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ATMOSPHERIC MODELS FOR ENGINEERING APPLICATIONS

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ABSTRACT

This paper will review the historical development of reference and standard atmosphere models and their applications. The evolution of the U.S. Standard Atmosphere will be addressed, along with the Range Reference Atmospheres and, in particular, the NASA Global Reference Atmospheric Model (GRAM). The extensive scope and content of the GRAM will be addressed since it represents the most extensive and complete "Reference" atmosphere model in use today. Its origin was for engineering applications and that remains today as its principal use.

1. INTRODUCTION

Since the mid 19th century there has been considerable effort devoted to the development of standard and reference atmosphere models. The first "Standard Atmospheres" were established by international agreement in the 1920's. Later some countries, notably the United States, also developed and published "Standard Atmospheres". The term "Reference Atmospheres" in used to identify atmosphere models for specific geographical locations. Range Reference Atmosphere Models developed during the 1960's are examples of these descriptions of the atmosphere. The NASA Global Reference Atmospheric Model (GRAM) is the optimum reference atmosphere and is global in extent. This paper discusses the various atmospheric models, scopes, applications and limitations relative to use in aerospace industry activities.

2. HISTORICAL DISCUSSION

A "Standard Atmosphere" is defined as a vertical distribution of atmospheric temperature, pressure, and density which by international agreement is taken to be representative of the Earth's atmosphere. The first "Standard Atmospheres" established by international agreement were developed in the 1920's primarily for purposes of pressure altimeter calibrations, aircraft performance calculations, aircraft and rocket design, ballistic tables, etc.. Later some countries, notably the United States, also developed and published "Standard Atmospheres". The term "Reference Atmosphere" is used to identify vertical descriptions of the atmosphere for specific geographical locations or globally. These were developed by organizations for specific applications, especially as the aerospace industry began to mature after WWII. The term "Standard Atmosphere" has in recent years also been used by national and international organizations to describe vertical descriptions of atmospheric trace constituents, the ionosphere, atomic oxygen, aerosols, ozone, winds, water vapor, planetary atmospheres, etc.

A standard unit of atmospheric pressure is defined as that pressure exerted by a 760 millimeter column of mercury at standard gravity (980.665 cms^{-2}) at 45.5425° N latitude and sea level at a temperature of 273.15° K (0° C). The recommended unit for meteorological use is 1013.25 hectopascals (millibars). Standard temperature is used in physics to indicate a temperature of 0° C, the ice point, and a pressure of one standard atmosphere (1013.25 hectopascals). In meteorology, the term standard temperature has no generally accepted meaning, except that it may refer to the temperature at zero pressure-altitude in the standard atmosphere (15° C) with a density of 1225.00 gm^{-3}. The standard sea-level values of temperature, pressure, and density that have been used for decades are: temperature of 288.15° K, or 15° C; pressure of 1013.25 millibars, or 760 millimeters of Hg; and density of 1225.00 gm^{-3}.

As early as the middle of the 19th century, a Standard Atmosphere was needed as a basis for calibrating aneroid barometers used in measuring altitudes. These instruments provided the means of obtaining a rough measure of the height of mountains and other land areas. They were later used for altitude determination in manned balloon flights. Similar atmospheres in England as well as in the United States were computed on the basis of a constant temperature independent of altitude. Shortly after the beginning of the 20th century, several atmospheres were developed on the basis of observed or assumed temperature-altitude profiles, in which the temperature decreased with increasing altitude. These atmospheres were adopted by France, Italy, and Germany. The development of the airplane, plus the desire to improve the direct reading accuracy of barometer altimeters, stimulated the

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measurement of atmospheric temperature to the greatest possible altitude at various locations, particularly in England, France, Germany, and Italy.

With the more general use of airplanes during World War I from 1914 to 1917, the need for one standard atmosphere to serve as the basis for comparison of aircraft performance became evident. The general international desire for unity of national atmospheres following the end of World War I, as well as the unreality and complexity of several of the existing aeronautical atmospheres, prompted the study of the problem with the aim of recommending a simple compromise model. The result of this study was the adoption of an atmosphere model for France in 1920 as the official standard atmosphere in aircraft performance tests. Italy also adopted this atmosphere model in 1920 and England in 1921. It was not until 1925, however, that this atmosphere model was adopted in England as the basis for altimeter calibration. In 1924 the International Commission for Aerial Navigation (ICAN) adopted the model as the basis for an international standard known as the ICAN Standard Atmosphere. Though never adopted by the United States (U.S.), this standard served much of the world until 1952 when slight differences were reconciled and it was modified slightly under the International Civil Aviation Organization (ICAO), which included the United States. This standard atmosphere formed the basis of the tables given in National Advisory Committee for Aeronautics (NACA) Report 1235.

