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Space Vehicle Terrestrial Environment Design Requirements Guidelines (Draft 11/14/05a)

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The terrestrial environment is an important driver of space vehicle structural, control, and thermal system design. NASA is currently in the process of producing an update to an earlier Terrestrial Environment Guidelines for Aerospace Vehicle Design and Development Handbook. This paper addresses the contents of this updated handbook, with special emphasis on new material being included in the areas of atmospheric thermodynamic models, wind dynamics, atmospheric composition, atmospheric electricity, cloud phenomena, atmospheric extremes, and sea state. In addition, the respective engineering design elements are discussed relative to terrestrial environment inputs that require consideration. Specific lessons learned that have contributed to the advancements made in the application and awareness of terrestrial environment inputs for aerospace engineering applications are presented.

Nomenclature

km = kilometer
MAHRSI = Middle Atmosphere High Resolution Spectrograph Investigation
NASA = National Aeronautics and Space Administration
NE = natural environment
NLC = noctilucent clouds
nm = nanometer
NRL = Naval Research Laboratory
PMC = polar mesospheric clouds
PMSE = polar mesospheric summer echos
RCS = reaction control system (fuel)
RSS = root sum squared
TPS = thermal protection system
UV = ultraviolet

I. Introduction

The terrestrial environment is a key forcing function in the design and development of a launch vehicle. The scope of the terrestrial environment includes : winds; atmospheric models and thermodynamic properties; thermal radiation; U.S. and world surface extremes; humidity; precipitation, fog, and icing; cloud phenomena and cloud cover models; atmospheric electricity; atmospheric constituents; aerospace vehicle exhaust and toxic chemical release; tornadoes and hurricanes; geologic hazards; and sea state. These environments play a significant role in the design and operation of aerospace vehicles and in the integrity of aerospace systems. Terrestrial environment design criteria guidelines are based on statistics and models of atmospheric and climatic phenomena relative to various aerospace design, development, and operational issues. The NASA Terrestrial Environment Handbook 1001[1, 2] provides these environments for use by design engineers, mission planners, and program management.

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The terrestrial environment criteria guidelines presented in the handbook were formulated based on discussions with and requests from engineers[3] involved in aerospace vehicle development and operations. Therefore, they represent responses to actual engineering problems and not just a general compilation of environmental data. The NASA Centers, various other Government agencies, and their associated contractors responsible for the design, mission planning, and operational studies use this handbook extensively. Since the handbook is based on pre-1990 data and models, it is currently being updated for completion in 2006.

II. Engineering Importance

It is important to recognize the need to define the terrestrial environment very early in the design and development cycle of any aerospace vehicle. This is especially true for a new configuration. Using the desired operational capabilities, launch locations, and flight profiles for the vehicle, specific definitions of the terrestrial environment can be provided which, if the aerospace vehicle is designed to accommodate, will ensure the desired operational capability within the defined design risk level. It is very important that those responsible for the terrestrial environment definitions for the design of an aerospace vehicle have a close working relationship with program management and design engineers. This will ensure that the desired operational capabilities are reflected in the terrestrial environment requirements specified for design of the vehicle.[4-8]

An aerospace vehicle's response to terrestrial environment design criteria must be carefully evaluated to ensure an acceptable design relative to desired operational requirements. The choice of criteria depends upon the specific launch and landing location(s), vehicle configuration, and expected missions(s). Vehicle design, operation, and flight procedures can be separated into particular categories for proper assessment of environmental influences and impact upon the life history of each vehicle and all associated systems. These include categories such as (1) purpose and concept of the vehicle, (2) preliminary engineering design, (3) structural design, (4) control system design, (5) flight mechanics, orbital mechanics, and performance (trajectory shaping), (6) optimization of design limits regarding the various natural environmental factors, and (7) final assessment of natural environmental capability for launch and flight operations.

Another important matter that must be recognized is the necessity for having a coordinated and consistent set of terrestrial environment requirements for use in a new aerospace vehicle's design and development. This is particularly important where diverse groups are involved in the development, and is of utmost importance for any international endeavor. A "central control point" having responsibility for the definition and interpretation of the terrestrial environment inputs is critical to the successful design and operation of any new aerospace vehicle. Without this control, different terrestrial environment values or models can be used with costly results, in terms of money, time, and vehicle performance. This central control point should also include responsibility for mission analysis, test support requirements, flight evaluation, and operational support relative to terrestrial environment requirements.

During the early stages of a new aerospace vehicle's design and development, tradeoff studies to establish sensitivities of various terrestrial environment-forcing functions are important. Feedback from these studies is key to establishing the necessary terrestrial environment requirements for the vehicle's final design. Including a single source (central control point) responsible for the preliminary design tradeoff study terrestrial environment inputs and their interpretation is important. This will preclude a multitude of problems in the final design and development process, and will enable terrestrial environment requirements to be established with a minimum amount of communications problems and misunderstanding of design issues.

The close association between the design and test engineering groups and those responsible (central control point) for the terrestrial environment inputs is key to the success of the vehicle's development process. This procedure has been followed in many NASA aerospace vehicle developments and is of particular importance for any new aerospace vehicle. Figure 1 illustrates necessary interactions relative to terrestrial environment definition and engineering application. Feedback is critical to the process and ability to produce a viable vehicle design and operational capability.

Finally, although often not considered to be significant, it is of major importance that all new aerospace vehicle design review meetings include a representative from the terrestrial environment group (central control point) assigned to support the program. This will ensure good understanding of design requirements and timely opportunity to incorporate terrestrial environment inputs and interpretations, which are tailored to the desired operational objectives, into the design process. It is also necessary that any proposed deviations from the specified terrestrial environment requirements, including those used in preliminary design tradeoff studies, be approved by the responsible terrestrial environment central control point to ensure that all program elements are using the same

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baseline inputs. This will also help the program manager understand the operational impact of any change in terrestrial environment requirements before implementation into the design. Otherwise, gross errors and deficiencies in design can result from use of different inputs selected from various diverse sources by those involved in design and other performance studies.

