

High Altitude Atmospheric Modeling

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1. Introduction

The purpose of this study is to compare existing total density data with several recent empirical models in order to assess current data coverage, the accuracy of current empirical models, and where improvements may be possible. The altitude range included in this study is 120 to 1200 km. While techniques based on atmospheric drag effects provide total density rather directly, the in situ mass spectrometer techniques provide densities of individual constituents that must be summed to give total density, and this was done for this study.

Several comparison studies have been made in the past (Marcos et al., 1978; Hickman et al., 1979; Prag, 1983; Marcos, 1987) with somewhat different data sets and models, although there is some overlap in data and models with the current study. A general result of previous studies was that density models have an accuracy of around 15%, and this has not improved much over the last 20 years. This study attempts to refine and quantify this assessment. It produced extensive plots of data minus model residuals as a function of various parameters to allow detailed comparisons and assessments.

This report describes the various products produced and gives some general highlights of results. However, any study of this kind produces rich detail and apparent anomalies that cannot be easily summarized, and interested readers should consult the more detailed plots.

2. Data sets studied

2.1. General characteristics

The data sets utilized in the current report and areas of useful data are summarized in Table 1.

The Jacchia Drag data are total densities, deduced by the Smithsonian Astrophysics Observatory (Jacchia and Slowey, 1965; 1970; 1972; 1975) from the change of satellite orbital elements as a result of air drag. The particular data set used in this study was originally sent on tape by Jacchia to F. Barlier in France, who kindly made a copy available to this author. These data are believed to constitute the major proportion of the data used by Jacchia in the generation of his models. The time (and thus spacial) resolution of density derived from orbit change is generally rather coarse with densities determined no more often than every three hours, and often one day in contrast to tens of seconds or better for in situ data. Absolute densities depend directly on the assumed drag coefficient. Jacchia (1977) used 2.2 for atomic oxygen and a dependence on composition (altitude) as specified by Cook (1976). Unfortunately, the Cook paper has a number of possible algorithms and selectable parameters. The exact algorithm for drag coefficients used by Jacchia is not specified in any known publication. This situation could be important for determining drag and/or density at lower and higher altitudes where atomic oxygen is not the major constituent, and the Jacchia models (which were utilized to determine the composition dependent drag coefficient) do not always give the correct composition. The data were gathered during the decline of solar cycle 19 and the rise of solar cycle 20 over a wide range of latitudes.

Table 1. Summary of data sets.

Name	Method	Dates	Altitude	F10.7	Max Lat	Num Pts
Jacchia	Drag	61001-70365	244-1200	70-176	90	22124
Barlier	Drag	64033-73058	123-735	68-176	90	11647
OGO-6	MS	69159-71177	394-1090	108-170	82	292470
AE-C MESA	Accel	73353-76271	129-250	70- 93	68	111105
AE-C OSS	MS	74001-75161	130-837	70- 93	68	133405
AE-D MESA	Accel	75280-76029	140-250	72- 79	90	36743
AE-D OSS	MS	75291-76029	140-550	72- 78	90	49875
Cactus	Accel	75178-79021	226-600	69-197	30	1069330
AE-E MESA	Accel	75335-78032	134-250	69-130	20	70240
AE-E OSS	MS	75343-79049	134-544	69-197	20	181990
AE-E NACE	MS	75335-81155	134-	69-225	20	242931
DE-2 NACS	MS	81220-83047	199-864	128-230	90	292830
MSIS Comb	MS	69178-83047	135-963	69-230	90	33181

Drag - indicates density by orbit decay.

Accel - indicates density by in situ accelerometer.

MS - indicates in situ mass spectrometer.

The Barlier Drag data are total densities analogous to the Jacchia densities but derived independently (Barlier et al., 1973) for generally different satellites. These data are primarily useful for studying density variations, as absolute values were normalized to Jacchia (1971) in an overall sense. The data were taken during most of solar cycle 20 over a wide range of latitudes.

The OGO-6 satellite (Carignan and Pinkus, 1968; Hedin et al., 1974) was the first to obtain a long time series of fairly reliable mass spectrometer measurements. Perigee for most of the mission was near 400 km, and so this satellite obtained more mass spectrometer data above 400 km than other missions before or since. Total mass density was calculated as a summation of measured atomic oxygen, helium, and molecular nitrogen. Measurements were taken during the peak and decline of solar cycle 20 at all latitudes except the extreme polar region.

The Atmospheric Explorer AE-C, -D, and -E satellites each carried an in situ accelerometer (MESA) (Champion and Marcos, 1973), open source mass spectrometer (OSS) (Nier et al., 1973), a closed source mass spectrometer (NACE) (Pelz et al., 1973) for composition measurements, and a closed source mass spectrometer (NATE) (Spencer et al., 1973) for temperature and wind measurements. The closed source geometry was thought to provide a better determination of absolute density, while the more open source could better detect reactive species. Absolute values from all three instruments are comparable within the original target calibrations of about 15%. The NACE instrument failed early in the AE-C flight. The entire AE-D satellite failed after only about 3 months in operation. All three instruments were highly successful on AE-E with more data reduced for NACE. Total mass density from the mass spectrometers was calculated as a summation of measured atomic oxygen, helium, argon, and molecular nitrogen. Total density from MESA was based on a drag coefficient of 2.2 (Marcos et al., 1977). Measurements were taken during solar cycle minimum at all latitudes and during the rise of cycle 21 at low and midlatitudes.

The Castor satellite launched by CNES carried an accelerometer (CACTUS) (Boudon and Barlier, 1979; Villain, 1980; Berger and Barlier, 1981) for in situ density measurements. Measurements were taken during the rise of solar cycle 21 at low latitudes.

The Dynamics Explorer 2 satellite carried a mass spectrometer (NACS) (Carignan et al., 1981) for in situ density and composition measurements, a second mass spectrometer (WATS) (Spencer et al., 1981) for in situ temperature and zonal wind measurements, and a Fabry-Perot spectrometer (FPI) (Hays et al., 1981) for F-region temperature and meridional wind measurements. The absolute density calibration of the mass spectrometers was not adequate due to a failure of laboratory equipment and cannot be given much reliance. Total mass density was calculated as a summation of measured atomic oxygen, helium, argon, and molecular nitrogen. Measurements were taken during the peak and decline of solar cycle 21 at all latitudes. They provide the only set of high solar activity high latitude mass spectrometer measurements available.

The MSIS combined density data set consists of separate data sets for each atmospheric constituent that were formed from subsets selected from mass spectrometer measurements on the OGO-6, AE-C, -D, -E, and DE-2 satellites

described above, as well as the ESRO-4 (Trinks and von Zahn, 1975), San Marco-3 (Newton et al., 1974), and AEROS-A (Spencer et al., 1974) satellites and numerous rockets. Data subsets were selected to provide the widest possible coverage in geographical and geophysical parameters. These combined data sets were used in the generation of the MSIS-86 model. While there is no parallel set of total densities because the data were not originally selected with this goal in mind (and thus without simultaneity in time for the various constituents), the distribution and coverage of oxygen density are assumed to represent the overall coverage in total density that could be obtained using the mass spectrometer data. There is a similar combined data set for temperature combining subsets from the AE-C, -D, -E, and DE-2 satellites, rockets, and Millstone Hill, St. Santin, Arecibo, Jicamarca, and Malvern incoherent scatter stations.

2.2. Coverage

More details on data coverage in terms of latitude, local time, day of year, longitude, and UT can be found in the coverage plots and data comparison plots described in Appendix C, which are provided on microfich for each data set.

The coverage of the MSIS combined data set for atomic oxygen, which is essentially the coverage for good prediction of total density from the MSIS-86 model, has been examined in more detail by sorting the data into bins based on latitude, local time, day of year, universal time (UT), daily magnetic index (A_p), mean F10.7, daily minus mean F10.7, and altitude. The results of this binning procedure are computer readable files described in Appendix A. In general, coverage is relatively poor at high magnetic activities, at altitudes below 200 km and above 800 km, and at high latitudes for low solar activity.

3. Model comparisons

3.1. Model descriptions

A large number of empirical models have been developed over the years. The genealogy of these models is illustrated in Figure 1. Hickman et al. (1979) have given a brief but thorough description of the most common models available at that time. Five specific models are selected for comparison with data in the current study.

MSIS-86

The MSIS-86 model (Hedin, 1987) is the latest in the series of empirical models of neutral temperature and density in the thermosphere (above 85 km) and lower exosphere based on in situ mass spectrometer and incoherent scatter data. The model is dependent on user-provided values of day, time (UT), altitude, latitude, longitude, local solar time, magnetic index (A_p), a three solar rotation average 10.7-cm radio flux (F10.7), and previous day F10.7. A history of three hour magnetic indices (a_p) can be used for somewhat better detail during magnetic storms. The model calculates neutral temperature, total density, and densities of N_2 , O_2 , O, N, He, Ar, and H. The model is based on a fit of in situ composition and temperature data from eight scientific satellites (OGO-6, San Marco-3, Aeros-A, AE-C, -D, -E, ESRO-4, and DE-2) and numerous rocket probes, as well as five ground-based incoherent

Historical Development of Empirical Thermosphere Models

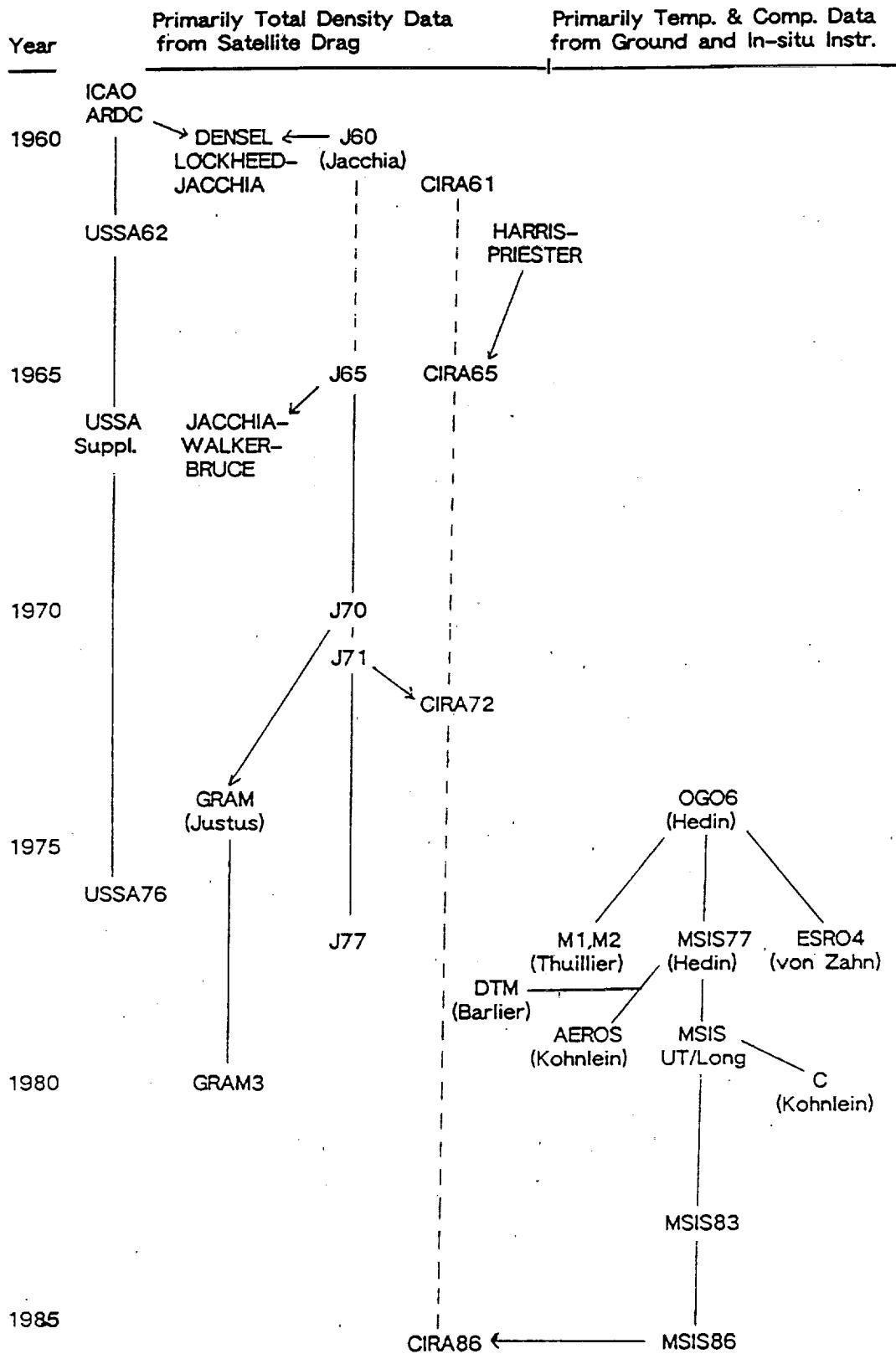


Fig. 1. History of empirical models.

scatter stations (Millstone Hill, St. Santin, Arecibo, Jicamarca, and Malvern). The model supersedes the MSIS-83 model by inclusion of high latitude, high solar activity data from the Dynamics Explorer satellite, and the addition of atomic nitrogen to the gas species included in the model. The MSIS-86 model was selected by COSPAR for inclusion in the next CIRA which has yet to be published.

MSIS-83

The MSIS-83 model (Hedin, 1983) is an empirical model of neutral temperature and density in the thermosphere (above 85 km) and lower exosphere based on in situ mass spectrometer and incoherent scatter data. The model is dependent on user-provided values of day, time (UT), altitude, latitude, longitude, local solar time, magnetic index (A_p), a three solar rotation average 10.7-cm radio flux ($F_{10.7}$), and previous day $F_{10.7}$. A history of three hour magnetic indices (a_p) can be used for somewhat better detail during magnetic storms. The model calculates neutral temperature, total density, and densities of N_2 , O_2 , O , He , Ar , and H . The model is based on a fit of in situ composition and temperature data from seven scientific satellites (OGO-6, San Marco-3, Aeros-A, AE-C, -D, -E, and ESRO-4) and numerous rocket probes, as well as five ground-based incoherent scatter stations (Millstone Hill, St. Santin, Arecibo, Jicamarca, and Malvern). The model supersedes the MSIS-77 model by inclusion of data from the AE-D, AE-E, and ESRO-4 satellites, as well as additional data from incoherent scatter stations that cover a wide range of solar activities and the inclusion of longitude/UT variations. The MSIS-83 model extends the previous description of neutral parameters below 120 km to the base of the thermosphere in a continuous manner.

MSIS-77

The MSIS-77 model (Hedin et al., 1977a; 1977b) is an empirical model of neutral temperature and density in the thermosphere (above 120 km) and lower exosphere based on in situ mass spectrometer and incoherent scatter data. The model is dependent on user-provided values of day, altitude, latitude, local solar time, magnetic index (A_p), a three solar rotation average 10.7-cm radio flux ($F_{10.7}$), and previous day $F_{10.7}$. The model calculates neutral temperature, total density, and densities of N_2 , O_2 , O , He , Ar , and H . The model is based on a fit of in situ composition and temperature data from five scientific satellites (AE-B, OGO-6, San Marco-3, Aeros-A, and AE-C), as well as four ground-based incoherent scatter stations (Millstone Hill, St. Santin, Arecibo, and Jicamarca). The model supersedes the OGO-6 model, which was based on data from only one satellite. The OGO-6 model is now totally obsolete.

The MSIS-77 model used in this study specifically did not include the longitude/UT variations (Hedin et al., 1979), which are sometimes associated with this model name.

J77

The J77 model (Jacchia, 1977) is the latest in a series of empirical models of neutral temperature and density in the thermosphere (above 90 km) and lower exosphere based on atmospheric drag effects on satellite orbits. The model is dependent on user-provided values of altitude, latitude, sun

declination, hour angle of sun, fraction of tropical year, invariant or geomagnetic latitude, magnetic index (kp), a six solar rotation average of F10.7, and previous day F10.7. The model calculates neutral temperature, total density, and densities of N_2 , O_2 , O, He, Ar, and H. The model is based primarily on total densities derived from changes in satellite orbits (approximately 16 satellites during the 1960's) with an attempt to represent changes in composition observed by OGO-6 and ESRO-4. The model differs from the J71 and J70 models by the inclusion of elaborate formulations to describe composition changes with local time and magnetic activity.

