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Ascent Wind Model for Launch Vehicle Design

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A vector wind model has been developed for launch vehicle design. The model produces wind profiles for evaluation of vehicle control and trajectory variables required for assessment of proposed designs for new NASA launch vehicles. The wind model is based on the concept that the wind components of vectors at two altitudes have a probability distribution function that is quadravariate normal. Given a wind vector at one altitude, the conditional distribution of the wind components at any other altitude is bivariate normal. A process is described for derivation of vector wind profiles based on the statistical model. The process produces wind profiles that are a reasonable substitute for measured wind profile samples. The model wind profiles produce dispersions in aerodynamic load indicators (ALI) that cover the dispersion range of ALI calculated from an extensive sample of Jimsphere wind profiles; this is accomplished at a selected altitude with only 12 model wind profiles compared to 1800 measured Jimsphere profiles. This represents an opportunity for a considerable reduction of computational effort during design phases that require many iterations to establish a launch vehicle design philosophy.

Nomenclature

CMUJ, CMVJ	=	conditional means of *UJ* and *VJ* at *HJ*, respectively
CSDUJ, CSDVJ	=	conditional standard deviations of *UJ* and *VJ* at *HJ*, respectively
CRUJVJ	=	conditional correlation coefficient of *UJ*, *VJ* at *HJ*
DU, DV	=	components of vector wind change between altitudes *HI* and *HJ*
MUI, MVI	=	sample means of *UI* and *VI*, respectively
MUIE, MVIE	=	means of monthly enveloping ellipse at *HI*
P	=	probability
RUIVIE	=	correlation coefficient of the monthly enveloping ellipse at *HI*
RUIVI	=	sample intralevel correlation coefficient of *UI, VI*
RUIUJ, RUIVJ *RVIVJ, RVIUJ*	=	sample interlevel correlation coefficient of *UI, UJ; UI, VJ; VI, VJ;* and *VI, UJ*, respectively
SDUI, SDVI	=	sample standard deviations of *UI* and *VI*, respectively
SDUIE, SDVIE	=	standard deviations of the monthly enveloping ellipse at *HI*
Sigma	=	symmetric variance covariance matrix
SXY	=	sample covariance of variables *X* and *Y*
UCJ, VCJ	=	components of the conditional wind vector at *HJ*
UI, VI	=	zonal and meridional wind components at *HI*, respectively
UL, US, VL, VS	=	largest and smallest *UI* and *VI* at *HI*
VWS	=	magnitude of the vector wind change (shear) between *HI* and *HJ*

Introduction

THE most useful engineering design application of a wind profile model is the establishment of preliminary design ranges for angle of attack Alpha, angle of sideslip Beta, aerodynamic pressure *Q*, and the two aerodynamic load indicators that are the products *Q**Alpha and *Q**Beta. These and other flight variables are derived from ascent flight six-degree-of-freedom trajectory simulations using wind model profiles. The trajectory variables are used in the evaluation of load indicators at locations of expected vehicle wind sensitivity. A load indicator is an algorithm that relates external loads such as *Q* to stress at a specific point on the vehicle structure; for the National Space Transportation System (NSTS), the algorithms are for rigid body loads.[1] Elastic body loads are determined from flutter and vibration analyses using model wind profiles that have been augmented to include small scale wind perturbations. Another useful application is in the estimation of flight performance reserve (FPR) for propellant to ensure orbital insertion by protecting for flight dispersions attributable in part to wind profile dispersions.[2,3]

Following the preliminary vehicle design using a wind profile model, trade studies can be made to establish a requirement to bias steering to reduce wind loads. The usual procedure is to establish first stage steering based on the profile of monthly mean winds in the pitch and yaw planes. Wind profile models have been developed for alternatives other than the monthly mean.[4] When sufficient engineering data have been established, structural loads and performance assessments are made using samples of high resolution wind profile measurements. Currently, for Kennedy Space Center (KSC), this data sample is 150 Jimsphere profiles per month.