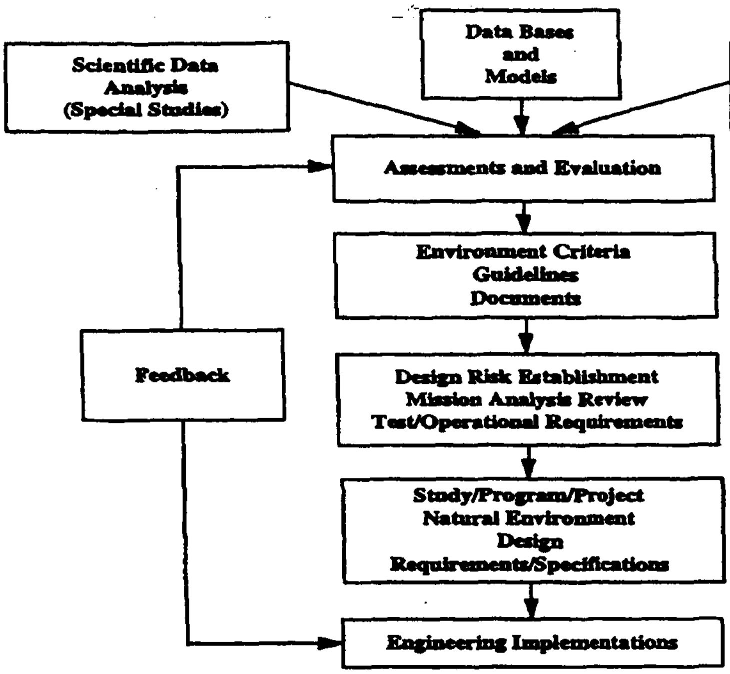

Figure 1. Natural terrestrial environment definition and analysis for aerospace_vehicle engineering application.

The flight profile of any aerospace vehicle includes the terrestrial environment. Thus, all aerospace vehicle operations will always be influenced to some degree by the terrestrial environment with which the vehicle interacts. As a result, the definition of the terrestrial environment and its interpretation is one of the key aerospace vehicle design and development inputs. This definition plays a significant in design studies associated with the areas of structures, control systems, trajectory shaping (performance), aerodynamic heating, and takeoff/landing capabilities. The aerospace vehicle's capabilities that result from the design, in turn, determine the terrestrial environment constraints and flight opportunities for tests and operations.[4-8]

III. Issues

For terrestrial environment extremes, there is no known physical upper or lower bound except for certain environmental conditions. For example, wind speed does have a strict physical lower bound of zero. Essentially all observed extreme conditions have a finite probability of being exceeded. Consequently, terrestrial environment extremes used for engineering design must be accepted with the knowledge that there is some risk of the values being exceeded. The acceptance of this risk is, in the final analysis, an important aerospace vehicle program decision.

The measurement of many environmental parameters is not as accurate as desired. In some cases, theoretical model estimates are believed to be more representative for design use than those indicated by empirical distributions from short periods of record. Therefore, theoretical values have been given considerable weight in selecting extreme values for some parameters; i.e., the peak surface winds. Criteria guidelines are presented for various percentiles based on available data samples. Caution should be exercised in the interpretation of these percentiles in aerospace

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vehicle studies to ensure consistency with physical reality and the specific design and operational problems of concern.

Aerospace vehicles are not normally designed for launch and flight in severe weather conditions such as hurricanes, thunderstorms, ice storms, and squalls. Environmental parameters associated with severe weather that may be hazardous to aerospace vehicles include strong ground and in-flight winds, strong wind shears and gusts, turbulence, icing conditions, and electrical activity. Terrestrial environment guidelines usually provide information relative to those severe weather characteristics that should be included in design requirements and specifications if required to meet the program's mission operational requirements.

Knowledge of the terrestrial environment is also necessary for establishing test requirements for aerospace vehicles and designing associated support equipment. Such data are required to define the fabrication, storage, transportation, test, and preflight design condition and should be considered for both the whole vehicle system and the components which make up the system. This is one of the uses of guideline data on terrestrial environment conditions for the various major geographic locations applicable to the design of a new vehicle and associated supporting equipment.

The group having the central control point responsibility and authority for terrestrial environment design requirement definition and interpretation must also be in a position to pursue environment input-related applied research studies and engineering assessments and updates. This is necessary to ensure accurate and timely terrestrial environment inputs tailored to the program's needs. Design engineers and program management that assume they can simply draw on the vast statistical databases and numerous models of the terrestrial environment currently available in the literature, without interpretation and tailoring to specific vehicle design needs, can prove to be a major deterrent to the successful development and operation of an aerospace vehicle.

Although ideally a vehicle design should accommodate all expected operational environment conditions, it is neither economically nor technically feasible to design an aerospace vehicle to withstand all terrestrial environment extremes. For this reason, consideration should be given to protection of vehicles from some extremes. This can be achieved by use of support equipment and specialized forecast personnel to advise on the expected occurrence of critical terrestrial environment conditions. The services of specialized forecast personnel may be very economical in comparison with more expensive vehicle designs that would be necessary to cope with all terrestrial environment possibilities.

The terrestrial environment is a very major environmental driver for an aerospace vehicle's design and is the focus of this handbook. However, the natural environment above 90 km must also be considered for aerospace vehicles. The orbital operating phase of an aerospace vehicle operating includes exposure to space environment, such as atomic oxygen, atmospheric density, ionizing radiation, plasma, magnetic fields, meteoroids, etc., plus a few man made environments, such as orbital debris. Specific aerospace vehicle terrestrial and space environments design requirements are normally specified in the appropriate vehicle design criteria documentation.

