NASA
Technical
Memorandum

NASA TM-82577

INVESTIGATION OF THERMOSPHERIC WINDS RELATIVE TO SPACE STATION ORBITAL ALTITUDES

By Michael Susko

Atmospheric Sciences Division
Systems Dynamics Laboratory

March 1984

(NASA-TM-82577) INVESTIGATION OF THERMOSPHERIC WINDS RELATIVE TO SPACE STATION ORBITAL ALTITUDES (NASA) 19 p HC A02/MF A01 CSCL 04B

N84-25220

Unclas
G3/47 19283

National Aeronautics and
Space Administration
George C. Marshall Space Flight Center

MSFC - Form 3190 (Rev. May 1983)

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.
NASA TM- 82577

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Investigation of Thermospheric Winds Relative to Space Station Orbital Altitudes

5. REPORT DATE
March 1984

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Michael Susko

8. PERFORMING ORGANIZATION REPORT #

9. PERFORMING ORGANIZATION NAME AND ADDRESS
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.

13. TYPE OF REPORT & PERIOD COVERED
Technical Memorandum

12. SPONSORING AGENCY NAME AND ADDRESS
National Aeronautics and Space Administration
Washington, D.C. 20546

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
Prepared by Atmospheric Sciences Division, Systems Dynamics Laboratory, Science and Engineering

16. ABSTRACT

An investigation of thermospheric winds, relative to the space station orbital altitudes, has been made in order to provide information that may be useful in an environmental disturbance assessment. Current plans are for this low Earth orbiting facility to orbit at an inclination of 28.5 deg. The orbital altitudes have not yet been defined due to the evolutionary configuration of the Space Station. The upper and lower bounds of the orbital altitudes will be based on constraints set by the drag and expected orbital decay and delivery altitude capability of the Shuttle. It is estimated that the orbital altitude will be on the order of 500 km. This report deals with neutral winds in the region from about 80 to 600 km which have been derived from satellite drag data, Fabry-Perot interferometers, sounding rockets, ground-based optical Doppler techniques, incoherent scatter radar measurements from Millstone Hill combined with the mass spectrometer and lithium trail neutral wind measurements. The equations of motion of the low Earth orbiting facility are also discussed in this report.

17. KEY WORDS
Thermosphric Winds
Space Station Orbital Altitudes

18. DISTRIBUTION STATEMENT
Unclassified -- Unlimited

19. SECURITY CLASSIF. (of this report)
Unclassified

20. SECURITY CLASSIF. (of this page)
Unclassified

21. NO. OF PAGES
18

22. PRICE
NTIS

MSFC - Form 3292 (May 1969)

For sale by National Technical Information Service, Springfield, Virginia 22151

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

PRECEDING PAGE BLANK NOT FILMED

TECHNICAL MEMORANDUM

INVESTIGATION OF THERMOSPHERIC WINDS RELATIVE TO SPACE STATION ORBITAL ALTITUDES

I. INTRODUCTION

Thermospheric winds related to the Space Station orbital altitudes is one of the potential environmental disturbances which should be assessed relative to design requests is addressed in this report. Although the orbital altitudes are not yet precisely defined due to the evolutionary configuration of the Space Station, the lower and upper limits of the orbital altitudes will be based on the constraints set by the drag and orbital decay of the Space Station and the payload delivery criteria of the Shuttle. With these constraints, the lower and upper limits of the orbital altitudes of the Space Station may be between 250 n.mi ≅ 460 km and 300 n.mi ≅ 555 km. Szirmay and Blair (1983) indicate the Space Station will experience environmental disturbances from the atmosphere, gravity gradient, the magnetic field and solar radiation. It will also experience torques due to boost from lower altitudes to higher altitudes. In addition, the on orbit aerodynamic torque varies with the ambient atmospheric density and density depends not only on altitude but solar activity, Turner and Vaughan (1983).

The neutral atmosphere is discussed in Section II. The discussion of the Space Station's equation of motion and the summary of the data on the thermospheric winds at orbital altitudes are presented in Sections III and IV. Section V gives the recommendations of magnitudes and directions of thermospheric winds at orbital altitudes.

II. THE NEUTRAL ATMOSPHERE

The thermosphere is that region above the mesopause extending from about 80 km to about 600 km. Information about thermospheric winds are derived from (1) satellite drag data, Smith and West (1982); (2) Millstone Hill incoherent scatter radar measurements of the ionospheric parameters, Babcock and Evens (1979), Roble, et al. (1977, 1974), Evans (1978); (3) Fabry-Perot Interferometer (FPI), Hays, et al. (1979), Hernandez and Roble (1977), Killeen, et al. (1982), Rees, et al. (1982), Hernandez, et al. (1979), Jacka, et al. (1978), Cocks and Jacka (1978), and Bates, et al. (1978); (4) Sounding rockets, Lloyds, et al. (1971); Ground-based optical Doppler technique, Smith, et al. (1980), and Hernandez and Roble (1977); (5) DEB-Winds and Temperature Spectrometer (WATS), Spencer, et al. (1982), and (6) Atmospheric Explorer C data of ion temperature and drift velocities, St. Maurice, et al. (1982).

Based on these measurements, models of the thermospheric winds, such as Three Dimensional Circulation Model, Dickinson, Ridley and Roble (1981), NCAR's Thermospheric General Circulation Model (TGCM), Roble, et al. (1982); OGO-6 Empirical Thermospheric Model, Antoniadis, (1976); Mass Spectrometer and Incoherent Scatter (MSIS) model, Babcock, Jr., et al. (1979); Global Thermospheric Model of Winds and Temperature, Neal (1975); Full Non-linear Treatment of the Global Thermospheric Wind System, Plum (1974); Winds Generated by Absorption Extreme Ultraviolet Radiation (EUV), Strauss, et al. (1975); Global Thermospheric Dynamic Calculations, Hernandez and Roble (1979); Model Computations from Incoherent Radar Scatter Data, Bates (1977); and Model Ion Drag Effects on Thermosphere, Rishbeth (1978), were developed and the distribution of winds as a function of time, altitude, and latitude were calculated.

