Shuttle Subsonic Horizontal Wind Estimation

G. Mel Kelly* and John T. Findlay†
Analytical Mechanics Associates, Inc., Hampton, Virginia
and
Harold R. Compton‡
NASA Langley Research Center, Hampton, Virginia

Deterministic and weighted least squares methods for obtaining estimates of the horizontal winds encountered during the Shuttle entry phase are described. The estimates are based on in situ air data system measurements of angle of attack, sideslip angle, and true airspeed, in conjunction with inertial trajectory parameters obtained from the postflight trajectory reconstruction. Accuracies in the wind estimates obtained from each method are assessed using both theoretical arguments and flight results. Comparisons of derived winds with meteorological measurements taken during the first four Shuttle entries have demonstrated 1) the usefulness of the wind estimators for evaluating meteorological measurements below 50,000 ft, and 2) the potential for adequate wind determinations in the absence of independent wind measurements.

Nomenclature

ACME = aerodynamic coefficient measurement experiment
ADS = air data system
ALT = approach and landing test
BET = best estimate trajectory
h = altitude above the Fischer ellipsoid
IMU = inertial measurement unit
kft = kilofeet
LAIRS = Langley atmospheric information retrieval system
P_∞, ρ = ambient pressure, density
q = dynamic pressure
r = magnitude of geocentric radius vector to the spacecraft
STS = Space Transportation System
T = atmospheric temperature
u,v,w = spacecraft inertial velocity components, north, east, vertical, respectively
u_B,v_B,w_B = air relative velocity components along spacecraft X,Y,Z body axes, respectively
u_w,v_w = geographic wind components, u_w positive southward, v_w positive westward
V_E = equivalent airspeed
V_T = true airspeed
WLS = weighted least squares
α = angle of attack
β = sideslip angle
μ = mean
σ = standard deviation
Φ = geocentric latitude
ψ,θ,ϕ = Euler angles relating spacecraft to geocentric north, east, vertical (downward) system: ψ positive clockwise from north, θ positive above the horizon, ϕ positive right-wing down
Ω_p = Earth rotational rate

I. Introduction

AERODYNAMIC and aerothermodynamic investigations based on the NASA Space Transportation System (STS) entry flights impose many interesting and challenging requirements to obtain accurate postflight information. Compton et al.[1] discussed in detail the reconstruction of the inertial trajectory profile to provide the inertial state and attitude history that best fit the radar tracking measurements during entry. The merging of these data with the best available atmospheric information to obtain the important air-relative parameters required by both aerodynamicists and aerothermodynamicists was also discussed. Thus, the final product, the best estimate trajectory (BET), is based on an ensemble of in situ and remote measurements, viz, spacecraft angular rates, accelerations, and angular accelerations as derived from the triredundant inertial measurement unit (IMU) data; ground-based radar and optical tracking data; and both rocketsonde and rawinsonde atmospheric measurements. Reference 1 contains a brief discussion of the meteorology data evaluation required. It is the purpose of this paper to further quantify the dependence of the BET parameters on the available atmospheric information, with particular emphasis on the necessity of accurately measured winds during the subsonic flight regime, i.e., during the lowermost 50 kft altitude region.

Two wind determination methods are discussed. One method, the deterministic algorithm, requires some measure of air-relative attitude angles, specifically, the angle of attack α and the sideslip angle β. For the Shuttle these data are determinable using in situ pressure measurements from the Orbiter air data system (ADS). The ADS is deployed at ~100 kft ($M \sim 3.5$) and provides usable data below $M \sim 2.5$. This information is obtained as calibrated postflight files. An extension of the deterministic algorithms employs a batch estimate and utilizes, in addition to α and β, the measured true airspeed V_T. The advantages for either method are that no knowledge of the ambient atmospheric parameters is required and, more significantly, in situ measurements that reflect the actual environment through which the spacecraft traversed are utilized. Remote meteorology measurements, principally winds, are necessarily displaced from the actual trajectory in both time and space. Thus these data must be evaluated to establish confidence in the final BET air-relative parameters necessary for such investigations as the aerodynamic coefficient measurement experiment (ACME),[2] as well as similar research throughout the aerospace community.

The following section discusses the influence of erroneous winds on the ultimate accuracy of such aerodynamic research and provides the necessary rationale for the meteorology data

Submitted Sept. 9, 1982. Revision received Jan. 25, 1983.

*Senior Analyst.
†Senior Analyst. Member AIAA.
‡Aerospace Engineer. Member AIAA.

evaluation activities. Section III discusses the mathematical formulation of the two methods. Results are presented in Sec. IV for the four Shuttle entry flights to date.

II. Rationale for Wind Estimation

The accuracy and timeliness of the inertial and tracking measurements permit postflight trajectory determination without reference to any meteorology data. The effects of the actual atmosphere encountered are measured by the spacecraft accelerometers and gyros, as well as by the tracking radars. However, accurate inertial trajectory parameters, although necessary, are not sufficient for aerodynamic researchers. Postflight extraction of the Shuttle aerodynamic coefficients, and comparisons of these results with preflight aerodynamic data base values, requires some measure of the dynamic pressure, Mach number, true angle of attack α, and sideslip angle β. These air-relative parameters require accurate atmospheric density, temperature, and wind measurements, which are normally obtained from the available meteorological data via a Langley atmospheric information retrieval system (LAIRS) file based on rawinsonde and rocketsonde measurements.[3] The meteorological measurements are assembled and translated to the Shuttle ground track and vertical profile and combined with models above 300 kft to define the atmosphere. Although neither time nor spatially optimum, these measurements represent a reasonable source of data for air-relative parameter computations. However, inaccuracies in the meteorological measurements and uncertainties involved in translating the ambient atmosphere in time and space to the Shuttle entry path contribute to uncertainties in air-relative parameter determinations. Further, although rawinsonde wind measurements are incorporated on the LAIRS file, these data can be suspect because, even if a balloon is released at touchdown, a reasonable time (~ 1 h) is required for ascent. This suggests that, if the measured winds are to be adequate, a stable atmospheric condition must prevail.