Good engineering judgment must be exercised in the application of terrestrial environment requirements to an aerospace vehicle design analysis. Consideration must be given to the overall vehicle mission and system performance requirements. Knowledge is still lacking on the relationship between some of the terrestrial environment parameters that are required as inputs to the design of aerospace vehicles. Also, interrelationships between vehicle parameters and terrestrial environment variables cannot always be clearly defined. Therefore, a close working relationship and team philosophy must exist between the design and operational engineer and the respective organization's terrestrial environment central control point specialists.

IV. Terrestrial Environment Handbook Content

The scope of the terrestrial environment handbook encompasses the key elements affecting the structural, control systems, thermal, and associated systems design and development requirements. Aerospace vehicle design guidelines are provided in the handbook for various terrestrial environment phenomena. Information on mission analysis, prelaunch monitoring, and flight evaluation relative to terrestrial environment inputs is also provided. In general, the document does not specify how the designer should use the terrestrial environment data in regard to a specific aerospace vehicle design. Such specifications may be established only through analysis and study of a particular vehicle design problem. Although of operational significance, descriptions of some atmospheric conditions have been omitted since they are not of direct concern for an aerospace vehicle system's design, the primary emphasis of this handbook. Induced environments (vehicle caused) may be more critical than the natural environment for certain vehicle operational situations. In some cases, the combination of natural and induced environments will be more severe than either environment alone. Table 1 presents a summary of the handbook's technical contents.

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Table 1. NASA Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development

Section	Title
1	Introduction
2	Winds
3	Atmospheric Thermodynamic Properties and Models
4	Solar and Thermal Radiation
5	U.S. and World Surface Extremes
6	Humidity
7	Precipitation Fog and Icing
8	Cloud Phenomena and Cloud Cover Models
9	Atmospheric Electricity
10	Atmospheric Constituents
11	Aerospace Vehicle Exhaust and Toxic Chemical Release
12	Occurrence of Tornadoes and Hurricanes
13	Geologic Hazards
14	Sea State
15	Mission Analysis, Prelaunch Monitoring, and Flight Evaluation
16	Conversion Units

V. Handbook Example

A. Mesospheric Clouds Introduction

This sub-section presents and discusses an example concerning the update done on the mesosopheric clouds subsection of the handbooks' Cloud Section 8. The mesospheric cloud phenomena called 1. Noctilucent Clouds (NLC), 2. Polar Mesospheric Clouds (PMC) and 3. Polar Mesospheric Summer Echos (PMSE), all occur at cold upper mesospheric altitudes *(80-85 km altitude)*, at high latitudes and during each Hemisphere's summer. These cloud regions can be of a concern for re-entering spacecraft (i.e., Space Shuttle) as it may pass through these clouds at high speeds and the cloud particles may affect the craft or its performance. At hypersonic speeds these clouds may present a corrosion/abrasion hazard (erosion) to forward TPS surfaces, increase drag, and may result in abnormal operation of turbojet or scramjet engines (ingestion of particles). The concentration of ice particles could upset guidance, with roll and angle of attack transients, increased RCS propellant usage and ranging errors. The magnitude of these effects would depend on the cloud particle size, number density and composition. Simulations have shown the vehicle actually skipping off the cloud. The Space Shuttle Program has elected to avoid them entirely, so the Shuttle does not currently reenter through the high-latitude zone of NLC occurrence. The threat of NLC's has greatly impacted the operation of the space shuttle[9]. Therefore their properties: cloud particle size (including volume density), extent (seasonal/latitudinal/altitudinal/layer thickness) of these mesospheric clouds are presented here, along with their frequency and risk/probability of occurrence.

B. Mesospheric Cloud Background and Observational Facts.

1) Noctilucent Clouds

The highest clouds on earth (average 83 km height) are mesospheric clouds which occur in the cold, high-latitude regions surrounding both geographical poles. The clouds occur seasonally during their respective summer seasons (June-August in the northern hemisphere, and December-February in the south). From the ground they are seen typically low on the horizon, within the twilight arch near the sun's position below the horizon. These clouds are given different names, depending upon their mode of observation. Noctilucent clouds are their ground-based manifestation, visible as bright cloud features seen against the comparatively dark sky during twilight, when the sun's rays still strike the clouds and the lower atmosphere is in darkness. At latitudes greater than about 70°, the summer sky never becomes sufficiently dark to view NLC at any time of the year. At the lower latitude boundary, about 55°, the air is normally too warm at any season to support water-ice particles. These observing constraints restrict visibility to solar depression angles between 6 and 16°. At night they are invisible, due to the absence of sunlight. However, active lidar techniques reveal their presence at all times, regardless of local time or solar illumination. The 55-70° *latitude* region is called the NLC 'zone of visibility', or simply the NLC 'zone'.

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Occasionally, NLC are seen outside the "classical" NLC zone. In June, 1999 they were photographed and measured by a lidar as far south as 41° North[10]. NLC are most frequent at the center of the NLC zone, around 60° latitude. The behavior is roughly defined as a Gaussian, centered on ~15 days following solstice (see Figure 3). Southern NLC occurrence appears to be quite similar, relative to the summer solstice, although there are too few observations available to perform a statistical analysis. Satellite observations provide a much better north/south comparison. Fogle and Haurwitz (Ref. 11) have also classified noctilucent clouds into five types: TYPE I. (Veils), TYPE II. (Bands), TYPE III. (Billows), TYPE IV. (Whirls), and TYPE V. (Amorphous).