The code used for this model was generated from the original publication without later unpublished modifications.

J70

The J70 model (Jacchia, 1970) is an empirical model of neutral temperature and density in the thermosphere (above 90 km) and lower exosphere based on atmospheric drag effects on satellite orbits. The model is dependent on user-provided values of altitude, latitude, sun declination, hour angle of sun, fraction of tropical year, magnetic index (kp), a three solar rotation average of F10.7, and previous day F10.7. The model calculates neutral temperature, total density, and densities of N_2 , O_2 , O, He, Ar, and H. The model is based on total densities derived from changes in satellite orbits (approximately 16 satellites during the 1960's). The model essentially differs from the later J71 (Jacchia, 1971) by a smaller value of the O/O_2 ratio at 150 km. The J70 model superseded the earlier J65 model (Jacchia, 1965) by extending the model calculations below 120 km.

This model is the thermosphere end of the Marshall Space Flight Center GRAM model, and the code for this model was obtained from MSFC.

3.2. Residual plots

Each of the data sets described above was divided into subsets according to altitude and then compared to the five models in order to calculate data residuals by taking the logarithm (base e) of the ratio of the measured total density to model total density. The mean residual, standard deviation of the residuals (square root of the sum of squares of each residual minus the mean residual), and RMS (square root of the sum of squares of the residuals) were calculated, and the residuals used to generate histogram plots of the residuals and a large number of plots of residuals versus various coordinates. The detailed description of the plots is given in Appendix C, and the plots themselves are largely in microfich format. The binned data used for the histogram plots (Figures C1 and C2 of Appendix C) are also in a series of ASCII computer files as described in Appendix B.

The total number of data points in some data sets was very large (Table 1). For handling and plotting convenience, a subset of points was usually selected at random to bring the total points under 20,000. Previous experience and statistics suggest this should be adequate for the current comparisons. In any large data set, there are almost always a number of points that are erroneous because of occasional problems somewhere in the electronic or data-handling systems. Thus data points whose residuals from both MSIS-86 and J70 were more than 10 times the estimated experimental error

were discarded. Normally, only a few percent, and in no case more than 10%, of the points were dropped in this test. For each data set the exact same set of points was finally compared with each of the five models and thus should provide a reasonable relative comparison of the models. Judgments as to the relative value of various data sets is more problematic without considerable individual attention to the nature of the problem points.

The model densities were calculated using the same (three solar cycle) average F10.7 and one-day lag for each model. Also, most of the comparisons were done using the daily Ap/Kp rather than the three-hour index. Limited tests indicated a possible improvement of a percent or two (for all models except MSIS-77, which was not designed to use the more detailed index) in overall standard deviations using the appropriate three-hour index.

3.3. Results

A summary of the mean residuals for each of the data subsets under magnetically quiet ($A_p \leq 10$) conditions is given in Table 2 as the logarithm (base e), along with the rank (1 best to 5 worst) of each model with respect to this data subset in parenthesis after the residual. At the bottom is an accumulation of how many data sets were ranked 1 to 5 for each model. These rankings are plotted in Figure 2 and show that, except for MSIS-77, there is an approximately equal chance that any one of the models would give the lowest mean residual for any of the data subsets. Also in the table is the number of points and, in parenthesis after the number of points, the fraction of the original data set used in the calculation.

The average over all data subsets for the models is -.02, -.01, -.12, -.01, -.04 for MSIS-86, -83, -77, J77, and J70, respectively. In other words, the average difference in absolute densities between the existing data sets and models is generally only a few percent. Averages based on mass spectrometer data are about 4% (.04 in logarithms) less than averages based on drag data only. This is well within any a priori estimates of calibration errors. Examination of specific data sets like Jacchia drag (used for generating the Jacchia models but not the MSIS models) or AE-E NACE (used for generating MSIS models but not Jacchia models) confirms that there is little difference in absolute values overall across models. The exception is MSIS-77, which was generated with a database which did not have complete solar activity coverage, but not surprisingly does well with, for example, AE-C data that were used in generating this model.

A summary of the overall standard deviations of the residuals for each of the data subsets under magnetically quiet ($A_p \leq 10$) conditions is given in Table 3 in the same format as Table 2, and the rankings are plotted in Figure 3. Here we see a systematic trend toward lower standard deviations in the later MSIS models. Taking a given data subset at random, one is more likely to obtain the smallest standard deviations in the residuals using MSIS-86. There are, of course, specific exceptions to this generalization such as the high altitude Jacchia drag data, where MSIS-86 and J70 are equivalent at 400-800 km and J70 is best above 800 km, and the counter example of OGO-6, where MSIS-86 is best in the 400-800 km range. Small differences in ranking, such as between J77 and J70, may not be significant, and it should be remembered that in many cases the difference between best and worst is only a few percentage points. Also, the data subsets are not entirely independent

Table 2. Overall mean (magnetically quiet).

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia drag	200-400	3197	-.05 (3)	-.05 (3)	-.21 (4)	-.03 (1)	-.04 (2)
	400-800	6516	-.05 (1)	-.06 (2)	-.23 (3)	-.05 (1)	-.06 (2)
	800-1200	3386	.04 (2)	.04 (2)	-.04 (2)	-.03 (1)	-.05 (3)
Barlier drag	120-200	1050	.02 (1)	-.03 (2)	-.02 (1)	-.04 (3)	-.07 (4)
	200-400	4761	.04 (3)	.02 (1)	-.06 (4)	-.04 (3)	.03 (2)
	400-800	1447	.10 (2)	.10 (2)	-.04 (1)	.10 (2)	.15 (3)
OGO-6 ms	200-400	1978(.20)	.20 (2)	.20 (2)	.04 (1)	.09 (2)	.15 (3)
	400-800	12863(.07)	.20 (2)	.20 (2)	.04 (1)	.21 (3)	.25 (4)
AE-C MESA accel	120-200	5746(.25)	.11 (3)	.11 (3)	.05 (2)	.05 (2)	.00 (1)
	200-250	6101(.55)	.02 (1)	.04 (3)	-.08 (4)	.03 (2)	-.03 (2)
AE-C OSS ms	120-200	6447(.65)	-.01 (1)	-.01 (1)	-.05 (3)	-.02 (2)	-.07 (4)
	200-390	6279(.2)	.02 (2)	.06 (3)	-.08 (4)	.09 (5)	.01 (1)
AE-D MESA accel	120-200	11024(.7)	-.03 (3)	.00 (1)	.00 (1)	.02 (2)	-.02 (2)
	200-250	4399	-.08 (3)	-.04 (2)	-.11 (4)	.01 (1)	-.04 (2)
AE-D OSS ms	120-200	11787	-.01 (1)	.01 (1)	.01 (1)	.04 (2)	.01 (1)
	200-390	10923(.75)	-.06 (3)	-.02 (1)	-.20 (4)	.03 (2)	-.03 (2)
AE-D NACE ms	120-200	4614	-.12 (3)	-.09 (1)	-.10 (2)	-.15 (4)	-.18 (5)
	200-400	5591	-.21 (3)	-.14 (1)	-.33 (5)	-.17 (2)	-.22 (4)
Cactus accel	200-400	11276(.10)	-.05 (2)	-.05 (2)	-.26 (4)	-.03 (1)	-.08 (3)
	400-600	9808(.10)	-.02 (2)	-.01 (1)	-.36 (4)	.01 (1)	-.07 (3)
AE-E MESA accel	120-200	11455(.45)	.02 (2)	.02 (2)	-.01 (1)	-.01 (1)	-.03 (3)
	200-250	8363	-.01 (2)	.00 (1)	-.06 (4)	.05 (3)	-.01 (2)
AE-E OSS ms	120-200	11812(.62)	-.01 (2)	.00 (1)	-.07 (4)	-.05 (3)	-.07 (4)
	200-400	9741(.12)	-.03 (2)	-.03 (2)	-.15 (3)	-.01 (1)	-.03 (2)
AE-E NACE ms	120-200	7533	-.05 (1)	-.05 (1)	-.05 (1)	-.05 (1)	-.07 (2)
	200-400	10158(.14)	-.09 (3)	-.09 (3)	-.22 (4)	-.02 (2)	-.07 (1)
	400-600	10243(.20)	-.17 (4)	-.14 (3)	-.32 (5)	-.12 (2)	-.08 (1)
DE-2 NACS ms	200-400	6079(.08)	-.23 (3)	-.23 (3)	-.33 (4)	-.15 (1)	-.22 (2)
	400-800	3149(.20)	-.17 (4)	-.15 (3)	-.38 (5)	-.09 (1)	-.14 (2)

Rank summary:

1-6	1-11	1-8	1-11	1-5
2-11	2-10	2-3	2-11	2-12
3-10	3-8	3-3	3-5	3-7
4-2	4-0	4-12	4-1	4-5
		5-3	5-1	

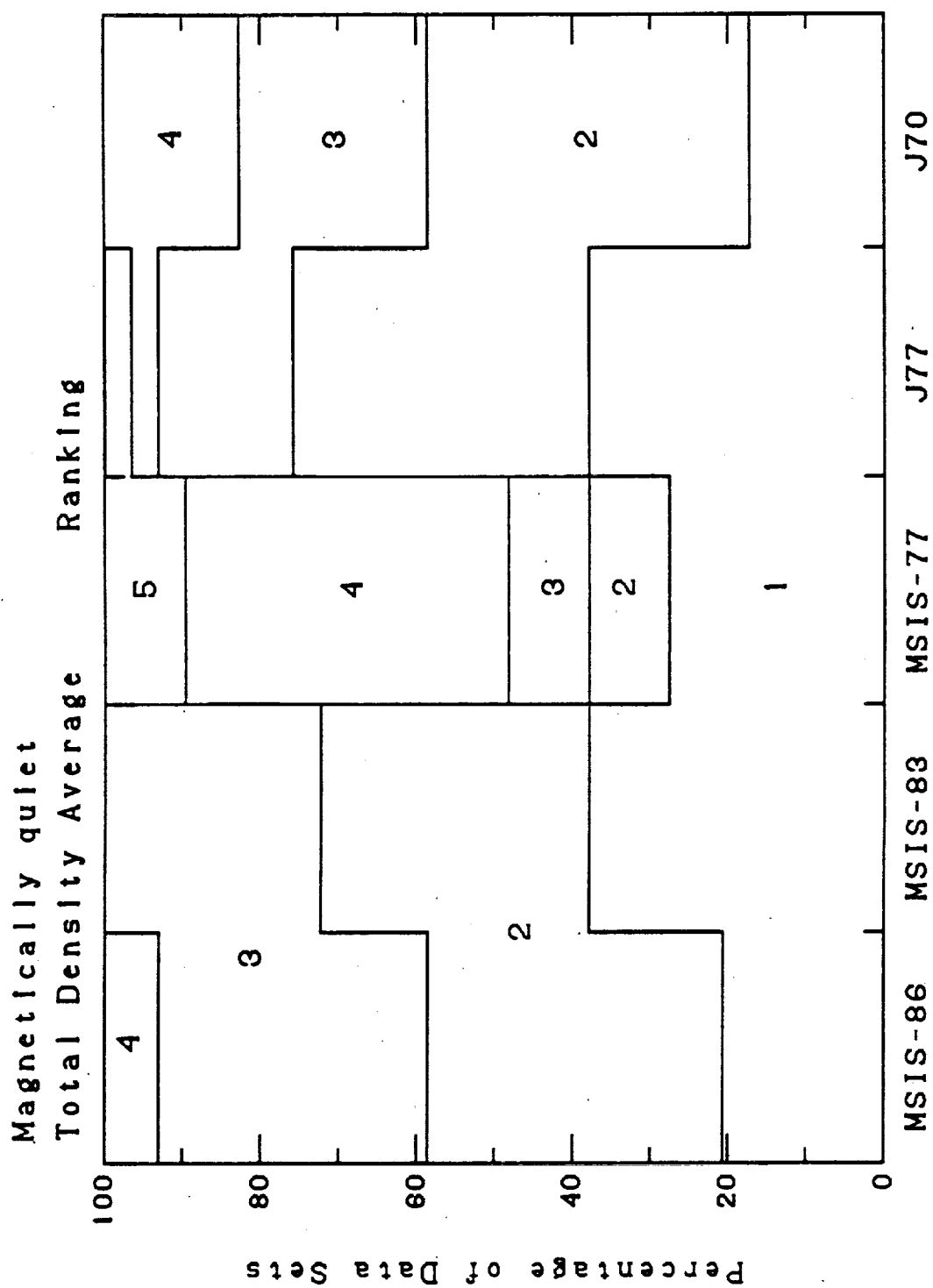


Fig. 2. Model ranking for average density, magnetically quiet.

Table 3. Overall Standard Deviation (magnetically quiet).

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia drag	200-400	3197	.15 (1)	.16 (2)	.18 (3)	.15 (1)	.16 (2)
	400-800	6516	.26 (2)	.26 (2)	.29 (3)	.25 (1)	.26 (2)
	800-1200	3386	.27 (3)	.26 (2)	.30 (4)	.29 (3)	.22 (1)
Barlier drag	120-200	1050	.22 (1)	.23 (2)	.22 (1)	.22 (1)	.23 (2)
	200-400	4761	.20 (1)	.20 (1)	.21 (2)	.21 (2)	.21 (2)
	400-800	1447	.31 (1)	.31 (1)	.33 (3)	.32 (2)	.31 (1)
OGO-6 ms	200-400	1978(.20)	.14 (1)	.14 (1)	.14 (1)	.16 (2)	.17 (3)
	400-800	12863(.07)	.17 (1)	.18 (2)	.18 (2)	.20 (3)	.21 (4)
AE-C MESA accel	120-200	5746(.25)	.16 (2)	.16 (2)	.15 (1)	.18 (3)	.18 (3)
	200-250	6101(.55)	.21 (1)	.21 (1)	.21 (1)	.21 (1)	.21 (1)
AE-C OSS ms	120-200	6435(.65)	.12 (2)	.12 (2)	.10 (1)	.13 (3)	.13 (3)
	200-390	6279(.2)	.14 (1)	.14 (1)	.14 (1)	.15 (2)	.16 (3)
AE-D MESA accel	120-200	11024(.7)	.15 (2)	.15 (2)	.14 (1)	.15 (2)	.14 (1)
	200-250	4399	.18 (1)	.19 (2)	.18 (1)	.18 (1)	.18 (1)
AE-D OSS ms	120-200	11787	.11 (1)	.11 (1)	.11 (1)	.13 (2)	.11 (1)
	200-390	10923(.75)	.17 (1)	.18 (2)	.18 (2)	.17 (1)	.17 (1)
AE-D NACE ms	120-200	4614	.17 (2)	.17 (2)	.16 (1)	.16 (1)	.16 (1)
	200-400	5591	.21 (2)	.22 (3)	.23 (4)	.20 (1)	.21 (2)
Cactus accel	200-400	11276(.10)	.14 (1)	.15 (2)	.18 (4)	.16 (3)	.16 (3)
	400-600	9808(.10)	.24 (1)	.25 (2)	.28 (5)	.26 (3)	.27 (4)
AE-E MESA accel	120-200	11455(.45)	.12 (1)	.12 (1)	.12 (1)	.14 (2)	.14 (2)
	200-250	8363	.18 (1)	.18 (1)	.19 (2)	.20 (3)	.20 (3)
AE-E OSS ms	120-200	11812(.62)	.15 (3)	.14 (2)	.13 (1)	.16 (4)	.17 (5)
	200-400	9741(.12)	.19 (2)	.18 (1)	.21 (4)	.20 (3)	.21 (4)
AE-E NACE ms	120-200	7533	.11 (1)	.11 (1)	.15 (2)	.17 (4)	.16 (3)
	200-400	10158(.14)	.20 (2)	.19 (1)	.20 (3)	.20 (2)	.20 (2)
	400-600	10243(.20)	.19 (2)	.19 (2)	.22 (4)	.18 (1)	.20 (3)
DE-2 NACS ms	200-400	6079(.08)	.14 (1)	.16 (2)	.23 (5)	.20 (4)	.19 (3)
	400-800	3149(.20)	.17 (1)	.21 (3)	.22 (4)	.21 (3)	.19 (2)
			1-18	1-11	1-12	1-9	1-8
			2-9	2-16	2-5	2-8	2-8
			3-2	3-2	3-4	3-9	3-9
			4-0	4-0	4-6	4-3	4-3
					5-2		5-1