In the lower atmosphere, ambient parameters (T, P_∞, ρ) can be quantified to a few percent using the measured atmospheric data. However, winds must be accurately known. They affect the computed q and, more importantly, the air-relative attitude angles. The entry reconstruction software[4] provides a fully coupled six-degree-of-freedom inertial trajectory by integrating the measured forces and moments. However, the process assumes no aerodynamic "stiffness" per se. No atmospheric (wind) information is required or utilized during the entry reconstruction. Thus, computations of the air-relative attitude angles can result in untoward deviations from those that one would expect. Typically large sideslip angles and/or major deviations from predicted pitch trim attitudes based on the flight conditions and spacecraft configuration occur when zero winds are assumed. When such is the case, it is *known* that large winds were encountered. When the inertial parameters are combined with some remotely sensed wind profile using the usual kinematic expressions, which at least satisfies the proper definitions of α and β, one then can evaluate the resulting air-relative parameters to determine if the measured winds are adequate. All available wind measurement sources must be considered in such a process.

For Shuttle flights to date, jimsphere balloon measurements have provided an alternate measurement source. Deviations in either α or β from that suggested by the ADS (and other sources) require the type of meteorology data evaluation as reported herein. First indications of inadmissible wind measurements are suggested in the sideslip computations. For example, preliminary winds on the first flight resulted in an approximate 4.5 deg sideslip angle that was inconsistent with both the measured lateral acceleration and the recorded rudder deflections in the immediate interval. In fact, the final measured winds (from both rawinsonde and jimsphere balloons) for STS-3 produced sideslip angle deviations in excess of 4.1 deg. Although not as readily apparent, it should be obvious that the implied angle of attack from both sources would be in error. Again, it is emphasized, that merging of the atmosphere (winds) with the inertial trajectory (for which the inertial attitude is accurately known to a few tenths of a degree) can induce large air-relative attitude angles due to the "passive" nature in which the spacecraft is oriented with the air-relative velocity vector.

The consequence of not providing for some evaluation of the winds, i.e., acceptance of the measurements and resulting air-relative parameters per se, compromises the flight derived aerodynamics. Inaccuracy of the flight-extracted values could preclude the use of the Shuttle as a "flying" wind tunnel or, conversely, accurate determinations can greatly enhance aerodynamic research.

III. Wind Estimation Algorithms

Data Requirements

The wind estimators require both inertial trajectory and air-relative parameters. The required inertial parameters are: geographic position (r, Φ), inertial velocity components in local horizontal (u, v, w), and Euler angles (ψ, θ, ϕ) relating the spacecraft body axes to the local horizontal. The calibrated ADS parameters α, β, and V_T are used as observables for deriving winds, using either a deterministic or weighted least squares method.

Deterministic Algorithm

In this approach α and β are observables and the horizontal wind components (u_w, v_w) are the solution parameters. At each point along the trajectory, the deterministic solution to the 2×2 system of equations is obtained as follows:

$$\alpha = \tan^{-1}(w_B/u_B) \qquad \beta = \tan^{-1}(v_B/\sqrt{u_B^2 + v_B^2}) \tag{1}$$

and, since the vertical wind component is not considered, body velocity components are

$$\begin{bmatrix} u_B \\ v_B \\ w_B \end{bmatrix} = G \begin{bmatrix} u + u_w \\ (v - r\Omega_p \cos\Phi) + v_w \\ w \end{bmatrix} \tag{2}$$

where $G = G(\psi, \theta, \phi)$ is the 3×3 transformation matrix from local horizontal to spacecraft body axes. Equations (1) and (2) relating α, β to u_w, v_w are nonlinear and are solved iteratively using Newton's method. At iteration $k+1$, the wind estimates are

$$\begin{bmatrix} u_w \\ v_w \end{bmatrix}_{k+1} = \begin{bmatrix} u_w \\ v_w \end{bmatrix}_k + P^{-1} \begin{bmatrix} \Delta\alpha \\ \Delta\beta \end{bmatrix} \tag{3}$$

where

$$P = \begin{bmatrix} \dfrac{\partial \alpha}{\partial u_w} & \dfrac{\partial \alpha}{\partial v_w} \\ \dfrac{\partial \beta}{\partial u_w} & \dfrac{\partial \beta}{\partial v_w} \end{bmatrix} \tag{4}$$

and

$$\Delta\alpha = \alpha - \alpha_k \qquad \Delta\beta = \beta - \beta_k \tag{5}$$

α_k and β_k are obtained using the wind estimates from the kth iteration. At each time point the process is initialized with the converged winds from the previous time point and typically converges in about three iterations. Uncertainties in the wind estimates are obtained via a direct map of an assumed diagonal error covariance matrix of the observations,

$$\Gamma_{u_w,v_w} = (P^{-1})\Gamma_{\alpha,\beta}(P^{-1})^T \quad (6)$$

Advantages of the deterministic method are: 1) no mathematical model of the winds is required; 2) in situ wind estimates are obtained; and 3) the technique may be used as a starter for batch estimation by defining breakpoints for a wind model. The disadvantages are: 1) all errors, both systematic and random, in either the ADS observables or the inertial trajectory parameters map directly into winds; 2) a mathematical singularity exists when the flight path angle equals zero; and 3) the magnitude of the air-relative velocity is an unconstrained output of the process.

Weighted Least Squares (WLS) Algorithm

A mathematical model for the winds is required in this method. A standard model, normally used in simulation programs, has been adopted. Wind components are specified at fixed, but arbitrary, altitude breakpoints and are assumed to vary linearly between breakpoints. Estimates and uncertainties in the winds at these breakpoints are the outputs of the estimator.

In general α, β, and V_T are used as observables and realistic accuracies are used in forming the data weighting matrix. The solutions obtained are referred to as BATCH/3 solutions. By downweighting V_T, however, the WLS analogs of deterministic winds are obtained since, effectively, only α and β are being utilized. Solutions obtained using this procedure, which are really smoothed deterministic solutions, are referred to as BATCH/2 solutions and will not be discussed.

Provision has been made to include a priori information about the winds. A priori constraints have been used, however, only to hold wind estimates at the measured values near touchdown. Otherwise, very large a priori wind uncertainties are used.