In particular, Dickinson (1981) has indicated that the dominant drive of the atmospheric processes in the thermosphere is solar radiation at wavelengths less than 0.10 μm (the extreme ultraviolet or EUV). This radiation dissociates molecules into atoms and ions and induces their decomposition into lighter species. It also deposits considerable heat into neutral species. Dickinson, in his Thermospheric General Circulation Model (TGCM), has good agreement between his model and actual data. According to Dickinson, et al. (1981), the difference between the dynamics structure of the upper and lower atmosphere is mainly due to the difference of solar heating in optically thick and optical thin regions. Smith (1982), reported some heating results from waves in the lower atmosphere. Heated air rises and flows towards cooler regions where it descends, just as in the troposphere. Above 300 km viscosity tends to make the motion uniform i.e., slablike. Collisions with ions tend to reduce the velocity difference between ions and neutrals, the effect is strongest in the sunlight ionosphere where the ion density is highest. The ions are tied to the geomagnetic field or drift where there are electric fields, as in the polar region. In geomagnetically quiet times, the flow is away from the sunlit region.

Anomolous strong winds are associated with geomagnetic storms. Increases in winds as well as atmospheric density are noted in the upper atmosphere during geomagnetic storms. As reported by Spencer, et al. (1982), the Dynamics Explorer 2 made possible for the first time, global in situ measurements of upper thermosphere neutral particle winds. Zonal and vertical wind components and the kinetic temperature are being measured by the Wind and Temperature Spectrometer (WATS), Spencer, et al. (1982), while the Fabry-Perot Interferometer, Hays, et al. (1981), provides the meridional component. By appropriately combining these wind components, a measure of the vector wind along the spacecraft orbit was obtained and presented by Killeen, et al. (1981). The altitude range of these wind data extends from perigee (~ 300 km) to about 750 km. Spencer, et al. (1982), illustrates the zonal data in the south polar region of the global flow system. The peak velocity exceeds 1 km/sec in the polar region while at mid to low latitudes, the zonal and vertical components are seen to be negligibly small.

Smith and West (1982) indicated that near the auroral oval a horizontal wind speed on the order of 1.5 km/sec was observed to occur at approximately 150 km altitude simultaneously with a large increase in the ambient density during a very large magnetic storm. Theoretical calculations suggest the possibility of associated vertical wind speeds on the order of 50 to 75 m/sec. Measurements as shown in Figure 1 have been made on quiet, light, moderate and extreme geomagnetic storms by Babcock (1979), Roble, et al. (1982), Killeen, et al. (1982), Smith, et al. (1980), Hernandez and Roble (1977), Kelley, et al. (1976).

Figure 1 is a summary of the investigation of measured thermospheric winds and model thermospheric winds where for quiet days, the approximate velocities are from 40 to 200 m/sec. These were observed by Roble, et al. (1978), Spencer, et al. (1982), Hays, et al. (1979), Hernandez and Roble (1977), Lloyd, et al. (1971), Rees, et al. (1982), Jacka, et al. (1978), Cocks, et al. (1978), Roble, et al. (1977), and Kelley, et al. (1976), Bittencourt and Tensley (1977), Emery, (1978), Piereira, (1980), and Sawaki (1981). For geomagnetic storms, the approximate categories are quiet days, minimum (light), moderate (average), and very high activity (extreme) ranging from 40 to 200 m/sec, 200 to 400 m/sec, 400 to 650 m/sec, and 650 m/sec and above, respectively. Section IV presents in detail a summary of data on the thermospheric winds at the planned orbital altitudes for the Space Station.

It is generally observed that the extreme wind velocities (> 400 m/sec) are associated with magnetic substorm phenomena at high magnetic latitudes. It is rare that winds > 400 m/sec are observed equatorward of a magnetic latitude of ~ 50 deg. The extreme winds are believed to be produced by electric fields created during the magnetic substorm process.