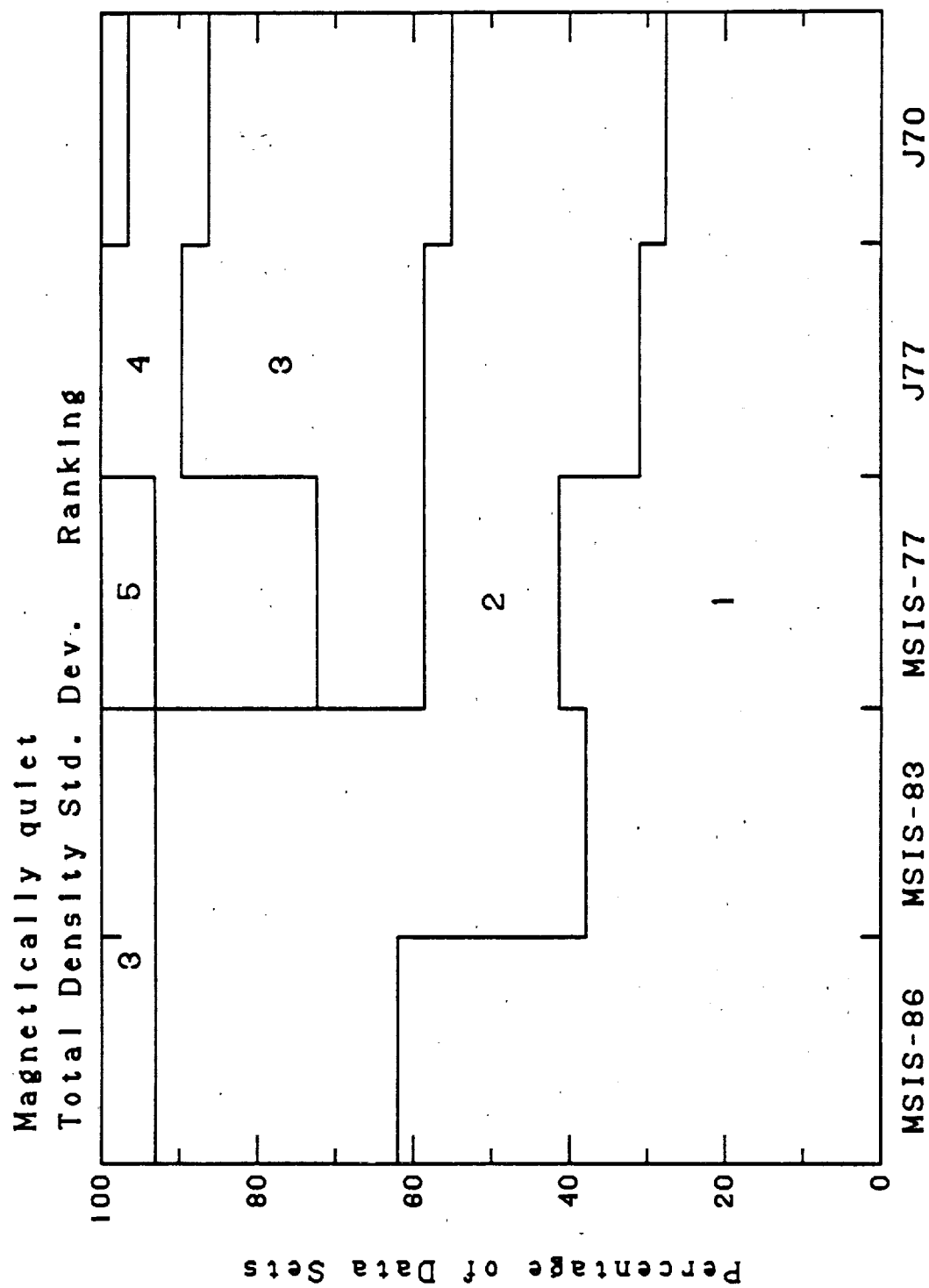


Fig. 3. Model ranking for standard deviations, magnetically quiet.

because of the grouping of instruments on the same satellite. Yet, for reasons not understood, the various instruments on a given satellite do not always give the same density, and it is not usually clear which one is right.

A summary of the mean residuals for each of the data subsets under magnetically active ($A_p > 10$) conditions is given in Table 4 in the same format as Table 2, and rankings are plotted in Figure 4. The features are much the same as for quiet conditions. The average over all data subsets for the models is $-.03$, $-.01$, $-.07$, $.01$, $-.08$ for MSIS-86, -83, -77, J77, and J70, respectively. The MSIS-77 and J70 models have the most change in mean value (about 4%) with increasing magnetic activity.

A summary of the overall standard deviations of the residuals for each of the data subsets under magnetically active ($A_p > 10$) conditions is given in Table 5 in the same format as Table 2, and the rankings are plotted in Figure 5. The features are much the same as for magnetically quiet conditions except J77 has systematically higher standard deviations.

The models were also ranked for several specific types of variations in Tables 6-10 and Figures 6-10 using data for all magnetic activities. Here the standard deviation of the means of the binned data were calculated and used for ranking. Table 6, for example, was taken from the plots showing average residuals in 1-hour bins as a function of local time (e.g., Figure C4 of Appendix C). If the data and model variations as a function of latitude were the same, and the coverage for other important parameters, such as local time, is either the same for each bin or correctly modeled, then the plotted averages should be equal, and the standard deviation of these average values zero. Coverage in other parameters is rarely perfect, but this plot and ranking still emphasize selected types of variations. The local time ranking (Table 7) corresponds to Figure C5, the mean F10.7 ranking (Table 8) to Figure C6, the daily F10.7 ranking (Table 9) to Figure C7, and the magnetic activity (A_p) ranking (Table 10) to Figure C19. The models are about equal in predicting overall latitude variations (Figure 6), except for J77, which is somewhat worse. For local time variations (Figure 7) and daily F10.7 variations (Figure 9), the later models are systematically better. For mean F10.7 variations, the models are about equal, except MSIS-77 is worse. For magnetic activity variations (Figure 10), the later models are only slightly better, and J77, worse.

A summary of the data comparisons on a data-set by data-set basis is given in Appendix D with the attempt to identify variations that could fruitfully be examined further. The most frequently noted residual trends (in order) involved altitude, daily F10.7 (daily minus mean), magnetic activity, and annual (or semiannual) variations. The altitude trends could be a combination of measurement problems and model problems. All of these trends deserve careful study by looking for similarities and differences between the different data sets. Since these trends are handled by the model(s) in an overall sense, the presence of a trend in a particular data set presumably indicates that the magnitude of that variation (like the semiannual variation) depends on some other unidentified factor. Both this data set summary and the preceding discussion of overall means and standard deviations provide only a hint of the rich detail, exceptions, and anomalies that can be found in the comparison plots.

Table 4. Overall mean (magnetically active).

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia drag	200-400	3197	-.05 (3)	-.04 (2)	-.16 (5)	.02 (1)	-.12 (4)
	400-800	6516	-.04 (1)	-.04 (1)	-.16 (3)	.06 (2)	-.16 (3)
	800-1200	3386	.04 (2)	.06 (3)	.02 (1)	.07 (4)	-.12 (5)
Barlier drag	120-200	681	.00 (1)	-.06 (3)	-.03 (2)	-.14 (5)	-.09 (4)
	200-400	2761	-.02 (2)	-.04 (3)	-.09 (5)	.00 (1)	-.06 (4)
	400-800	824	.04 (2)	.05 (3)	-.05 (3)	.11 (4)	.00 (1)
OGO-6 ms	200-400	757(.20)	.00 (1)	-.03 (2)	-.17 (4)	-.05 (3)	-.03 (2)
	400-800	6557(.07)	.15 (4)	.14 (3)	.02 (1)	.23 (5)	.12 (2)
AE-C MESA accel	120-200	5746(.25)	.14 (5)	.13 (4)	.10 (2)	.11 (3)	.07 (1)
	200-250	6101(.55)	.02 (1)	.05 (3)	-.03 (2)	.07 (4)	-.05 (3)
AE-C OSS ms	120-200	6447(.65)	.01 (2)	.01 (2)	.00 (1)	.01 (2)	-.02 (3)
	200-390	6279(.2)	.06 (3)	.10 (4)	.02 (2)	.16 (5)	.00 (1)
AE-D MESA accel	120-200	11024(.7)	-.03 (3)	.00 (1)	.04 (4)	.03 (3)	-.02 (2)
	200-250	4399	-.08 (4)	-.03 (1)	-.05 (2)	.06 (3)	-.06 (3)
AE-D OSS ms	120-200	11787	-.01 (2)	.02 (3)	.06 (4)	.06 (4)	.00 (1)
	200-390	10923(.75)	-.06 (2)	.00 (1)	-.12 (5)	.09 (4)	-.08 (3)
AE-D NACE ms	120-200	4614	-.09 (4)	-.05 (2)	-.02 (1)	-.06 (3)	-.13 (5)
	200-400	5591	-.19 (3)	-.11 (2)	-.22 (4)	-.07 (1)	-.23 (5)
Cactus accel	200-400	8701(.10)	-.02 (1)	-.02 (1)	-.15 (4)	-.03 (2)	-.14 (3)
	400-600	8348(.10)	.00 (1)	.03 (2)	.23 (5)	.15 (3)	-.21 (4)
AE-E MESA accel	120-200	11455(.45)	.06 (3)	.07 (4)	-.03 (2)	-.06 (3)	-.02 (1)
	200-250	8363	.03 (2)	.05 (4)	.01 (1)	.04 (3)	-.03 (2)
AE-E OSS ms	120-200	11812(.62)	.02 (2)	.02 (1)	-.03 (4)	-.11 (3)	-.06 (4)
	200-400	9741(.12)	-.03 (1)	-.03 (1)	-.12 (3)	-.03 (1)	-.09 (2)
AE-E NACE ms	120-200	7533	-.04 (1)	-.04 (1)	-.08 (2)	-.15 (4)	-.09 (3)
	200-400	10158(.14)	-.09 (3)	-.07 (1)	-.18 (5)	-.08 (2)	-.11 (4)
	400-600	10243(.20)	-.18 (3)	-.15 (2)	-.29 (4)	-.14 (1)	-.14 (1)
DE-2 NACS ms	200-400	12286(.08)	-.28 (3)	-.28 (3)	-.35 (4)	-.15 (1)	-.26 (2)
	400-800	9077(.20)	-.17 (3)	-.16 (2)	-.31 (5)	-.02 (1)	-.22 (4)

Rank summary:

1-8	1-9	1-5	1-7	1-6
2-8	2-8	2-7	2-4	2-6
3-9	3-8	3-3	3-9	3-7
4-3	4-4	4-8	4-6	4-7
5-1		5-6	5-3	5-3

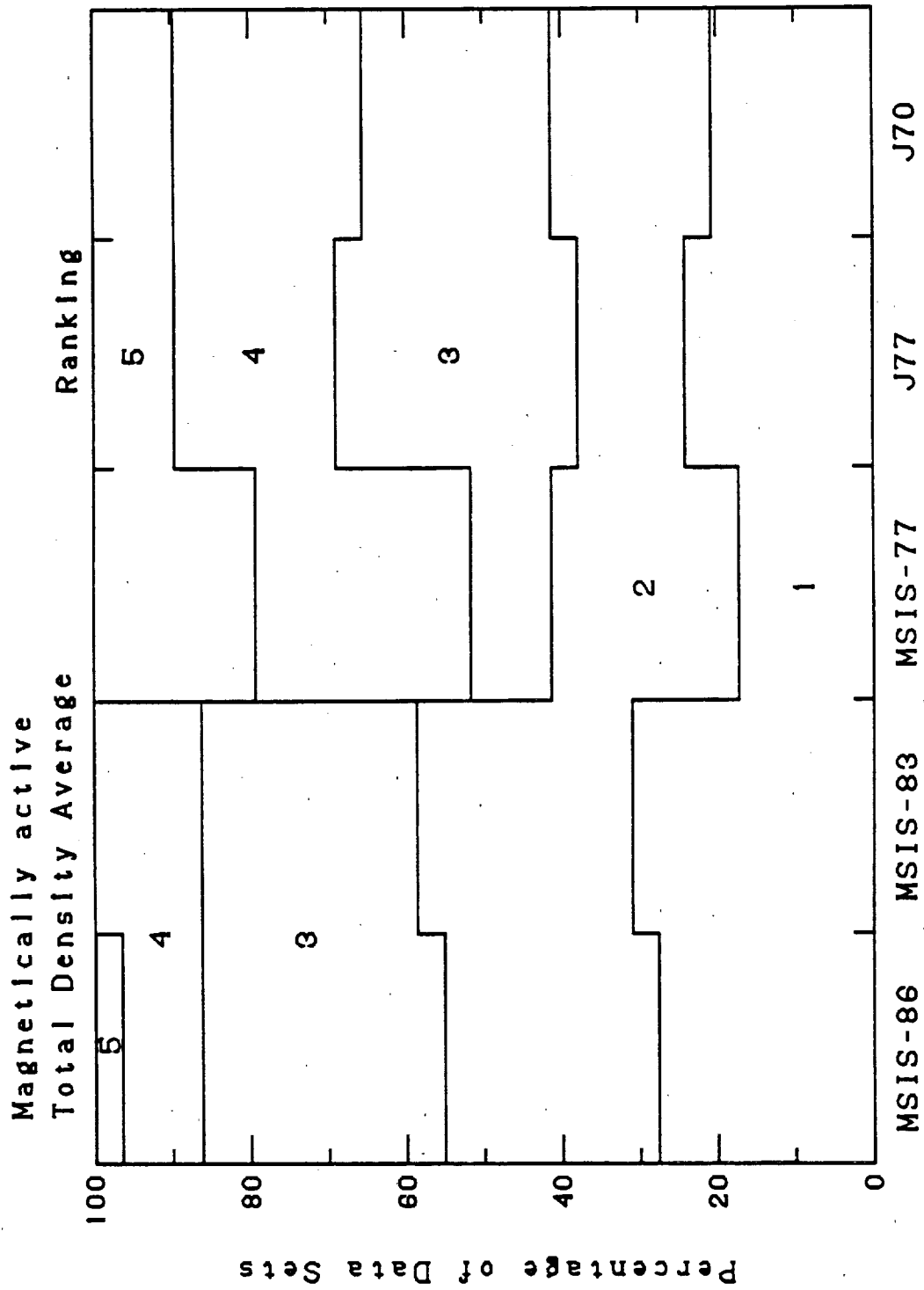


Fig. 4. Model ranking for average density, magnetically active.

Table 5. Overall Standard Deviation (magnetically active).