This paper describes a new vector wind profile (VWP) model that is based on the properties of the quadravariate normal distribution; the new model is a revision of the VWP model used in development of the NSTS.[5]

Statistical Model

It is assumed that the wind components *U*1, *V*1 at altitude 1 and *U*2, *V*2 at altitude 2 are quadravariate normal (QN) distributed. The QN distribution is defined by 14 statistical parameters; namely, the means, *MU*1, *MV*1, *MU*2, and *MV*2; the standard deviations, *SDU*1, *SDV*1, *SDU*2, and *SDV*2; and the correlation coefficients, *RU*1*V*1, *RU*2*V*2, *RU*1*U*2, *RV*1*V*2, and *RV*1*U*2. Given a wind vector (*UG*, *VG*) at a reference altitude *H*1, the distribution of *U*2, *V*2 at any other altitude *H*2 is conditional bivariate normal (CBN). The five parameters of the CBN are the conditional means *CMU*2 and *CMV*2, the conditional standard deviations *CSDU*2 and *CSDV*2, and the conditional correlation coefficient *CRU*2*V*2. The conditional means are calculated from the equations

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$$CMU2 = MU2 + (T1 + T2)/(1 - RU1V1*RU1V1) \quad (1)$$

$$T1 = (RU1U2 - RU1V2*RU1V1) *(UG - MU1)*SDU2/SDU1 \quad (2)$$

$$T2 = (RU1V2 - RU1U2*RU1V1) *(VG - MV1)*SDU2/SDV1 \quad (3)$$

$$CMV2 = MV2 + (T3 + T4)/(1 - RU1V1*RU1V1) \quad (4)$$

$$T3 = (RV1U2 - RV1V2*RU1V1) *(UG - MU1)*SDV2/SDU1 \quad (5)$$

$$T4 = (RV1V2 - RV1U2*RU1V1) *(VG - MV1)*SDV2/SDV1 \quad (6)$$

The conditional standard deviations $CSDU2$ and $CSDV2$ and the conditional correlation coefficient $CRU2V2$ are calculated from the symmetric variance covariance matrix Sigma.

$$CSDU2 = SQRT[\text{Sigma}(1,1)] \quad (7)$$

$$CSDV2 = SQRT[\text{Sigma}(2,2)] \quad (8)$$

$$CRU2V2 = \text{Sigma}(1,2)/(CSDU2*CSDV2) \quad (9)$$

$$\text{Sigma}(1,1) = SU2 - SU1U2*(SU1U2 *SV1/D - SU2V1*SU1V1/D) -SV1U2*(-SU1U2*SU1V1/D + SU1V2*SU1/D) \quad (10)$$

$$\text{Sigma}(2,2) = SV2 - SU1V2 *(SU1V2*SV1/D - SV1V2*SU1V1/D) -SV1V2*(-SU1V2*SV1U1/D + SV1V2*SU1/D) \quad (11)$$

$$\text{Sigma}(1,2) = SU2V2 - SU1V2 *(SU1U2*SV1/D - SU2V1*SU1V1/D) -SV1V2*(-SU1U2*SU1V1/D + SU2V1*SU1/D) \quad (12)$$

$$D = SU1*SV1 - SU1V1*SU1V1 \quad (13)$$

where $SU1$, $SV1$, $SU2$, and $SV2$ are the variances, and $SU1V1$, $SU2V2$, $SU1U2$, $SV1V2$, $SU1V2$, and $SV1U2$ are the covariances of the wind components at altitudes $H1$ and $H2$. The general equation for the covariance of variables X and Y is

$$SXY = RXY*SDX*SDY \quad (14)$$

where RXY is the correlation coefficient, and SDX and SDY are the standard deviations of X and Y. Note that of the five statistical parameters that define the conditional ellipse, only $CMU2$ and $CMV2$ are functions of the given wind vector (UG, VG). A comparison of the original[5] and revised VWP models is presented in Table 1.

Wind Profile Construction

Wind profile construction is a straightforward application of the statistical model. According to the model the wind components at $H1$ are bivariate normal (BN); thus P (*100) percent of the wind vectors terminate within a probability ellipse (PE) that is defined by the five statistical parameters $MU1$, $MV1$, $SDU1$, $SDV1$, and $RU1V1$. A given wind vector is selected which terminates on the PE for, $P = 0.99$; the selection is made by specifying a clocking angle CA measured counterclockwise from the centroid ($MU1$, $MV1$) of the PE, as illustrated in Fig. 1. The components UG and VG of the given wind vector are

$$UG = MU1 + RS*\cos(CA) \quad (15)$$

$$VG = MV1 + RS*\sin(CA) \quad (16)$$

where

$$RS = 1/A*SQRT[-2*\ln(1-P)] \quad (17)$$

$$P = 0.99, \quad A = SQRT(TA*TB) \quad (18)$$

$$TA = 1/(1 - RU1V1**2) \quad (19)$$

$$TB = [\cos(CA)**2]/(SDU1**2) -2RU1V1*\cos(CA)*\sin(CA)/(SDU1*SDV1) +[\sin(CA)**2]/(SDV1**2) \quad (20)$$