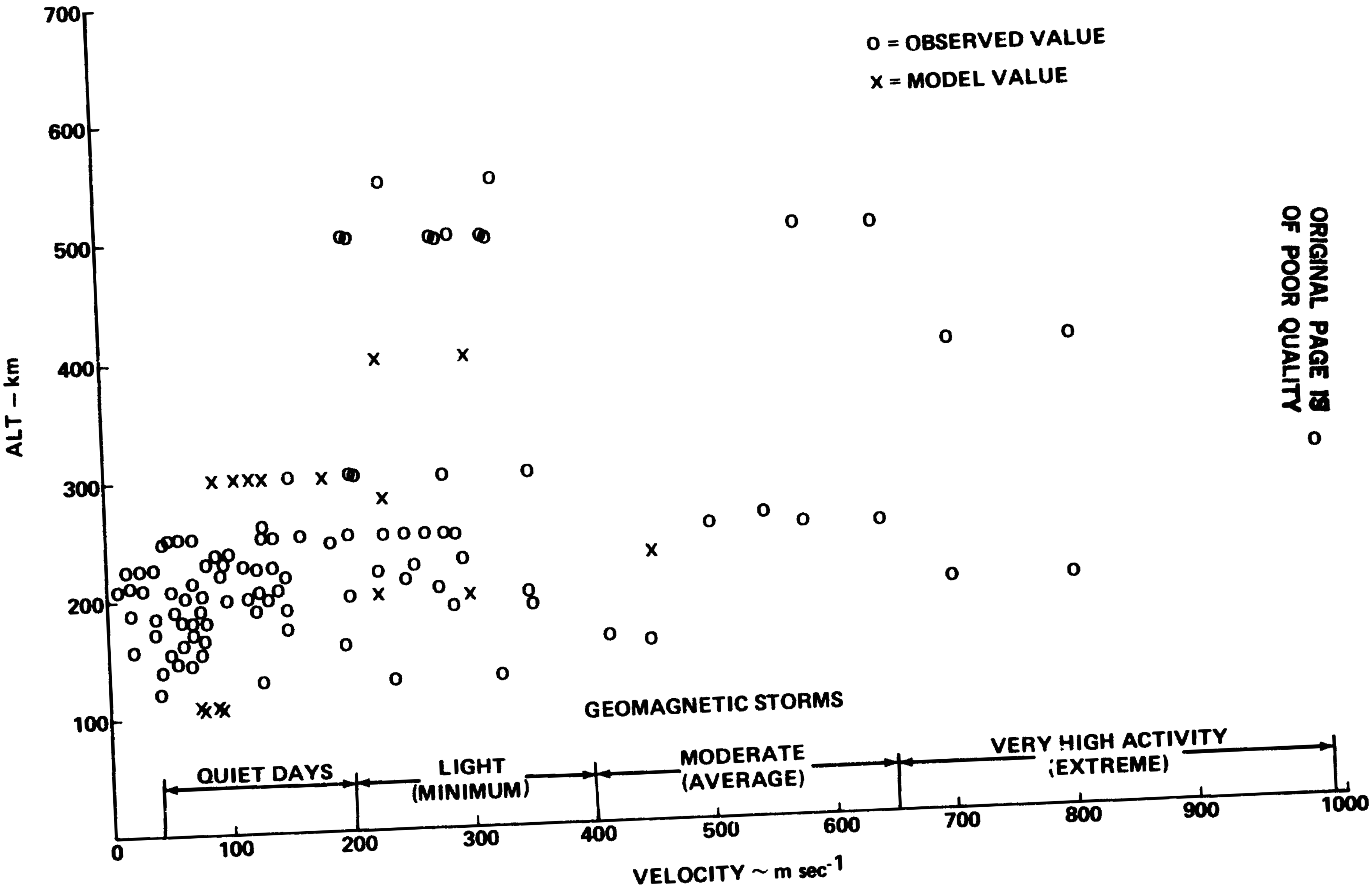


Figure 1. Measured and model derived thermospheric winds.

ORIGINAL PAGE IS OF POOR QUALITY

III. DISCUSSION OF EQUATION OF MOTION AND THE ATTITUDE CONTROL PROVIDED BY THE FORCING FUNCTION, T_2

The orbital aerodynamics environment and the characteristics of the control systems for the initial station and operation are influenced by wind flow characteristics. The NASA Task Force's initial space station baseline configuration is illustrated in Figure 2. Some of NASA's questions being addressed in solving the space station's equation of motion (E. Mettler, 1983) are as follows:

1) Varying orbital mass properties and migrating center of mass (c.m.) location due to station buildup and Shuttle docking.

2) Time-varying dynamic disturbances, such as torques and center of gravity, vary with operations control modes/crew activities, linear accelerations/vibrations. The winds would be another time-varying disturbance.

3) Flexible structures, such as solar arrays, raditators, berthing truss, remote manipulator system (RMS) and track-servicing lines, and payload interfaces.

4) Inaccuracies in structural damping.

5) Dynamically "dirty" environment (jitter, attitude motion) for users where aerodynamic disturbances should be minimized.

The core station rigid-body controller is provided by the attitude control (T_2). The basic equation of motion and the forcing function T_2 is

$$M\ddot{x} + D\dot{x} + Kx = \begin{bmatrix} 0 \\ 0 \\ 0 \\ T_2 \\ 0 \\ 0 \end{bmatrix}$$