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia	200-400	2464	.18 (1)	.19 (2)	.20 (3)	.21 (4)	.18 (1)
drag	400-800	4007	.29 (2)	.30 (3)	.31 (4)	.29 (2)	.28 (1)
	800-1200	2549	.29 (2)	.30 (3)	.33 (5)	.32 (4)	.23 (1)
Barlier	120-200	1050	.22 (2)	.22 (2)	.22 (2)	.23 (3)	.21 (1)
drag	200-400	2767	.20 (1)	.21 (2)	.22 (3)	.23 (4)	.21 (2)
	400-800	824	.30 (2)	.29 (1)	.32 (4)	.31 (3)	.30 (2)
OGO-6	200-400	757(.20)	.19 (1)	.19 (1)	.20 (2)	.21 (3)	.21 (3)
ms	400-800	6557(.07)	.20 (1)	.21 (2)	.20 (1)	.22 (3)	.21 (2)
AE-C MESA	120-200	12359(.25)	.16 (2)	.16 (2)	.15 (1)	.21 (4)	.18 (3)
accel	200-250	11585(.55)	.21 (2)	.21 (2)	.20 (1)	.23 (3)	.21 (2)
AE-C OSS	120-200	12370(.65)	.13 (2)	.13 (2)	.11 (1)	.16 (4)	.14 (3)
ms	200-390	6279(.2)	.15 (1)	.16 (2)	.17 (3)	.19 (4)	.16 (2)
AE-D MESA	120-200	8907(.7)	.15 (1)	.15 (1)	.15 (1)	.17 (2)	.15 (1)
accel	200-250	3723	.19 (1)	.19 (1)	.19 (1)	.20 (2)	.19 (1)
AE-D OSS	120-200	7608	.13 (1)	.13 (1)	.13 (1)	.15 (3)	.14 (2)
ms	200-390	7476(.75)	.22 (2)	.21 (1)	.21 (1)	.23 (3)	.21 (1)
AE-D NACE	120-200	4016	.13 (1)	.13 (1)	.13 (1)	.14 (2)	.14 (2)
ms	200-400	5566	.22 (2)	.22 (1)	.23 (2)	.24 (3)	.22 (1)
Cactus	200-400	8701(.10)	.17 (1)	.17 (1)	.19 (2)	.21 (3)	.19 (2)
accel	400-600	8348(.10)	.28 (1)	.29 (2)	.30 (3)	.31 (4)	.30 (3)
AE-E MESA	120-200	8289(.45)	.13 (1)	.13 (1)	.13 (1)	.16 (3)	.15 (2)
accel	200-250	5582	.17 (1)	.18 (2)	.18 (2)	.20 (4)	.19 (3)
AE-E OSS	120-200	7868(.62)	.16 (2)	.15 (1)	.15 (1)	.19 (4)	.18 (3)
ms	200-400	7854(.12)	.19 (1)	.20 (2)	.22 (4)	.23 (5)	.21 (3)
AE-E NACE	120-200	6766	.13 (1)	.13 (1)	.17 (3)	.19 (4)	.16 (2)
ms	200-400	9079(.14)	.23 (2)	.22 (1)	.24 (3)	.23 (2)	.23 (2)
	400-600	7987(.20)	.23 (1)	.23 (1)	.27 (2)	.23 (1)	.23 (1)
DE-2 NACS	200-400	12286(.08)	.16 (1)	.17 (2)	.21 (5)	.20 (4)	.18 (3)
ms	400-800	9077(.20)	.24 (1)	.27 (3)	.28 (4)	.26 (2)	.24 (1)
Rank summary:			1-18 2-11 3-0 4-0	1-14 2-12 3-3 4-0	1-11 2-6 3-6 4-4 5-2	1-1 2-6 3-10 4-11 5-1	1-10 2-11 3-8 4-0

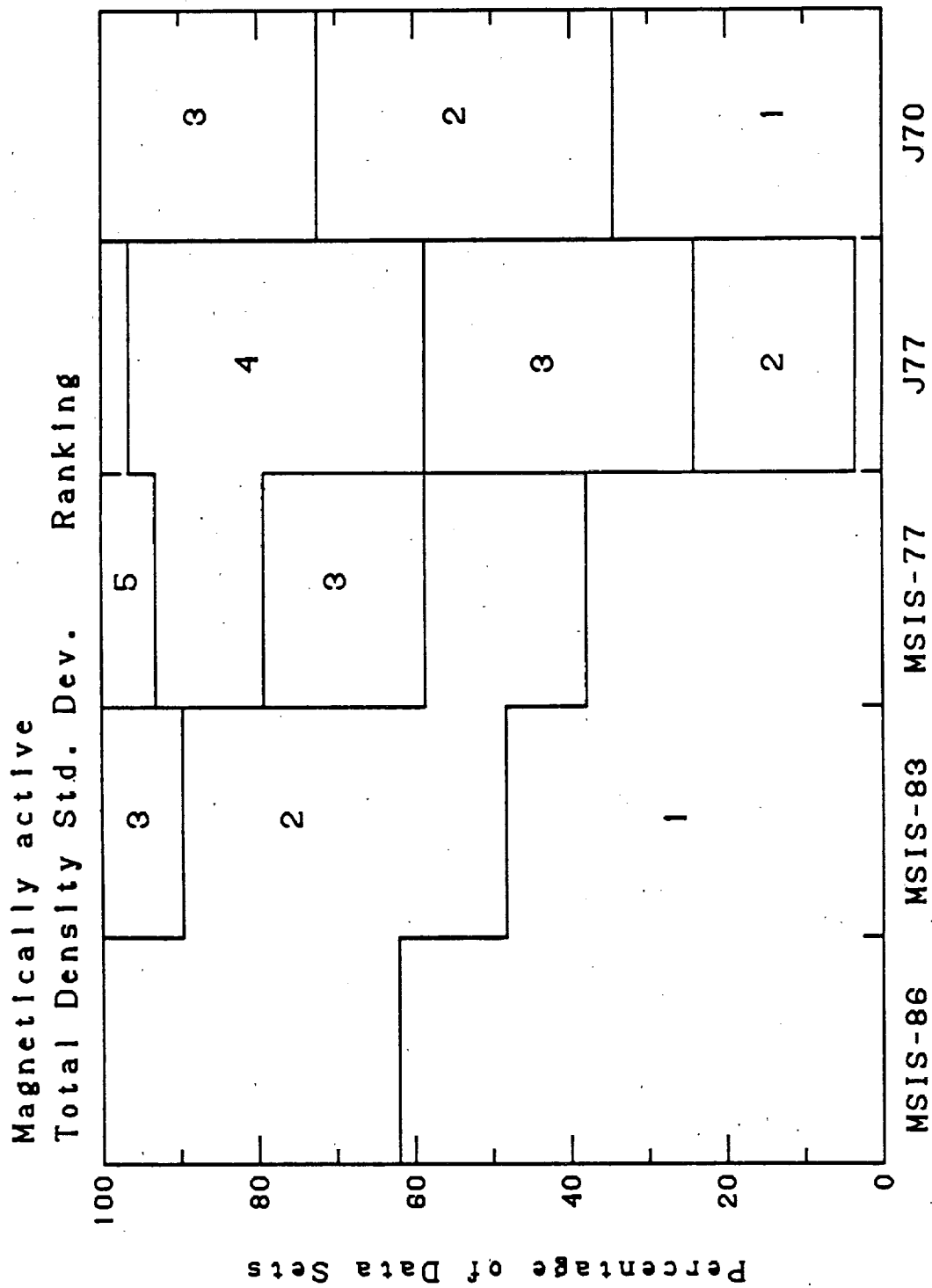


Fig. 5. Model ranking for standard deviations, magnetically active.

Table 6. Latitude Standard Deviation.

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia	200-400	5661	.03 (1)	.04 (2)	.05 (3)	.04 (2)	.03 (1)
drag	400-800	10529	.05 (2)	.07 (3)	.08 (4)	.04 (1)	.04 (1)
	800-1200	5935	.08 (3)	.06 (2)	.08 (3)	.08 (3)	.05 (1)
Barlier	120-200	1731	.07 (2)	.07 (2)	.06 (1)	.10 (3)	.07 (2)
drag	200-400	7528	.03 (1)	.03 (1)	.03 (1)	.03 (1)	.04 (2)
	400-800	2271	.08 (3)	.08 (1)	.07 (2)	.08 (3)	.08 (3)
OGO-6	200-400	2735(.20)	.04 (1)	.06 (2)	.07 (3)	.08 (4)	.06 (2)
ms	400-800	19420(.07)	.03 (2)	.03 (2)	.02 (1)	.05 (3)	.06 (4)
AE-C MESA	120-200	18105(.25)	.04 (1)	.04 (1)	.04 (1)	.12 (3)	.09 (2)
accel	200-250	17686(.55)	.03 (1)	.05 (3)	.04 (2)	.07 (4)	.04 (2)
AE-C OSS	120-200	19050(.65)	.05 (2)	.04 (1)	.04 (1)	.08 (3)	.08 (3)
ms	200-390	18897(.2)	.04 (3)	.01 (2)	.03 (2)	.04 (3)	.03 (2)
AE-D MESA	120-200	19931(.7)	.04 (2)	.05 (3)	.04 (2)	.08 (4)	.03 (1)
accel	200-250	8122	.05 (1)	.07 (3)	.05 (1)	.06 (2)	.05 (1)
AE-D OSS	120-200	19365	.04 (2)	.04 (2)	.02 (1)	.07 (3)	.04 (2)
ms	200-390	18399(.75)	.06 (3)	.05 (2)	.04 (1)	.06 (3)	.06 (3)
AE-D NACE	120-200	8630	.10 (4)	.09 (3)	.06 (1)	.07 (2)	.11 (5)
ms	200-400	11157	.06 (1)	.09 (4)	.06 (1)	.08 (3)	.07 (2)
DE-2 NACS	200-400	18365(.08)	.03 (1)	.05 (2)	.05 (2)	.06 (3)	.05 (2)
ms	400-800	12226(.20)	.03 (1)	.04 (2)	.04 (2)	.08 (3)	.03 (1)
Rank summary:			1-9	1-4	1-10	1-2	1-6
			2-6	2-10	2-6	2-3	2-9
			3-4	3-5	3-3	3-12	3-3
			4-1	4-1	4-1	4-3	4-1
					5-0	5-0	5-1

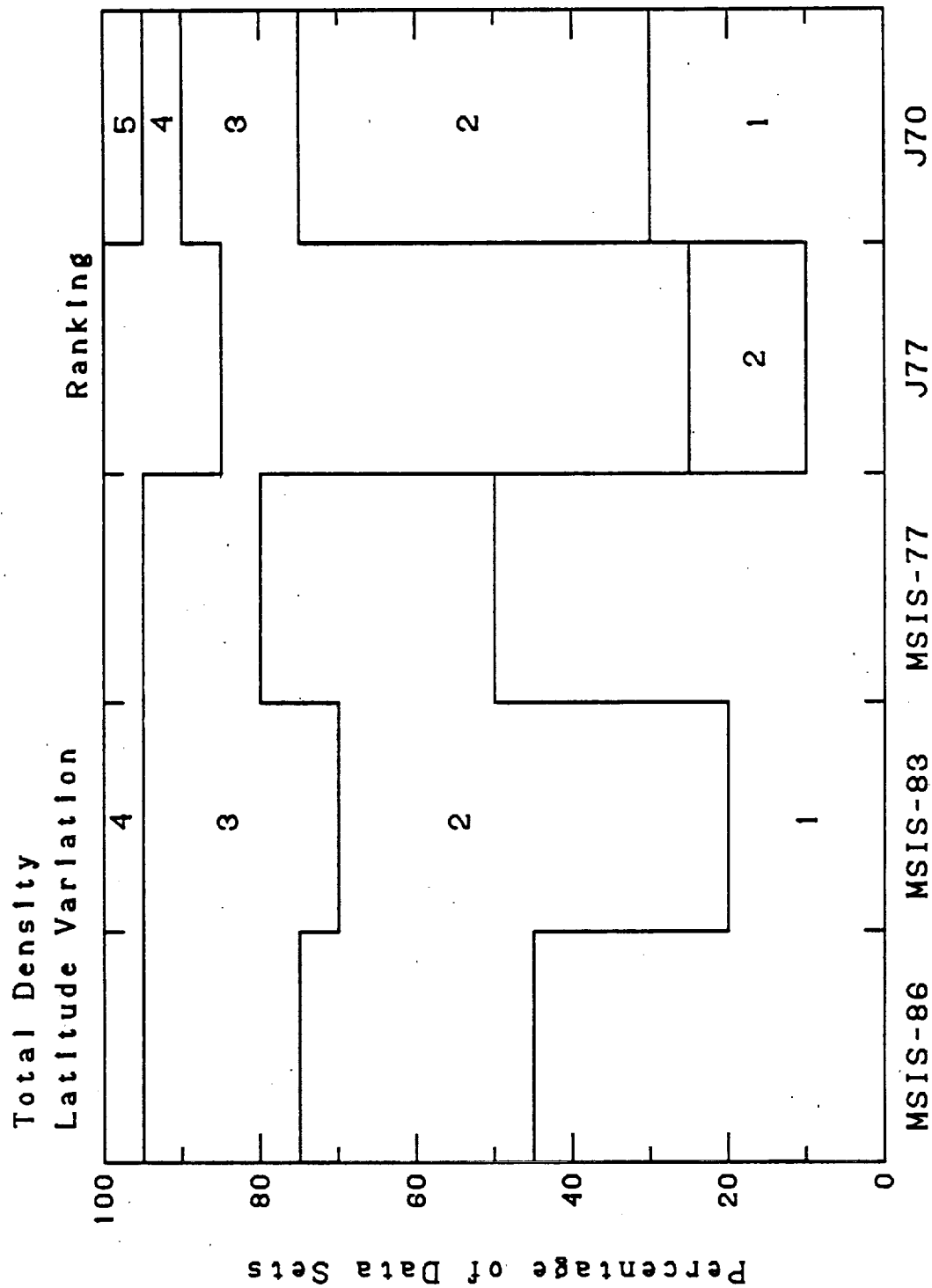


Fig. 6. Model ranking for latitude variations.

Table 7. Local Time Standard Deviation.

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia drag	200-400	5661	.03 (1)	.04 (2)	.03 (1)	.05 (3)	.04 (2)
	400-800	10529	.06 (2)	.07 (3)	.07 (3)	.07 (3)	.03 (1)
	800-1200	5935	.07 (2)	.07 (2)	.14 (4)	.12 (3)	.05 (1)
Barlier drag	120-200	1731	.06 (1)	.07 (2)	.06 (1)	.08 (3)	.09 (4)
	200-400	7528	.02 (1)	.03 (1)	.02 (2)	.04 (2)	.03 (2)
	400-800	2271	.04 (1)	.04 (1)	.06 (3)	.06 (2)	.04 (1)
OGO-6 ms	200-400	2735(.20)	.13 (2)	.12 (1)	.12 (1)	.12 (1)	.12 (1)
	400-800	19420(.07)	.04 (1)	.04 (1)	.04 (1)	.06 (2)	.06 (2)
AE-C MESA accel	120-200	18105(.25)	.03 (2)	.03 (2)	.02 (1)	.07 (3)	.07 (3)
	200-250	17686(.55)	.04 (2)	.04 (2)	.03 (1)	.07 (3)	.07 (3)
AE-C OSS ms	120-200	19050(.65)	.04 (1)	.04 (1)	.04 (1)	.05 (2)	.06 (3)
	200-390	18897(.2)	.02 (1)	.03 (2)	.02 (1)	.05 (3)	.05 (3)
AE-D MESA accel	120-200	19931(.7)	.10 (1)	.11 (2)	.12 (3)	.15 (4)	.10 (1)
	200-250	8122	.09 (2)	.10 (3)	.10 (3)	.09 (2)	.08 (1)
AE-D OSS ms	120-200	19365	.10 (2)	.09 (1)	.09 (1)	.09 (1)	.10 (2)
	200-390	18399(.75)	.11 (2)	.11 (2)	.10 (1)	.13 (4)	.12 (3)
AE-D NACE ms	120-200	8630	.10 (4)	.09 (3)	.06 (1)	.08 (2)	.10 (4)
	200-400	11157	.12 (1)	.13 (2)	.13 (2)	.12 (1)	.13 (2)
Cactus accel	200-400	19977(.10)	.02 (1)	.03 (2)	.05 (3)	.09 (5)	.07 (4)
	400-600	18156(.10)	.03 (1)	.04 (2)	.09 (4)	.08 (3)	.08 (3)
AE-E MESA accel	120-200	19744(.45)	.03 (1)	.04 (2)	.04 (2)	.04 (2)	.08 (3)
	200-250	13945	.05 (1)	.06 (2)	.06 (2)	.10 (3)	.10 (3)
AE-E OSS ms	120-200	19680(.62)	.02 (1)	.03 (2)	.04 (3)	.10 (5)	.09 (4)
	200-400	17595(.12)	.02 (1)	.03 (2)	.04 (3)	.09 (4)	.09 (4)
AE-E NACE ms	120-200	14290	.03 (1)	.03 (1)	.06 (2)	.10 (4)	.09 (3)
	200-400	19237(.14)	.03 (1)	.04 (2)	.06 (4)	.07 (5)	.05 (3)
	400-600	18230(.20)	.04 (2)	.03 (1)	.10 (4)	.04 (2)	.05 (3)
DE-2 NACS ms	200-400	18365(.08)	.06 (1)	.06 (1)	.10 (3)	.07 (2)	.07 (2)
	400-800	12226(.20)	.08 (1)	.09 (2)	.10 (3)	.09 (2)	.09 (2)

