# Use of Distance-measuring Equipment (DME) for Correcting Errors in Position, Velocity, and Wind Measurements from Aircraft Inertial Navigation Systems

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## ABSTRACT

Aircraft distance-measuring-equipment (DME) data are used to update position, velocity, and wind measurements from inertial navigation systems (INS) measurements. Data from conventional single-channel DME sets, suitably calibrated, are shown to be adequate to resolve the Schuler oscillation and correct INS positions to better than 1-km accuracy. The satellite-based NAVSTAR global position system (GPS) is rapidly superseding other systems for external position reference. However, DME is reliable and very accurate and has been recorded on many research datasets. The principal limitation of the DME is that it is restricted to land-based navigation. The regression technique used does not necessitate multiple DME receivers or station switching and involves few restrictions on the collection of the data. However, the results improve when more than one station is used. Comparisons with other navigation systems (interferometer and loran) demonstrate the method's skill in resolving INS errors. Intercomparisons among several research aircraft flying in close formation support the method's usefulness in correcting biases in INS data.

## 1. Introduction

Analysis of meteorological data from research aircraft often requires knowledge of aircraft velocity and position so that the time series of measurements can be converted to the spatial domain. A variety of instruments are used for this. Early research aircraft used the radio navigational instruments available in the cockpit. These include VOR (very high frequency omnidirectional range) and DME (distance-measuring equipment) that measure, respectively, bearing and distance to a fixed navigational station. Doppler navigational radars later measured ground velocity components directly. Long-range hyperbolic navigation systems such as loran (long-range navigation) and Omega are also available. The inertial navigation system (INS) measures accelerations that are integrated first to obtain velocity; integration of velocity then yields position. As discussed by Lenschow (1986), the INS has the advantage of higher frequency response and output of aircraft attitude angles. The satellite-based NAVSTAR global positioning system (GPS) is just now becoming generally available. However, there is a large body of aircraft data in which only the traditional navigation measurements (VOR, DME, and less often INS) are available.

For wind measurement on aircraft, simultaneous measurements are taken of aircraft velocity vectors relative to the ground and relative to the air, which are subtracted to get the wind (see, e.g., Axford 1968; Lenschow 1986). The INS measures acceleration and attitude angles with sufficient bandwidth to capture aircraft motions at a high rate (~10 Hz), although accelerometer biases, gyroscope drift, and the Schuler oscillation are serious contributors to errors at low frequencies. External position reference and velocity reference data are required to remove these errors.

Nicholls (1978, 1983) used ground speed measurements from Doppler radar and Loran C to correct for long-term drift in the position information from an inertial platform. In postflight renavigation, Fankhauser et al. (1985) involved data from FAA transponder records, radar returns of the aircraft "skin paint," and a specially designed interferometric tracking system (Johnson and Fink 1982) as independent bases for correcting aircraft track and winds. More recently, Shaw (1988) has reported on the use of Loran C for the same purpose.

Here, we investigate the use of DME as a reference for INS position and velocity correction. DME has the

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advantage over other conventional instruments in that it is reliable, very accurate, and generally available over land. The DME data used did not necessitate repetitive station switching or multiple sets to produce accurate position updating, nor use of the error-prone VOR bearing measurements that usually accompany DME. We describe a regression technique that solves for INS position and velocity errors using DME as the only reference. Although the procedures developed here have potential for real-time application, our analyses consider only renavigation of archive datasets.

Our motivation for developing this method was to correct data from past land-based projects in which DME has proved in our experience to be the most reliable and accurate reference available. The main shortcoming of our work here is the absence in this data of a ground-velocity reference. For the future, GPS is rapidly superseding other external positioning systems, but DME presently has the advantage of wide availability in these existing datasets.

## 2. Measurements

Data for this paper are from the University of Wyoming King Air (*N2UW*), the University of North Dakota Citation (*N77ND*), the NCAR King Air (*N312D*), and the multiple-aircraft positioning system (MAPS) described by Johnson and Fink (1982).

### *a. Inertial navigation system*

The INS's used on all three aircraft are three-accelerometer local-level systems manufactured by Litton (LTN-51 on *N2UW* and *N312D,* and LTN-72 on *N77ND*), which are typical of the commercial inertial navigational platforms manufactured during the past 30 or so years and utilized on research aircraft. Predominant error sources are initial misalignment, gyroscope drift and accelerometer measurement biases, scale-factor errors, and random errors.