Given N sets of simultaneous observations of α, β, and V_T, the WLS algorithm for obtaining winds in an M-breakpoint model is

$$\Delta x = (A^T W A + \tilde{\Gamma}_x^{-1})^{-1} A^T W \Delta z \quad (7a)$$

where

$$\Delta x = [\Delta u_{w_1} \Delta v_{w_1} \Delta u_{w_2} \Delta v_{w_2} \ldots \Delta u_{w_M} \Delta v_{w_M}]^T \quad (7b)$$

$$\tilde{\Gamma}_x = \mathrm{diag}[\tilde{\sigma} u^2_{w_1} \tilde{\sigma} v^2_{w_1} \tilde{\sigma} u^2_{w_2} \tilde{\sigma} v^2_{w_2} \ldots \tilde{\sigma} u^2_{w_M} \tilde{\sigma} v^2_{w_M}] \quad (7c)$$

$$W = \begin{bmatrix} 1/\sigma^2\alpha & 0 & 0 \\ 0 & 1/\sigma^2\beta & 0 \\ 0 & 0 & 1/\sigma^2 V_T \end{bmatrix} \quad (7d)$$

$$A^T W A = \sum_{i=1}^{N} A_i^T W A_i \qquad A^T W \Delta z = \sum_{i=1}^{N} A_i^T W \Delta z_i \quad (7e)$$

and

$$A_i = \left(\frac{\partial \alpha_i^T}{\partial x} \; \frac{\partial \beta_i^T}{\partial x} \; \frac{\partial V_{T_i}^T}{\partial x} \right)^T \qquad \Delta z_i = \left(\Delta\alpha_i \Delta\beta_i \Delta V_{T_i} \right)^T \quad (7f)$$

In the above development Δx is the $2M \times 1$ vector of corrections to the wind estimates, $\tilde{\Gamma}_x$ a $2M \times 2M$ diagonal a priori covariance matrix of the wind estimates, W a 3×3 constant data weighting matrix, $A^T W A$ the $2M \times 2M$ normal matrix, $A^T W \, \Delta z$ the $2M \times 1$ right-hand-side vector, A_i the $3 \times 2M$ matrix of partials of the ith set of observations with respect to the wind solution parameters, and Δz_i the 3×1 vector of observation residuals for the ith set. At each observation time t_i with corresponding altitude h_i, there are only six nonzero observation partials in the A_i matrix. This is due to the fact that winds at altitude are functions only of the winds at the breakpoints enclosing that altitude. That is,

$$u_w(h_i) = u_w(h_m) + \frac{(h_i - h_m)}{(h_n - h_m)} [u_w(h_n) - u_w(h_m)] \qquad (u_w \to v_w) \quad (8)$$

where $h_m \le h_i \le h_n$. Equation (7) is initialized with zero wind estimates (except near touchdown) and is iterated to convergence. Normally three iterations are sufficient.

The advantages of the WLS technique are: 1) all available wind information is incorporated through the use of α, β, and V_T as observables; 2) random errors in the observations do not affect wind estimates; 3) provision can be (and has been) made to solve for observation biases; and 4) in situ wind estimates are obtained. The disadvantages are: 1) the need for a mathematical model that adequately characterizes the unknown wind profile; 2) the order of the system of equations that must be solved can be very large, e.g., a breakpoint model with winds specified at 2000 ft intervals from 0 to 50 kft results in a system of order 52; and 3) formal uncertainties in the wind estimates obtained are overly optimistic.

IV. Flight Results

Overview

Figure 1 shows the *measured* wind magnitudes over the specified altitude range during the subsonic portion of entry for the first four flights of Space Shuttle Columbia. STS-1 and STS-2 landed at Edwards Air Force Base, Calif., on April 14 and Nov. 14, 1981, respectively; STS-3 landed at White Sands, N. Mex., on March 30, 1982; STS-4 landed at Edwards on July 4, 1982. Altitudes shown in all figures are heights above the Fischer ellipsoid.

As part of the meteorological data evaluation performed for each flight, wind estimates are generated for comparisons with the measured winds on the LAIRS file. Comparisons are also performed against alternate sources of measured winds not included in the LAIRS wind data base, e.g., jimsphere balloon measurements. Consistency among the various sources is the desired result. The existence of significant discrepancies, however, can be interpreted in several ways. On a day when winds are highly variable, the discrepancies could be due to both time and spatial separation between the Shuttle path and the wind measurements. Differences could also be due to systematic errors in the ADS parameters, inaccuracies in the wind measurements, or errors in the inertial trajectory

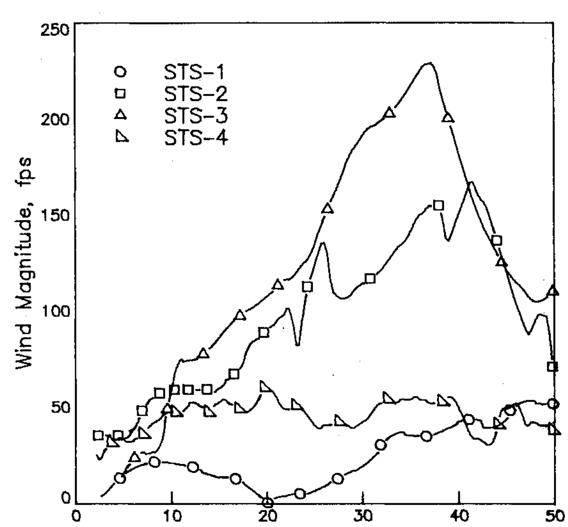

Fig. 1 LAIRS (rawinsonde) wind profiles for STS-1, 2, 3, and 4.

Table 1 Prefit ADS residuals for wind estimation

Flight	$\Delta\alpha$, deg		$\Delta\beta$, deg		ΔV_T, ft/s	
	μ	σ	μ	σ	μ	σ
STS-1	−0.20	0.65	−0.34	1.57	−11.1	14.6
STS-2	−1.15	2.27	−1.20	3.49	−4.4	76.3
STS-3	+0.10	3.22	+4.08	2.79	−65.1	78.5
STS-4	−1.21	1.16	−1.23	1.65	+10.6	38.2

parameters that are treated as perfectly known inputs to the wind estimation algorithms. Experience has shown that errors in the inertial trajectory parameters are so small relative to the other candidates that they may be ignored.