The components $UC2$ and $VC2$ of the conditional wind vectors at all other altitudes $H2$ terminate on the 99% conditional PE

Table 1 Comparison of original[5] and revised VWP models

Attribute	Original (as applied in NSTS)	Revised
Statistical model	Simplified quadravariate normal defined by 11 statistical parameters	Quadravariate normal defined by 14 statistical parameters
Profile construction	Each component of vector wind shear between altitudes $H1$ and $H2$ is conditional normal, given the corresponding component of the wind vector at $H1$	Components of wind vector at $H2$ are conditional bivariate normal, given the wind vector at $H1$
Simplifying assumptions	All interlevel cross-component correlations and the intralevel cross-component correlation at $H2$ are negligible Conditional ellipse for shears is made circular by taking the root summed square of the conditional standard deviations	None
Choice of vector on conditional ellipse	Vector shear on conditional shear circle is in plane with the given wind vector, i.e., 180 deg from the given wind vector	Wind vector on conditional ellipse is for clocking angle 180 deg from the clocking angle of the given wind vector

for a selected clocking angle 180 deg from the clocking angle of the given wind vector at $H1$; the conditional PE is defined by the five conditional statistics calculated from Eqs. (1–13). $UC2$ and $VC2$ are calculated from

$$UC2 = CMU2 + RSC*\cos(CC) \tag{21}$$

$$VC2 = CMV2 + RSC*\sin(CC), \text{ where} \tag{22}$$

$$RSC = 1/AC*SQRT[-2*ln(1-P)] \tag{23}$$

$$P = 0.99, \qquad CC = CA + 180$$

$$AC = SQRT(TAA*TBB) \tag{24}$$

$$TAA = 1/(1 - CRU2V2**2) \tag{25}$$

$$TBB = (\cos(CC)**2)/(CSDU2**2) - 2CRU2V2*\cos(CC)*\sin(CC)/(CSDU2*CSDV2) + (\sin(CC)**2)/(CSDV2**2) \tag{26}$$

A schematic of the profile construction for a given wind vector at 12 km (CA = 30 deg) and the conditional wind vector at 10 km (CC = 210 deg) is illustrated in Fig. 1; the statistics used for the schematic are listed in Table 2.

To construct a complete profile, this process is repeated between all altitude pairs including the reference altitude ($H1$), which is 12 km in this example, and all other altitudes from 0 to 27 km, at 1-km intervals. The configuration of the computer code for implementation of the model produces 12 profiles for each of 28 reference altitudes from 0 to 27 km (336 profiles); the 12 profiles are for 12 clocking angles for the given wind vector at 30-deg increments from 0 to 330 deg.

It can be demonstrated that the locus of the conditional means at $H2$, given the wind vectors on the P (*100)-percent probability ellipse at $H1$ for all clocking angles, is an ellipse. This concept is illustrated in Fig. 2 for 12 clocking angles, $H1$ = 12 km and $H2$ = 10 km; selection of the coordinates of any four symmetrically opposing conditional means is sufficient to define the ellipse that passes through all the conditional means.

Profile construction using this methodology is appropriate for monthly reference periods; the designer may choose as few as two months (for example, Feb and July) to represent the annual wind dispersion. Since annual wind samples are not quadravariate normal distributed, application of this methodolgy is not recommended for an annual reference period. The recommended approach for estimation of annual vector wind profile dispersion is to derive the given wind vector from

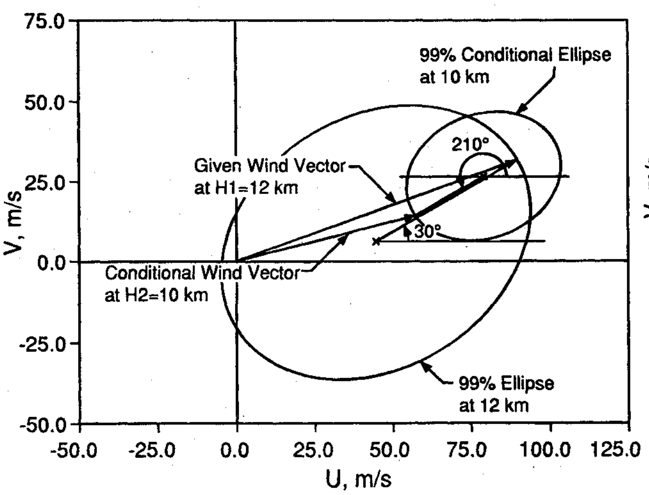

Fig. 1 Schematic of profile construction between a reference altitude of 12 km and an altitude of 10 km, clocking angle 30 deg, KSC, February.