Prediction of actual errors from real flights is not possible without external reference because the precise source of all the instrumental errors is not typically known. Britting (1971) demonstrated the character of these errors under various conditions of accelerometer bias and gyroscope drift. The predominant modes involve the Schuler period $2\pi(R_e/g)^{1/2} = 84.4$ min, where $R_e$ is the distance from the center of the earth and $g$ is the acceleration due to gravity and the Foucault terms that modulate the Schuler oscillation with a 34-h period at latitude $\lambda = 45°$. Lenschow (1986) describes these more fully.

The actual errors are also complicated functions involving the exact velocity history of the aircraft and that cannot be accurately predicted. Thus, external references (such as the DME used here) are needed to empirically correct for the errors either in real time or in postflight analysis.

### *b. DME*

The DME transmitter on the aircraft transmits a pulse pair to a ground-based station that is then retransmitted back to the aircraft with a known delay. In modern systems, the principal error involves only the measurement of time, and with calibration is accurate to 0.50 km with no significant problems associated with drift. The main source of error is the effect of terrain on radio-wave propagation, which is negligible under most conditions where the aircraft is $\leqslant 100$ km from the station. The DME on *N2UW* was manufactured by King (model 705A), and on *N77ND* and *N312D* by Collins (model DME-40).

## 3. Analysis

There are two steps in producing estimates of INS position errors. The first calculates the INS latitude and longitude errors by minimizing in a least-squares sense the difference between the distance to a station measured by the DME, and the distance to the station estimated by the INS. Small time segments of the flight ($\approx$5 min) are used to perform these calculations. The second step takes the intermittent errors from the first step and interpolates to produce a continuous and smooth time-dependent function to represent INS error at any point in the flight.

These procedures are performed in postflight analysis. Data are 1-s–averaged values obtained from archive tapes. All DME slant-range measurements have been converted to horizontal range. Aircraft altitude errors have not been considered since they contribute negligibly to the total error.

### *a. Position error estimation with DME*

One way to view this method is as triangulation, but generalized from the standard technique in two important ways. First, an arbitrary number of distance measurements is used instead of just three. A nonlinear regression technique is used to optimally combine the measurements, as explained in the following. Second, this method determines the *relative* position of a target instead of its *absolute* position. In effect, this method triangulates the apparent location of a DME station as seen by INS data. This apparent location minus the true DME station location provides the sought for INS corrections. Each sample consists of: 1) the distance to the DME station calculated from the INS latitude and longitude using a fitting function involving the errors as constant coefficients; and 2) the distance to the station calculated from the DME and aircraft altitude.

The model used is

$$D_i = f(\hat{\lambda}_i, \hat{l}_i; \lambda_{\mathrm{DME},i} + \epsilon_\lambda, l_{\mathrm{DME},i} + \epsilon_l) + e_i \quad (1)$$

where $\hat{\lambda}_i$ and $\hat{l}_i$ are the INS measurements of latitude and longitude of the aircraft, and $\lambda_{\mathrm{DME},i}$ and $l_{\mathrm{DME},i}$ are the precisely known latitude and longitudes of the DME stations referenced at each point, respectively. Thus, a standard problem in nonlinear regression is obtained, whereby each observation $D_i$ is given as a nonlinear function of the unknown INS corrections $\epsilon_\lambda$ and $\epsilon_l$, plus a measurement error $e_i$. The data are analyzed to eliminate biases and scale factor errors prior to application. For our data it is reasonable to treat the measurement errors in DME distances as random and uncorrelated between observations. Then a suitable method for solving the regression problem is nonlinear least squares. That is, we take as our "best" estimates of the INS corrections those values of $\epsilon_\lambda$ and $\epsilon_l$ which minimize

$$\sum_{i=1}^{N} [D_i - f(\hat{\lambda}_i, \hat{l}_i; \lambda_{\mathrm{DME}} + \epsilon_\lambda, l_{\mathrm{DME}} + \epsilon_l)]^2. \qquad (2)$$

The least-squares estimates are denoted as $\hat{\epsilon}_\lambda$ and $\hat{\epsilon}_l$, respectively. A short period of time ($\approx$5 min) is required to obtain a valid estimate of the mean error with sufficient time resolution to adequately resolve the INS errors.