Comparisons of ADS results with alternate sources of data over the first four missions indicate that, for wind estimation purposes, the ADS parameters can be treated (conservatively) as 0.5 deg (1σ) in α and β and ~10 ft/s (1σ) for V_T. Also since deterministic estimates of the winds of STS-1 and 2 departed significantly from the measured winds for altitudes above 50 kft ($M>1.0$), this altitude has been generally considered the upper altitude threshold for evaluation.

A discussion of the derived winds obtained for each of the first four flights is presented in the following subsections. First, quality of fit to the ADS parameters is shown for both the deterministic and BATCH/3 estimates. Next, the wind estimates are shown together with the winds obtained using rawinsonde (LAIRS) and jimsphere measurements. Finally, the uncertainties in the derived winds are discussed and it is shown that, except for STS-3, the measured winds lie within the 1σ uncertainty bands in the deterministic estimates.

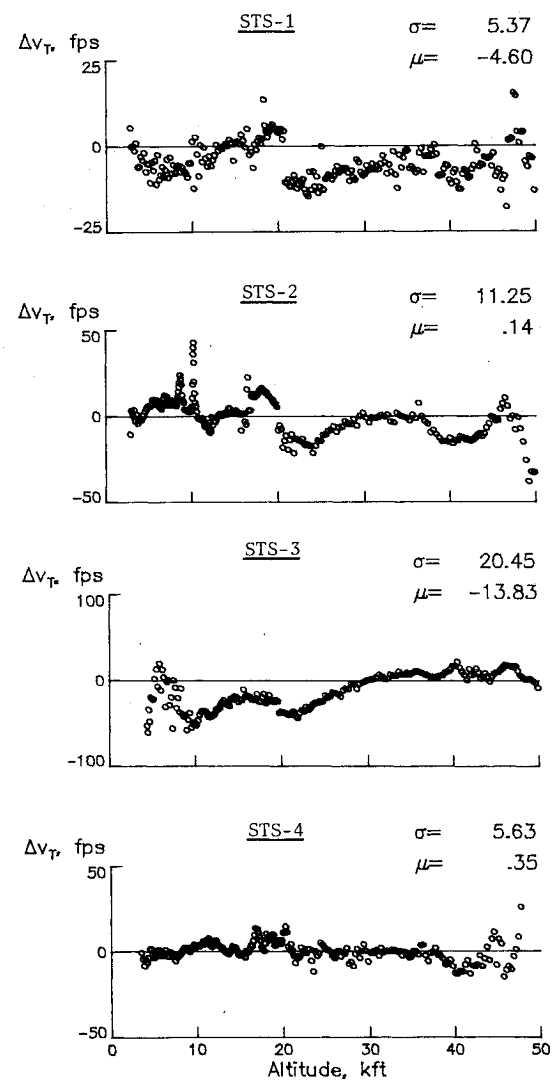

Fig. 2 ADS V_T residuals with respect to deterministic (α,β) wind estimates.

ADS Data Fitting Results

The inertial BET contains planet-relative values of α, β, and V_T which are based on zero winds. As mentioned previously, the wind estimators assume the differences between the ADS parameters and these planet-relative parameters from the inertial BET to be due entirely to horizontal winds. In the context of wind estimation, these differences are prefit residuals, i.e., the differences between the observed values (ADS) and computed values obtained using a no-wind assumption.

Prefit residuals for flights 1-4 are given in Table 1. The mean μ and standard deviation σ of the differences are shown for each parameter. These differences from the ADS values are primarily due to neglecting the winds shown in Fig. 1. The largest departures are those for STS-3, the flight which encountered the highest magnitude winds during the subsonic phase.

Postfit residuals obtained from the deterministic method are shown in Fig. 2. Recall that in the deterministic approach the ADS values of α and β are fit exactly with horizontal winds; airspeed is a "passive" parameter not utilized in the method. Therefore, the only nonzero "residuals" are in airspeed. Theoretically, if the ADS values of α and β contain only random errors, the airspeed differences resulting from the application of winds that fit α and β exactly should be near-zero mean. Large means are indicative of inconsistencies between the ADS angles and ADS airspeed. The airspeed residuals for STS-1, STS-2, and STS-4 indicate reasonable consistency in the ADS parameters for these flights. The small discontinuities near 20 kft ($M\sim0.6$ on each flight) are due to refined calibrations obtained from recent analyses of the ALT flights. For the ALT program the Shuttle (Enterprise) was equipped with a nose boom which provided "truth" data for calibration of the ADS. The refined "add-on" calibrations to α, V_T are applied only when $0.4<M<0.6$, i.e., from 20 kft to

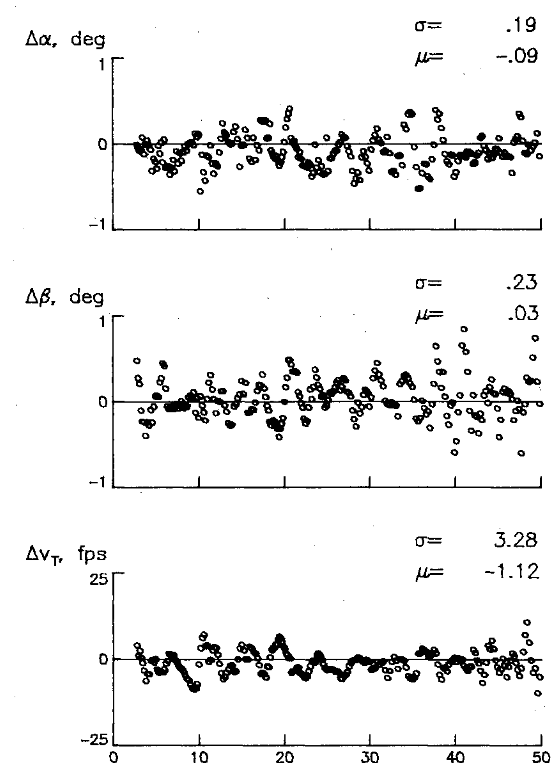

Fig. 3 Final STS-1 residuals from BATCH/3 wind estimator.

touchdown. Actually, the V_T add-on is generated from the incremental correction to the equivalent airspeed V_E. On STS-2 the peculiar signature in the airspeed differences near 10 kft is due to a mathematical singularity in the deterministic method when the flight path angle equals zero. Erratic deterministic wind estimates are obtained when the flight path angle approaches this indeterminate condition, which occurs at approximately 12 kft. Figure 2 shows large differences in airspeed between the ADS values and the values obtained using deterministic winds for STS-3. There are several plausible explanations for these differences, one of which is that the consistency between the ADS attitude and ADS airspeed data varies with environment (winds) and flight conditions.