Rank summary:

1-19
2-9
3-0
4-1

1-9
2-17
3-3
4-0

1-11
2-5
3-9
4-4
5-0

1-3
2-10
3-9
4-4
5-3

1-6
2-7
3-11
4-5
5-0

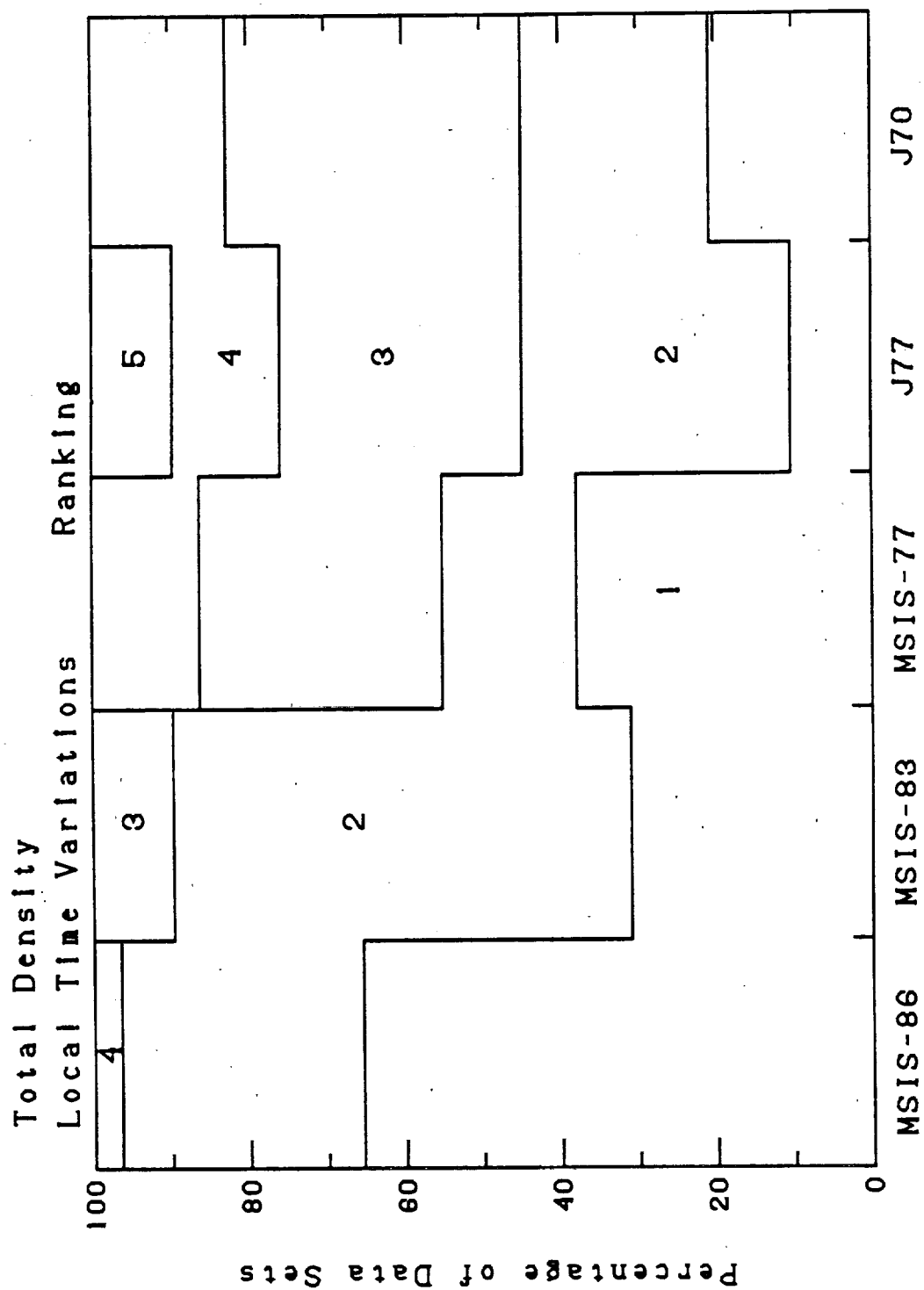


Fig. 7. Model ranking for local time variations.

Table 8. Mean F10.7 Standard Deviation.

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia drag	200-400	5661	.05 (2)	.04 (1)	.05 (2)	.06 (3)	.05 (2)
	400-800	10529	.11 (2)	.11 (2)	.13 (3)	.09 (1)	.11 (2)
	800-1200	5935	.08 (2)	.08 (2)	.11 (3)	.13 (4)	.07 (1)
Barlier drag	120-200	1731	.05 (3)	.04 (2)	.06 (4)	.03 (1)	.03 (1)
	200-400	7528	.03 (1)	.04 (2)	.04 (2)	.04 (2)	.03 (1)
	400-800	2271	.07 (2)	.07 (2)	.08 (3)	.07 (2)	.06 (1)
OGO-6 ms	200-400	2735(.20)	.04 (1)	.06 (3)	.05 (2)	.05 (2)	.05 (2)
	400-800	19420(.07)	.10 (2)	.10 (2)	.08 (1)	.13 (3)	.10 (2)
AE-C MESA accel	120-200	18105(.25)	.01 (2)	.01 (2)	.00 (1)	.02 (3)	.04 (4)
	200-250	17686(.55)	.04 (2)	.04 (2)	.05 (3)	.02 (1)	.04 (2)
AE-C OSS ms	120-200	19050(.65)	.05 (3)	.05 (3)	.03 (1)	.04 (2)	.06 (4)
	200-390	18897(.2)	.01 (1)	.02 (2)	.05 (3)	.02 (2)	.02 (2)
Cactus accel	200-400	19977(.10)	.09 (4)	.09 (4)	.08 (3)	.06 (2)	.06 (1)
	400-600	18156(.10)	.11 (3)	.10 (2)	.11 (3)	.07 (1)	.11 (3)
AE-E MESA accel	200-250	13945	.09 (1)	.09 (2)	.09 (2)	.09 (3)	.04 (3)
AE-E OSS ms	200-400	17595(.12)	.06 (1)	.06 (1)	.06 (1)	.06 (1)	.06 (1)
AE-E NACE ms	200-400	19237(.14)	.07 (2)	.06 (1)	.09 (4)	.08 (3)	.08 (3)
	400-600	18230(.20)	.06 (2)	.05 (1)	.08 (4)	.07 (3)	.08 (4)
DE-2 NACS ms	200-400	18365(.08)	.07 (1)	.08 (2)	.15 (4)	.09 (3)	.08 (2)
	400-800	12226(.20)	.08 (1)	.10 (2)	.11 (3)	.12 (4)	.10 (2)
Rank summary:			1-7 2-9 3-3 4-1	1-4 2-13 3-2 4-1	1-4 2-4 3-8 4-4	1-5 2-6 3-7 4-2	1-6 2-8 3-3 4-3

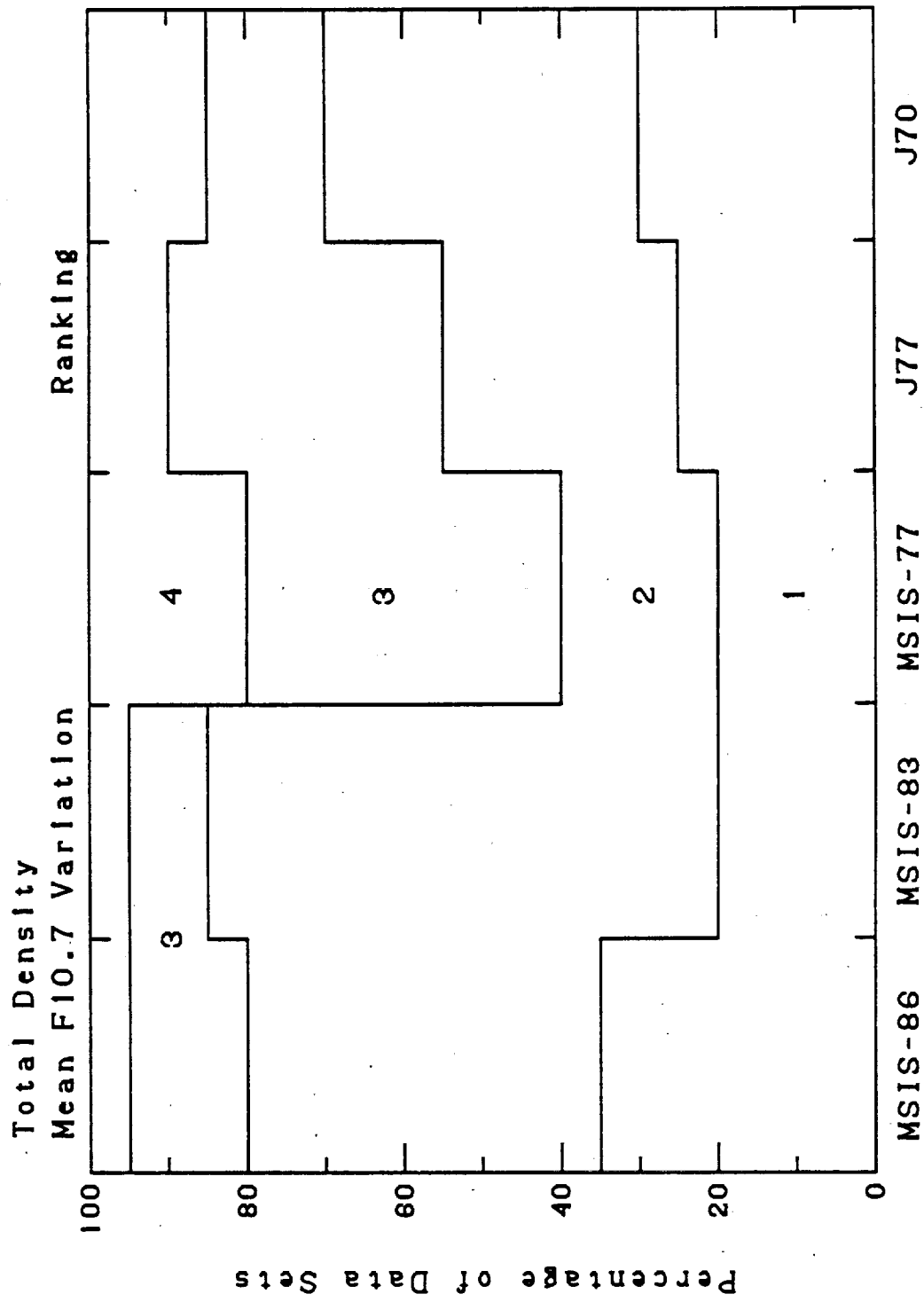


Fig. 8. Model ranking for mean F10.7 variations.

Table 9. Daily Minus Mean F10.7 Standard Deviation.

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia drag	200-400	5661	.06 (2)	.06 (2)	.05 (1)	.08 (4)	.07 (3)
	400-800	10529	.09 (3)	.08 (2)	.13 (5)	.06 (1)	.10 (4)
	800-1200	5935	.07 (1)	.07 (1)	.11 (4)	.09 (2)	.10 (3)
Barlier drag	120-200	1731	.04 (1)	.04 (2)	.04 (1)	.05 (3)	.05 (4)
	200-400	7528	.01 (1)	.01 (1)	.03 (2)	.08 (3)	.09 (4)
	400-800	2271	.08 (1)	.07 (1)	.06 (3)	.15 (2)	.18 (1)
OGO-6 ms	200-400	2735(.20)	.07 (2)	.07 (2)	.06 (1)	.13 (3)	.14 (4)
	400-800	19420(.07)	.03 (1)	.04 (2)	.05 (3)	.11 (4)	.12 (5)
AE-C MESA accel	120-200	18105(.25)	.06 (3)	.05 (2)	.04 (1)	.05 (2)	.08 (4)
	200-250	17686(.55)	.09 (3)	.08 (2)	.05 (1)	.05 (1)	.10 (4)
AE-C OSS ms	120-200	19050(.65)	.06 (4)	.05 (3)	.03 (1)	.04 (2)	.06 (4)
	200-390	18897(.2)	.05 (2)	.05 (2)	.04 (1)	.05 (2)	.04 (1)
AE-D MESA accel	120-200	19931(.7)	.10 (3)	.11 (4)	.10 (3)	.06 (2)	.05 (1)
	200-250	8122	.12 (3)	.14 (4)	.08 (2)	.06 (1)	.06 (1)
AE-D OSS ms	120-200	19365	.01 (1)	.02 (2)	.02 (2)	.01 (1)	.02 (2)
	200-390	18399(.75)	.04 (2)	.05 (3)	.01 (1)	.01 (1)	.01 (1)
AE-D NACE ms	120-200	8630	.06 (4)	.06 (3)	.05 (1)	.04 (2)	.04 (4)
	200-400	11157	.09 (1)	.10 (2)	.04 (2)	.06 (1)	.05 (2)
Cactus accel	200-400	19977(.10)	.11 (4)	.08 (3)	.08 (3)	.06 (1)	.07 (2)
	400-600	18156(.10)	.10 (2)	.08 (1)	.12 (4)	.11 (3)	.11 (3)
AE-E MESA accel	120-200	19744(.45)	.02 (2)	.01 (1)	.02 (2)	.04 (3)	.05 (4)
	200-250	13945	.02 (1)	.02 (1)	.02 (1)	.05 (3)	.04 (2)
AE-E OSS ms	120-200	19680(.62)	.03 (2)	.02 (1)	.03 (2)	.05 (3)	.06 (4)
	200-400	17595(.12)	.03 (1)	.03 (1)	.04 (2)	.10 (4)	.08 (3)
AE-E NACE ms	120-200	14290	.01 (1)	.01 (1)	.03 (3)	.03 (3)	.02 (2)
	200-400	19237(.14)	.08 (2)	.08 (2)	.09 (3)	.09 (3)	.07 (1)
	400-600	18230(.20)	.06 (1)	.07 (2)	.07 (2)	.08 (3)	.11 (4)
DE-2 NACS ms	200-400	18365(.08)	.06 (1)	.07 (2)	.08 (3)	.08 (3)	.10 (4)
	400-800	12226(.20)	.08 (2)	.09 (3)	.06 (1)	.10 (4)	.11 (5)
Rank summary:			1-12 2-9 3-5 4-3	1-9 2-13 3-5 4-2	1-11 2-8 3-7 4-2 5-1	1-7 2-7 3-11 4-4 5-0	1-6 2-5 3-4 4-12 5-2