In 1922 the United States NACA Standard Atmosphere (or first U. S. Standard Atmosphere) was published. It was officially approved on 2 December 1924 by the Executive committee of NACA as described in NACA TR-218. The War and Navy Departments, the Weather Bureau and the Bureau of Standards adopted it for use in aeronautical calculations. Table 1 gives a time history of the documented technical reports dealing with the updates to this U.S. Standard Atmosphere. In 1952 the International Civil Aeronautical Organization (ICAO) produced the ICAO Standard Atmosphere and in 1964 an extension to 32 km. Subsequent to this time there have been a succession of Standard and Reference Atmospheres, some extending to altitudes above 1000 km, produced by the U.S. Committee on Extension to the Standard Atmosphere (COESA), Committee on Space Research (COSPAR), Comitet Standartov (USSR), International Standardization Organization (ISO), U. S. Air Force Research and Development Command (ARDC), U. S. Range Commanders Council (RCC), and U. S. National Aeronautics and Space Administration (NASA) plus others. COESA was established in 1953 and led to the publication of the 1958, 1962, 1966 and 1976 versions of the U.S. Standard Atmosphere.

In 1975 the International Standards Organization published a Standard Atmosphere for altitudes from –2 to 50 km that is identical to the ICAO Standard Atmosphere from –2 to 32 km. Subsequently the ISO published in 1982 a family of five *Reference Atmospheres for Aerospace Use* for altitudes up to 80 km and latitudes of 15, 30, 45, 60, and 80° N.

The portion of the U. S. Standard Atmosphere up to 32 km is identical with the ICAO Standard Atmosphere, 1964; and identical below 50 km with the ISO Standard Atmosphere, 1973. For this reason, in addition to providing an excellent description of the atmosphere model development extending beyond conventional aircraft operations, the U.S. Standard Atmosphere, 1976 is used here to illustrate the vertical distribution of atmospheric temperature. Figure 1 provides an illustration of the temperature-height profiles to 100 km of the COESA U. S. Standard Atmosphere, 1976, and the lowest and highest mean monthly temperatures obtained for any location between the Equator and pole.

For altitudes above approximately 100 km, significant variations in the temperature, and thus density, occur due to solar and geomagnetic activity over the period of a solar cycle. Variations in the temperature-height profiles for various degrees of solar and geomagnetic activity are presented in Figure 2. Profile (A) gives the lowest temperature expected at solar cycle minimum; profile (B) represents average conditions at solar cycle minimum; (C) represents average conditions at a typical solar cycle maximum; and (D) gives the highest temperatures to be expected during a period of exceptionally high solar and geomagnetic activity.

In the early 1970's, during the initial development of the Space Shuttle vehicle, it was determined that the various reference atmosphere models developed up to that time frame might not be sufficient to use for a vehicle which could land at any location on the Globe. This prompted the development of the NASA/MSFC Global Reference Atmosphere Model (GRAM), and its many revisions. GRAM gives the engineer a monthly average atmospheric profile (thermodynamic parameters and wind), with their variability, either at any given lat/long location or along any inputted trajectory. GRAM-99 will be described in more detail in the next section.

In 1996 the American Institute of Aeronautics and Astronautics (AIAA) published a Guide to Reference and Standard Atmosphere Models. This document provides information on the principal features for a number of global, regional, middle atmosphere, thermosphere, test ranges, and planetary atmosphere models. Summary information on these reference and standard atmosphere models is given relative to geographic region, altitude range, parameters, species, temporal variation, output data, and principal application. The NASA Standards Program Handbook (NASA-HDBK-1001) dated August 2000 and entitled: "Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development" contains a Section 3 entirely devoted to "Thermodynamic Properties and Atmospheric Models", It can be viewed and downloaded at : http://standards.nasa.gov.

Currently some of the most commonly used Standard and Reference Atmospheres include the ICAO Standard Atmosphere, 1952/1964, the ISO Standard Atmosphere, 1975, the U. S. Standard Atmosphere, 1976, the COSPAR International Reference Atmosphere (CIRA), 1986 *, the NASA/MSFC Global Reference Atmosphere Model (GRAM), 1999 ** and the RCC/MG Range Reference Atmospheres (see Table 2 for a complete Range listing). ***