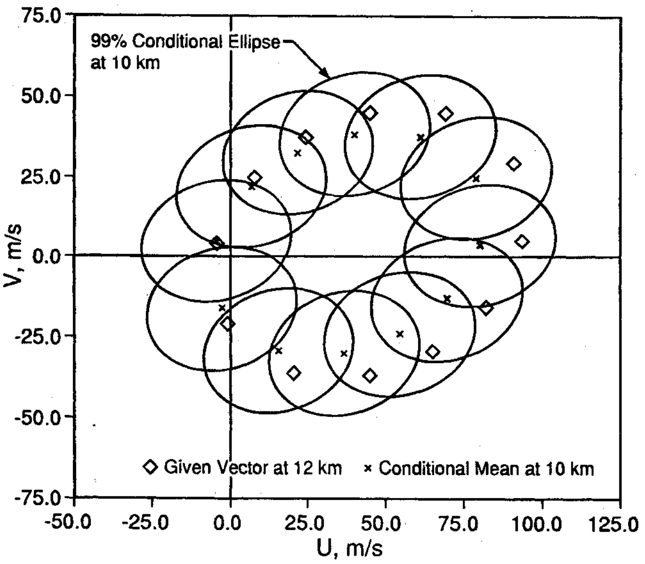

Fig. 2 Conditional means and conditional ellipses at 10 km derived from 12 given wind vectors to the 99 pct probability ellipse at 12 km, KSC, Feb.

Table 2 Statistics for construction of a wind profile vector at 10 km ($H2$), given a wind vector at a 12 km ($H1$)

Database: KSC 19-yr serially complete Rawinsonde (1956–74), February

Given wind vector (m/s), for CA = 30 deg on the 99% ellipse at 12 km [Eqs. (15–20)]: UG = 90.74, VG = 29.99

14 Quadravariate normal statistics:

	(m/s)	(m/s)	(m/s)	(m/s)	
BN statistics at 12 km,	$MU1$	$MV1$	$SDU1$	$SDV1$	$RU1V1$
	44.84	3.49	16.52	14.55	0.227
BN statistics at 10 km,	$MU2$	$MV2$	$SDU2$	$SDV2$	$RU2V2$
	38.18	3.39	16.44	13.88	0.216
Interlevel correlation coifficients between like and unlike components:		$RU1U2$	$RV1V2$	$RU1V2$	$RV1U2$
		0.880	0.872	0.232	0.182
Derived BN statistics of conditional ellipse at 10 km [Eqs. (1–14)]:	$CMU2$ (m/s)	$CMV2$ (m/s)	$CSDU2$ (m/s)	$CSDV2$ (m/s)	$CRU2V2$
	79.05	24.88	7.79	6.79	0.119

Derived vector (m/s) for CC = 210 deg on 99% conditional ellipse at 10 km [Eqs. (21–26)]: $UC2$ = 58.30, $VC2$ = 12.90

an ellipse that envelopes the monthly probability ellipses for a selected probability level. The means *MUE* and *MVE* and the standard deviations *SDUE* and *SDVE* of the monthly enveloping ellipse at a selected reference altitude are

$$MU1E = (UL + US)/2 \quad (27)$$

$$MV1E = (VL + VS)/2 \quad (28)$$

where *UL, US,* and *VL, VS* are the largest and smallest monthly component means and

$$SDU1E = (UL - MU1E)/LE \quad (29)$$

$$SDV1E = (VL - MV1E)/LE \quad (30)$$

$$LE = SQRT[-2*ln(1 - P)] \quad (31)$$

The monthly correlation coefficients between *U* and *V* are essentially in agreement with the annual value; therefore, the annual value is used for the correlation coefficient for the enveloping ellipse, *RU1V1E*. The monthly and enveloping wind ellipses at 12 km for $P = 0.99$, illustrated in Fig. 3, are derived from the 19-yr (1956–74) serially complete Rawinsonde data base for KSC; the enveloping ellipse is shown to accurately represent the extremes of the monthly ellipses. Since it can be demonstrated that the wind shears generated by the model are largest during the winter months, it is appropriate to use QN statistics for a winter month in combination with given wind vectors from the enveloping ellipse in the development of a monthly enveloping vector wind profile model; February QN statistics are used in the enveloping model described next.