Postfit residuals from the weighted least squares method are shown in Figs. 3-6 for STS-1, STS-2, STS-3, and STS-4, respectively. BATCH/3 results obtained using ADS values of α, β, and V_T as observables with assumed 1σ accuracies of 0.5 and 0.5 deg and 10 ft/s, respectively, are given for each flight. For STS-1 and STS-2, a 20-breakpoint wind model, with 2500 ft spacing between breakpoints, was utilized. In an attempt to properly characterize the winds for STS-3, 25 breakpoints with approximately 2500 ft spacing above 15 kft and 1000 ft spacing below 13 kft were used. Furthermore, surface winds on STS-3 were constrained to the measured values of 20 ft/s and 190 deg direction. For STS-4 a 25-breakpoint wind model, with 2000 ft spacing between breakpoints, was used. As with STS-3, surface winds were constrained to the measured values, which were 20 ft/s and 250 deg direction. The fit statistics given in Figs. 3, 4, and 6 show that the fits to the ADS parameters are well within the assumed data accuracies and exhibit near-zero mean residuals for STS-1, STS-2, and STS-4. Because of the imposition of a piecewise linear wind model, the residuals will never be truly random, even if the ADS parameters have only random errors. Figure 5 shows that for STS-3 the ADS parameters cannot be fit to near-zero mean. In fact, the results indicate the same inconsistencies among the ADS parameters as did the deterministic results. The deterministic results showed that a perfect fit to α and β yielded large airspeed differences. The BATCH/3 results show that a fit to α, β, and V_T yields biased mean residuals in all three parameters, particularly α. The general nature of the α residuals shown in Fig. 5, particularly below 30 kft, is indeed very similar to the airspeed residuals shown in Fig. 2. The indication is that either α or V_T, or both, contain some systematic errors.

Estimated and Measured Winds

Figures 7-10 show the estimated and measured wind magnitudes obtained for each flight. The symbols containing a + are used to designate winds obtained from either rawinsonde (as processed in LAIRS) or jimsphere balloon measurements. Open symbols are used to designate winds derived from the ADS parameters using either the deterministic or weighted least squares estimation algorithms.

STS-1 wind magnitudes are shown in Fig. 7. The noisy profile, of course, is that obtained from the deterministic estimator. In general, all sources of wind information are in very good agreement. Overall, BATCH/3 estimates tend to corroborate the measured winds better than the deterministic estimates. The close agreement between the derived and measured winds not only increases confidence in the measured winds but also shows the viability of the wind estimation procedures for evaluating the measured winds.

Figure 8 shows the wind magnitudes obtained from each source for STS-2. For this flight there are significant discrepancies between the two sources of measured winds. In particular, the large gradients evident in the LAIRS (rawinsonde) winds near 25 and 40 kft are not substantiated by the jimsphere measurements. In fact, the jimsphere profile above 35 kft is radically different from LAIRS. Moreover, the deterministically derived winds are in excellent agreement with the jimsphere measurements, particularly above 20 kft. BATCH/3 estimates (which were unconstrained near the surface) also tend to support both the deterministic and jimsphere winds. Therefore, by corroborating one source of measured winds and contradicting another, the usefulness of the wind estimators has once again been demonstrated. It is worthwhile to mention that the jimsphere data rate is such that significant wind structure is detectable. For example, the

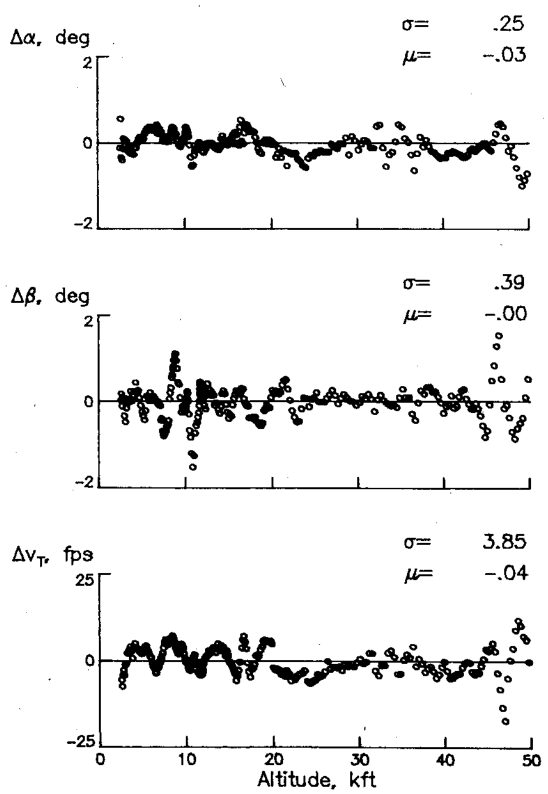

Fig. 4 Final STS-2 residuals from BATCH/3 wind estimator.