3. GRAM-99 REFERENCE ATMOSPHERE

The NASA-MSFC Global Reference Atmospheric Model (GRAM) was developed for use by design engineers, mission planners, or atmospheric investigators as a world-wide reference atmospheric model (see Figure 3). It was last revised in 1999. GRAM presents realistic monthly atmospheric and wind vertical profiles (up to 2500 km altitude), or values over any global location or along any path or trajectory desired. The parameters variability about the monthly mean Is also derived. The second capability of GRAM is its ability to generate many Monte-Carlo type of realistic atmospheric or wind realizations which obey the equations of the atmosphere. GRAM-99 uses the GUACA (0-27km), MAP (20-120km) and MET-99 (>90km) over its altitude ranges. Eleven atmospheric constituents can also be obtained from GRAM. A variable-scale perturbation model provides both large-scale (wave) and small-scale (stochastic) deviations from the mean values for thermodynamic variables and horizontal and vertical wind components. The small-scale perturbation model includes improvements in representing intermittency ("patchiness"). A major new feature in GRAM-99 is an option to substitute Range Reference Atmosphere (RRA) data for conventional GRAM climatology when a trajectory passes sufficiently near any RRA site. GRAM can be run as a stand-alone program or as a subroutine in various engineering programs.

An example of the GRAM-99 capability for engineering use is shown in Figures 4, 5, and 6. These figures present a realistic X-37 descent trajectory lat/long (fig. 4) from a 57 degree inclination orbit in January with a landing at Edwards AFB California. Vehicle altitude and time into re-entry are indicated in the figure. Figure 5 gives the mean January atmospheric density field (as a ratio of the U.S. Standard Atmosphere 1976 density) in which the vehicle's trajectory will traverse when descending.

Figure 6 presents the monthly variability (2-sigma density envelopes) of the ambient density along this same trajectory, with one random Monte-Carlo density perturbation realization as shown in this figure (also as a ratio of the U.S. 1976 density). One can observe its variability along the given trajectory, and note That ambient density values presented here statistically exceed the 2-sigma boundaries as one would expect. Copies of the GRAM-99 document or computer code are available upon request to Dale Johnson at NASA MSFC, Huntsville, AL 35812, dale.johnson@msfc.nasa.gov.

* previously issued as CIRA 1961, CIRA 1965 and CIRA 1972.

** previously issued as GRAM-86, GRAM-88, GRAM-90 and GRAM-95.

*** Some site specific annual reference atmospheres (and Hot and Cold atmospheres) have been created by NASA/Marshall Space Flight Center for NASA sites of interest, as for Patrick AFB/NASA Kennedy Space Center, Vandenberg AFB and Edwards AFB.

4. CONCLUSION

The intent of this paper is to present a summary historical account regarding the establishment of International and domestic Standard and Reference Atmospheres. These atmospheres were developed to provide a standard type of atmospheric input for the various aeronautical and space vehicle design, development, and operational applications. The NASA Global Reference Atmospheric Model (GRAM-99) has been presented as an example of a unique, global, multi-dimensional reference atmospheric model, including its characteristics and engineering applications.

This paper is an update of the Johnson et. al., "Reference and Standard Atmosphere Models" paper presented at the 10th AMS Conference on Aviation, Range, and Aerospace Meteorology.

5. BIBLIOGRAPHY OF DOCUMENTS, INCLUDING REFERENCES THEREIN, ON WHICH THE CONTENTS OF THIS ARTICLE IS BASED

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TABLE 1. Timeline History of U.S. Standard Atmosphere Publications.

Date	Title	Report No.	Author
1922/6	Notes on the Standard Atmosphere	NACA TN-99	Diehl
1922	Standard Atmosphere (SA)	NACA Rpt-147	Gregg
1925	Standard Atmosphere Tables & Data	NACA Rpt-218	Diehl
1926	Tables for Calibrating Altimeters etc	NACA Rpt-246	Brombacher
1932	Some Approximate Equations for the Std Atmos	NACA Rpt-376	Diehl
1936	Altitude-pressure Tables Based on US Std Atm	NACA Rpt-538	Brombacher
1947/1	Tentative Tables for the Prop of Upper Atmosphere	NACA TN-1200	Warfield
1954/5	Manual of ICAO Std Atm Calc by NACA	NACA TN-3182	Anon
1955	Standard Atmosphere-Tables to 65800'	NACA Rpt-1235	Anon
1956/12	The ARDC Model Atmosphere, 1956	AFSG TN56-204 #86	Minzner
1958	US Extension to ICAO Std Atm - to 300 km	USGovPO	Minzner
1959/8	The ARDC Model Atmosphere, 1959	AFCRC TR59-267 #115	Minzner
1962/12	US Standard Atmosphere, 1962	USGovPO	Anon
1966	US Standard Atmosphere Supplements, 1966	USGovPO	Anon
1976	The 1976 Standard Atmos. Above 86-km Altitude	NASA SP-398	Minzner
1976	US Standard Atmosphere, 1976	USGovPO	Anon

TABLE 2. Listing of Published IRIG & RCC Range Reference Atmospheres.