2) Polar Mesospheric Clouds

Polar Mesospheric Clouds are almost certainly the same clouds as NLC but as viewed from space. Because it is possible to distinguish clouds from the atmospheric background even during the daytime hours while the atmosphere is fully sunlit, space-based instrumentation allows PMC's to be viewed in their entirety, all the way to the pole. PMC's are occasionally seen from space in the 40-45° band, around summer solstice[12]. It is now established that north-south hemispheric differences in PMC properties occur. In particular, the north has more clouds (by roughly 40%), and are inherently brighter than their southern counterparts. Additionally, lidar observations at the South Pole show that PMC's are several kilometers higher than in the north[13]. These differences are explained by different earth-sun distances during the respective summers, and also by the different dynamical states of the lower atmosphere in the Arctic and Antarctic.

As far as is known, there are no inherent differences between PMC and NLC, although there are not enough simultaneous space and ground-based observations to definitely rule out physical differences. Because PMC are generally observed poleward of the NLC zone, PMC are located closer to the cold source regions where the temperature approaches 100K. Summertime temperatures at mesopause heights are lower than in winter, which accounts for the distinct seasonality of mesospheric clouds. Maximum numbers of PMC/NLC normally occur two to three weeks following summer solstice. Cloud composition is water-ice, at least this has been empirically verified for very bright clouds[14]. The particles are expected to be pure ice, with moderately non-spherical shapes. Very small dust cores of silicate matter may exist at the inner core since these particles seem to be necessary to begin the nucleation process.

A good historical review of observing NLC is found in Fogle and Haurwitz (Ref. 11). More up-to-date references which include knowledge gained from the space era are Gadsden and Schroder (Ref. 15), Thomas (Ref. 16 and 17). More recent scientific journals contained numerous scientific papers describing modern developments are Thayer (Ref. 18) and DeLand (Ref. 19). The typical characteristics of NLC are given in table 3, based on ground-based observations in the Northern Hemisphere from Fogle and Haurwitz (Ref. 11) and Thomas and Olivero (Ref. 20). Note that some of the table values have been updated to reflect modern information.

3) Polar Mesospheric Summer Echo's

Polar Mesospheric Summer Echo's are very strong radar echoes which appear during the NLC season. They are closely related to charged ice particles which reduce the diffusivity of electrons such that very small spatial scale structures in the electron gas can exist. The radar echoes are caused by highly structured plasma density fluctuations, concentrated in thin layers, thought to be controlled by the breakup of upward propagating gravity waves and tides. Some of the morphology of PMSE's is similar to that of NLC's. At polar latitudes, they occur with 100% probability during mid-summer. More information is given in Lubken (Ref. 21).

4) Vertical Structure of Noctilucent Clouds

In-situ NLC measurements have been made during the NLC-93 rocket campaign at Esrange Sweden.[22] The results indicate little vertical variation (vertically homogeneous) of the population throughout most of the 1.6 km NLC layer (existing from 82.6 km to 84.2 km, with the brightness peak around 83.0 km.) The lower part of the cloud exhibited an increase in particle size and a decrease in particle density towards the cloud base, as these larger cloud particles are being sedimented out of the cloud at the end of their life cycle. This has also been observed by optical means independently by von Savigny (Ref. 23). For a chosen mean water content of 4 ppm mixing ratio (the normal range of variability is 0.5 to 5 ppm around 80 km altitude), the particle radii of 55-65 nm are inferred at the brightness peak near 83.0 km, with particle number densities between 35 and 70 cm^{-3} at the peak. NLC particle radii normally range from 50 and can perhaps even reach 220 nm in extreme circumstances. Since water vapor is not measured, it needed to be assumed to deduce the particle properties. For an assumed range of mean water contents

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of 2 and 10 ppm, peak radii of 74 and 44 nm and the number densities of 14 and 360 cm^{-3} are deduced, respectively[22].

C. Physical Properties of Mesospheric Clouds.

Although the chemical composition of the cloud particles has been established to be water-ice, their size distribution is not well known. However, numerous experiments over the past several decades have determined that the effective spherical radii range between 20 nm and 100 nm, with a typical size range near 30-50 nm. The smaller ice nanoparticles are believed to be ubiquitous in the supersaturated regions of the summertime polar region[24]. Although invisible by optical means, their presence is inferred from the existence of PMSE, mentioned earlier.

Summarized in table 2 are estimates of physical properties of mesospheric clouds and their environment. All quantities refer to the NLC zone and the summertime polar mesosphere. The column mass of the clouds are more reliable than the particle radius, since they are constrained by the available water content.

Table 2. Estimates of Physical Properties of Mesospheric Clouds (NLC/PMC) and Their Environments:

- Properties:
    - Cloud heights: 81-86 km, average = 83 km.
    - Cloud column mass: $2\text{x}10^{-9}$ to $6\text{x}10^{-8}$ grams/cm^2 range
    - Ice particle size: 20-100 nm, with most in the 35- to 70-nm range
    - Ice particle concentration: 100-200 cm^{-3} (5- to 500-cm^{-3} range)
    - Ice particle column number: 10^6- to 10^8-cm^{-2} range
    - Water mixing ratio: 1 to 4 ppmv (up to 10-15 ppmv in the presence of cloud processing)
    - Temperature at cloud heights: <150 K (< -122 °C)
    - Temperature at mesopause height (88km): 100 to 140K (-172 °C to -132°C)
    - Cloud thickness: 0.5 -2.5 km
    - Cloud extent: 100's to 1000's of km, with small scale structure down to meters.