Model Vector Wind Profiles

Model vector wind profiles for a reference altitude of 12 km, for the months of February and July, and an enveloping model are illustrated in Fig. 4; the reader can identify the clocking angle for the given wind vector at 12 km associated with each profile by matching the wind component values in Fig. 4 with the wind components listed in Table 3. In July, the wind profile dispersion is small, and the wind at 12 km has an easterly component (negative *U*) in 7 of the 12 profiles; in February, the dispersion is large, and the westerly component (positive *U*) is dominant at 12 km in most of the profiles, with exceptions for a clocking angle of 180 deg which has a small but dominant easterly component, 120 and 150 deg which have dominant southerly (positive *V*) components, and 210 and 240 deg which have dominant northerly (negative *V*) components.

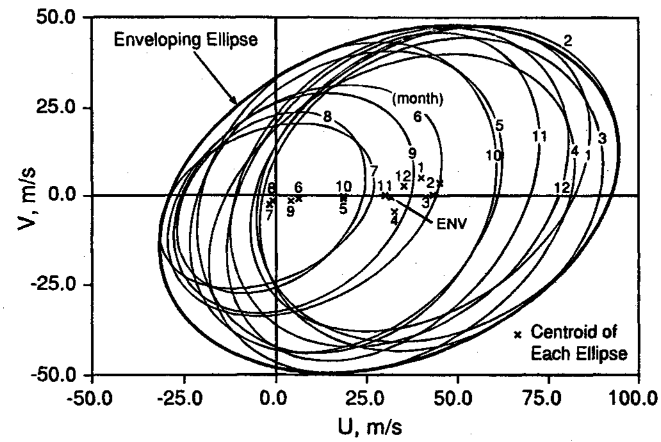

Fig. 3 Monthly and enveloping 99% probability ellipses, KSC, 12 km, derived from 19-yr (1956–74), 2/day serially complete rawinsonde data sample.

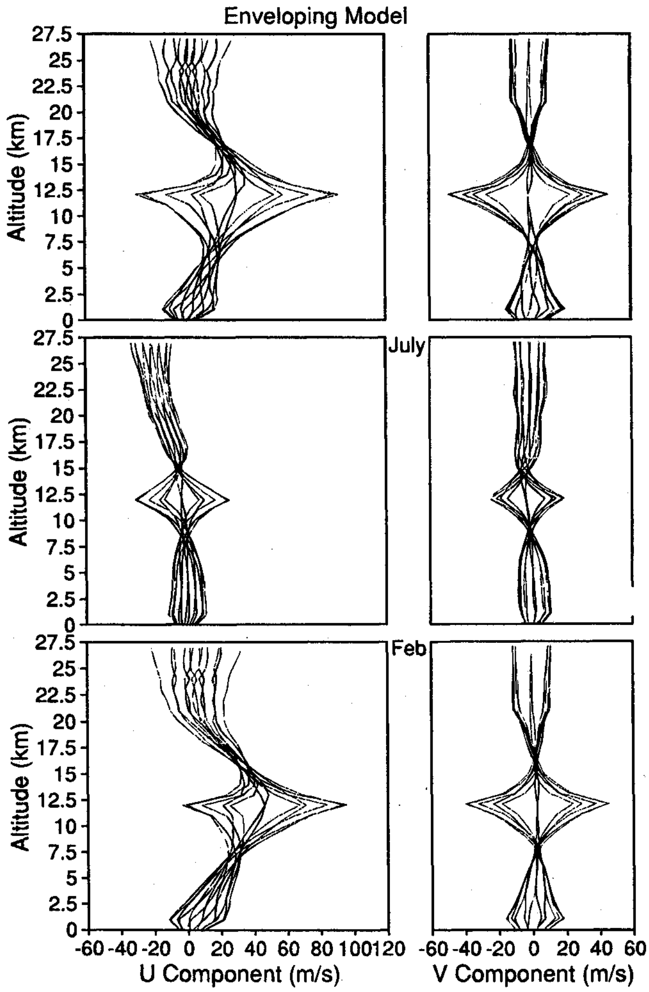

Fig. 4 Monthly (Feb., July) model and enveloping model vector wind profiles for a reference altitude of 12 km.