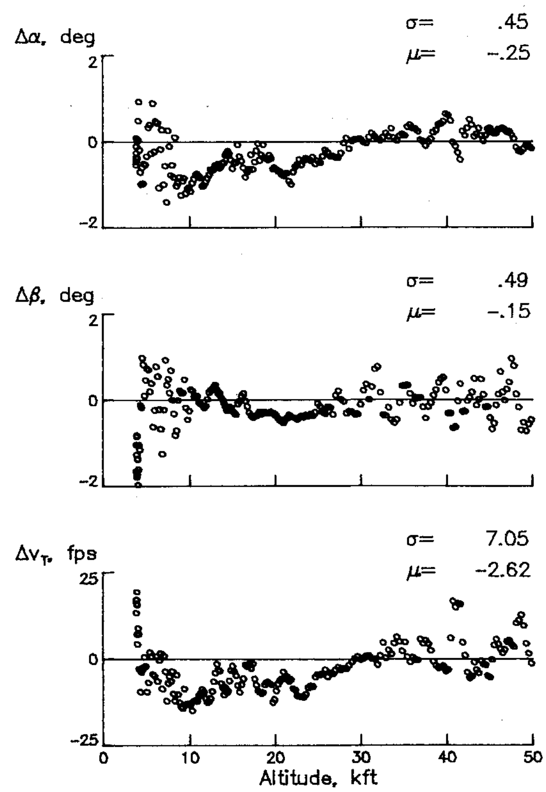

Fig. 5 Final STS-3 residuals from BATCH/3 wind estimator.

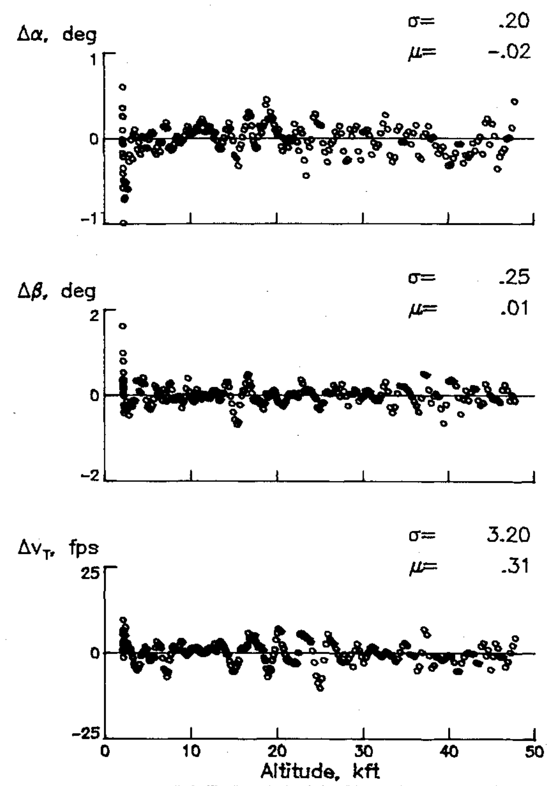

Fig. 6 Final STS-4 residuals from BATCH/3 wind estimator.

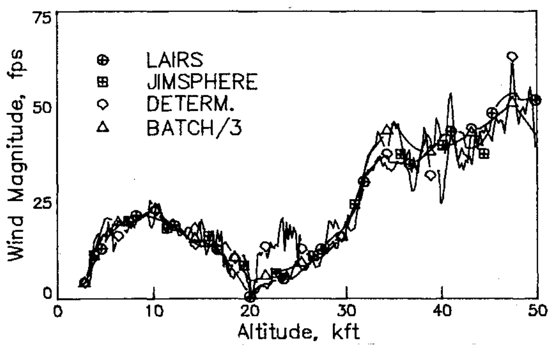

Fig. 7 STS-1 measured and derived winds.

available data for STS-1, STS-2, and STS-4 provided measurements at ~20 ft altitude intervals and for STS-3 at ~200 ft intervals.

STS-3 wind magnitudes are shown in Fig. 9. In evaluating these results, which are rather disconcerting, several important factors must be kept in mind. First, very high winds at White Sands on March 29, 1982, the scheduled day of landing, caused the landing to be delayed until March 30. Second, the wind measurements taken on the day of landing were not of high quality. Third, both the deterministic and weighted least squares fits to the ADS parameters indicated a level of inconsistency in the ADS parameters much greater than that obtained on STS-1 and STS-2. Finally, the application of either set of measured winds to the planet-relative parameters obtained from the inertial BET resulted in air-relative values of α and β that departed significantly from the ADS values. As shown in Fig. 9, the only areas of agreement in the winds obtained from all sources are for altitudes near 15,000 and 35,000 ft. The discrepancies between the two sources of measured winds, although fairly substantial, are not nearly as large as those between the derived and measured winds. The winds actually used on the Langley BET for this flight were the BATCH/3 estimates. The BATCH/3 estimates represented what is believed to be the most reasonable compromise. First, they represented a best fit to all three ADS parameters, α, β, and V_T. Second, they yielded dynamic pressures that closely matched the ADS values. Finally, they resulted in aerodynamic performance coefficients that were more consistent with preflight values.

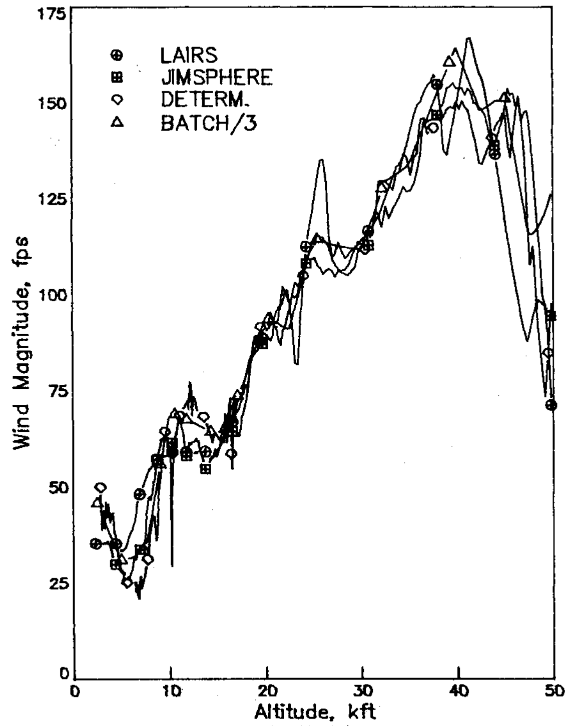

Fig. 8 STS-2 measured and derived winds.

Figure 10 shows the wind magnitudes obtained from each source for STS-4. Agreement between the derived and estimated winds is similar to that shown for STS-1 and STS-2. For this flight, measurements from three jimsphere balloons, with launch times ranging from 180 min before to 15 min after spacecraft landing, were made available. The jimsphere measurements shown in Fig. 10 are for the balloon launched closest in time to the Shuttle path. At fixed altitude fairly large time variations in wind magnitude existed in the measurements obtained from the three balloons. Wind magnitude differences were as much as 30 ft/s for altitudes above ~12 kft. The time variability in the measured winds for this flight further justifies the need for in situ wind determinations.

