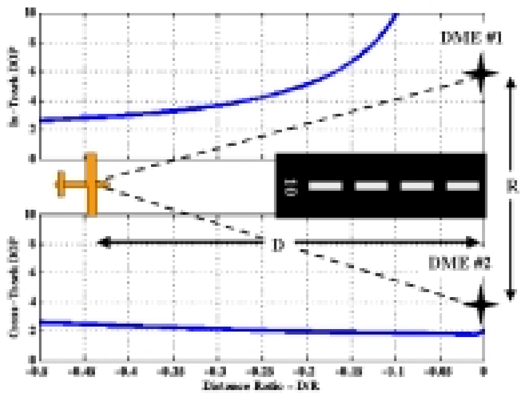

Figure 4: Dilution of Precision for 2 DME Position Fixing.

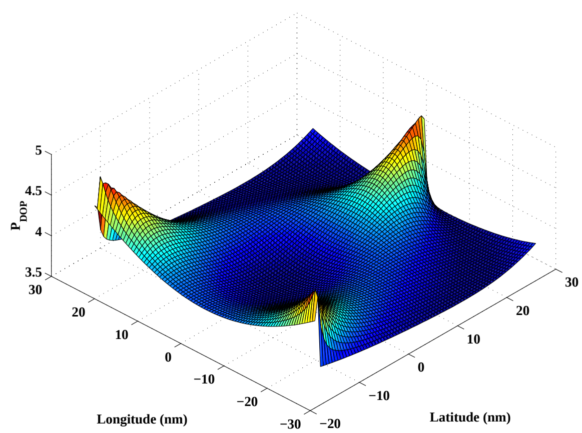

Figure 5: Dilution of Precision for 3 DME Position Fixing.

The relative location of the DME and the user determines the accuracy of the triangulation solution. Figure 4 shows the dilution of precision for the position fixing problem when two range measurements and an altimeter are used. Figure 5 shows the GDOP for a three DME triangulation with barometric altitude measurements. The DMEs are located at the vertices of an equilateral triangle. While the coverage provided by a three DME geometry is ideal if the airport is located at the center of the triangle, locating it elsewhere will also have favorable GDOP compared to a two DME case. From this analysis, it is clear that triple coverage is a superior geometry. However, double coverage can be adequate in certain scenarios.

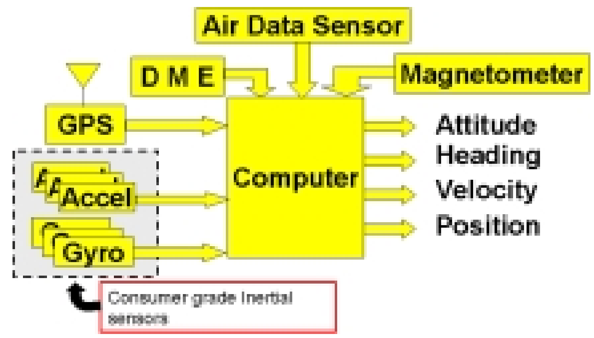

Figure 6: DME-DR System Hardware Architecture.

5. Architecture of the DME-DR Navigator

Obtaining continuous or very frequent range measurements from two or more DME transponders is difficult in practice. Most DME receivers are capable of tracking only one DME station at a time. Specialized airborne receivers called scanning DMEs capable of tracking multiple stations at a time exist, but these are expensive items and used almost exclusively in the newest commercial jet liners. One solution is to carry multiple DME receivers so that two or more simultaneous range measurements from two separate DME ground stations will be available. This scheme is problematic because DME is a query/response system with finite capacity. Therefore, high bandwidth position information by continuous triangulation from multiple DME during a GPS outage can saturate the ground-based DME transponders when they are needed the most.

The solution is to combine inertial or dead reckoning sensors with DME in a complementary filter. The high bandwidth information needed for guidance and control on the aircraft will be provided by the inertial or dead reckoning sensors. The DME range measurements will be used intermittently to provide position updates thereby bounding the drift error that is present in inertial or dead reckoning systems. A schematic diagram of such a system is shown in Figure 6.