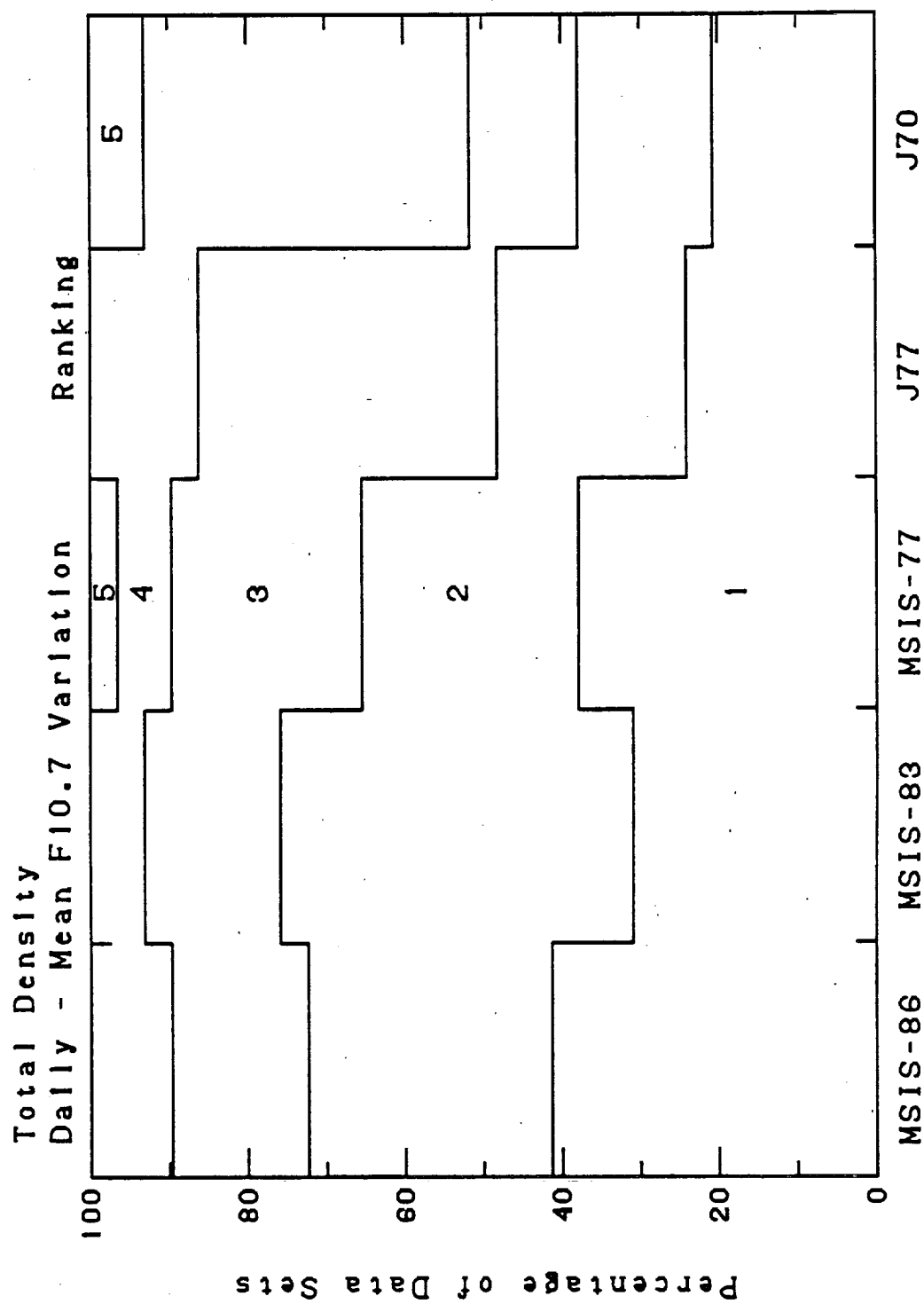


Fig. 9. Model ranking for daily - mean F10.7 variations.

Table 10. Ap Standard Deviation.

	Alt	Pts	MSIS-86	MSIS-83	MSIS-77	J77	J70
Jacchia drag	200-400	5661	.10 (1)	.11 (2)	.14 (3)	.16 (4)	.10 (1)
	400-800	10529	.19 (3)	.18 (2)	.21 (5)	.20 (4)	.17 (1)
	800-1200	5935	.21 (3)	.19 (2)	.22 (4)	.24 (5)	.16 (1)
Barlier drag	120-200	1731	.09 (2)	.08 (1)	.08 (1)	.12 (3)	.08 (1)
	200-400	7528	.08 (1)	.09 (2)	.11 (3)	.12 (4)	.09 (2)
	400-800	2271	.11 (2)	.09 (1)	.11 (2)	.12 (3)	.13 (4)
OGO-6 ms	200-400	2735(.20)	.12 (2)	.12 (1)	.14 (2)	.15 (3)	.14 (2)
	400-800	19420(.07)	.12 (1)	.13 (2)	.14 (3)	.16 (4)	.14 (3)
AE-C MESA accel	120-200	18105(.25)	.07 (2)	.07 (2)	.06 (1)	.17 (4)	.11 (3)
	200-250	17686(.55)	.10 (2)	.10 (2)	.09 (1)	.14 (4)	.12 (3)
AE-C OSS ms	120-200	19050(.65)	.09 (3)	.08 (2)	.06 (1)	.15 (5)	.10 (4)
	200-390	18897(.2)	.08 (2)	.07 (1)	.10 (3)	.12 (4)	.08 (2)
AE-D MESA accel	120-200	19931(.7)	.07 (1)	.07 (1)	.08 (2)	.11 (3)	.08 (2)
	200-250	8122	.09 (1)	.09 (1)	.09 (1)	.10 (2)	.09 (1)
AE-D OSS ms	120-200	19365	.10 (1)	.10 (1)	.10 (1)	.10 (1)	.11 (2)
	200-390	18399(.75)	.16 (2)	.15 (1)	.15 (1)	.19 (3)	.16 (2)
Cactus accel	200-400	19977(.10)	.11 (3)	.09 (1)	.10 (2)	.12 (4)	.10 (2)
	400-600	18156(.10)	.18 (2)	.16 (1)	.17 (2)	.25 (4)	.17 (2)
AE-E MESA accel	120-200	19744(.45)	.07 (1)	.07 (1)	.07 (1)	.17 (3)	.12 (2)
	200-250	13945	.13 (2)	.12 (1)	.12 (1)	.13 (2)	.12 (1)
AE-E OSS ms	120-200	19680(.62)	.13 (3)	.12 (2)	.11 (1)	.13 (3)	.16 (4)
	200-400	17595(.12)	.11 (2)	.10 (1)	.11 (2)	.16 (3)	.11 (2)
AE-E NACE ms	120-200	14290	.08 (1)	.08 (1)	.09 (2)	.17 (4)	.12 (3)
	200-400	19237(.14)	.17 (3)	.16 (2)	.14 (1)	.16 (2)	.20 (4)
	400-600	18230(.20)	.11 (2)	.12 (3)	.14 (4)	.10 (1)	.10 (1)
DE-2 NACS ms	200-400	18365(.08)	.09 (1)	.11 (3)	.13 (4)	.16 (5)	.10 (2)
	400-800	12226(.20)	.15 (1)	.20 (3)	.23 (5)	.21 (4)	.18 (2)

Rank summary:

1-10	1-14	1-11	1-2	1-7
2-11	2-10	2-7	2-3	2-12
3-6	3-3	3-4	3-8	3-4
4-0	4-0	4-3	4-11	4-4
		5-2	5-3	5-0

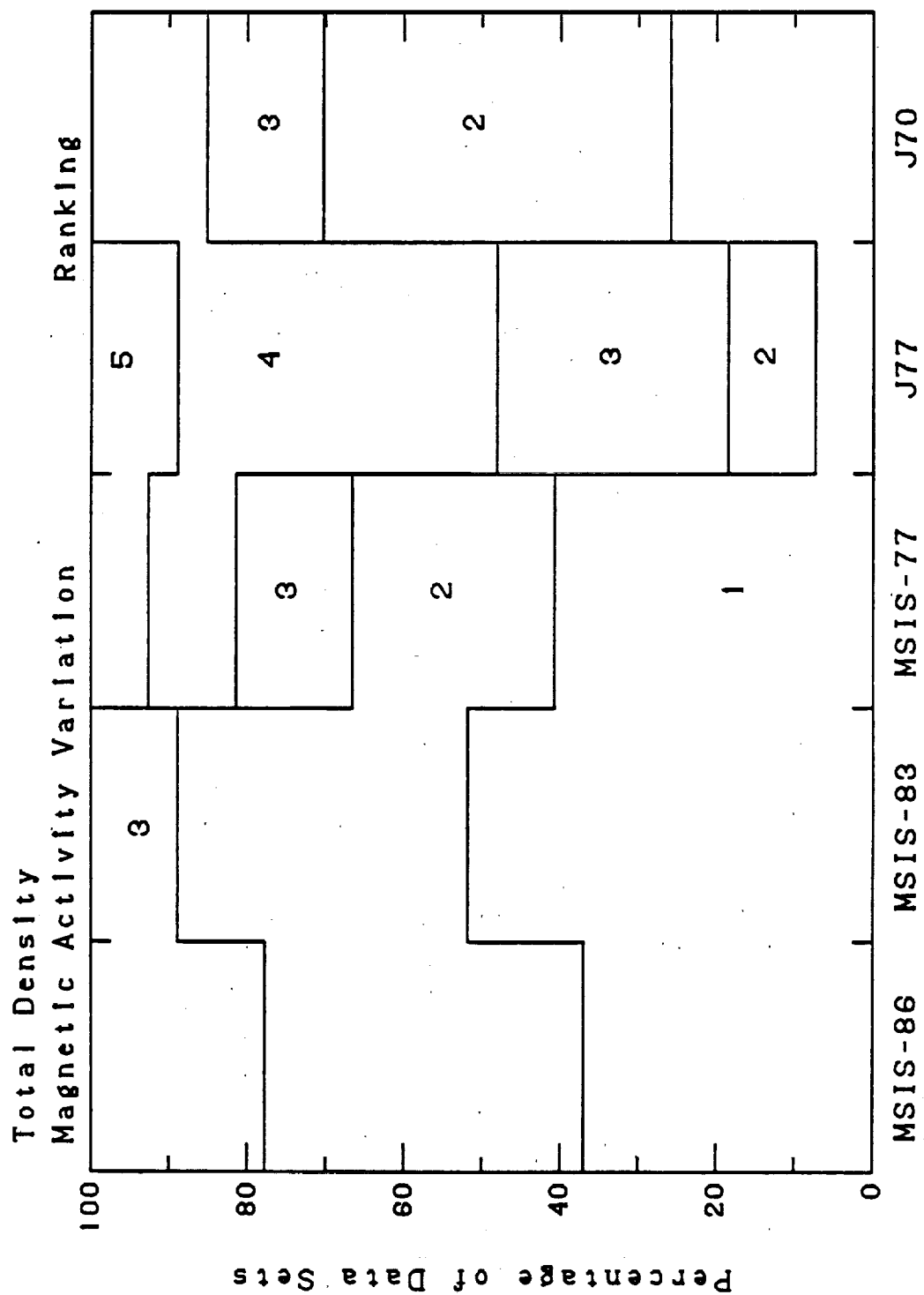


Fig. 10. Model ranking for magnetic activity variations.

The ap history (in the case of MSIS-86 and -83) or lagged ap/kp (in the case of J77 and J70) was tried for the Cactus data (low inclination orbit) and DE-2 NACS data (polar orbit) in place of the more convenient daily Ap/Kp. For Cactus the result for the magnetically active data ($A_p > 10$) was a .02 (2%) decrease in the overall standard deviation for MSIS-86 and -83, and a .01 (1%) drop for J77. No change for the other models. For DE-2 there was a .01 decrease for MSIS-86 and no change for the others. Plots against ap were a bit smoother. It is apparent that on an overall statistical basis using the three-hour ap's provides only a small improvement and no change in relative rankings of the models. During a magnetic storm, of course, use of the three-hour ap/kp can give dramatically better results, particularly for the timing of the onset. However, since high magnetic activity levels occur less frequently than low magnetic activity levels, the use of the three-hour indices has only a modest effect on overall statistics.

4. Summary of model strengths and weaknesses

MSIS-86

The MSIS-86 model is systematically better overall than any of the other models in modeling of total density variations, and equivalent to the others in absolute values. The standard deviation with respect to the Jacchia drag data (200-400 km) is .15 (15%) under magnetically quiet conditions and .18 (18%) under active conditions. The median standard deviation in comparison to all the data sets under magnetically quiet conditions is about .17 (17%), and the mean absolute error is -.02 (-2%). Some data sets, usually with limited coverage, have lower standard deviations. The most obvious deficiency is at high altitude, where the database for generating this model is weak, but where the accuracy of the data from both mass spectrometers and drag techniques also needs careful assessment. The model is significantly better than the Jacchia models in local time variations, particularly at lower altitudes. Although not the focus of this study, a ranking of models for predictions of temperature and composition variations based on the MSIS combined data set would show a very strong preference for this model.

MSIS-83

The MSIS-83 model is overall slightly worse than MSIS-86. The standard deviation with respect to the Jacchia drag data (200-400 km) is .16 (16%) under magnetically quiet conditions and .19 (19%) under active conditions. The median standard deviation in comparison to various data sets under magnetically quiet conditions is about .18 (18%) and the mean absolute error is -.01 (-1%). However, this study did not emphasize, nor does an overall assessment give a large weight to, the polar variations, which were the focus of the changes between MSIS-83 and MSIS-86.

MSIS-77

The MSIS-77 model is slightly worse than MSIS-83 in overall standard deviations, but distinctly worse in absolute densities. The standard deviation with respect to the Jacchia drag data (200-400 km) is .18 (18%) under magnetically quiet conditions and .20 (20%) under active conditions. The median standard deviation in comparison to various data sets under magnetically quiet conditions is about .18 (18%) and the mean absolute error

is $-.12$ (-12%). The greater errors here are largely a consequence of the more limited data base, lacking coverage at high solar activities, as well as coverage at high latitudes. The lack of longitude terms in the model shows up most clearly in comparisons with DE-2 data. This model does as well or better than other models in comparisons with the OGO-6 and AE-C data on which it was heavily based, but not as well as other models in comparisons with data sets having wider coverage such as the Jacchia drag data. Although fitting the low altitude (below 200 km) Atmospheric Explorer variations satisfactorily, the model formulation was not as general as used in the later models and cannot be extrapolated below the AE altitudes (about 140 km).

J77

The J77 model has the highest standard deviations under magnetically active conditions, but also with respect to latitude and local time variations. The standard deviation with respect to the Jacchia drag data (200-400 km) is $.15$ (15%) under magnetically quiet conditions and $.21$ (21%) under active conditions. The median standard deviation in comparison to various data sets under magnetically quiet conditions is about $.18$ (18%), and the mean absolute error is $-.01$ (-1%). The attempt to include better composition and temperature variations through the cumbersome, time consuming, and nonphysical pseudo-temperature technique was only partly successful and appears to have detracted from the description of total densities.

J70

The J70 model is slightly worse overall than MSIS-77 in total density comparisons, but better than J77. The standard deviation with respect to the Jacchia drag data (200-400 km) is $.16$ (16%) under magnetically quiet conditions and $.18$ (18%) under active conditions. The median standard deviation in comparison to various data sets under magnetically quiet conditions is about $.19$ (19%), and the mean absolute error is $-.04$ (-4%). This model is distinctly better than other models at higher altitudes (above 800 km) and usually worse at the lowest altitudes (less than 200 km). Between 200 and 800 km, J70 and MSIS-86 have equivalent standard deviations in comparison to the drag related data sets, except Cactus, where J70 is slightly worse. J70 is by far the worst model for temperature and composition variations.

5. Conclusion

Five empirical models were compared with 13 data sets, including both atmospheric drag based data and mass spectrometer data. The products of this study included plots and ASCII files describing database coverage, extensive comparison plots of data and models, and ASCII files of binned residuals.

Although the most recently published model, MSIS-86, was found to be the best overall model, the general conclusion of previous studies was reaffirmed: the best current accuracy is around 15% . A definite, but small (few percent), improvement in total density accuracy of newer over older models was discernible in this study.

It is clear that a model (like MSIS-77), which was generated from a limited database, can be as good or better than other models for some data

sets, but not as good for a wider range of data. Similarly, a later model (like MSIS-86) may do worse than the earlier MSIS-77 on an earlier data set (e.g., AE-C) because measurement errors or unidentified geophysical factors make the newer data sets not completely consistent with the older data sets. This illustrates the obvious conclusion that a model based on or optimized for a limited set of data can be very good for that data, but poor for other data. Likewise, the addition of new data may make the model worse for older data. However, unless we have reasons to discount certain measurements, the broader based model is more likely to be best in comparison to a new independent data set (or for a random prediction), and this is illustrated by comparisons with the Cactus data, which were used for neither the MSIS or Jacchia models.