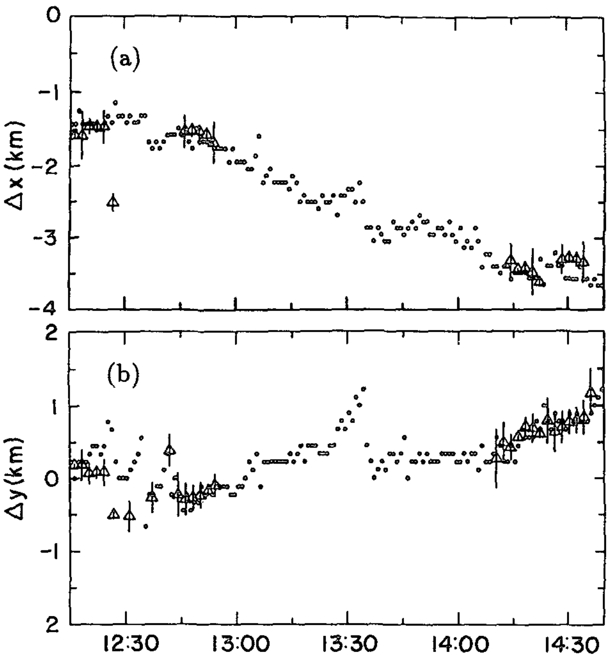

FIG. 2. Difference (km) between Loran C and INS position on 25 March 1986 (small dots). (a) The $x$ (east) component and (b) $y$ (north) component as a function of time. Triangles are results of nonlinear least-squares fit to DME data. Vertical bars represent uncertainty in these estimates.

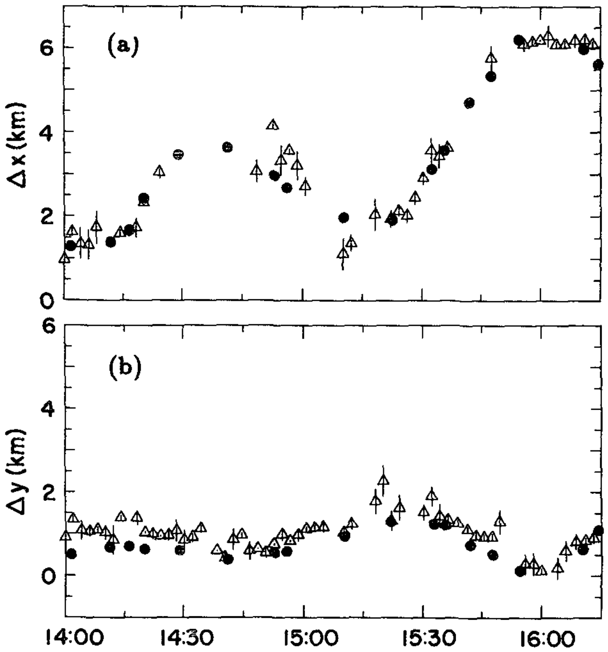

FIG. 1. Difference (km) between MAPS and INS data on 24 June 1982 (large dots). (a) The $x$ (east) component and (b) $y$ (north) component as a function of time. Triangles are results of nonlinear least-squares fit to DME data. Vertical bars represent uncertainty in these estimates.

It is interesting to note the similarity of Eq. (1) with the earthquake location problem. In that problem, the arrival times of seismic waves observed at various stations in a seismic network are used to infer the location, depth, and origin time of a seismic event. When the origin time and depth of the event are known, the earthquake location problem takes the same form as (1) with $D_i$ as the travel time (arrival time minus origin time) observed at the $i$th station, $(\lambda_i, l_i)$ as the location of the $i$th station, and $(\lambda_{\mathrm{DME}} + \epsilon_\lambda, l_{\mathrm{DME}} + \epsilon_l)$ as the coordinates of the seismic event. The function $f$ in the earthquake problem computes the travel time between two points on the earth's surface using standard travel-time curves. The use of nonlinear least squares for solving the earthquake location problem was formulated by Geiger (1910, 1912) and is the standard technique in use today.

With this method, it is *not necessary* to know the azimuth of the aircraft from a specific DME station. The motion of the aircraft past a single station simulates the multiple-station data that would be needed to determine a position if triangulation were used. By having multiple distance measurements, the calculation of position error is overspecified. The desired certainty in the position error estimates is the only factor that determines the number of data points needed.

As in triangulation (and earthquake location for that matter) certain restrictions on the configuration of observation sites is necessary to obtain accurate solutions. Specifically, the observation sites (airplane locations at which DME measurements are taken) must sweep out a range of azimuths from the DME station. If the observation points are collinear or nearly collinear with the DME station, then the azimuthal coverage will be poor and the data will be unable to resolve both com-