In such a system, position updates will come from DME triangulation. Between the DME updates, an INS or dead reckoning is used to propagate the position solution. In [8] is was shown that high quality (and expensive) inertial sensors are required to make this an acceptable navigator.

A low cost version of this system, suitable for GA use, must rely on a traditional dead reckoning scheme where heading and velocity measurements are used to

Sensor or Component	Existing Equipment	Estimated Cost (Dollars)
GPS Receiver	Yes	0
DME Receiver	Yes	0
Consumer Grade AHRS[(1)]	No	1.5 k
Additional Hardware	No	0.5 k
Total Cost		2.0 k

Table 1: Components and Estimated Additional Cost of Sensor Required for a DME-DR Navigator.[(2)]
(1) Includes IMU (Accelerometers and Gyros), Air Data Sensors and a Magnetometer Triad.
(2) This is the cost of the sensors required for the system and not what such a device would sell for.

propagate a position solution forward in time. Heading information can be derived from a magnetometer, a fluxgate compass or an Attitude Heading Reference System (AHRS) such as the one described in [9]. Velocity measurements will be provided by an air data sensor. Corrections for wind and track angle will be provided by an estimator that combines the DME position fixes with the dead reckoning solution. It is estimated that the sensor cost breakdown for constructing this system is as shown in Table 1.

6. DME-DR Mechanization and Filter Formulation

In this section the details of the Extended Kalman Filter (EKF) for mechanizing the DME-DR navigator are described. First the non-linear measurement equations are presented. The measurement equations are then linearized with respect to the selected state vector. Finally, the time update equations for propagating the navigation sates and covariances between measurement updates are described.

Measurement Equation
As noted earlier, the measurements needed for position determination by triangulation are two DME ranges (R_1 and R_2) and barometric altitude (h). When these measurements are used to form a non-linear measurement equation of the form $\vec{z}(t) = h(\vec{x}(t))$, the vector $\vec{z}(t)$ becomes:

$$\vec{z}(t) = \begin{bmatrix} \sqrt{{R_1}^2 - (h - p_{d1})^2} \\ \sqrt{{R_2}^2 - (h - p_{d2})^2} \end{bmatrix} = \begin{bmatrix} Rxy_1 \\ Rxy_2 \end{bmatrix} \quad (1)$$

and the measurement matrix $h(\vec{x}(t))$ becomes:

$$h(\vec{x}(t)) = \begin{bmatrix} \sqrt{(p_n - p_{n1})^2 + (p_e - p_{e1})^2} \\ \sqrt{(p_n - p_{n2})^2 + (p_e - p_{e2})^2} \end{bmatrix} \quad (2)$$

$$= \begin{bmatrix} \hat{R}xy_1 \\ \hat{R}xy_2 \end{bmatrix}. \quad (3)$$

The variables p_n, p_e and p_d are the current position of the DME-DR navigator. The variables p_{ni}, p_{ei} and p_{di} are the North-East-Down coordinates of the i^{th} DME which is located at a range of R_i from the DME-DR navigator. Implementation of an EKF requires linearizing Equation 3 so that it is in the form of $\vec{\delta z}(t) = H(t)\,\vec{\delta x}(t)$. The state vector $\vec{\delta x}(t)$ is selected to be

$$\delta\vec{x} = [\delta p_n \; \delta p_e \; \delta V_{w_N} \; \delta V_{w_E}]^T, \quad (4)$$

where V_{w_N} and V_{w_E} are the north-south and east-west components of the velocity of the wind. Linearizing Equation 3 yields the Jacobian matrix $H(t)$ of the following form:

$$H(t) = \begin{bmatrix} H_{11} & H_{12} \end{bmatrix}. \quad (5)$$

The submatrix H_{11} is given by:

$$H_{11} = \begin{bmatrix} \frac{(p_n - p_{n1})}{\hat{R}xy_1} & \frac{(p_e - p_{e1})}{\hat{R}xy_1} \\ \frac{(p_n - p_{n2})}{\hat{R}xy_2} & \frac{(p_e - p_{e2})}{\hat{R}xy_2} \end{bmatrix}. \quad (6)$$