The excellent overall agreement of the mass spectrometer based MSIS models with the drag data, including both the older data from orbital decay and the newer accelerometer data, suggests that the the absolute calibration of the (ensemble of) mass spectrometers and the assumed drag coefficient in the atomic oxygen regime are consistent to 5%. While the time may soon be at hand to base a model on both the mass spectrometer and drag data, puzzling disagreements in detail still remain at both high and low altitudes.

This study illustrates a number of the reasons for the current accuracy limit. There appear to be sizable differences (order 20%) in overall absolute values between some mass spectrometer missions (e.g., OGO-6 and DE-2) and most of the models and differences on the order of 10 to 15% between mass spectrometers and drag measurements under certain conditions. This illustrates the importance of reliable calibration techniques for mass spectrometers and for the drag coefficient (especially when atomic oxygen is not the major constituent) and the need for measurement accuracy at the level desired for the model. There are trends still existing between certain data sets and models with respect to F10.7, Ap, and annual/semiannual variations. These trends are apparently different from data set to data set and are presumably the result of ancillary geophysical factors, which may or may not be easily found and taken into account.

The largest variations in total density in the thermosphere are already accounted for to a very high degree by existing models. In statistical terms, more than 90% of the original variance in latitude, local time, F10.7, etc., are explained by existing models. The primary variations were already well known at the time that J65 (Jacchia, 1965) was formulated and this must explain in large part why progress has not been rapid in the ensuing two decades (except in related areas like temperature, composition, and wind). Progress will likely continue to be modest in the future, although there are areas with greater potential for improvement such as where we still have insufficient data (like the lower thermosphere or exosphere), where there are disagreements in technique (such as the exosphere) that can be resolved, or wherever generally more accurate measurements become available.

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Appendix A. Description of coverage files.

The following files contain the results of binning oxygen data used in generating the MSIS-86 model. There are five files:

COVALLSA.DAT - binning for all mean F10.7 values.
COVLOSA.DAT - binning for mean F10.7 less than 100.
COVMLSA.DAT - binning for mean F10.7 between 100 and 140.
COVMHSA.DAT - binning for mean F10.7 between 140 and 180.
COVHISA.DAT - binning for mean F10.7 greater than 180.

Each 80 byte record contains a 6 digit integer describing the bins based on altitude, F10.7 difference from the mean, day of year, local time, magnetic activity (Ap), and universal time (UT), and 12 integers which indicate by a 0 or 1 whether data was available in a 15 degree wide latitude bin between -90 and 90 degrees (e.g., the first of the twelve integers refers to -90 to -75 degrees and the last integer to 75 to 90 degrees). The fortran format statement was (I8,12I6). The 6 digit bin code is AFDLPU where:

A = 1 indicates altitude less than 200 km.
2 indicates altitude between 200 and 400 km.
3 indicates altitude over 400 km.
F = 1 indicates daily minus mean F10.7 less than -20.
2 indicates daily minus mean F10.7 between -20 and 20.
3 indicates daily minus mean F10.7 greater than 20.
D = 1 indicates days from 1 to 91.
2 indicates days from 91 to 182.
3 indicates days from 182 to 273.
4 indicates days greater than 273.
L = 1 indicates local time between 0 and 4.
2 indicates local time between 4 and 8.
3 indicates local time between 8 and 12.
4 indicates local time between 12 and 16.
5 indicates local time between 16 and 20.
6 indicates local time between 20 and 24.
P = 1 indicates daily Ap less than 10.
2 indicates daily Ap between 10 and 60.
3 indicates daily Ap between 60 and 110.
4 indicates daily Ap greater than 110.
U = 1 indicates UT between 0 and 14400 seconds.
2 indicates UT between 14400 and 28800 seconds.
3 indicates UT between 28800 and 43200 seconds.
2 indicates UT between 43200 and 57600 seconds.
2 indicates UT between 57600 and 72000 seconds.
2 indicates UT between 72000 and 86400 seconds.

There are 62208 possible bins and the overall coverage in each file was:

COVALLSA.DAT - 13187 or 21.2% for all solar activities.
COVLOSA.DAT - 4838 or 7.8% for low solar activity.
COVMLSA.DAT - 2235 or 3.6% for medium-low solar activity.
COVMHSA.DAT - 6384 or 10.3% for medium-high solar activity.
COVHISA.DAT - 3356 or 5.4% for high solar activity.

Appendix B. Description of histogram files.

Corresponding to each Figure C1 and C2 (see Appendix C) an ASCII file was produced containing informations on comparisons of a single data subset with the five models. The file names start with HISTRHO followed by an abbreviation of the data set and the lowest altitude. Each file contains the following information:

Data set name and model name;
Day interval;
Ranges for Ap, altitude, or other factors;
Number of points and overall standard deviation;
Root mean square error;
Title (unscaled histogram);
Two column list giving interval start and fraction of points in interval. -99999 and 99999 used for data beyond -1 to 1;

Data set name and model name;
etc.

The following is a partial listing of file HISTRHOAECMESA120:

AEC MESA RHO - MSIS-86
DAYS 73358 74334
MAGNETIC INDEX (Ap) 0.0000 10.0000 INCLUDED
ALTITUDE(km) 120.0000 200.0000 INCLUDED
NUMBER POINTS = 5746 STD DEV = 0.1592570 AVERAGE = 0.1072040
RMS ERROR = 0.1919779
UNSCALED HISTOGRAM
-99999.0000 0.0000
-1.0000 0.0174
-0.9800 0.0000
-0.9600 0.0174
-0.9400 0.0174
-0.9200 0.0000
-0.9000 0.0174
-0.8800 0.0174
-0.8600 0.0174
-0.8400 0.0000
-0.8200 0.0348
-0.8000 0.0174
-0.7800 0.0174
-0.7600 0.0348
-0.7400 0.0000
-0.7200 0.0000
-0.7000 0.0348
-0.6800 0.0000
-0.6600 0.0000
-0.6400 0.0000
-0.6200 0.0174
-0.6000 0.0000
-0.5800 0.0000
-0.5600 0.0522
-0.5400 0.0174

-0.5200	0.0870
-0.5000	0.0348
-0.4800	0.0174
-0.4600	0.0174
-0.4400	0.0000
-0.4200	0.0174
-0.4000	0.1392
-0.3800	0.0000
-0.3600	0.0348
-0.3400	0.1566
-0.3200	0.0522
-0.3000	0.1044
-0.2800	0.0696
-0.2600	0.1740
-0.2400	0.3133
-0.2200	0.2785
-0.2000	0.4525
-0.1800	0.5395
-0.1600	0.7832
-0.1400	0.9572
-0.1200	1.3401
-0.1000	2.0536
-0.0800	2.2973
-0.0600	3.1326
-0.0400	3.6199
-0.0200	4.1072
0.0000	5.4647
0.0200	5.6387
0.0400	6.0564
0.0600	5.8998
0.0800	5.8127
0.1000	5.9172
0.1200	5.3080
0.1400	5.3777
0.1600	5.0818
0.1800	3.9680
0.2000	3.7591
0.2200	3.3415
0.2400	3.1500
0.2600	2.7323
0.2800	2.4365
0.3000	1.8448
0.3200	1.5837
0.3400	1.0964
0.3600	0.9050
0.3800	0.6961
0.4000	0.5221
0.4200	0.4351
0.4400	0.4699
0.4600	0.2436
0.4800	0.1392
0.5000	0.1218
0.5200	0.0696
0.5400	0.0870

0.5600	0.0348
0.5800	0.0522
0.6000	0.0348
0.6200	0.0348
0.6400	0.0348
0.6600	0.0000
0.6800	0.0174
0.7000	0.0522
0.7200	0.0174
0.7400	0.0000
0.7600	0.0348
0.7800	0.0174
0.8000	0.0348
0.8200	0.0522
0.8400	0.0696
0.8600	0.0174
0.8800	0.0522
0.9000	0.0000
0.9200	0.0000
0.9400	0.0696
0.9600	0.0348
0.9800	0.0696
99999.0000	0.0000

Appendix C. Description of data comparison and coverage plots.

An example of the of the data coverage and model comparison plots which were prepared for this project is shown in Figures C1 to C34 for the case of the Jacchia drag data 200 to 400 km subset compared to the MSIS-86 model. Some plots for other cases do not have all the information described here because of changes made as the project progressed. These plots are from a general plot program and some of the information is not of importance for this project.

In the following descriptions the term data residuals indicates the logarithm (base e) of the ratio of measured to model densities (or measured to model difference in the case of temperature). The residuals are generally averaged into appropriate bins and plotted as an average with an error bar. Error bars show the standard deviation of the data within each bin and the plot number indicates the logarithm (base 2) of the number of points in each bin.

On each plot the data set acronym, measured quantity (RHO means total density), and model are given at the top center of the plot. At the top right are the plot date and data file name. There are generally three lines of compressed information at the bottom of each plot with the following meaning (* indicates particular relevance for this project):

- GRP - local data set identification number
- * ALT LIM - altitude limits for this plot
- ISK - number points skipped for extreme deviation
- * SEL - if first integer is none zero data were limited by the following two numbers. 7 indicates a test on magnetic activity and thus Fig. A1 is for Ap from 0 to 10 and A2 covers Ap from 11 to 400. 2 indicates a test on latitude.
- * PTS PLT - indicates actual number of data points involved in this plot.
- * AVG - overall average of logarithms of data to model ratio for this plot.
- * SD - overall standard deviations of logarithms of data to model ratio for this plot
- A - binning intervals for abscissa and ordinate if applicable.
- SW - MSIS switch settings
- * D1,D2 - date limits for plotted data
- ST,SX,SY - points skipped for SEL test, or beyond abscissa or ordinate limits.
- SM - smoothing factor in contour plots (1.00 is none).
- * DATA-MODEL - residual plot using given model identification number or zero for no model.
- * SD:DATA-MODEL - contour plot of standard deviations of data residuals within each data bin.
- * AVG,SD - for binned data, average and standard deviation of binned data averages.
- AVXL,AVXH - points beyond low and high abscissa on histogram plots.

- * RMS - root mean square error for all points (from AVG and SD values).
- * DSD,MSD,R - for binned data, standard deviation of bin averages of raw data, standard deviation of bin averages of model values, and correlation coefficient between data and model based on bin averages.

1.00 PLOTTED: 3/18/88
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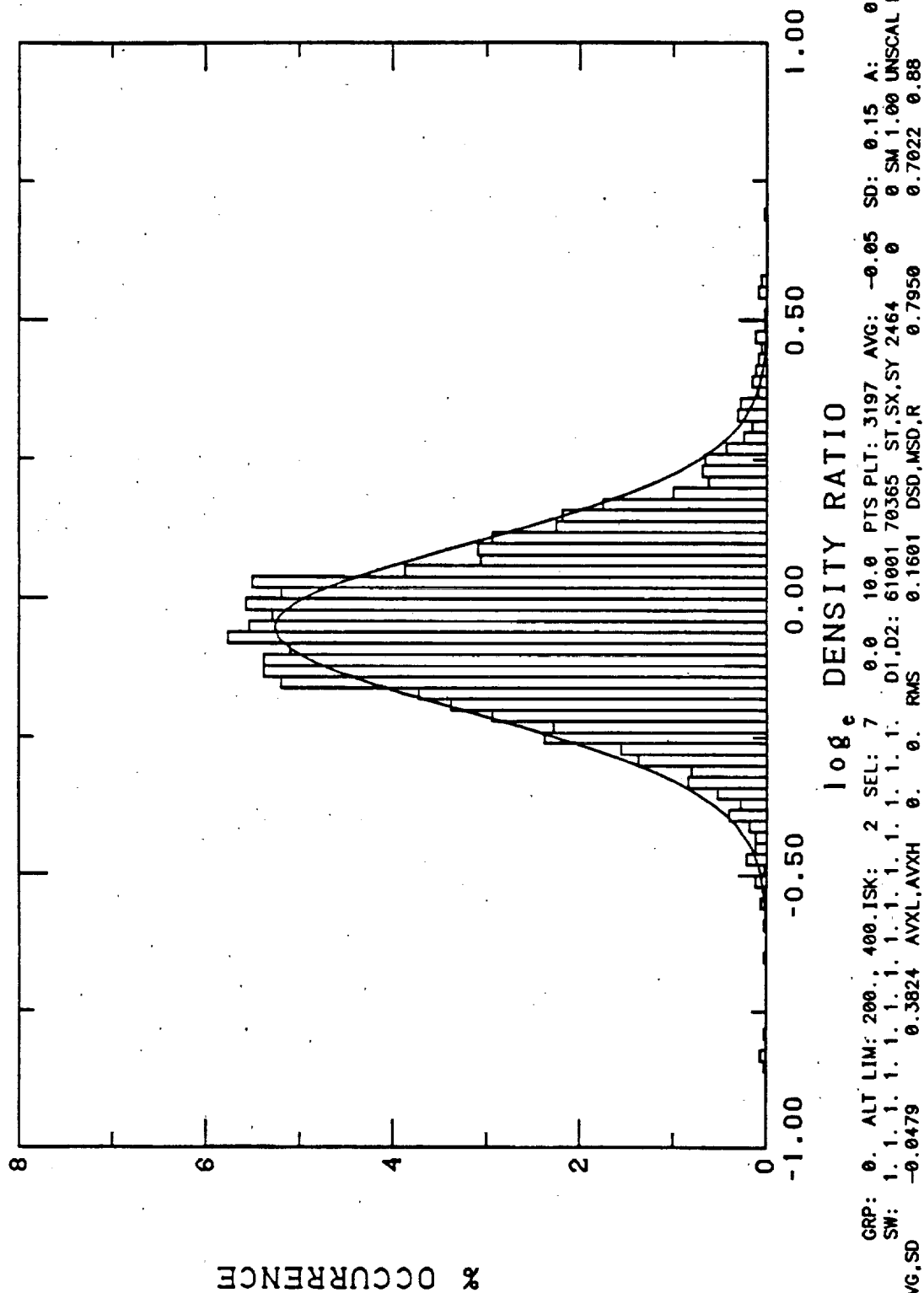


Fig. C1. Histogram showing the occurrence frequency of binned values of the data residuals for low magnetic activity ($A_p < 11$).