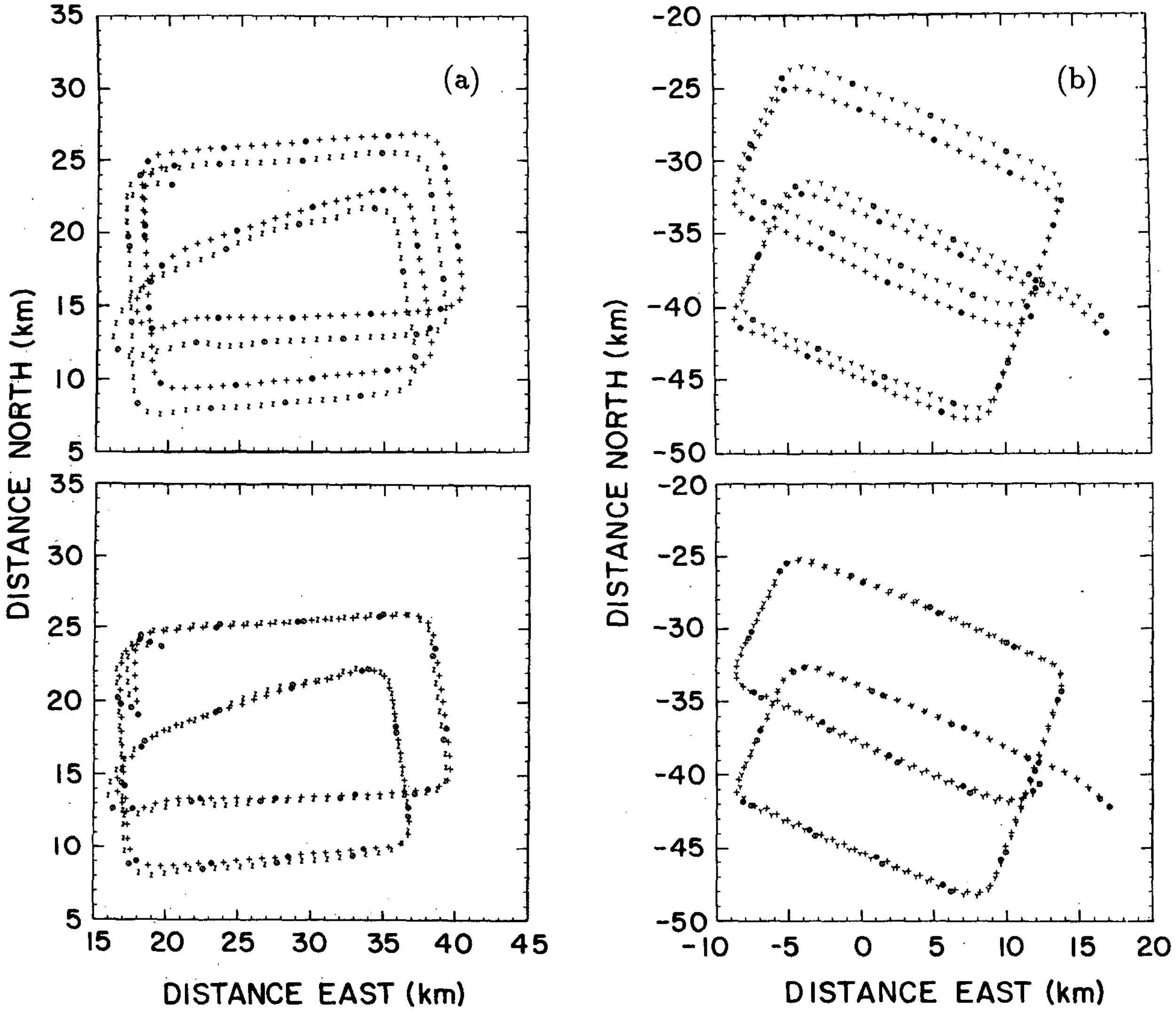

FIG. 3. Aircraft flights tracks before (top) and after (bottom) correction. (a) 17 July 1987, *N77ND* ($z$) and *N312D* (+); (b) 24 July 1987, *N2UW* ($y$) and *N312D* (+); and (c) 7 July 1987, *N2UW* ($y$), *N312D* (+), and *N77ND* ($z$).

ponents of the INS correction vector. The restrictions to flight operations, then, are few. The only requirements are simply that: 1) the aircraft is moving and 2) that it is flying predominantly crosswise to the radials (i.e., not to or from the station). Both of these conditions are necessary since flying precisely to or from the station (or being stationary) provides no information about how the errors in latitude and longitude are partitioned. This is the only restriction on the flight track. To bypass this constraint, software on the aircraft could be used to automatically sense when the aircraft track is along a radial and to switch the DME to another station. This software has proved to be very effective in our application. Alternatively, an operator on the aircraft could make the switch manually.

The unknown errors $\epsilon_\lambda$ and $\epsilon_l$ are then computed using the aforementioned regression method. Aircraft measurements of INS latitude, longitude, and DME distance are logged once per second. The processing procedure eliminates data on legs oriented along DME radials and also rejects data in turns on aircraft, which display biases in this mode.