1. Argentia, New Foundland
2. Ascension Island, South Atlantic
3. Barking Sands, Hawaii
4. Cape Canaveral, Florida
5. China Lake, California
6. Dugway Proving Ground, Utah
7. Edwards AFB, California
8. Eglin AFB, Florida
9. Eniwetok, Marshall Islands, Pacific
10. Fairbanks, Alaska
11. Fort Churchill, Canada
12. Fort Greeley, Alaska
13. Fort Huachuca, Arizona
14. Johnston Island, Pacific
15. Kodiak, Alaska
16. Kwajalein, Marshall Islands, Pacific
17. Lihue Kauai, Hawaii
18. Nellis AFB, Nevada
19. Point Arguello, California
20. Point Mugu, California
21. Roosevelt Roads, Puerto Rico
22. Shemya, Alaska
23. Taguac, Guam, Pacific
24. Thule, Greenland
25. Vandenberg AFB, California
26. Wake Island Pacific
27. Wallops Island, Virginia
28. White Sands, New Mexico
29. Yuma PG, Arizona

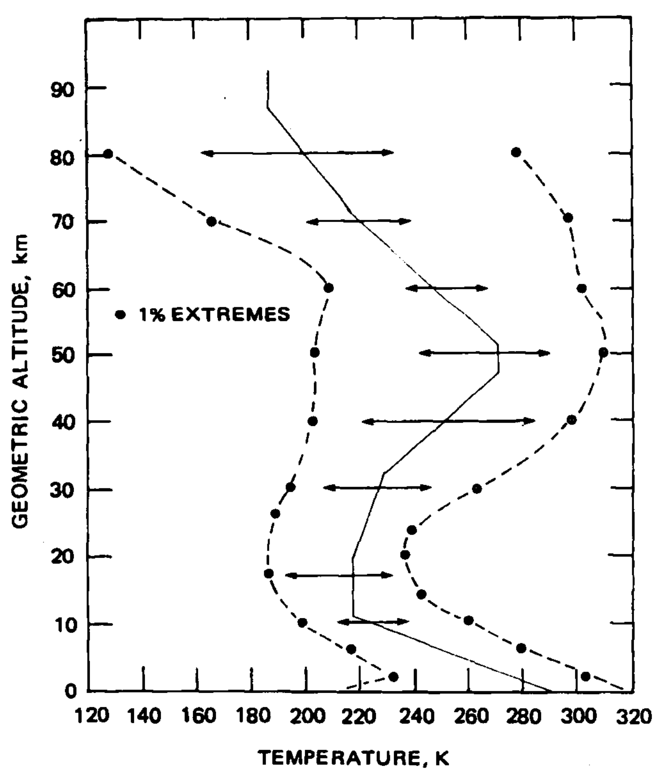

FIGURE 1. Range Of Systematic Variability Of Temperature Around The U. S. Standard Atmosphere, 1976 (Source U.S. Standard Atmosphere, 1976)

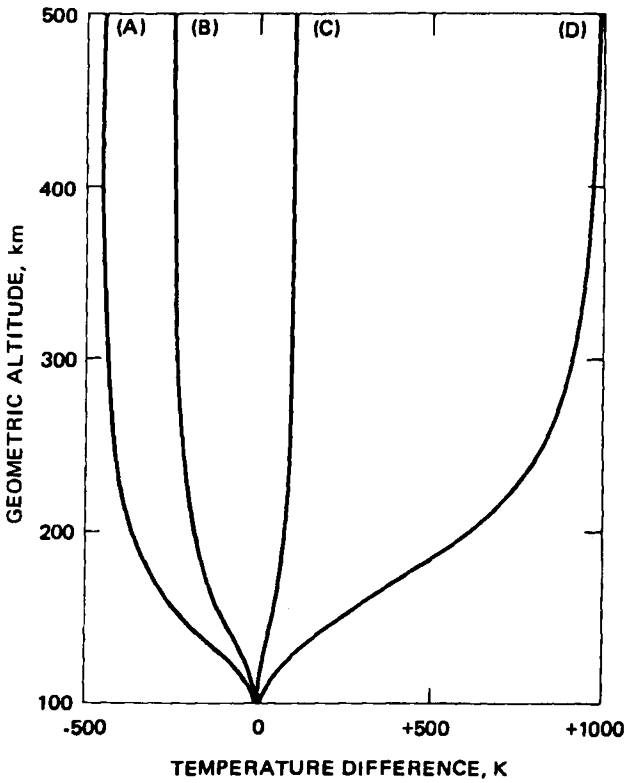

FIGURE 2. Departures Of The Temperature-Altitude Profiles From That Of The U.S. Standard Atmosphere, 1976, For Various Degrees Of Solar Activity (Source: U. S. Standard Atmosphere, 1976)