ORIGINAL PAGE IS OF POOR QUALITY

where

$$T_2 = - K_T (K_R \dot{x}_4 + K_P x_4)$$

and

$$x_4 = \theta_2$$

where

M = mass

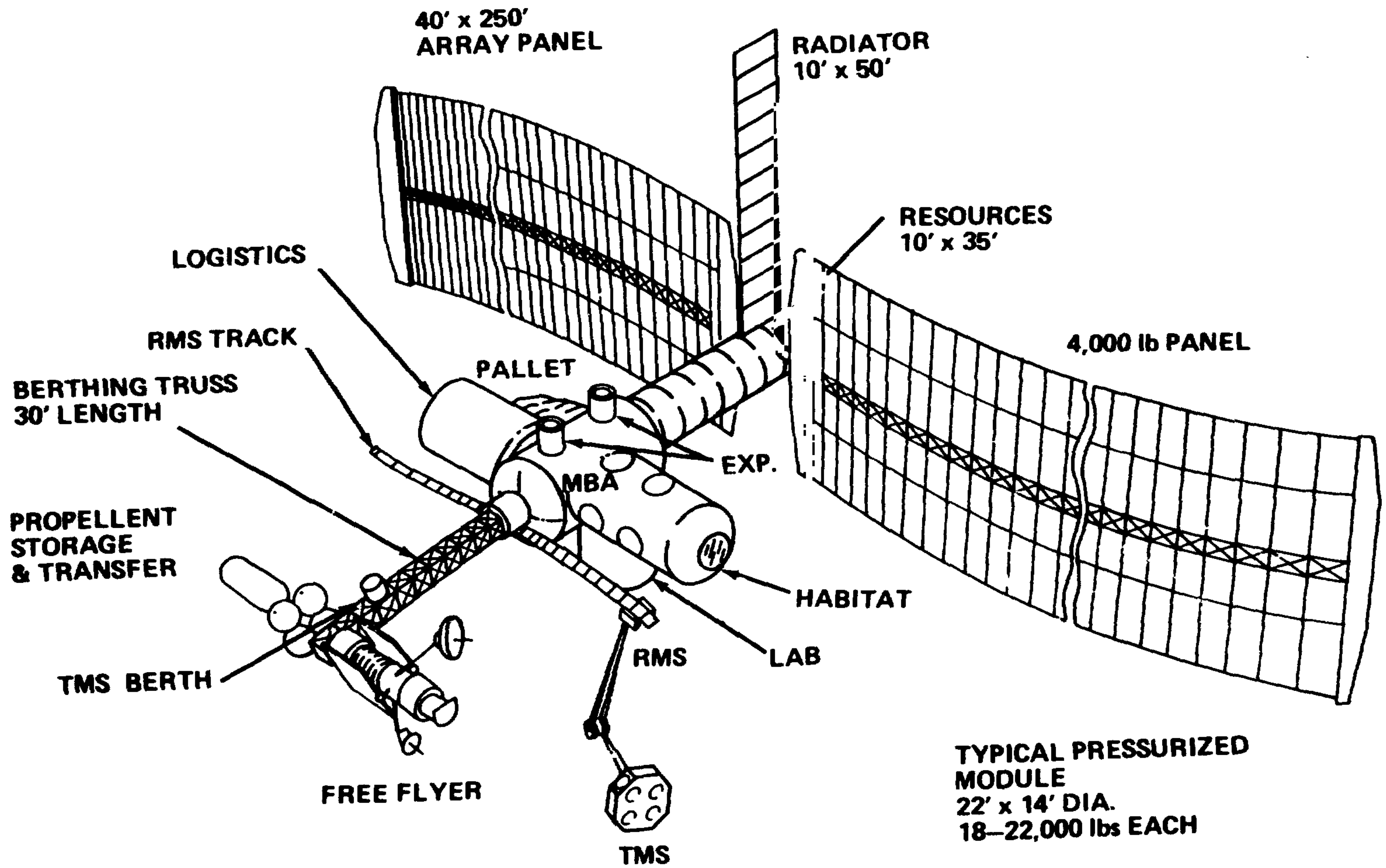


Figure 2. Task forcc initial space station baseline configuration.

$\ddot{x}$ = acceleration of displacement

D = damping coefficient

$\dot{x}$ = velocity of displacement

K = spring rate

x = displacement

T_2 = control parameter (forcing function)

K_T = control system constant (torquer gain)

K_R = control system constant (rate gain)

K_P = control system constant (position gain)

Ref. = reference attitude

x_4 = measured displacement

I_2 = moment of inertia

S = Laplace transform

θ_2 = peak attitude error.

Figure 3 is the control block diagram.

Some of the space station design obstacles being studied are (Nicaise, 1983):

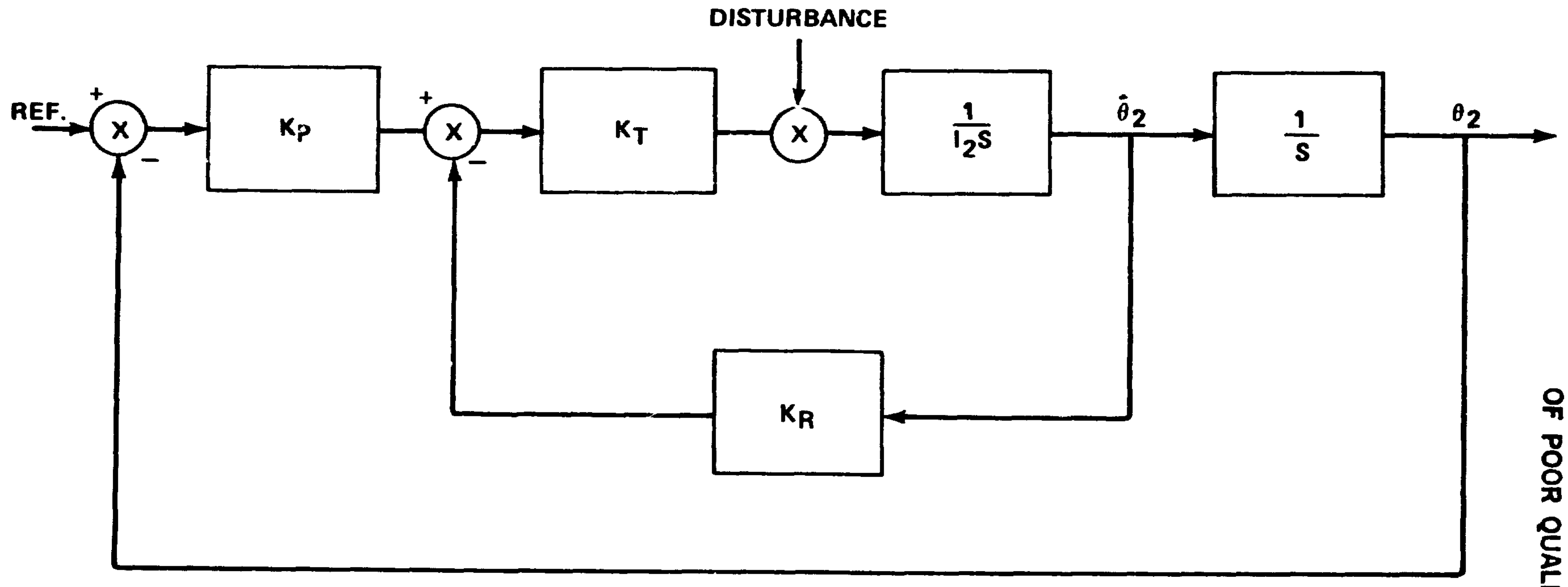
1) Despin of radiators for earth-fixed modes.

2) Control moment gyros (CMGs) are located on central body which is independent of radiator or solar array orientation.

3) Solar arrays rotate individually as opposed to a single unit.

4) Solar arrays may be repositioned from early to final configuration.

Solar array positioning may be effected by thermospheric winds because of large center of pressure (cp) to center of gravity (cg) offset on the early missions. The on orbit wind environment affects the wind varying dynamic disturbances of torque and drag and is presented in Section V. Section V also gives the recommendations of the wind magnitudes and directions of thermospheric winds at orbital altitudes.