The problem of solving equations, which are nonlinear in their parameters, is described by Bevington (1969). Bevington's Fortran subroutine CURFIT, adopted for use in this analysis, combines a gradient search with an analytical solution developed by linearizing the fitting functions. The procedure is repeated progressively closer to the final solution until the best fit is obtained.

A solution to Eq. (1) requires that sufficient measurements are available to obtain the desired significance of the result. The trade-off is between confidence in the results and the requirement that errors in latitude

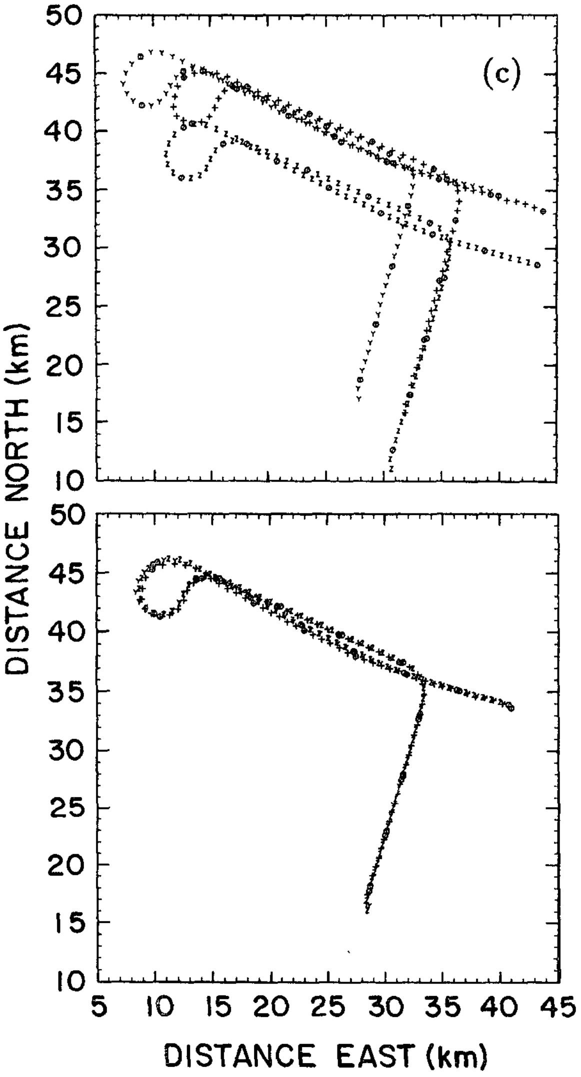

FIG. 3. (*Continued*)

and longitude do not change appreciably in the period chosen. Experience with this procedure has shown that about 250–500 points (4–8 min of data) are needed, a sufficiently short period of time to produce an average error with sufficient time resolution to yield a representative error function. Optimal DME switching strategies could reduce this period.

The estimates of uncertainty in $\epsilon_\lambda$ and $\epsilon_l$ in Eq. (1) are a product of this analysis. These errors are used as weights in the determination of the coefficients in the time-dependent fitting functions discussed in the following. In this manner, the best possible estimates of errors can be obtained for any time in the flight record.

It was found that while the results are very sensitive to errors in the DME slant distance measurement these errors are on the order of 0.5% and, in this case, omitting this correction does not appreciably change the results. DME sets can be accurately calibrated. However, in the datasets investigated here, small scale-factor errors were apparent. Since the regression method partitions all the errors into the INS latitude and longitude, best estimates of the DME bias had to be made. For the purposes here, scale factors were found that minimized the overall variance. These scale factors were typically within 0.5% of the nominal output from the DME. Careful DME calibration before each project would eliminate this step.

The corrected INS latitudes and longitudes were converted to Cartesian $x$ and $y$ positions for the purposes of the plots that follow. Corrections for atmospheric refractive index effects on DME distance were not made here because we arbitrarily chose flight segments close to the station. There are no requirements for station switching, although, for reasons previously mentioned, specific switching strategies could improve results.

### *b. Time-dependent fitting function for position*

The errors computed from the first model apply to specific blocks of time. The objective is a function that predicts the error at any time during the flight. Thus, a piecewise polynomial (cubic) fitting procedure (de Boor 1977) was implemented to derive the fitting functions. This *b*-spline procedure was also used by Shaw (1988) in his analysis of loran corrections to inertial data.