Table 3. Typical Noctilucent/Polar Mesospheric Cloud Characteristics.

o Color	Bluish-white
o Height (average)	82.7 km, maximum 95 km, minimum 79 km
o Latitude of observations	50 to 80°; optimum about 60°
o Season of observation (Northern Hemis.)	mid-May through mid-August
(Southern Hemis.)	mid-November through mid-February
o Time of visibility	While the solar depression angle varies from 6° to 16°
o Spatial extent	10^4 to more than 4 x 10^7 km^2; can cover considerable parts of latitudinal belts north of 45°
o Duration	Several minutes to more than 5 hours
o Average velocity	40 m s^{-1} towards the southwest.[1]
o Thickness in the vertical	0.5 to 2.0 km
o Vertical wave amplitude	1.5 to 3.0 km
o Ambient temperature when NLC present	150 K
o Polarization	Strongly linearly polarized in same sense as, but more than twilight sky.

[1] Individual bands often move in different directions and at speeds differing from the NLC display as a whole. Apparent motions of NLC across the sky are not necessarily indicative of wind speeds, because wave patterns move with their own specific phase speeds, even at times, moving against the mean wind vector.

Table 4. Mesospheric Cloud Seasonal Climatology. Comparison of PMC seasonal properties for 1981–1985 with NLC (1885–1972). Times are given in days after summer solstice[20].

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	South PMC	North PMC	North NLC
Beginning date[1]	-32	-23	-38
Ending date	61	64	50
Time of maximum	7-16	16-22	16-20
Duration of season (days)	93	87	88
Lower latitude boundary	60°	55°	50° [2]
Months observed	Dec-Feb	May-Aug	May-Aug
Interannual variability	±20 %	±20 %	factors up to 4
Altitude, km [3]	83.5-85	83-84	81.5-85.5

[1] Begins at high latitude 10 to 20 days before lower latitude observation. South season begins somewhat earlier and ends earlier than North season (see Figure 8.1).

[2] This indicates the latitude of the observer, not the clouds which occur 3-5° poleward.

[3] The height data were taken from Figure 4 in the reference by Chu (Ref. 13).

D. Mesospheric Cloud Frequency, Climatology and Probabilities.

Polar Mesospheric Cloud occurrence rate, defined as the number of clouds viewed in a time interval, divided by the total number of observations, may be thought of as a probability of viewing a cloud from space. The daily occurrence rate is rarely 100%, meaning that the cloud distribution is "patchy", undoubtedly due to wave perturbations on a variety of spatial and temporal scales. The experience of the Ultraviolet Spectrometer Experiment on board of the SME spacecraft is summarized in Figure 2, where the five year (1981-1986) average PMC occurrence rate is plotted against day number measured from summer solstice[25]. Each solid curve refers to a 5-degree wide bin of north latitude. The dashed curves refer to the southern PMC seasons (six months separated in actual time). The curves are analytic functions which are fitted to the actual 5-year average frequencies, accumulated into five-day time bins. The actual behavior is much more complicated, and on any given year, can vary by as much as 20% from the smoothed function shown in Figure 2. A comparison of the PMC seasonal behavior in the vicinity of the NLC zone is made with the corresponding NLC frequency in Figure 3.

Here, the NLC frequency is not defined in the same way as the satellite quantity. It is defined as the number of clouds seen on that day over a large number of years, divided by the total number of years in the data set. Its interpretation is that it is the probability that on a given summer evening/morning (up to 4-5 hours total duration depending upon latitude), an NLC will be viewed at some location in the sky. Thus the numerical values should not be directly compared. However this comparison is useful because it shows that the seasonal run of activity of both PMC and NLC are similar, even peaking at nearly the same day relative to solstice. It should be mentioned that NLC sightings can be relatively rare during some seasons, particularly around the times of solar maximum activity[26]. Recently, the PMC data base verifies an inverse relationship between PMC occurrence frequency and solar activity (i.e., they are less often seen at solar maximum throughout the 11-year solar cycle). Stronger anti-correlation values are observed in the Northern Hemisphere (i.e., $R_{solar} = -0.87$)[27]. Even though the solar cycle seems to be an important factor in determining overall cloud activity, there are other important sources of inter-annual variability that are not at all understood. The seasonal climatology for NLC/PMC is given in table 4.

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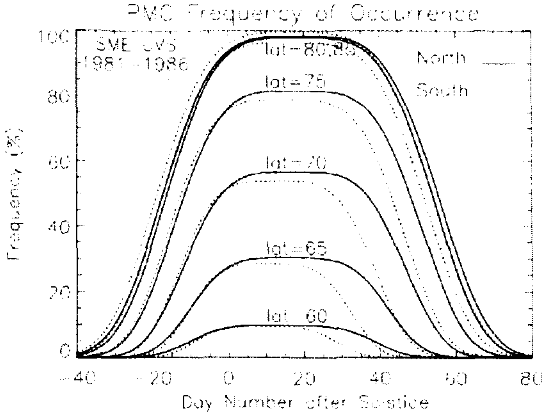

Figure 2 Northern and Southern Hemisphere 5-year Average PMC Occurrence Rate as a Function of Day Number After Summer Solstice. (from Shettle. Ref. 25).

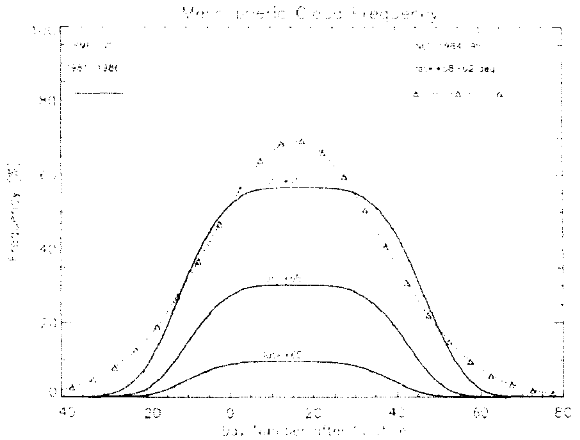

Figure 3 Northern Hemispheric 32-year NLC Seasonal Frequency Plotted with respect to PMC Occurrence Frequency. (from Shettle, Ref. 25).