K_T, K_P, & K_R ARE SELECTED FOR SYSTEM DESIGN

$$\frac{\theta_2}{REF}(s) = \frac{K_P K_T}{IS^2 + K_R K_T S + K_T K_R}$$

Figure 3. Control block diagram.

ORIGINAL PAGE IS
OF POOR QUALITY

IV. SUMMARY OF DATA ON THE THERMOSPHERIC WINDS AT ORBITAL ALTITUDES OF THE SPACE STATION

Information on the thermospheric winds at the orbital altitudes is given in MSFC's Space and Planetary Criteria Guidelines for Use in Space Vehicle Development, 1982 Revision (Volume 1) by Smith and West (1983). The report indicates the predicted meridional winds become large at night approximately 225 m/sec above 300 km at 0200 local time (LT) and then decrease to about 100 m/sec above 300 km at 1400 LT because of the increase in ion drag. Wind speeds at 300 km altitude and 40-deg latitude, average 50, 20 and 5 m/sec equatorward at summer solstice, equinox and winter solstice at higher altitudes, the increase in ion drag gives lower wind speeds.

King-Hele and Walker (1982), from their orbit satellite analysis of the upper atmosphere zonal winds from 85 satellite values, illustrate their results in Figure 4. The average values in Figure 4 are rather widely spread as would be expected from the wide spectrum of conditions taken together as the average. As the authors indicate, the curve drawn through them seems to provide a reasonable mean, this is called the average/average curve, that is averaged in local time (LT), and averaged in season.

The curve is made to decrease to near 1.0 revolutions per day (rev/day) at 120 km and is arbitrarily assumed to have zero slope at 700 km.

All the evening points in Figure 4 are denoted by upward-pointing triangles, morning values by downward-pointing triangles and average values by circles. All the "evening" points in Figure 4 are above the average/average curve, and all the "morning" curves are drawn as parallel as possible to the average/average curve and the authors assume that the distinction ceases to operate at heights below about 120 km. so that the curve merges there.

King-Hele, et al., (1983) defines three regimes of local time – morning, evening, and average. "Morning" applies when the local time at perigee, and in the region near perigee where the drag is important, is predominantly (> 75 percent) between local times of 06 and 12 hr. "Evening" applies when the local time is predominantly between 18 and 24 hr. "Average" covers all the remaining situations, namely:

1) Local time predominantly 0 to 6 hr;

2) Local time predominantly 12 to 18 hr;

3) Local time covering several 6 hr intervals (often 24 hr cycles) and not appreciably biased;

4) Near-circular orbits with eccentricity usually less than 0.006.

Unfortunately, the satellites do not place themselves neatly into required categories, and it was sometimes difficult to choose the correct regime. So the authors have done their best to assign each value of Λ (revolutions per day) to the correct category of local time.

Similarly the authors define three seasonal categories – summer, winter and average. "Summer" applies when the local seasonal situation of perigee is predominantly within 1.5 months of the summer solstice. "Winter" applies similarly for the winter solstice. "Average" covers the remaining situations, namely:

ORIGINAL PAGE IS OF POOR QUALITY

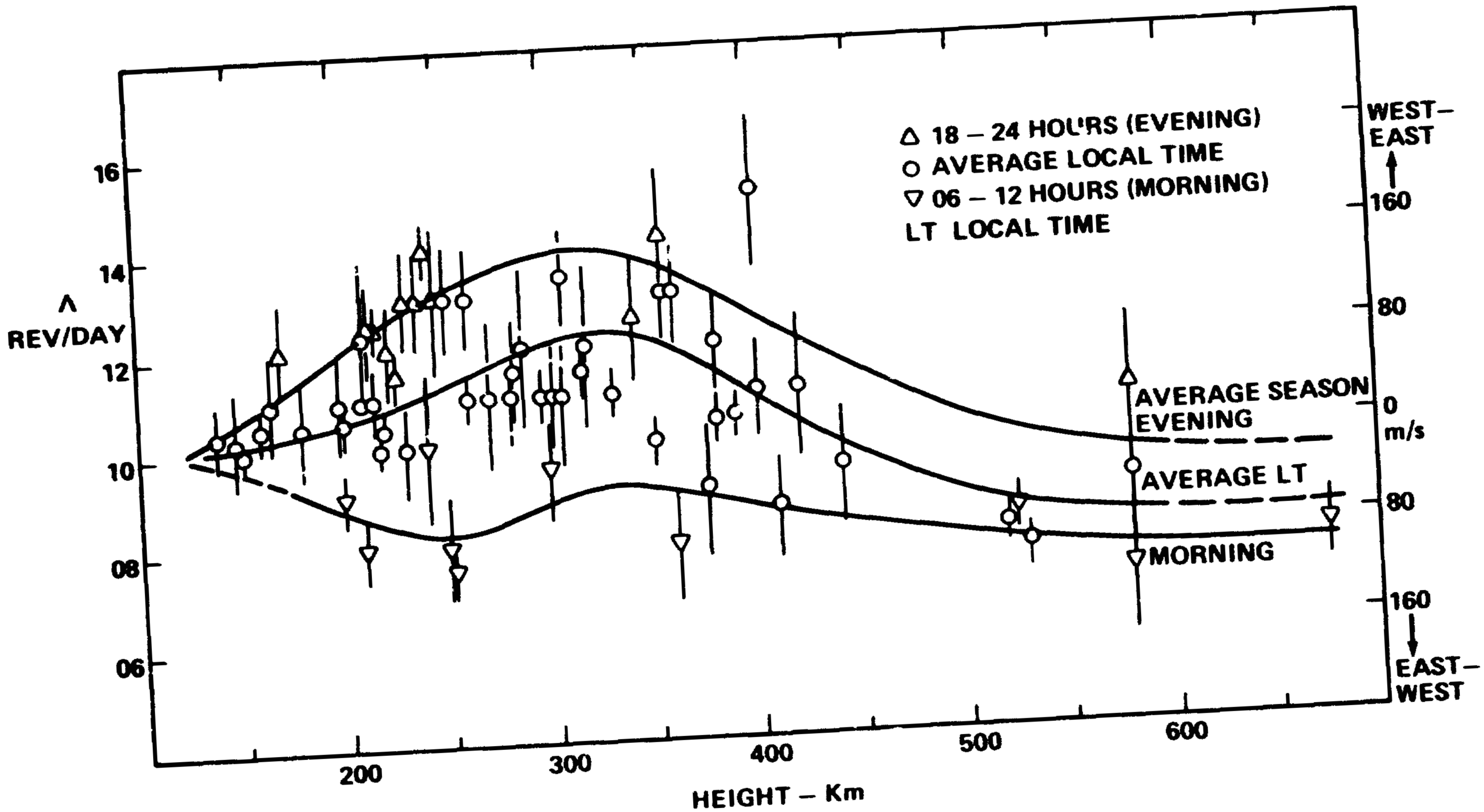


Figure 4. Variation of Λ (revolution/day) and zonal wind with height and local time, average season.

1) Date predominantly between 6 February and 6 May;

2) Date predominantly between 6 August and 6 November;

3) Values for equinox would appear in the "average" category, but the term "average" is preferable as so many results are obtained from analysis of orbits of several years.

The dynamical behavior of the upper atmosphere is presented by King-Hele, et al. (1983) in Figure 5 and should be of value as a guide to the general behavior of the upper atmosphere.

As the authors indicate, several of the curves in Figure 5 are tentative but the pattern that emerges is consistent. The curves for morning and evening represent the average conditions between 06 and 12 hr, or between 18 and 24 hr, and not the extremes; similarly for summer and winter. The average LT average season curve and the thermospheric wind at the lower limit of 460 km is about 40 m/sec (east to west wind) and at the upper limit of 555 km, the velocity is approximately 75 m/sec (east to west wind). It is important again to point out these orbital altitudes and velocities are of a value as a guide to the general dynamical behavior of the thermospheric winds in the upper atmosphere.

V. RECOMMENDATIONS OF MAGNITUDE AND DIRECTION OF THERMOSPHERIC WINDS AT ORBITAL ALTITUDES

King-Hele, et al., defined the three seasonal categories of thermospheric winds, summer, winter and average. As pointed out in his report, the pattern from satellite data is tentative but the pattern that emerges is consistant, according to King-Hele.

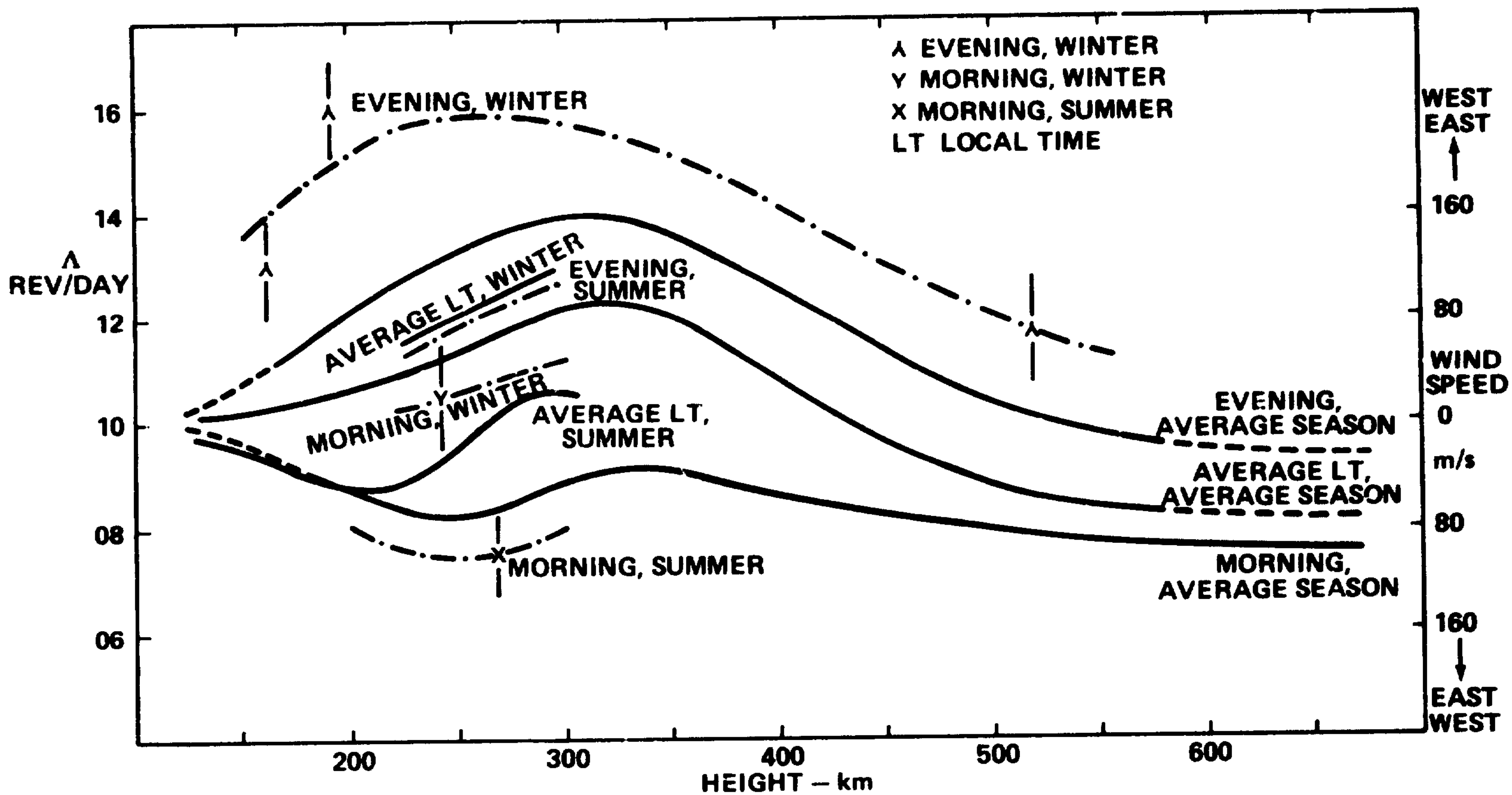
The wind direction and magnitude recommended at the lower altitude of 460 km for the space station is presented in Figure 5 and from Table 1.