We initially attempted to apply the analytical model as used by Fankhauser et al. (1985), which is expressed as $\epsilon_j(t) = a_{1,j}\sin(2\pi t/T) + a_{2,j}\cos(2\pi t/T) + a_{3,j} + a_{4,j}t$ for the $x$ and $y$ error components, $j = 1, 2$, where $T$ is the Schuler period. This model assumes a sinusoidal component with the Schuler period superimposed on a linear trend. It was found that while this model fits the errors to $\leqslant 1$ km over short periods of time, in some cases it is not general enough to adequately fit the complex behavior of the errors in a general sense. Further, all INS data examined for this paper do not consistently exhibit a strong Schuler periodicity. For these reasons, we have chosen to use the *b*-spline procedure, which makes no assumptions regarding the error behavior.

In a vertically stabilized inertial reference system, the velocity errors can be estimated as the time derivative of the position error (Britting 1971). The functions derived from the *b*-spline fit also are used for this purpose.

## 4. Results

To test the ability of the procedure to estimate the time-dependent errors in latitude and longitude, flights were chosen in which data from a highly accurate and independent position measuring system were available. In the Joint Airport Weather Study (JAWS) conducted in Denver in 1982, the NCAR multiple-aircraft positioning system (MAPS) was used (Johnson and Fink

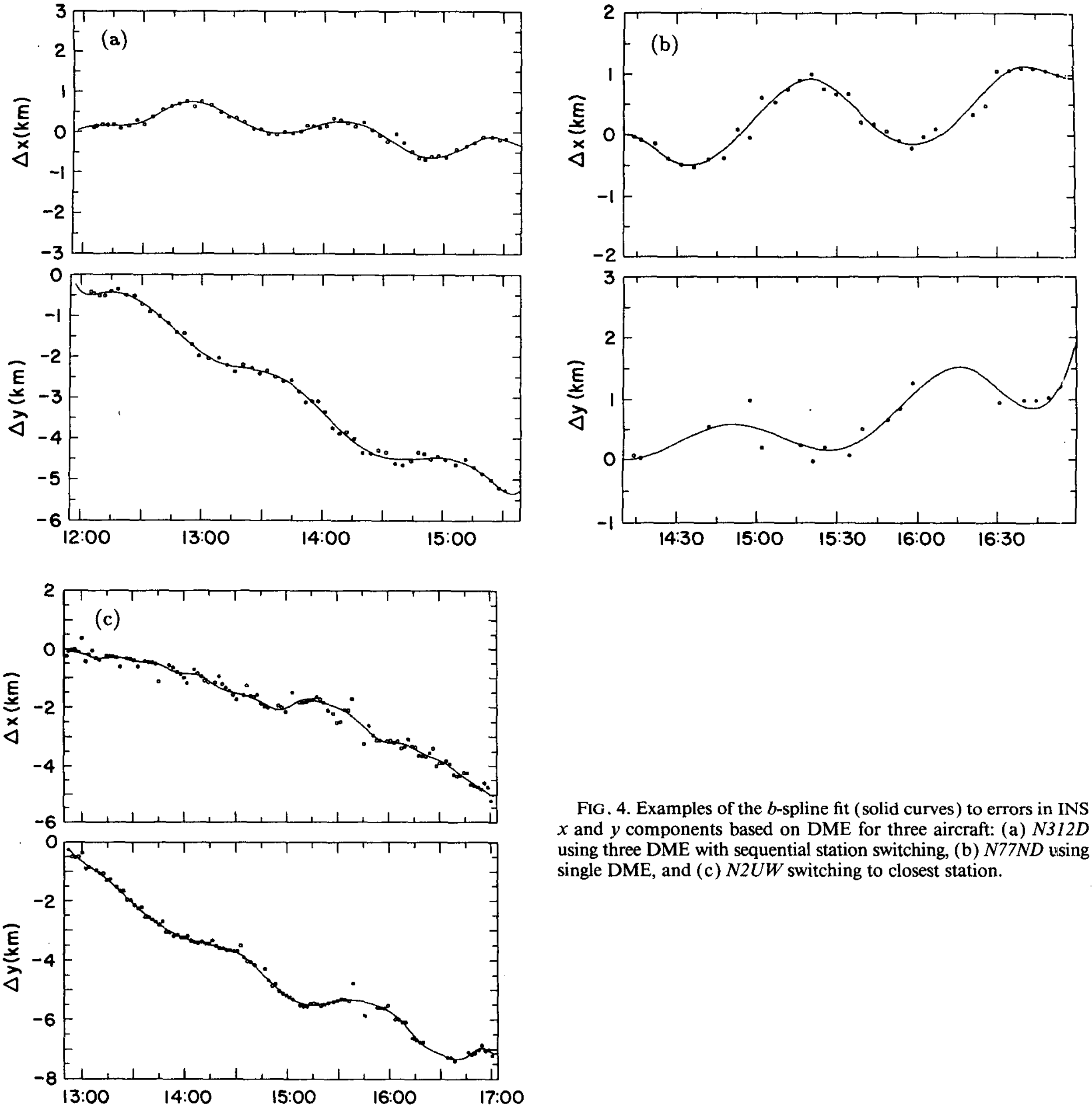

FIG. 4. Examples of the *b*-spline fit (solid curves) to errors in INS *x* and *y* components based on DME for three aircraft: (a) *N312D* using three DME with sequential station switching, (b) *N77ND* using single DME, and (c) *N2UW* switching to closest station.