E. Increasing Noctilucent Cloud Occurrence?

The occurrence of NLC's seem to be increasing. For the past 25 years, the UV brightness of the seasonally-averaged PMC observed by satellites have increased significantly in both hemispheres, amounting to roughly 1% per year[17,19]. This change is not observable from the ground because of the overall smallness of the effect, and because of observational difficulties present in ground-based data which mask such subtle effects. The reasons for the changes are not known, although it has been long suspected that water vapor increases, associated with growing methane levels are at least partly responsible. If methane is indeed the cause, and this is not yet proven, then this would verify a speculation that NLC are anthropogenic in origin[20]. Their NLC "discovery" in 1885 may have been their first appearance due to the methane increase caused by the industrial revolution, and specifically the increase in population with the associated growth of agriculture, mining, etc. The first observations may have also been influenced by the earlier Krakatoa eruption, occurring in 1883[28,29]. This subject is still a point of debate, and has caused many lively discussions at professional meetings. The point of contention is that natural variability of NLC from year to year masks any underlying trends, and that longer data sets (50 years or more) are needed to separate

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out natural variability from a systematic long-term effect[30]. On the other hand, it is claimed that if the trend is large enough, and most of the natural variability is understood (e.g. solar effects), then the effects may be separated in a statistically-significant way. Furthermore, a causal explanation is readily available in terms of methane buildup[31].

F. Polar Mesospheric Clouds From Shuttle Exhaust?

It has been determined by scientists at the Naval Research Laboratory[32] that the exhaust plume from NASA's space Shuttle (which is ~97 % water vapor) can travel northward to the Arctic thermosphere where it descends to form ice and creates PMC's. NRL's MAHRSI satellite instrument launched on STS-85 in August 1997 followed in its orbit the shuttle plume's rapid poleward transport and then observed a discrete region of ice clouds as they appeared in the Arctic mesosphere near the end of the mission. Water contained in these clouds was consistent with the amount injected into the thermosphere during the shuttle's east coast ascent. About half of the shuttle's water vapor exhaust was injected into the thermosphere between 108 to 114 km altitude, and was determined to be transported to the Arctic in a little over a day. The plume was about 1100 km long with a diameter of ~3 km. Ground based measurements of mesospheric water vapor also supported this. As the water vapor moves to the Arctic solar UV destroys some of the plume. The remaining plume falls from the warmer thermosphere down to the colder (down to -40°C) mesospheric regions where the water vapor condenses into ice particles and the clouds (PMC) form.

Stevens indicated that three years earlier MAHRSI also observed a large hydroxyl (OH) cloud at ~110 km altitude NE of the U.S. twenty hours after the STS-66 was launched in November 1994 from KSC. This OH cloud is at the same altitude as an extended trail of water vapor exhaust released from the shuttle's main engines less than ten minutes after launch. Because the upper mesosphere is relatively dry, the contribution to its local water vapor budget from launch vehicle exhaust may be significant.

Even more remarkable, the NRL group has found that the plume from the ill-fated Columbia launch in January, 2003, was carried to the southern hemisphere summertime polar region within 3 to 4 days. The plume (at ~110 km altitude containing ~400 tons of water vapor, was ~1000 km long and ~3 km in diameter) maintained its integrity, producing a burst of PMC during southern summer. In addition, lidar measurements at Rothra, Antarctica revealed metallic iron (produced by the main shuttle engines) was also contained in the transported plume, a marker which makes the identification undeniable[33]. Note that the shuttle, at the proper orbit inclination and during a PMC season, could help generate its own PMC field which it could possibly fly through upon its earth return. Stevens has shown that the Space Shuttle plume can contribute substantially (up to ~22%) to the observed PMC ice mass over a season.

VI. Areas Of Concern

Engineering technology is constantly changing. In some cases, the current trends in engineering design have increased vehicle susceptibility to terrestrial environment factors. Based on past experience, the earlier the terrestrial environment central control point specialists become involved in the design process, the less the potential for negative environmental impacts on the program downstream through redesign, operational work-around, etc.

In many cases, it is impossible to clearly define limiting extreme values for a particular terrestrial environment parameter that may occur during the desired operational lifetime of the vehicle. It may not be technically nor economically feasible to design a vehicle to withstand an extreme environment value. However, a lower value may be defined whereby the probability is small that the lower value will occur during the desired operational lifetime of the vehicle. Additional launch delay risks may also be acceptable versus the expense of additional design considerations. Because of these and other considerations, a value less than the extreme may be a more appropriate design requirement. The terrestrial environment specialist has the responsibility to provide the program manager and chief engineer with pertinent information so they can determine the highest risk value that is feasible for the program in that particular environment area. Therefore, it is very important that the aerospace vehicle program manager and the chief engineer have a good understanding of the operational risks due to the selected design terrestrial environment.

The following table provides a reference guide for the terrestrial environment specialist, program management, design engineers, and others on the development team for a new aerospace vehicle program. This information summarizes potential terrestrial environment areas of engineering concern when first surveying a vehicle project. As can be noted from this table, terrestrial environment phenomena may significantly affect multiple areas of an aerospace vehicle's design, and thus operational capabilities, including areas involving structure, control, trajectory shaping (performance), heating, takeoff and landing capabilities, materials, etc. A breakout of typical terrestrial environment concerns with respect to engineering systems and mission phases is shown in the table.

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Table 2. Natural terrestrial environments and aerospace vehicle development areas of concern.

