P2.7 THE 2006 CAPE CANAVERAL AIR FORCE STATION RANGE REFERENCE ATMOSPHERE MODEL VALIDATION STUDY AND SENSITIVITY ANALYSIS TO THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION'S SPACE SHUTTLE

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1. INTRODUCTION

Atmospheric parameters are essential in assessing the flight performance of aerospace vehicles. The effects of the Earth's atmosphere on aerospace vehicles influence various aspects of the vehicle during ascent ranging from its flight trajectory to the structural dynamics and aerodynamic heating on the vehicle. Atmospheric databases characterizing the wind and thermodynamic environments, known as Range Reference Atmospheres (RRA), have been developed at space launch ranges by a governmental interagency working group for use by aerospace vehicle programs (RCC-MG, 1983). The National Aeronautics and Space Administration's (NASA) Space Shuttle Program (SSP), which launches from Kennedy Space Center, utilizes atmospheric statistics derived from the Cape Canaveral Air Force Station Range Reference Atmosphere (CCAFS RRA) database to evaluate environmental constraints on various aspects of the vehicle during ascent (NASA, 1999).

The CCAFS RRA is constructed from rawinsonde and rocketsonde observations and contains statistical data on numerous atmospheric parameters at 1 km intervals from the surface to 30 km and at 2 km intervals from 30 to 70 km altitude (RCC-MG, 1983).

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The first version of the CCAFS RRA was developed in 1963 with revised versions published in 1971, 1983 and 2006. The 1983 CCAFS RRA version was accepted by the SSP for use in deriving hot and cold atmospheres and atmospheric density dispersions for use in vehicle certification analyses. Atmospheric thermodynamic profiles used in construction of the 1983 CCAFS RRA were also used in vehicle ascent design and certification analyses (NASA, 1999 and NASA, 1998).

During preparations for STS-114 in July 2005, atmospheric temperature observations and the derived atmospheric density values between 50-80 kft (15-24 km) in the weeks preceding launch were exceeding the density limits used for aerodynamic ascent heating constraints in vehicle certification analyses. Density certification limits were based on the monthly density mean +/- 2 standard deviations from the 1983 CCAFS RRA database. The density observations in early July 2005 were biased towards the July 1983 CCAFS RRA density mean + 2 standard deviation values between 50-65 kft.

Mission specific analyses were conducted to evaluate the impact of the density bias from the certification environment on the thermal certification of the heating rates and integrated heat loading on the vehicle to ensure the current atmospheric density environments would not adversely affect the vehicle. Results showed that the density bias results in small changes to heating rates and integrated heat loading. At the same time a revised CCAFS RRA database was being developed. The following sections describe the validation study and comparison analysis of the revised CCAFS RRA to the 1983 version in addition to a sensitivity analysis on the impacts to the vehicle performance with the updated CCAFS RRA and the atmospheric profiles used in construction of the 2006 CCAFS RRA.

2. RANGE REFERENCE ATMOSPHERE VALIDATION STUDY

The 1983 version CCAFS RRA, along with a set of RRAs from other select geographical locations, was produced by the Marshall Space Flight Center's Natural Environments (NE) Branch and published under the authority of the Range Commanders Council Meteorology Group (RCC-MG, 1983). Subsequent to the 1983 release, the RCC-MG has given functional responsibility for periodically updating the RRAs, and producing new RRAs for additional sites as requested, to the Air Force Combat Climatology Center (AFCCC) located in Asheville, NC. Around 2001, the AFCCC produced a preliminary update to the CCAFS RRA. During independent review of the update, the NE Branch discovered numerous errors in the dataset representations of the thermodynamic, wind, and humidity parameters. These errors were reported to the RCC-MG and the AFCCC, and through cooperation between the three organizations, a corrective action plan was developed. The AFCCC was to produce a new draft of the RRA datasets, the NE Branch would perform a series of validation studies on the new draft and report their findings to the AFCCC and the RCC-MG. Then the AFCCC would correct any newly detected errors and produce an updated draft dataset. This process would continue iteratively until all parties were satisfied with the quality of the resulting product, at which time the RCC-MG would officially publish the update version. It should be noted that from the onset, the AFCCC was supportive of this process and dedicated significant professional workload and computational resources to ensure the quality of the final product.

A statistical description of any complex system is difficult to produce and validate. The RRA dataset contains a large number of atmospheric parameters that are dynamically interrelated in non-linear ways. While large amounts of input observational data are available, no real objective "truth" exists. The validation studies performed by the NE Branch included a variety of approaches. Separate tests were conducted to determine if the data were physically realistic, statistically coherent, analytically consistent with previous datasets, and structurally conformal to the judgments of subject matter experts. Numerous analysts and meteorologists contributed to the iterative development/validation cycle, and documenting every test performed throughout the process would be rather tedious. Instead, the following section will outline a few representative examples of the types of tests and checks that were performed along with their results and implications for subsequent dataset development.