1982). The MAPS is a hyperbolic navigation system using a triad of ground stations. Aircraft position accuracy in the MAPS data shown here is estimated to be 100 m.

Figure 1 shows the differences between the recorded INS and MAPS-derived east and north position components. Also plotted on this figure are the DME-derived-position error estimates. These DME-derived INS error estimates, although not continuous, can produce a smooth function that closely resembles the MAPS fitting function to within 1 km. This analysis was based on data from a single DME set to a single frequency.

The adequacy of the single DME to resolve INS errors was further tested using loran data. In general, loran data is highly accurate under special circumstances involving terrain, location, and atmospheric conditions (absence of electrical activity in particular). Such optimal conditions existed in Oklahoma on a project in which the aircraft flew repeated low-level legs along roads while the crew maintained visual contact with the ground (Rodi and Parish 1988). In the data to follow, the loran receiver was carefully compensated for time delay errors for each station, and data are estimated to be accurate to 0.50 km.

Figure 2 shows the results of the comparison between loran and INS data. The scatter in the loran data is due to the 0.1-n mi (0.2-km) resolution of the data that were recorded. The DME estimates of error correspond well with the loran estimates and demonstrate that, when available, they are effective in defining the INS error.

Flights involving coordinated in-trail patterns were conducted during the Convective Initiation and Downburst Experiment (CINDE, Wilson et al. 1988). Although loran data were recorded by all aircraft involved in this project, examination of INS–loran difference values revealed unexplainable shifts in the loran data. Similar shifts amounting to 2–3-km uncertainty were also evident in data presented by Shaw (1988). Since we are attempting an objective analysis, we found it desirable to avoid subjective corrections to the loran data and chose to rely solely on DME as the independent database in CINDE.

Figure 3 shows the overlay tracks from research aircraft before and after the corrections from the DME were made. Cases include flights with two and three aircraft flying in close formation. The demonstrated improvement in aircraft track position in these cases supports the conclusion that reduction of error in aircraft position to $\leq 1$ km is routinely possible with this technique.

Examples of time-dependent error functions obtained from the *b*-spline fit are given in Fig. 4 for three of the aircraft tracks included in Fig. 3. Figure 4a is an example where sequential switching was done among three DME stations. In Fig. 4b only one DME station was used. The Schuler period is quite evident in both of these datasets. In contrast, data in Fig. 4c were based on selecting the nearest of three DME sites and do not show a strong Schuler component. The results in Fig. 4c point to the need for a more general fitting function than the sinusoidal model as applied, for example, by Fankhauser et al. (1985). It is clear that multiple DME switching provides the most information, but renavigation using the fit to the single-station data in Fig. 4b appears to provide sufficient time resolution to achieve $\approx 1$-km accuracy, as demonstrated by the improvement of the *N77ND* tracks in Fig. 3a.

Aircraft ground-speed errors are obtained from the derivatives of position error functions of the kind illustrated in Fig. 4. Associated errors in the wind components determined from position error functions for the multiple-aircraft intercomparison illustrated in Fig. 3c are given in Fig. 5. While other factors may contribute to uncertainty in horizontal air velocity components, it is seen that INS error in this example accounts for errors as large as 2 m s$^{-1}$ in wind velocity.

Table 1 summarizes results from the three intercomparison flight legs in Fig. 3c. Errors in INS position directly effect aircraft ground speed, and the first four columns in Table 1 show ground-speed components for the three aircraft involved before and after renavigation (boldface). It can be seen that, in general, corrected ground-speed components compare more closely. Mean wind-velocity errors for each leg (boldface) are also shown for reference, but there is no reason that they should compare directly since they are averages of the derivatives of the position error functions which vary differently with time. Variances of position and velocity were calculated and, as expected, did not change significantly following renavigation. The actual variance values are not shown in the interest of brevity.