The submatrix H_{12} is a 2×2 matrix of zeros. Since the final variables of interest to the user are position in the form of latitude (L) and longitude (λ), after each measurement update, the latest estimates of δp_n and δp_e are blended into latitude and longitude using the following equations:

$$L^{(+)} = L^{(-)} + \frac{\delta p_n}{R_0} \quad (7)$$

$$\lambda^{(+)} = \lambda^{(-)} + \frac{\delta p_e}{R_0 \cos(L^{(-)})} \quad (8)$$

In the above equations, the variable R_0 is the equatorial radius of the earth.

Time Update Equations
If it were possible to acquire high bandwidth DME range measurements, the measurement equations would be sufficient for position determination. The concern for DME saturation, however, places an upper limit on the frequency of DME range updates. Therefore, time update equations are needed for propagating the navigation states between the infrequent

measurement updates. The time update equation can be derived by noting that given a measurement of ground speed and track angle, one can resolve the velocity measurements into a north-south component and an east-west component. The velocity components are then integrated once to yield position. More precisely, the north component is given by:

$$V_{North}(t) = V\cos(\Psi). \tag{9}$$

The east component is given by:

$$V_{East}(t) = V\sin(\Psi). \tag{10}$$

In Equations 9 and 10, Ψ is the track angle (measured with respect to true north) and V is the aircraft's ground speed. The north-south component of velocity is substituted into the differential equation describing the time evolution of latitude and is integrated to yield latitude (L). Mathematically, this is given by:

$$L(t) = \int_{t1}^{t2} \left(\frac{\partial L}{\partial t}\right) dt = \int_{t1}^{t2} \left(\frac{V_{North}}{R_{NS} - h}\right) dt. \tag{11}$$

Similarly, the time evolution of the longitude state is a function of the east-west component of velocity and is given by:

$$\lambda(t) = \int_{t1}^{t2} \left(\frac{\partial \lambda}{\partial t}\right) dt = \int_{t1}^{t2} \left(\frac{V_{East}}{R_{EW} - h}\right) dt. \tag{12}$$

In the above equations, h is altitude. Since a North-East-Down coordinate system is being used, h is negative for altitudes above the reference ellipsoid. R_{NS} and R_{EW} are the north-south and east-west radii of the earth respectively.

Since ground speed and track angle are quantities that can not be measured directly, Equations 9 and 10 are recast in terms of a measurable quantities, airspeed (V_a) and heading (ψ). This leads to the following equations:

$$V_{North} = V_a\cos(\psi) + V_{w_N} \tag{13}$$

$$V_{East} = V_a\sin(\psi) + V_{w_E} \tag{14}$$

Propagation of the covariances requires a linear dynamical equation for the states defined in Equation 4. Such a relation can be obtained from a perturbation of velocity equations. Thus, perturbation of the north velocity equation results in the following:

$$\delta\dot{p}_n = \delta V_N = \delta V_a\cos(\psi) - V\sin(\psi)\delta\psi + \delta V_{w_N}. \tag{15}$$

A similar perturbation of the east velocity equation results in the following:

$$\delta\dot{p}_e = \delta V_E = \delta V_a\sin(\psi) + V\cos(\psi)\delta\psi + \delta V_{w_E}. \tag{16}$$