Uncertainties in Wind Estimates

The most realistic uncertainties in the estimates of the horizontal wind components are those obtained from the deterministic algorithm. The uncertainties obtained from the weighted least squares algorithm are for the wind components derived at the model breakpoints and are overly optimistic since they presume that the winds obey the model used. As discussed previously, the uncertainties in the deterministic winds are obtained by a point transformation of the assumed uncertainties in α and β.

Figures 11-14 show the 1σ uncertainty bands in the deterministic winds together with the measured winds obtained from LAIRS for each flight. Wind component uncertainties were obtained using the assumed uncertainties of 0.5 deg in α and β. Westward and southward wind components, which are the quantities estimated, are shown. The deterministic estimates are at the center of each uncertainty band and, in order to preserve clarity, are not shown. Figures 11, 12, and 14 show that the measured winds lie within the 1σ uncertainty bands about the deterministic winds for STS-1, STS-2, and STS-4. (If jimsphere winds rather than LAIRS

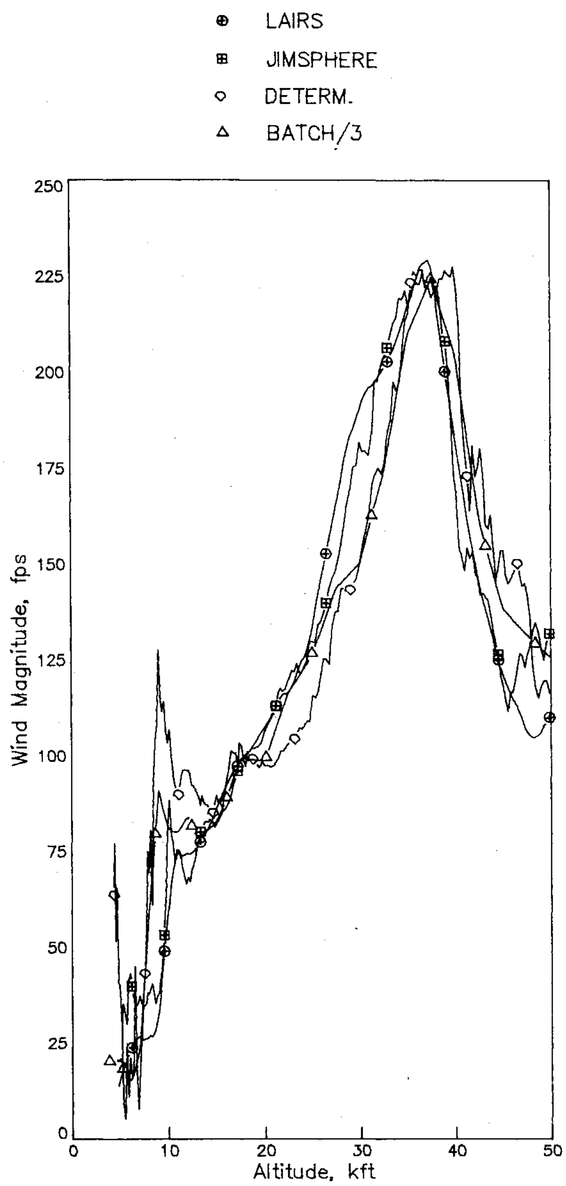

Fig. 9 STS-3 measured and derived winds.

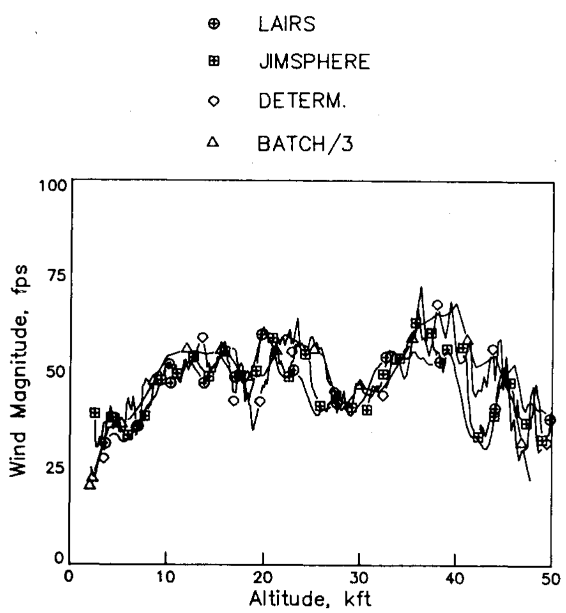

Fig. 10 STS-4 measured and derived winds.

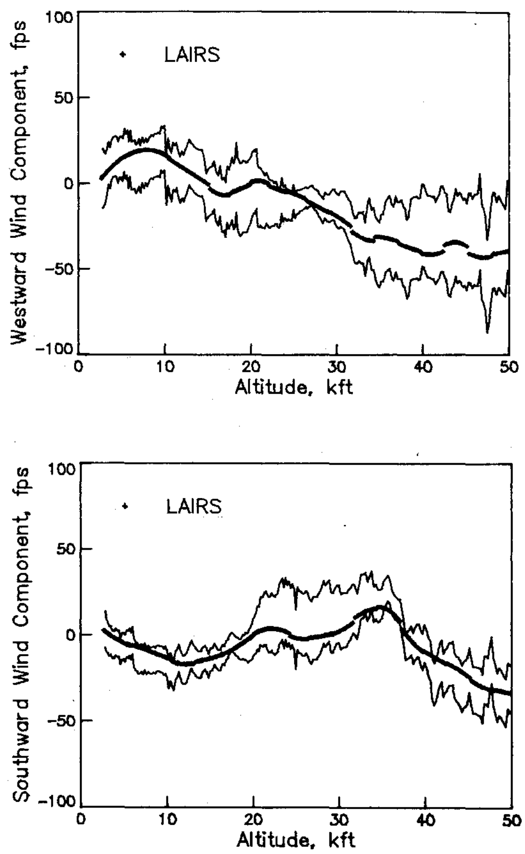

Fig. 11 STS-1 rawinsonde measurements with deterministic wind accuracy ($\pm 1\sigma$) superimposed.