## 5. Discussion

As a reference for correcting INS error, DME has the advantage over other independent sources for aircraft position in that it is almost universally available, reliable, and very accurate even though it is limited to land-based navigation. A large body of aircraft data exists for which DME is the most accurate updating reference for inertial data. Loran, Omega, and GPS are all inherently more accurate, but are not always available and reliable. Thus, we have developed a method to determine INS position and velocity errors from simple single-channel DME equipment.

The use of Kalman filters (Leach and MacPherson 1991), which model and solve for INS biases and drifts, has merit in producing more continuous error estimates. The implementation of Kalman filtering is considered to be a logical next step. The regression model presented here could be a useful input into a Kalman-type filter.

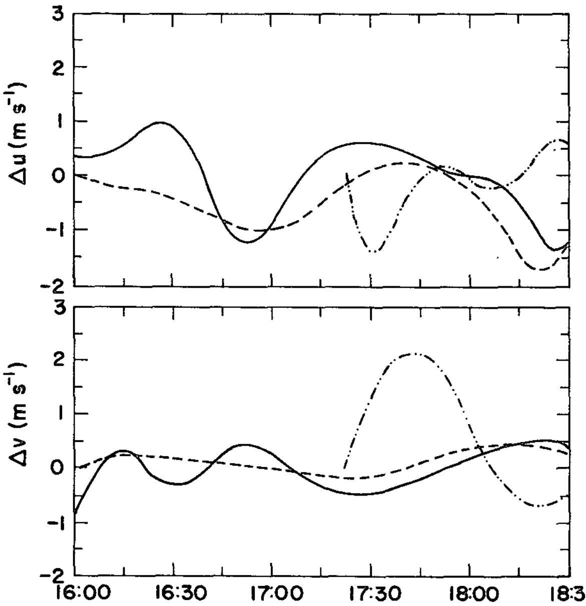

FIG. 5. Derivative of *b*-spline fit of position errors on 7 July 1987 showing contribution to errors in horizontal wind velocity as a function of time. Top is *x* component ($\Delta u$) and bottom is *y* component ($\Delta v$). *N2UW:* solid line; *N312D:* long dashed line; and *N77ND:* dot-dash line.

TABLE 1. Results of ground and wind velocity correction for three intercomparison legs.

| Aircraft | GSX | GSX$_c$ | GSY | GSY$_c$ | $u$ | $u_c$ | $v$ | $v_c$ | $\Delta u$ | $\Delta v$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | First leg | | | | | | |
| *N2UW* | −75.21 | **−75.33** | 32.35 | **32.62** | 7.93 | 7.81 | −1.46 | −1.19 | **−0.12** | **0.26** |
| *N312D* | −74.38 | **−75.12** | 32.09 | **32.46** | 8.93 | 8.18 | −1.19 | −0.81 | **−0.74** | **0.38** |
| *N77ND* | −74.69 | **−74.94** | 32.22 | **32.43** | 7.77 | 7.53 | −1.96 | −0.67 | **0.24** | **1.29** |
| | | | | Second leg | | | | | | |
| *N2UW* | 89.27 | **88.95** | −39.10 | **−38.76** | 7.07 | 6.76 | −0.03 | 0.31 | **−0.31** | **0.34** |
| *N312D* | 89.59 | **88.68** | −38.95 | **−38.49** | 7.16 | 6.26 | −0.28 | 0.18 | **−0.91** | **0.46** |
| *N77ND* | 87.53 | **87.68** | −38.75 | **−39.52** | 6.37 | 6.95 | 1.21 | 1.01 | **0.58** | **−0.20** |
| | | | | Third leg | | | | | | |
| *N2UW* | −23.15 | **−23.66** | −83.01 | **−82.63** | 9.15 | 8.64 | 0.53 | 0.91 | **−0.51** | **0.39** |
| *N312D* | −23.17 | **−24.28** | −82.66 | **−82.20** | 8.86 | 7.74 | 1.35 | 1.81 | **−1.11** | **0.46** |
| *N77ND* | −24.98 | **−24.52** | −81.41 | **−82.41** | 8.13 | 8.92 | 1.45 | 0.34 | **0.79** | **−1.11** |

GSX = $x$ component of aircraft ground-speed vector (m s$^{-1}$). GSX$_c$ = corrected $x$ component of ground speed (m s$^{-1}$).
GSY = $y$ component of aircraft ground-speed vector (m s$^{-1}$). GSY$_c$ = corrected $y$ component of ground speed (m s$^{-1}$).

We have not discussed in this paper the relative merits of the various switching methods for DME (closest station, single station, repetitive switching). Future work will be done to optimize the switching to improve the accuracy of the regression method and to quantify the benefits that result.

Also, when a dataset including external ground velocity measurements becomes available, we plan to do a complete study of the errors that result from the velocity error method described here.

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