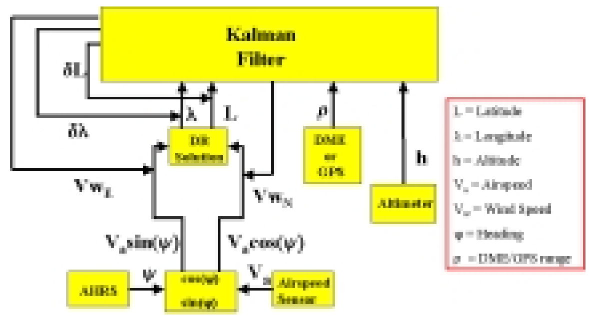

Figure 7: Navigation Filter Architecture

Since heading is being fed in from an external system using a filter described in [9], the perturbation of ψ is assumed to be zero. Furthermore, since the errors in V_a are small when compared to the error due to the winds, they will not be treated separately from the wind errors. Thus,

$$\delta\dot{p}_n = \delta V_{w_N}. \tag{17}$$

$$\delta\dot{p}_e = \delta V_{w_E}. \tag{18}$$

A dynamic model for δV_{w_N} and δV_{w_E} requires an error model of the wind field. In this paper, the error models described in [10] were used. Specifically, the winds are assumed to be a Gauss-Markov process with a variance and a correlation distance which are functions of altitude. A correlation time is derived by dividing the correlation distance by the estimated ground speed.

Given the above measurement and time update equations, it is a simple matter of implementing an EKF for blending in the range measurements with the dead reckoning solution [11]. A block diagram of the architecture of the filter that performs this navigation solution is shown in Figure 7.

7. Experimental Setup and Results

Experimental validation of the DME-DR navigator algorithm was conducted on post-processed flight test data collected using a Beechcraft QueenAir, a twin engine GA aircraft. The aircraft was equipped with a sensor suite which included a low cost magnetometer triad (Honeywell HMR2300), an air-data computer (Shadin ADC200) and a low cost Inertial Measurement Unit (CrossBow DMU-FOG). A very accurate record of the aircraft's trajectory was captured using GPS augmented by the Stanford University Wide Area Augmentation System (WAAS) prototype. In addition, a highly accurate record of the aircraft's

DME Update Scheme	Mean Error (NM)	Standard Deviation (NM)
Open Loop	2.3160	1.2574
Continuous (1 Hz update)	0.1233	0.0646
2 DME Intermittent (1/15 = 0.07 Hz update)	0.1333	0.0838
1 DME Intermittent (1/15 = 0.07 Hz update)	0.1426	0.0934

Table 2: Error Statistics for a DME-DR Navigator in Nautical Miles

heading, pitch and roll angles was captured by a navigation grade (0.01 deg/hr drift) Inertial Reference Unit (Honeywell YG1851 IRU). Although the aircraft was equipped with a low cost DME (Allied Signal KN-64), part of the study was to determine the effect of DME geometry on the navigation solution. Therefore, in the results that follow, the DME range measurements were simulated. Given the position coordinates of the simulated DME transponders, the accurate record of aircraft position recorded by GPS/WAAS was used to back-out the error-free DME ranges that would have been observed. The generated range measurements were then corrupted using DME range error models documented in [10, 12].

The flight test trajectory consisted of a series of 360° turns simulating a holding pattern followed by a straight in approach to runway 25L at Livermore airport in Livermore, CA. Heading was derived using an algorithm similar to the one documented in [9] which relied on low cost magnetometers and inertial sensors. In accordance with a highly simplified DME loading analysis contained in [5], DME scanning frequency was limited to once every 15 seconds to mitigate saturation.

Figure 8 shows the performance of the DME-DR navigator. The performance of various techniques for blending in the range measurements with the dead reckoning solution are shown. Table 2 summarizes the error statistics for this navigator. As can be seen from Table 2, the position error is at most on the order of 900 ft. Note that the open loop solution drifts and by the time the aircraft has landed, the open loop solution indicates that the airplane has passed the airport. This is indicative of a wind error for which the closed loop solution is compensating.

8. Conclusions

As the FAA moves to a sole-means GPS NAS, the need for the existing radio-navigation infrastructure will diminish. During the transition to a sole-means GPS NAS, a skeletal network of existing radio-navigation aids should be left in place to serve as a redundant means of navigation in the eventuality that GPS services are unavailable at a given location due to jamming or interference. The potential exists for making this skeletal network of radio-navigation aids very small by equipping general aviation aircraft with low cost inertial and dead reckoning navigation systems. One possible skeletal NAS architecture retains only DMEs in the vicinity of busy airports. This provides the capability of position fixing by triangulation which, in turn, is used to bound the drift of inertial or dead reckoning navigators.