TABLE 1. WIND DIRECTION AND MAGNITUDE OF THERMOSPHERIC WINDS AT 460 km

Time	Magnitude (m/sec)	Direction
Evening Winter	115	West to East
Evening Average Season	40	West to East
Average Local Time (average season)	40	East to West
Morning Average Season	80	East to West

The drag and torque are proportional to the square of the orbital velocity of the space station and the thermospheric wind. The orbital velocity (V_O) of the space station is approximately 7000 m/sec and the peak velocity of the thermospheric wind (V_W) is 115 m/sec. This is approximately a 3.2 percent change in the orbital velocity, assuming a tail wind.

An extreme wind of 900 m/sec during extreme solar activity may occur at high latitudes, Killeen, et al. (1984). This high drift could last for approximately 1/2 day. It is unlikely to have this type of event occur more than once a year.



ORIGINAL PAGE IS OF POOR QUALITY

Figure 5. Variation of Λ (revolution/day) and zonal wind with height, local time, season, evening and morning winter, and evening and morning summer.

As has been pointed out, it has been generally observed that the extreme wind velocities (> 400 m/sec) are associated with magnetic substorms phenomena at high magnetic latitudes. It is rare that winds > 400 m/sec are observed equatorward of a magnetic latitude of ~ 50 deg. This is approximately a 10.5 percent change in the orbital velocity assuming a tail wind.

The wind magnitudes and directions recommended at the upper orbital altitude of 555 km for the space station as presented in Figure 5 is listed in Table 2.

TABLE 2. WIND DIRECTION AND MAGNITUDE OF THERMOSPHERIC WINDS AT 555 km

Time	Magnitude (m/sec)	Direction
Evening Winter	50	West to East
Evening Average Season	20	East to West
Average Local Time (Average Season)	70	East to West
Morning Average Season	100	East to West

At the upper altitude of 555 km, an east to west wind of 100 m/sec is the largest wind magnitude in Table 2. An east to west component is approximately a 2.9 percent change in the orbital velocity. assuming a head wind.

Using King-Hele's Figure 5, a typical shear at 460 km, a Δ change in wind velocity of 10 m/sec occurs between a scale of distance of 10 km,

$$\text{Shear} = \frac{\Delta V}{\Delta M} = \frac{10}{10{,}000} = 0.001 \ \text{sec}^{-1}$$

An extreme wind of 900 m/sec wind during extreme solar activity may occur at high latitudes, Killeen, et al. (1984). This high drift could last for approximately 1/2 day. It is unlikely to have this type of event occur more than once a year.

REFERENCES

Antoniadis, D. A., 1976: Thermospheric winds and exospheric temperatures from incoherent scatter radar measurements in four seasons. Journal of Atmospheric and Terrestrial Physics, 28, 187-195.

Babcock, R. R., Jr., and J. W. Evans, 1979: Effects of geomagnetic disturbances on neutral winds and temperatures in the thermosphere observed over Millstone Hill. J. Geophys. Res., 84, 5349-5354.

Babcock, R. R., Jr., and J. W. Evans, 1979: Seasonal and solar cycle variations in the thermospheric circulation observed over Millstone Hill. J. of Geophys. Res., 84, A12, 7348-7352.

Bates, Howard F., 1978: Computed bounds in the F-region zonal wind during Joule heating. J. of Atmospheric and Terrestrial Physics, 40, 1123-1130.

Bittencourt and B. A. Tinsley, 1977: Nighttime thermosphere winds at low latitudes deduced from AE-C ionospheric measurements. J. of Geophys. Res., 82, 29.

Creekmore, S. P., J. M. Strauss, R. M. Harris, B. K. Ching, and Y. T. Chu, 1975: A global model of thermospheric dynamics-1. Wind and density fields derived from a phenomenological temperature. J. of Atmospheric and Terrestrial Physics, 37, 491-515.

Dickinson, R. E., E. C. Ridley and R. G. Roble, 1981: A three-dimensional general circulation model of the thermosphere. J. Geophys. Res., 86, 1499-1512.

Emery, Barbara A., 1978: Neutral thermospheric winds above Millstone Hill, 1. Mathematical model, uncertainties and representative results. J. of Geophys. Res., 83, A12.

Evans, J. W., 1978: Incoherent scatter contributions to studies of the dynamics of the lower thermosphere. Reviews of Geophysics and Space Physics, 16, 2, 195-216.

Hays, P. B., J. W. Meriwether, and R. G. Roble, 1979: Nighttime thermospheric winds at high latitudes. J. Geophys. Res., 84, A5, 1905-1913.

Hernandez, G., 1978: Simultaneous measurements of midlatitude thermospheric winds at 105° W and 79° W longitude. Geophys. Research Letters, 5, 11, 935-938.

Hernandez, G. and R. G. Roble, 1977: Direct measurements of nighttime thermospheric winds and temperatures of 3 monthly variations during solar minimum. J. of Geophys. Res., 82, 35, 5505-5511.

Hernandez, G. and R. G. Roble, 1978: Relationship between midlatitude thermospheric winds and the time rate of change of DST. Geophys. Research Letters, 5, 10, 835-837.