Vector Wind Shear

Vector wind shear (*VWS*) is used as an indicator of the fidelity of the vector wind profile model. *VWS* is defined as the magnitude of the wind change vector between altitudes *H*1 and *H*2,

$$VWS = SQRT\,(DU^{**}2 + DV^{**}2) \quad \text{where,} \quad (32)$$

$$DU = U2 - U1, \qquad DV = V2 - V1$$

A comparison of *VWS* calculated from the VWP model and Rawinsonde profiles for an altitude increment 1 km above and below a reference altitude of 12 km is illustrated in Fig. 5. The VWP model shears are for all clocking angles and all months; the Rawinsonde shears are for February and July. It is shown that the largest 1-km vector shears occur above the reference altitude for the model and the Rawinsonde sample for all cases. This characteristic wind profile behavior has been noted in early studies of KSC winds aloft.[6] The observed and model profile wind shears are in excellent agreement. The largest 1-km vector shear above 12 km produced by the model is 29.2 m/s; examination of the Rawinsonde data indicates eight values that exceed 29.2 m/s, which yields an empirical probability (*PEX*) of 0.00355, where, $PEX = 8/(N+1)$ and *N* is the combined sample size for February and July. (1074+1178).

The magnitude of the wind shear produced by the model is related to the probability level selected for the conditional ellipses, which is 99% for the present model configuration; a larger probability level would increase the wind shear.

Table 3 Components of given wind vector at 12 km, KSC

Clocking angle, deg (CA)	*U* Component			*V* Component		
	Feb	July	Envelope	Feb	July	Envelope
0	93.7	25.8	92.5	3.5	−3.0	−0.8
30	90.7	24.8	88.3	30.0	12.7	32.0
60	69.3	11.0	59.1	45.9	20.0	47.0
90	44.8	−2.3	31.5	46.5	19.0	45.7
120	24.5	−12.7	9.1	38.7	15.0	38.0
150	7.7	−22.1	−11.6	24.9	8.5	24.2
180	−4.0	−30.4	−29.4	3.5	−3.0	−0.8
210	−1.1	−29.4	−25.3	−33.0	−18.6	−33.6
240	20.3	−15.6	4.0	−39.0	−25.9	−48.5
270	44.8	−2.3	31.5	−39.5	−24.9	−47.3
300	65.2	8.1	53.9	−32.8	−20.9	−39.5
330	82.0	17.5	74.7	−18.0	−14.4	−25.7

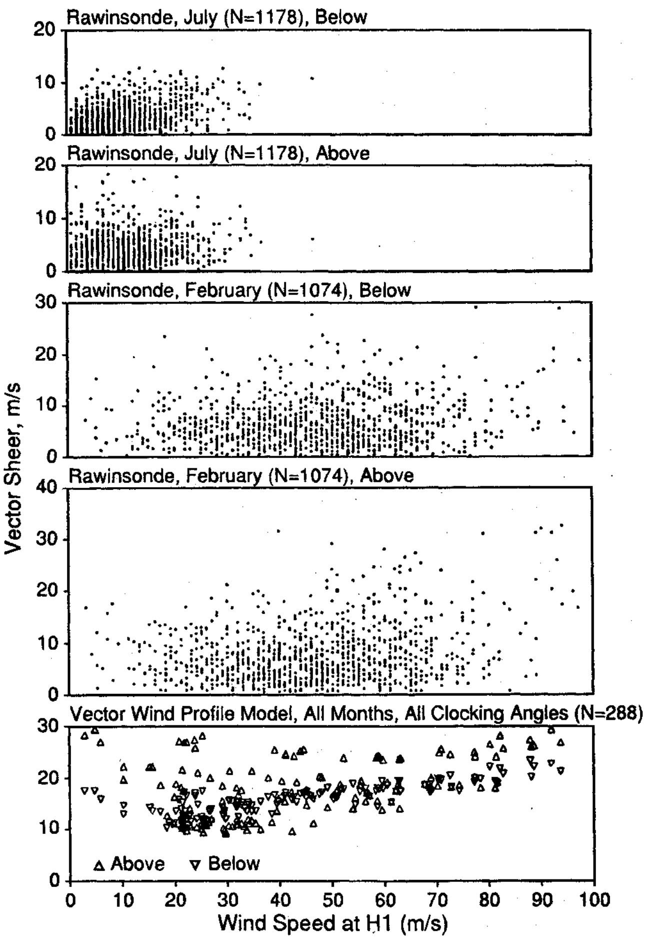

Fig. 5 Vector wind shear(m/s) 1 km above or below 12 km at KSC, calculated from the 19-yr (1956-74) serially complete rawinsonde data base for February and July, and the monthly vector wind profile model (H0 = 12 km).