This paper summarized the performance of DME-DR navigator that is based solely on low cost sensors. Such sensor suites are affordable and are finding their way into newer General Aviation aircraft. It was demonstrated that with the appropriate DME geometry, a DME-DR system can navigate with an accuracy on the order of 1/6 of a nautical mile. This system can be made for a cost of parts on the order of $2000. This result means that the total navigation suite would consist of a GPS receiver and a DME-DR system.

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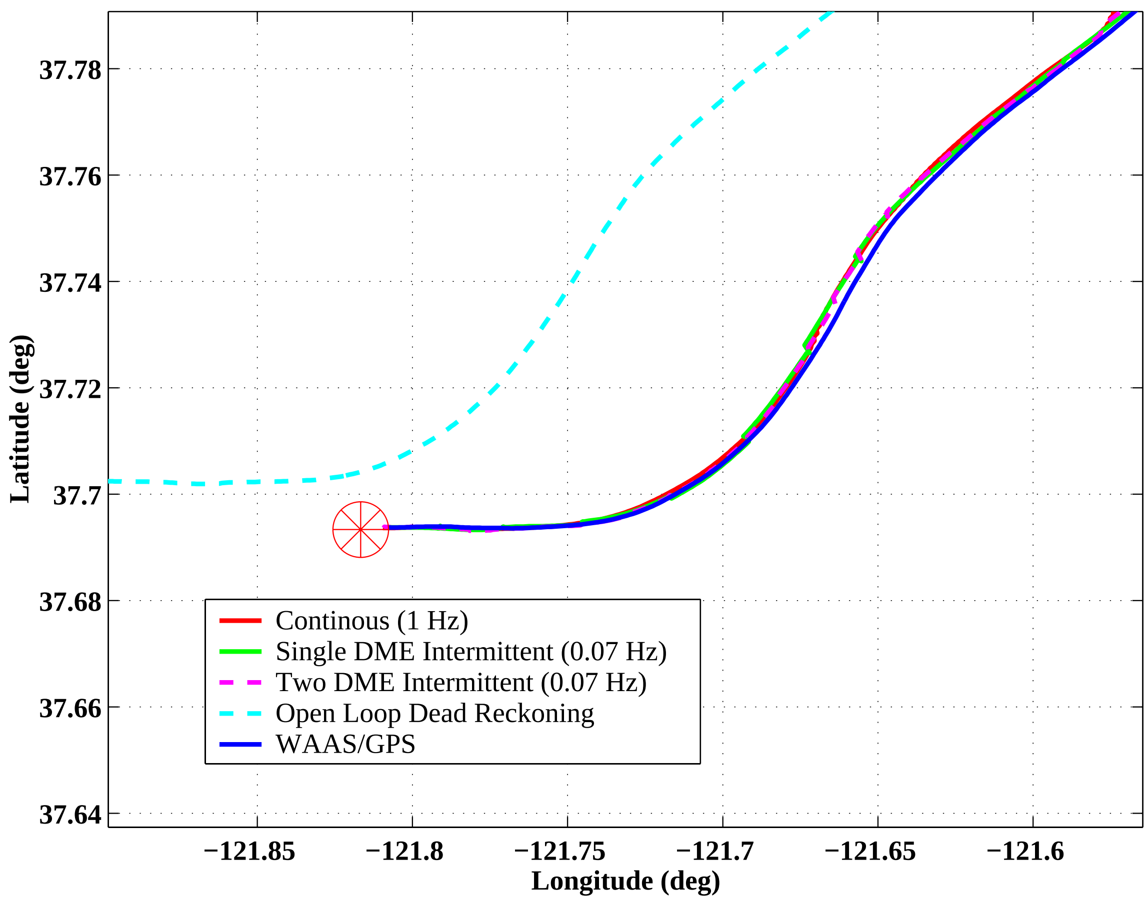

Figure 8: Performance of a DME-DR Navigator

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