X	Terrestrial Environment Parameter											P
Launch Vehicle Systems (Sub-)	**Winds & Gusts**	**Atmospheric Thermodyn**	**Atmosph Constit**	**Solar/ Thermal Radiation**	**Atmosph Electricy**	**Clouds & Fog**	**Humidity**	**Precip or Hail**	**Sea State**	**Severe Weather**	**Geologic Hazzards**	**Mission Phase**
System	X P	X P	X P	X P	X P	X P	X P	X P	X P	X P	X	Mission Analysis
Propulsion/ Engine Sizing	X	X P	P		X		X P			X		Manufacturing
Structures/ Airframe	X P	X P		X	X P		P	X P	X	X P	P	Testing
Performance/ Trajectory/G&N	X P	X P	P	P	X P	P	P	P	P	P	P	Transport & Ground Hdl
Aerodynamics	X P	X P	P	P	P		P	P	P	P		Rollout/On-pad
Thermal Loads/ Aerodynamic Heat	X P	X P	P	X P	P	P	P	P	P	P		Pre-launch DOL cnt dn
Control	X P	X P	P	P	X P	P	P	P		X P		Liftoff/ Ascent
Loads	X P	X P			P	P		P	X P	X P		Stages Recvry
Avionics	P	P	X	X	X P	P	X	P		X P		Flight
Materials	X	X P	X P	X P	X		X	X	X	X		Orbital
Electrical Power	P	P	X		X P	X		X P		P		Descent
Optics	P	X P	X P	X	P	X P	P	X P	P	P		Landing
Thermal Control	P	X P	P	X P	P		P	X P	P	P		Post-land
Telemetry, Tracking & Communication	P	X P	X P	P	X P	X P	P	X P	P	X P	P	Ferry/ Transport
	P				P		P	P		P	P	Facil/spt Eq
	P	P	P		P		P	P			P	Refurbishmt
Mission Operations	X P	X P	X P	X P	X P	X	X P	X P	X	X P	X P	Storage

VII. Lessons Learned

The Marshall Space Flight Center Natural Environments Branch and its predecessor organizations have over 45 yr experience in the development and interpretation of terrestrial environment requirements for use in the design and operation of aerospace vehicles. During this period, a large number of "lessons learned" have produced the basis for the contents of this handbook. A few of these lessons learned are summarized in the following list:

(1) Title: Wind Vectors Versus Engineering Vector Conventions

- Background. Flight mechanics use of wind vectors and conventional meteorological usage. In the case of flight mechanics, a vector is stated relative to direction force is being applied. However, for meteorology, the wind vector is stated relative to direction from which wind force is coming.
- Lesson. The proper interpretation and application of wind vectors is important to avoid a 180° error in structural loads and control system response calculations.

(2) Title: Design Requirements, Not Climatology

- Background. While based on climatology and models, both physical and statistical, natural environment requirements are part of the overall vehicle design effort necessary to ensure mission operational requirements are met. Thus, they must be selected and defined on this basis. Simply making reference to climatological databases will not produce the desired vehicle performance.
- Lesson. Members of the natural environments group assigned as the control point for inputs to a program must also be part of the vehicle design team and participate in all reviews, etc. to ensure proper interpretation and application of natural environment definitions/requirements relative to overall vehicle design needs.

(3) Title: Early Input of Natural Environment Requirements Based on Interpretation of Mission Purpose and Operational Expectations

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- Background. Need to develop natural environment definitions and requirements for a program as soon as possible after one has the level one requirements for the program's mission. Thus, all concerned with the development will have common base with associated control on changes made to natural environment definitions/requirements and associated vehicle operational impacts.
- Lesson. The definition of the natural environment requirements for a vehicle that are necessary to meet the mission requirements is important for all concerned with the program. This provides visibility to all, especially program manager and systems engineers, relative to impact on the operation of vehicle and to natural environment design requirements on the program's mission.

(4) Title: Consistent Input for all Users More Important for Trade-Off and Design Studies than Different Inputs within the Noise Level of Knowledge on Natural Environment Topic

- Background. The natural environment is one of the key drivers for much of the design efforts on an aerospace vehicle's thermal, structural, and materials control. Variations in natural environment inputs used by different design groups can mask critical engineering design inputs if not avoided by consistent and coordinated natural environmental inputs and interpretations for engineering applications.
- Lesson. The need for a focused natural environment group which provides coordinated and consistent environment definitions/requirements/interpretations is key to having all concerned direct their efforts toward the same inputs, thus contributing to engineering applications that can readily be interpreted from a common base.

(5) Title: Ability to Test Planned New or Changes in Natural Environment Requirements Versus Results Important Before Implementing Them as Formal Requirements

- Background. Preliminary assessment of natural environments definitions and requirements must first be accomplished in collaboration with a responsible engineering group in order to identify design drives versus mission requirements. Based on this information, the appropriate natural environment definitions and requirements can be implemented and controlled accordingly.
- Lesson. To avoid problems with the engineering interpretation of natural environment definitions and requirements, the natural environments group responsible must first interact directly with an appropriate engineering group to ensure proper use and interpretation when formally implemented as part of the overall program requirements.

(6) Title: Need to Maintain Natural Environment Requirements for Design and Operation of Vehicle as Base from Which Other Requirements are Related Versus Treating Natural Environment Requirements as One Other Non-nominal Input to be Root Sum Squared (RSS) in Final Design Action

- Background. By taking this action, it provides a viable and robust operational vehicle capability that will meet the vehicle mission operational natural environment requirements. Otherwise, a vehicle will be produced that will have a lower operational capability based on natural environment conditions. It is the natural environment operational requirements that can be monitored and decisions made regarding launch operations, etc., or, in case monitorship is not practical or an emergency, the vehicle will be functional relative to probable natural environment conditions established on basis of past records and mission requirements.
- Lesson. Do not design an aerospace vehicle with the required operational natural environment definitions and requirements incorporated and RSS as part of the non-nominal inputs to the vehicle design decision.