Table 4 Nominal wind profile defined by the centroids of the KSC 99% enveloping ellipse at each altitude from 0 to 27 km at 1-km altitude intervals (derived from monthly bivariate normal statistics for the KSC Range Reference Atmosphere[8])

Altitude, km	*U* component, m/s	*V* component, m/s
0	−0.54	−0.64
1	2.84	1.31
2	6.27	1.58
3	9.00	1.80
4	12.39	2.34
5	16.10	3.00
6	19.46	3.61
7	22.59	4.23
8	25.79	4.56
9	28.83	4.48
10	31.16	3.65
11	31.56	2.02
12	30.98	0.52
13	27.80	−0.38
14	25.71	−0.62
15	22.63	0.29
16	20.40	0.86
17	17.38	0.90
18	13.84	0.98
19	8.59	0.97
20	3.67	0.71
21	0.99	0.13
22	1.79	−0.42
23	1.03	−0.26
24	2.45	0.06
25	4.14	0.42
26	4.97	0.64
27	5.86	1.26

Application

The enveloping vector wind model has been used in recent preliminary design analyses for the U.S. National Launch System[1] (NLS). Aerodynamic load indicators *Q**Alpha and *Q**Beta (*Q*A and *Q*B) were calculated with a six-degree-of-freedom trajectory simulation for a 90-deg flight azimuth, using 1800 (150/month) KSC Jimsphere wind profiles and 336 wind profiles from the enveloping model. Vehicle steering, established prior to trajectory simulation, is biased with respect to a nominal wind profile defined by the centroids of the KSC 99% enveloping wind ellipses (Table 4). The trajectory simulation includes vehicle control system response to correct for flight wind profile deviation from the nominal wind profile to ensure desired orbit insertion and to satisfy flight propellant reserve requirements. Control system response to off-nominal wind is an important contributor to aerodynamic loads because of the relationship between vehicle control and vehicle attitude, which includes Alpha and Beta.

*Q*A, *Q*B data at 12 km, near the altitude of maximum dynamic pressure (*Q*) are illustrated in Fig. 6; the 99% enveloping ellipse is constructed from the monthly *Q*A, *Q*B data using the

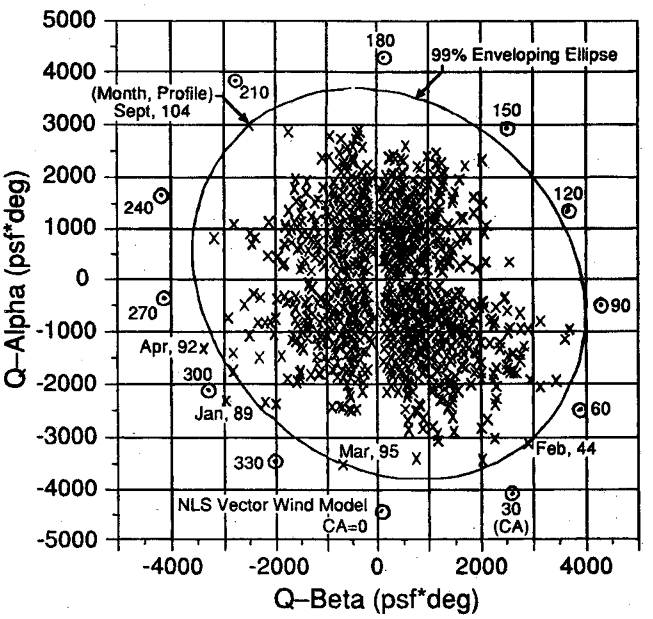

Fig. 6 Aerodynamic load indicators Q*ALPHA and Q*BETA at 12 km obtained from trajectory simulations using, 1800 KSC Jimsphere profiles (150/month), and the 12 enveloping vector wind model profiles for H1 = 12 km.