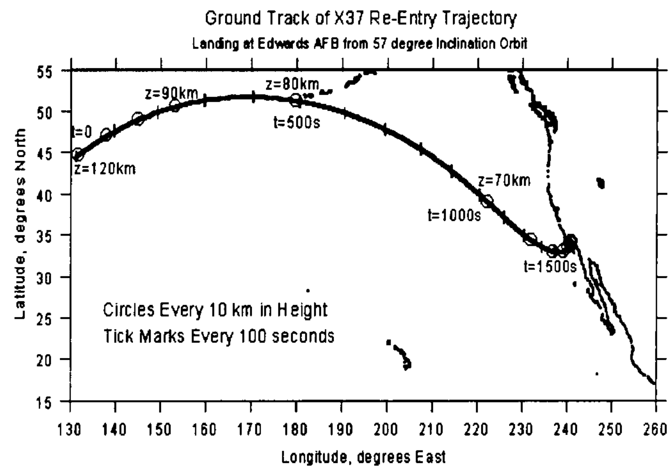

FIGURE 4. Case 1 – January Ground Track for X-37 57° inclination orbit Re-entry Trajectory with Landing at Edwards AFB California. Re-entry Time and altitude are indicated.

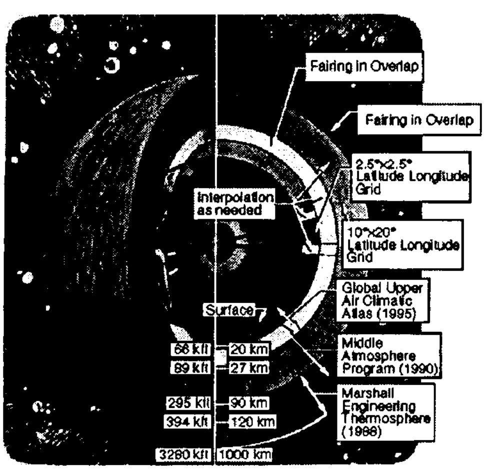

FIGURE 3. Schematic Structure of The NASA/MSFC Global Reference Atmospheric Model 1999 (GRAM-99)

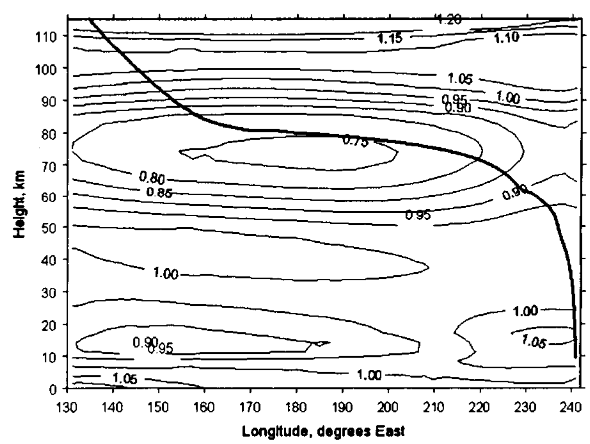

FIGURE 5. Mean January Height vs. Longitude Cross-section of Atmospheric Density as a ratio of the US76 Density for the X-37 Case 1 Re-entry Trajectory.

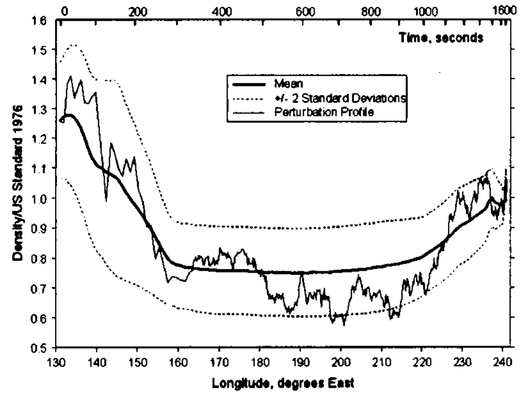

FIGURE 6. Mean January Atmospheric Density and 2-Sigma Density Envelopes vs. Longitude, and a Monte-carlo Density Perturbation Profile along the X-37 Case 1 Re-entry Trajectory, as a ratio of the U.S. Standard 1976 Density.