Hernandez, G. and R. G. Roble, 1979: Thermospheric dynamics investigations with very high resolution spectrometers. Applied Optics, 18, 20, 3376-3384.

Hernandez, G. and R. G.Roble, 1979: On divergence of thermospheric meridional winds at midlatitudes. Geophys. Research Letters, 6, 4, 294-296.

Jacka, F., A. R. D. Bower and P. A. Wilksch, 1979: Thermospheric temperatures and winds derived from OI λ 630 nm night airglow line profiles. J. of Atmospheric and Terrestrial Physics.

Kelley, M. C., 1977: Thermospheric wind measurements in the polar region. J. of Atmospheric and Terrestrial Physics, 39, 211-219.

Killeen, T. L., P. B. Hays, N. W. Spencer and L. E. Wharton, 1982: Neutral winds in the polar thermosphere as measured from Dynamics Explorer. J. Geophys. Res., Vol. 9, No. 9, 957-967.

King-Hele, D. G. and Doreen M. C. Walker, 1983: Upper-atmosphere zonal winds from satellite orbit analysis. Planet Space Sci., 31, 5, 509-535.

Killeen, T. L., R. W. Smith, P. B. Hays, N. W. Spencer, L. E. Wharton, and F. G. McCormac, 1984: Neutral winds in the high latitude winter F-region; coordinated observations from ground and space. Geophys. Research Letters, 11, 4, 311-314.

Lloyd, K. M., C. M. Low, B. J. McAvery, D. Rees and R. G. Roper, 1972: Thermospheric observations combining chemical seeding and ground-based techniques - 1. Winds, turbulence and the parameters of the neutral atmosphere. Planet Space Sci., 20, 761-789.

Mettler, E., 1983: Concept development study workshop "Controllability," presented at MSFC by JPL Automated Systems.

Nicaise, 1983: Space station design obstacles, presented at MSFC during Concept Development Study Workshop "Controllability," MSFC/PD12.

Neal, M. P., 1975: An observational data model of thermospheric winds and its comparison with theoretical models. J. of the British Interplanetary Society, 28, 97-118.

Pereira, E., M. C. Kelley, D. Rees, I. S. Mikksen, T. S. Jorgensen, and T. J. Fuller-Rowell, 1980: Observations of neutral wind profiles between 115- and 175-km altitude in the dayside auroral oval. J. of Geophys. Res., Vol. 85, No. A6, 2935-2940.

Plum, P. W. and I. Harris, 1975: Full non-linear treatment of the global thermospheric wind system - I. Mathematical method and analysis of forces. J. of Atmospheric and Terrestrial Physics, 37, 193-212.

Plum, P. W.and I. Harris, 1975: Full non-linear treatment of global thermospheric wind system - II. Results and comparisons with observations. J. of Atmospheric and Terrestrial Physics, 87, 213-235.

Rees, R., P. A. Rounce, P. Charleton, T. D. Fuller-Powell, I. McWhirter and K. Smith, 1982: Thermospheric winds during budget campaign: Ground-based Fabry-Perot observations supported by dynamical simulations with a three-dimensional,time-dependent thermospheric model. Journal of Geophys., 50, 202-211.

Rishbeth, H., 1978: Ion drag effects in the thermosphere. J. of Atmospheric and Terrestrial Physics, 41, 885-894.

Roble, R. G., B. A. Emery, J. E. Salah and B. M. Hays, 1974: Diurnal variation of the neutral thermospheric winds determined from incoherent scatter radar data. J. of Geophys. Res., Vol. 79, No. 19, 2868-2976.

Roble, R. G., J. E. Salah, B. A. Emery, 1977: The seasonal variation of the diurnal thermospheric winds over Millstone Hill during solar cycle maximum. J. of Atmospheric and Terrestrial Physics, 39, 503-511.

Roble, R. G., R. E. Dickinson and E. C. Ridley, 1982: Global circulation and temperature structure of thermosphere with high-latitude plasma convection. J. Geophys. Res., 87, A3, 1599-1614.

Sawako, Maeda, 1982: Large-scale TID's and upper atmospheric gravity waves. J. of Atmospheric and Terrestrial Physics, 44, 3, 245-255.

Smith, Robert E. and George S. West, 1983: Space and planetary environment criteria guidelines for use in space vehicle development. 1982 revision (volume 1), NASA TM 82478.

Spencer, N. W., L. E. Wharton, G. R. Carignan and J. C. Maurer, 1982: Thermospheric zonal winds, vertical motions and temperature as measured from Dynamics Explorer, J. Geophys. Res., 9, 9, 953-956.

Strauss, J. M., 1979: Dynamics of the thermosphere at high latitudes. Reviews of Geophysics and Space Physics, 16, 2, 183-194.

Strauss, J. M., S. P Creekmore, R. M. Harris, B. K. Ching, and Y. T. Chu, 1975: A global model of thermospheric dynamics - II. Wind density and temperature fields generated by EUV heating. J. of Atmospheric and Terrestrial Physics, 37, 1245-1253.

Stubbe, A., 1982: Interaction of neutral and plasma motions in the ionosphere. Handbuck Des Physik, Springen Verlog, Berlin, Heidelberg, New York.

St. Maurice, J. P., and W. B. Hansen, 1982: Ion frictional heating at high latitudes and its possible use for an in situ determination of neutral thermospheric winds and temperatures. J. of Geophys. Res., 87, A9, 7580-7602.

Stubbe, P., Linau/Harz, 1973: Atmospheric parameters from ionospheric measurements. Zeitschrift fur Geophysik, 39, 1043-1054.

Szirmay, Stephen Z. and James Blair, 1983: Space station technology. Astronautics and Aeronautics, 46-49.

Turner, Robert E. and William W. Vaughan, 1983: Development of environmental criteria guidelines for aerospace vehicle design. Preprints Ninth Conference on Aerospace and Aeronautical Meteorology, Omaha, Nebraska, Amer. Meteor. Soc., 261-267.