methodology described for wind data in Eqs. (27–31). The five Jimsphere profiles that produced the five extremes of QA, QB are identified by monthly profile number; the 12 values of QA, QB derived from the profiles of the enveloping wind model for a reference altitude of 12 km are identified by clocking angle. The enveloping wind model produces QA, QB that is consistently more extreme than even the most extreme values produced from the 1800 Jimsphere profiles. This result does not neccessarily point to a deficiency of the model or the Jimsphere database. If the Jimsphere QA, QB are used as a standard for the evaluation of the model, then it would not be difficult to make adjustments in the model profile construction process that would produce smaller QA, QB; for example, reduction of the probability level for the ellipse used in the definition of the given wind vector would reduce QA, QB. However, there may be a more appropriate standard for evaluation of the model; it is proposed that the standard be the enveloping ellipse of QA, QB derived from the database that was used to calculate the statistical parameters of the model, which is the 19-yr serially complete Rawinsonde database. The larger extremes in the 19-yr rawinsonde sample are attributed to the large sample size (approximately 650 statistically independent profiles per month), which is more than four times larger than the Jimsphere monthly total; this comparison of sample size is based on the criteria used in establishment of the Jimsphere database which required that profiles be separated by a time interval of at least 24 h.

Jimsphere profile number 89 in January and the envelope profile for a clocking angle of 300 deg for a reference height of 12 km produce similar values of QA, QB (Fig. 6); these wind profiles are illustrated in Fig. 7, along with the nominal profile used for wind biasing vehicle steering. The large scale feature that dominates the Jimsphere and the model profile is the strength of the negative V (northerly) component which is a crosswind relative to the vehicle, for a 90-deg launch azimuth. This crosswind, which is a deviation of 40 m/s from the nominal wind profile, produces a relatively large Beta response by the vehicle control system; since this occurs at an altitude where Q is near its maximum value, absolute QB is also large (eighth largest of the 1800 trajectory simulations using Jimsphere profiles). The maximum absolute Beta response produced by the model profiles is for clocking angles of 60 and 240 deg, which

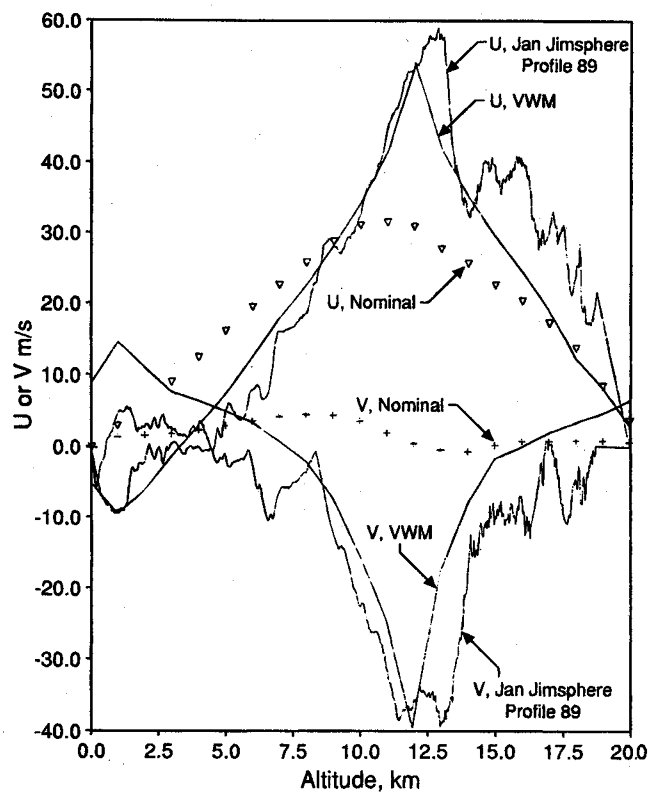

Fig. 7 Enveloping vector wind model (VWM) profile for 300 deg clocking angle (CA) and 12 km reference altitude (H1), KSC January Jimsphere profile 89, and nominal wind profile used to bias ascent vehicle steering.

have the largest deviation from the nominal crosswind component (47 and 48 m/s, respectively); absolute QB is largest at 90 deg relative to 60 deg, because the increase in Q at 90 deg attributed to the in-plane (U) wind component outweighs the slight decrease in Beta response. The QA extremes are at clocking angles of 0 and 180 deg which have the largest deviations of the in-plane wind component from the nominal wind profile (62.7 and −35 m/s, respectively).

Conclusion

The revised vector wind profile model produces wind profiles that are a reasonable substitute for measured wind profile samples. Model wind profiles produce dispersions in aerodynamic load indicators that cover the dispersion range calculated from an extensive sample of Jimsphere wind profiles; this is accomplished with only 12 model wind profiles compared to 1800 Jimsphere profiles for a selected reference altitude. This represents an opportunity for a considerable reduction of computational effort during design phases that require many iterations to establish a launch vehicle design philosophy.

Acknowledgments

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