2.1 *Wind speed and component statistics consistency test.*

The RRA dataset contains wind statistics for both the wind speed and for the individual U and V components. By knowing the mean values for the U and V components (U_μ and V_μ), the standard deviations of the two components (σ_U and σ_V), and the standard deviation of the wind speed (σ_{WS}), it is possible to reconstruct the wind speed itself using equation 1, as follows.

$$WS = \sqrt{U_\mu^2 + V_\mu^2 + \sigma_U^2 + \sigma_V^2 - \sigma_{WS}^2} \quad (1)$$

If the constituent wind statistics are coherent, then the computed wind speed should closely match the actual measured mean wind speed. Figure 1 shows a plot of computed versus mean

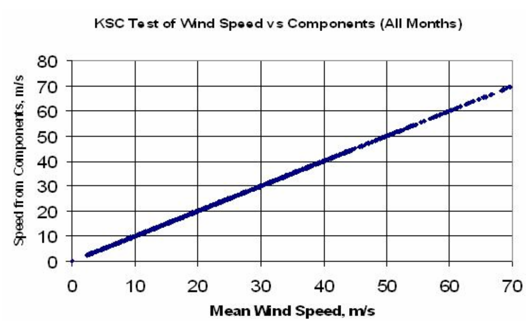

Fig. 1. Plot of wind speed as computed from wind speed and component statistics versus the measured mean wind speed showing a close identity relationship.

wind speeds from the 2006 CCAFS RRA. Data shown represent all months and all reporting altitudes up to 30 km. The graph clearly shows a close identity relationship implying that the wind speed and wind component statistics are coherent. Though not a definitive test, this result gives strong indication that the wind statistics adequately reflect the true population characteristics.

2.2 *Altitude -- Geopotential Height relationship test*

The RRA gives the computed value of the geopotential height (H) for each geometrical reporting altitude (Z) in the vertical domain. For a given latitude, the relationship between Z and H is well understood theoretically and one can be computed from the other using equation 2 as shown below.

$$H = \frac{Z\ g_{ref}}{g_{\phi}} \Big/ \left(1 + \frac{Z}{r_{\phi}}\right) \qquad (2)$$

Here, g_{ref} is the standard gravity for a reference geoid surface, g_{ϕ} is the surface gravity at latitude ϕ, and r_{ϕ} is the radius of the earth at latitude ϕ. Early in the validation process, a graph was made showing the difference Z-H for CCAFS/KSC as computed from the 1983 RRA, from the draft 2006 RRA, and from equation 2. The initial results are shown in Figure 2.

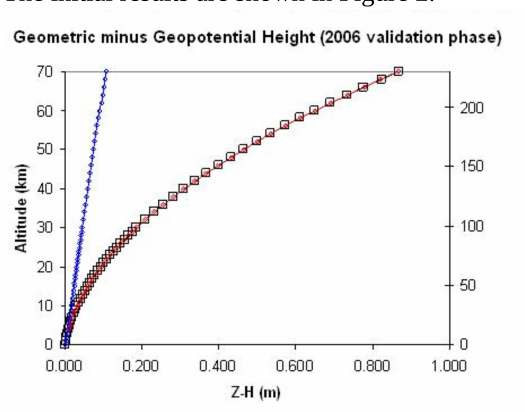

Fig. 2. The Z-H difference as a function of altitude as computed from theory (black square curve), as computed from the 1983 RRA (red curves), and as computed from the draft 2006 RRA (blue curve).

The 1983 RRA data shows the same curvilinear decrease with altitude of the Z-H difference as predicted from theory. However, the draft RRA data shows a slight linear decrease in the Z-H difference over the altitude domain. An analysis of the RRA processing software resulted in the discovery of a unit conversion error in the subroutine that computes H. Essentially, input values of Z, expressed in meters, were treated as though they were in km. This finding was reported to the AFCCC and the error was corrected. Figure 3 shows the Z-H differences as in Figure 2, but using the corrected 2006 RRA that was eventually released. All three data series coincide very closely.

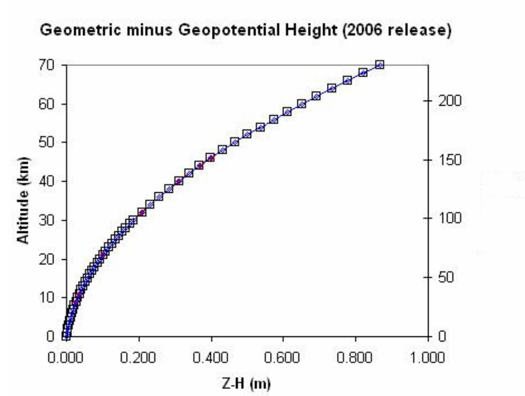

Fig. 3. The Z-H difference as a function of altitude as computed from theory (black curve), as computed from the 1983 RRA (red curve), and as computed from the released 2006 RRA (blue curve).