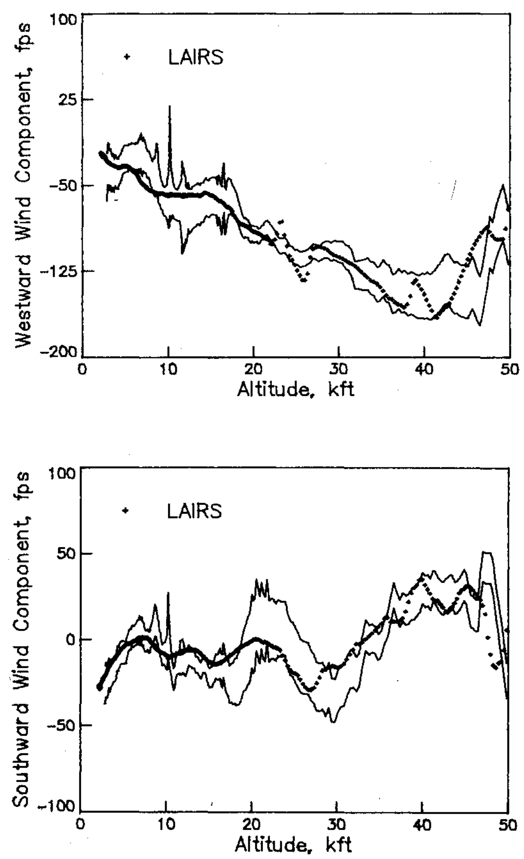

Fig. 12 STS-2 rawinsonde measurements with deterministic wind accuracy ($\pm 1\sigma$) superimposed.

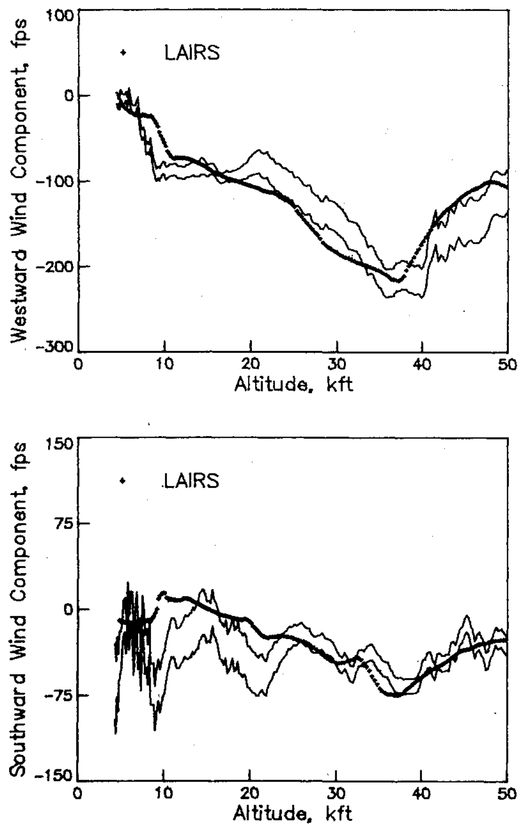

Fig. 13 STS-3 rawinsonde measurements with deterministic wind accuracy ($\pm 1\sigma$) superimposed.

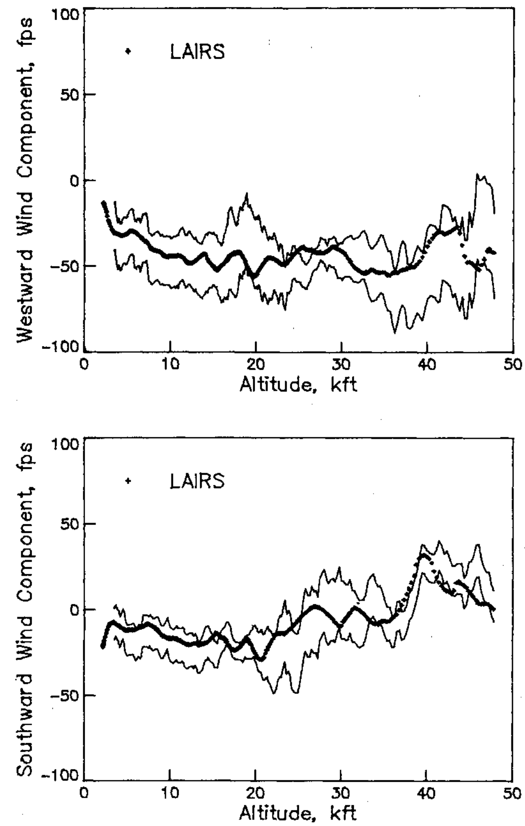

Fig. 14 STS-4 rawinsonde measurements with deterministic wind accuracy ($\pm 1\sigma$) superimposed.

winds were shown for STS-2, virtually all measurements would lie within the 1σ bands.) Figure 13 shows again, this time statistically, the large departure of the measured winds from the deterministic estimates for STS-3.

V. Summary

Measured horizontal winds during the subsonic region of the NASA Shuttle Orbiter entry flights can be evaluated for use in BET generation to enhance the air-relative parameter computations. Using the air data system parameters (α, β, and V_T) and the methods discussed herein, accurate wind determinations were shown for the first four STS missions. As a result, in the event the measured winds are inadequate (or unavailable), sufficient wind determinations are possible. Evaluation of measured winds, or estimation based on in situ measurements, enhances the flight-derived aerodynamic coefficient determinations for comparison with preflight data base predictions.

Acknowledgments

This work was accomplished under NASA Contract NAS1-16087. The authors wish to acknowledge the various Rockwell personnel for their consultation as well as for making the postflight calibrated side-probe information available in a most timely manner. Principally, credits go to Leonard Gaines, aerodynamic group leader, and Al Dean, lead analyst for the ADS activities. The assistance of Dave Richardson of the Air Force Flight Test Center is acknowledged for providing the jimsphere data. Analysis and programming support by Judy McConnell, AMA, Inc., is also acknowledged.

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