(7) Title: Natural Environment Elements That Cannot be Monitored Prior to Operations Decision Must be Minimum Risk Level That is Consistent with Mission Capability Requirements, Including Those Natural Environment Elements Needed to Meet Safety and Emergency Situations

- Background. For an aerospace vehicle launch, most natural environment elements can be monitored and thus taken into account before launch decision relative to acceptable launch delay risks. The same is true for some on-orbit and deep-space spacecraft operational requirements. In such cases, lower probability occurrence environments may be considered, consistent with mission requirements, along with subsequent savings on design. Vehicle ascent winds through max Q versus reentry winds is an example of lower probability (higher risk of occurrence) versus higher probability (lower risk of occurrence) natural environment design requirements for a

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vehicle. However, minimum risk of occurrence for natural environments must be used for design to ensure operational capability when natural environments cannot be measured or monitor ship taken advantage for vehicle operations.

- Lesson. It is necessary to carefully analyze the mission requirements relative to vehicle operations and provide the natural environment definitions and requirements accordingly in collaboration with the vehicle program manager to ensure understanding of the implications of environments provided for design.

(8) Title: Maintain Natural Environment Requirements for Design as Separate Document but Integral to Overall Mission Requirements for Vehicle

- Background. The natural environment definitions and requirements for the Space Shuttle and Space Station were provided such that they could be controlled and available in separate program documents as part of the overall design requirements documentation. This not only provided direct access for all concerned with use of natural environment inputs into design and mission planning but also provided an easy control of inputs. Changes, where required, were readily possible with the change of one document that had application for all natural environment inputs to the program.
- Lesson. Each vehicle development program should have only one natural environments definition and requirements document and it should be an integral part of the overall mission requirements for the vehicle design, development, and operations.

(9) Title: Atmospheric and Space Parameter Analysis Model

- Background. The ability for a program manager to easily access information on the operational impact of a vehicle design change relative to the natural environment is an important tool for decision making. In addition, such a tool provides additional insight into mission planning activities, including launch and landing delay probabilities.
- Lesson. Knowledge by mission managers, chief engineers, mission planners, etc. on the availability of an Atmospheric and Space Parameter Analysis Model is a valuable decision-making tool and should be utilized in making the trade-off decision where the desired operational natural environment is a factor.

(10) Title: Reference Period for Design Statements of Natural Environment Definitions and Requirements Relative to Launch and On-Orbit, etc. Operations

- Background. For launch statements on natural environment definitions and requirements, the worst reference month should be used. This provides an operational capability relative to the natural environment that ensures that for any given month, the desired operational capability will be met. Thus, for the worst month reference period, the minimum risk of launch delay due to natural environment will occur with all other months having less probabilities of launch delay. The same situation exists for natural environments associated with on-orbit operational capability, and deep-space operations. In other words, for these cases the anticipated lifetime in these operational conditions must be taken into account along with the acceptable risk for comprising the mission relative to natural environment conditions exceeding the design requirements.
- Lesson. All launch natural environment definitions and requirements for the design of a vehicle must be made with respect to a worst month reference period. For natural environments associated with on-orbit and deep-space operations, the anticipated lifetime in these operational conditions must be taken into account along with acceptable risks for operations.

(11) Title: Life-Cycle Cost Estimates and Natural Environment Operational Constraints of Vehicle

- Background. Once a vehicle has been developed, the constraints relative to operations in the natural environment should be assessed based on the resulting capability of the vehicle. This is the case for launch, on-orbit, and deep-space aspects of the mission. An Atmospheric and Space Environment Parameter Analysis Model can be especially helpful in this regard. The resulting information should be incorporated into the development of the full life-cycle cost estimates and model for the vehicle program.
- Lesson. Consideration needs to be given to the natural environmental constraints on launch and spacecraft operations when developing full life-cycle cost estimates and models.

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(12) Title: Accelerated Schedule Without the Infrastructure

- Background. The decision to accelerate a program development schedule needs to be made in light of in-place competences, resources, and management operations. A number of contributing factors can affect this decision, including recognizing the issues and necessary work involved, availability of natural environment skills within the contractor community and interaction between the NASA program offices interfacing with contractors, and isolation of natural environments skills from systems engineering teams working the program.
- Lesson. Program systems engineering offices should have a "skills checklist" and routinely review government and contractor capabilities to assure all necessary expertise is available and tied in appropriately relative to natural environment and other engineering activities.

VIII. Conclusion

This paper presented the need and value of the various terrestrial environment design criteria that are used in the design, development, testing, and operations of a launch/aerospace vehicle. The NASA Terrestrial Environment Handbook 1001[1] gives the engineer, mission planner, or project manager the various natural terrestrial environment parameters, data bases, statistics, models, etc. needed as input for their respective studies. The handbook example given in this paper is the update to the mesospheric cloud sub-section. The other handbook technical sections are also being updated, and the handbook should be completed and published during 2006.

Note

This paper is based on a paper by the authors entitled "The Definition and Integration of Terrestrial Environment Design Inputs for Vehicle Design Considerations" to be presented at the 12th Conference on Aviation, Range, and Aerospace Meteorology, January 29--February 2, 2006.

Acknowledgments

The authors wish to acknowledge and thank Dr. Gary Thomas of the University of Colorado for his assistance in the update of the subsection on Mesospheric Clouds within the NASA Terrestrial Handbook 1001. Also our thanks to Dr. Mike Stevens of the Naval Research Laboratory, for his advice regarding the PMC contributing factor from the Shuttle plume.

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