2.3 *Gas Law constant test*

The RRA gives the ability to compute the universal gas constant, R, from equation 3 as shown below.

$$R = \frac{p}{\rho T} \qquad (3)$$

Here, P is the mean pressure (hPa), T is the mean temperature (deg K), and ρ is the mean density (g/m^3). R has a known value of 287 $m^2 s^{-2} K^{-1}$ for dry air, and is slightly larger for moist air. By comparing the computed value of R to the known theoretical value it can be determined if the RRA state variables are consistent with the gas law. Figure 4 shows a plot of computed R as a function of altitude up to 30 km. It can be seen that the RRA values accurately produce the curves expected from theory. Near the ground, moisture is present and causes a slight increase in R. At higher altitudes, where the atmosphere is dry, the known value of R is obtained for all months.

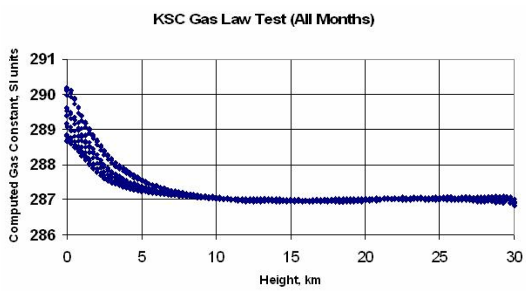

Fig. 4. Universal Gas Constant, R, computed from equation 3 and mean state variables from the 2006 RRA.

2.4 *Dataset differences*

Overall, the 1983 RRA version compared well with the 2006 version. However, there were some noteworthy differences, particularly in the thermodynamic variables. As an example, figure 5 shows profiles of temperature from 10-30 km altitude.

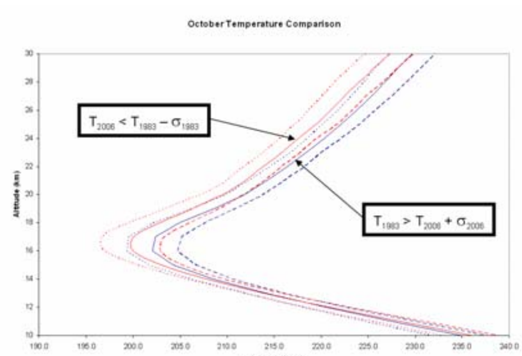

Fig. 5. Temperature profiles comparing 1983 (blue lines) RRA to 2006 (red lines) RRA. Shown for each version are the mean values (solid lines), the mean plus one standard deviation (dashed lines), and the mean minus one standard deviation (dotted lines).

Shown are the mean values and the mean +/- one standard deviation values for each version, for the month of October. It can be seen that from about 20-24 km, the two mean values are greater than one standard deviation apart. Similar results were obtained for all months, although the magnitudes of the differences varied, with October as the extreme case. In general, above around 15 km, the 2006 RRA was consistently colder than the 1983 version. Differences were also noted in the wind data fields, though the differences were less systematic and varied greatly from month to month.

3.0 IMPACT TO SPACE SHUTTLE ASCENT PERFORMANCE

The range reference atmosphere and related databases are used in ascent trajectory simulation and assessments of simulations (NASA, 1998). Mean monthly data is used during pre-flight product generation. The range reference atmosphere is used from the surface to 70km then ramped to the 1963 Patrick AFB atmosphere over 20km. This process results in nominal trajectory data products as well as ascent performance estimates. Concurrent profile data is used multiple ways to assess simulation results. Uncertainties due to temporal changes are captured in dispersions, called increments. These increments provide protection for assessments using a measured atmosphere at some time prior to the atmosphere that will affect the vehicle during ascent.

The range reference atmosphere is also used on day-of-launch. The atmosphere ramps from the top of the day-of-launch atmosphere to the range reference atmosphere over 5km. It then ramps to the Patrick AFB atmosphere at 70km as in the pre-flight case.

3.1 *Methodology*

Five sets of simulations were executed utilizing both the 1983 and 2006 monthly mean atmosphere and concurrent profile database. A matrix of the various runs is presented in Table 1. Note that the specified number is per month. The use of 150 profiles matches the current operations concept for determining launch probability. For the final simulation set, the full monthly database is used to determine differences between the full and truncated database in terms of performance and other relevant indicators.

Table 1 Simulation Matrix

Atmosphere	Wind & I-loads	RRA 1983	RRA 2006
Mean + 150 profiles	Mean + 150	X	X
Mean + 150 profiles	Mean	X	X
Mean + Full 90 kft database	Mean		X

The simulation set using 150 measured winds and associated Initiation loads (I-Loads) was executed primarily for data quality assurance. The output of the 1983 simulation set should match a previously executed simulation set. The atmosphere used for simulation configuration was then modified to use a 2006 atmosphere profile.

When a set of simulations is assessed, the mean of the set is used for comparison. For example, the performance number given for the July database is the mean of the performances using 150 measured atmospheres. This mean-of-150 should be distinguished from the single performance value using the mean monthly atmosphere for July.

Both the mean atmospheric data and the concurrent profiles were used to simulate a shuttle ascent. The simulation results were compared against all Go/No-Go criteria: alpha/beta/q-plane, loads indicators, and quality assurance rules. Statistics for each of the above criteria were generated.

Note the I-loads used for each simulation were generated using 1983 atmosphere database. Part of the delta seen between the databases can be attributed to using I-loads that weren't generated using the atmosphere simulated.

3.2 *Results*

3.2.1 *Measure Wind Simulations*

The measured wind simulation set gave results that match previous launch probability studies, confirming that the input data used was accurate. When the 2006 atmosphere were substituted in, very similar results were obtained. In most cases, the same wind that generated a No-Go condition with the 1983 atmosphere created a No-Go condition with the 2006 atmosphere. A few winds switched from a Go to a No-Go and vice versa. These were consistently cases with very small violations, i.e. the 1-2% change in margin was sufficient to change the launch status of a given wind.

3.2.2 *Performance*

Performance in this context describes the amount of additional weight the shuttle could potentially carry to orbit and is in the units of pounds. Current shuttle operations account for a difference in performance between pre-flight design, using a mean wind and atmosphere, and day-of-launch design, using a measured wind and atmosphere. The atmosphere-only contribution of this difference was assessed and is detailed in Table 2. For both 1983 and 2006, performance for a mean atmosphere is lower, on average, than for a measured atmosphere. Further, this delta is smaller for the 2006 atmosphere profile database indicating the 2006 concurrent profiles are more representative of the mean atmosphere. Using a truncated 2006 database affects predicted performance very little as compared with the full database.

Table 2. Performance Delta (lbs) Mean Minus Measured Atmosphere

	2006, 150	2006, Full	1983
January	-35	-43	0
February	-53	-63	-60
March	-1	-10	-52
April	-6	-6	-58
May	10	6	-110
June	-13	-19	-79
July	-29	-32	-83
August	-24	-35	-94
September	-17	-36	-49
October	-12	-6	-73
November	-14	-21	-109
December	-43	-58	-52
Average	*-20*	*-27*	*-68*

When comparing the two databases of atmosphere profiles (Table 3), a loss of performance of approximately 70 lbs appears from the 1983 database to the 2006 database.

Table 3. Performance Delta (lbs)
Mean of 150 Atmospheres
RRA 2006 Minus RRA 1983

January	-48
February	-91
March	-51
April	-52
May	-37
June	-66
July	-54
August	-69
September	-86
October	-61
November	-94
December	-92
Average	*-67*

3.2.3 *Quality Assurance Rules*

Each ascent simulation is assessed against various rules to ensure the vehicle is performing within system and experience envelopes. Comparisons are calculated as a percentage of a limit. These percentages were compared between the databases and sorted to determine which percentages increased or decreased the most.

Of the 63 rules verified, 57 differed by less than 2%. Four of those that differed greater than 2% are staging conditions: flight path angle (2%), altitude (4%), altitude rate (5%), and velocity (4%). Another difference relates to atmospheric density (4%). Note that the altitude rate at staging is one of the dependent variables used during I-load design iteration. If the 2006 mean atmosphere were used to generate I-loads, one would expect the differences at staging to be smaller.

3.2.4 *Maximum Dynamic Pressure*

The maximum dynamic pressure during each simulation was recorded. The values achieved using the 2006 database matched within one half of one percent the values achieved using the 1983 database.

4. CONCLUSION

From a space shuttle ascent performance perspective, there is very little change between the 1983 CCAFS RRA and the 2006 CCAFS RRA. However, at the time of the observations this was not known and therefore an analysis on the effects to space shuttle ascent performance was necessary to ensure no additional precautions were to be implemented by the Space Shuttle Program. The 2006 CCAFS RRA database has been implemented by the program to use in any future mission specific trajectory analyses as this database better characterizes the atmosphere the vehicle will experience during ascent. Furthermore, this model will be use by future launch vehicles NASA is currently developing.

5. REFERENCES

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