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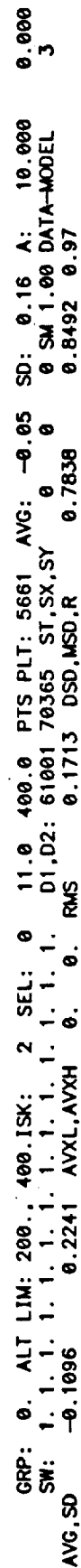
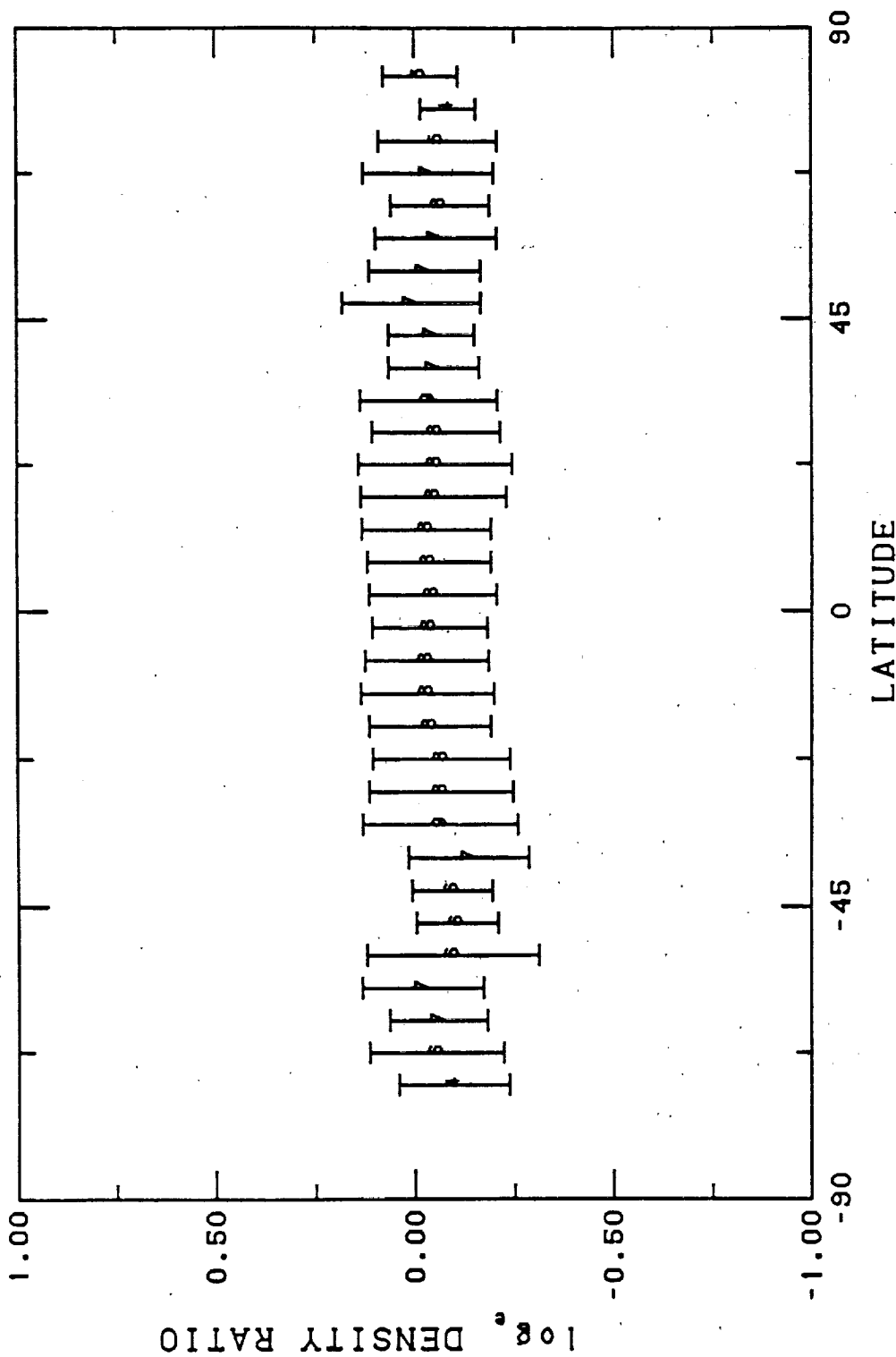


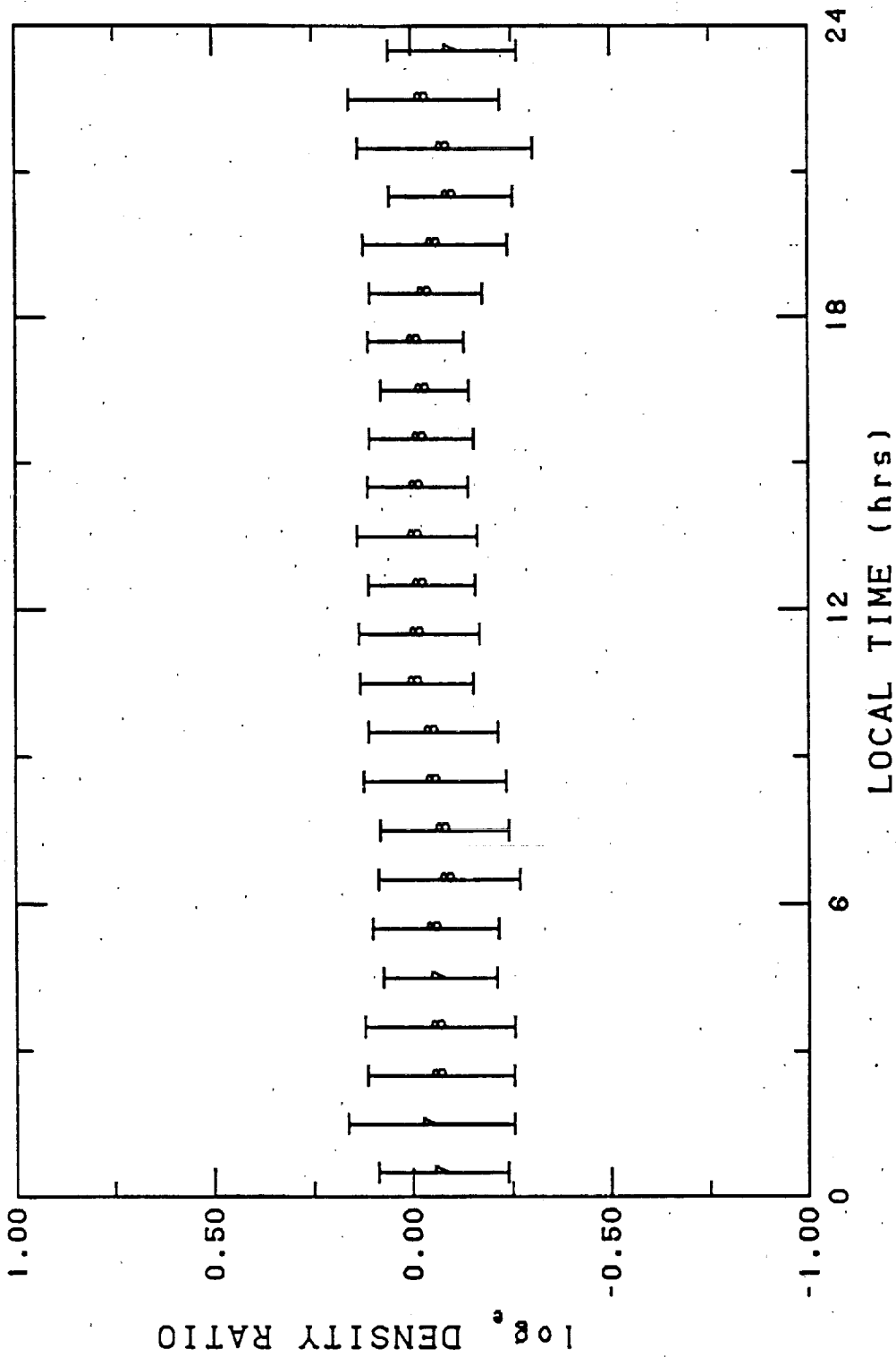
Fig. C3. Data residuals vs altitude for all magnetic activity levels averaged in altitude bins (5, 10, or 20 km depending on altitude range).



```
GRP: 0. ALT LIN: 200., 400.ISK: 2 SEL: 0 11.0 400.0 PTS PLT: 5661 AVG: -0.05 SD: 0.16 A: 5.000 0.000
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 61001 70365 ST,SX,SY 0 0 0 SM 1.00 DATA-MODEL 3
AVG.SD -0.0537 0.0290 AVXL,AVXH 0. RMS 0.1713 DSD,MSD,R 0.4902 0.4929 1.00
```

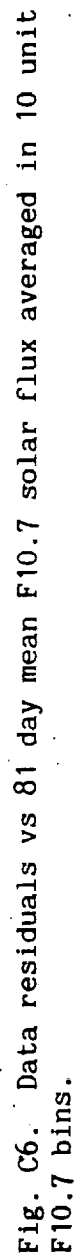
Fig. C4. Data residuals vs latitude for all magnetic activity levels averaged in 5 degree latitude bins.

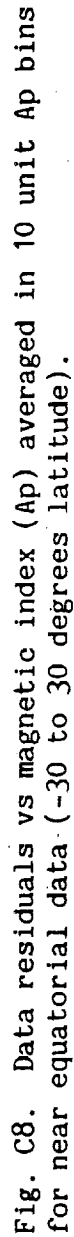
JAC DRAG RHO - MSIS-86



```
GRP: 0. ALT LIM: 200.. 400.ISK: 2 SEL: 0 11.0 400.0 PTS PLT: 5661 AVG: -0.05 SD: 0.16 A: 1.000  
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. D1.D2: 61001 70365 ST.SX.SY 0 0 0 SM 1.00 DATA-MODEL 3  
-0.0514 0.0290 AVXL.AVXH 0. 0. RMS 0.1713 DSD.MSD.R 0.3193 0.2988 1.00  
AVG.SD
```

Fig. C5. Data residuals vs local time for all magnetic activity levels averaged in 1 hr local time bins.





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JAC DRAG RHO - MSIS-86

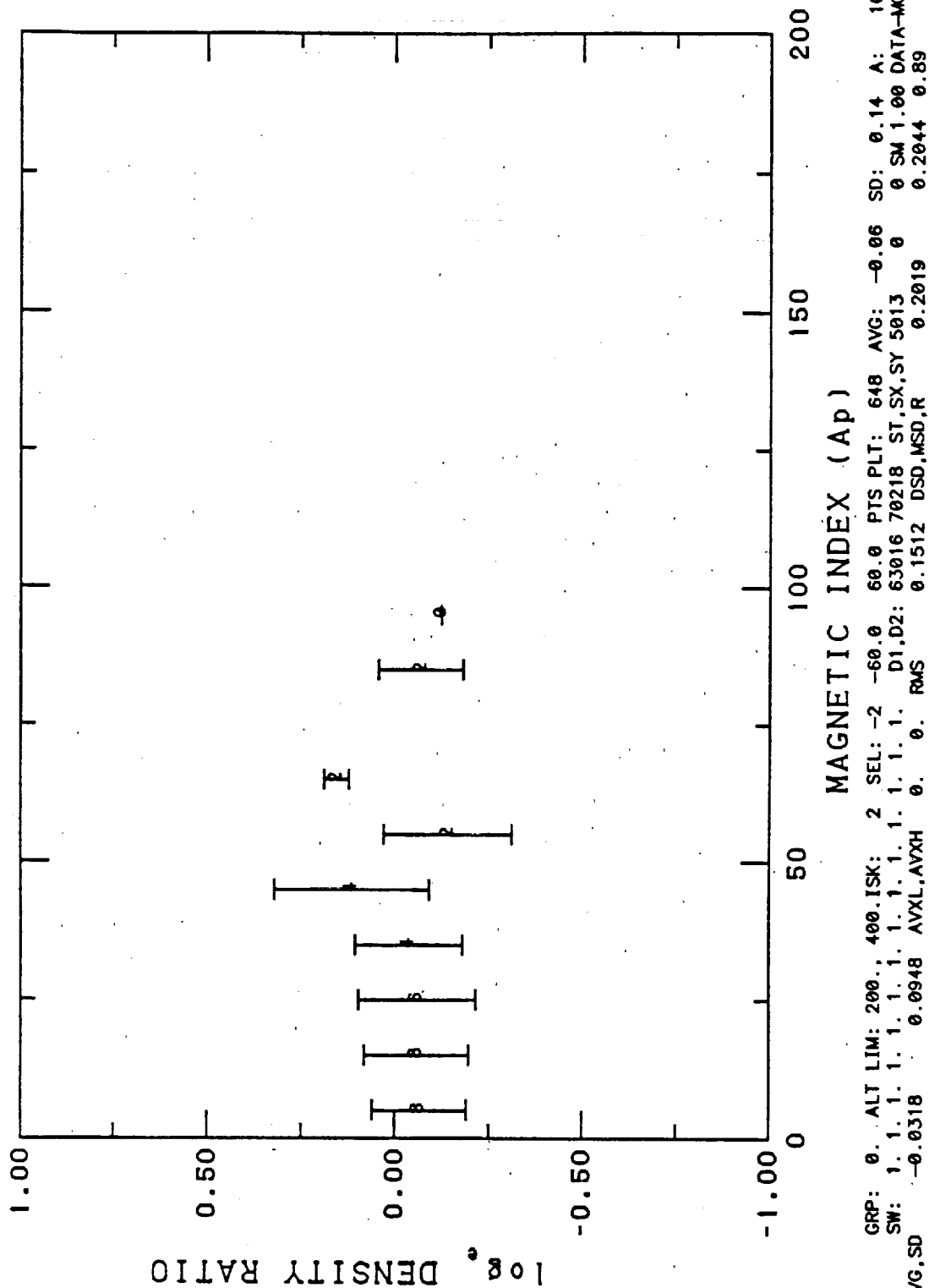
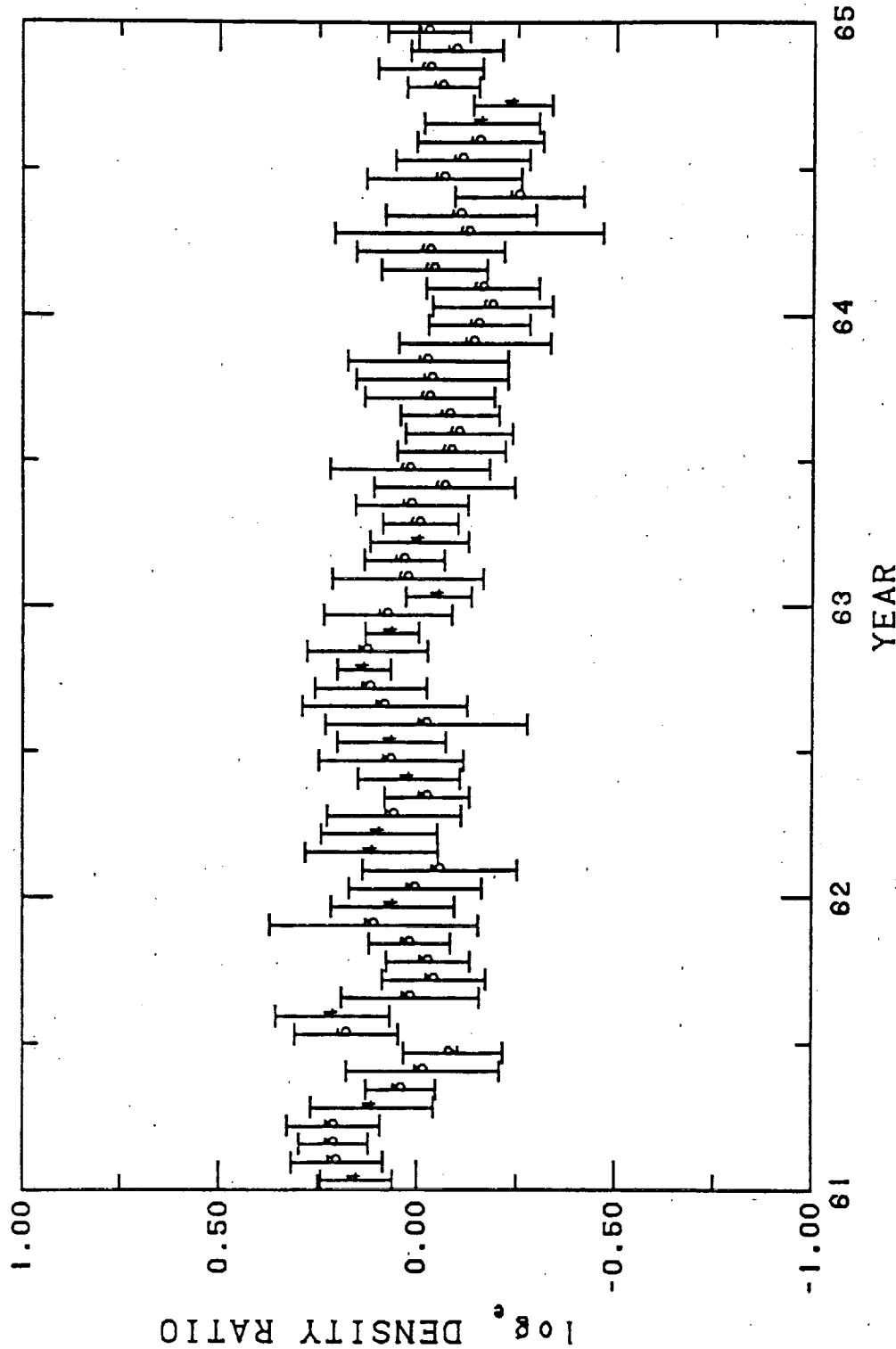


Fig. C9. Data residuals vs magnetic index (Ap) averaged in 10 unit Ap bins for high latitude data (exclude -60 to 60 degrees latitude).

11-
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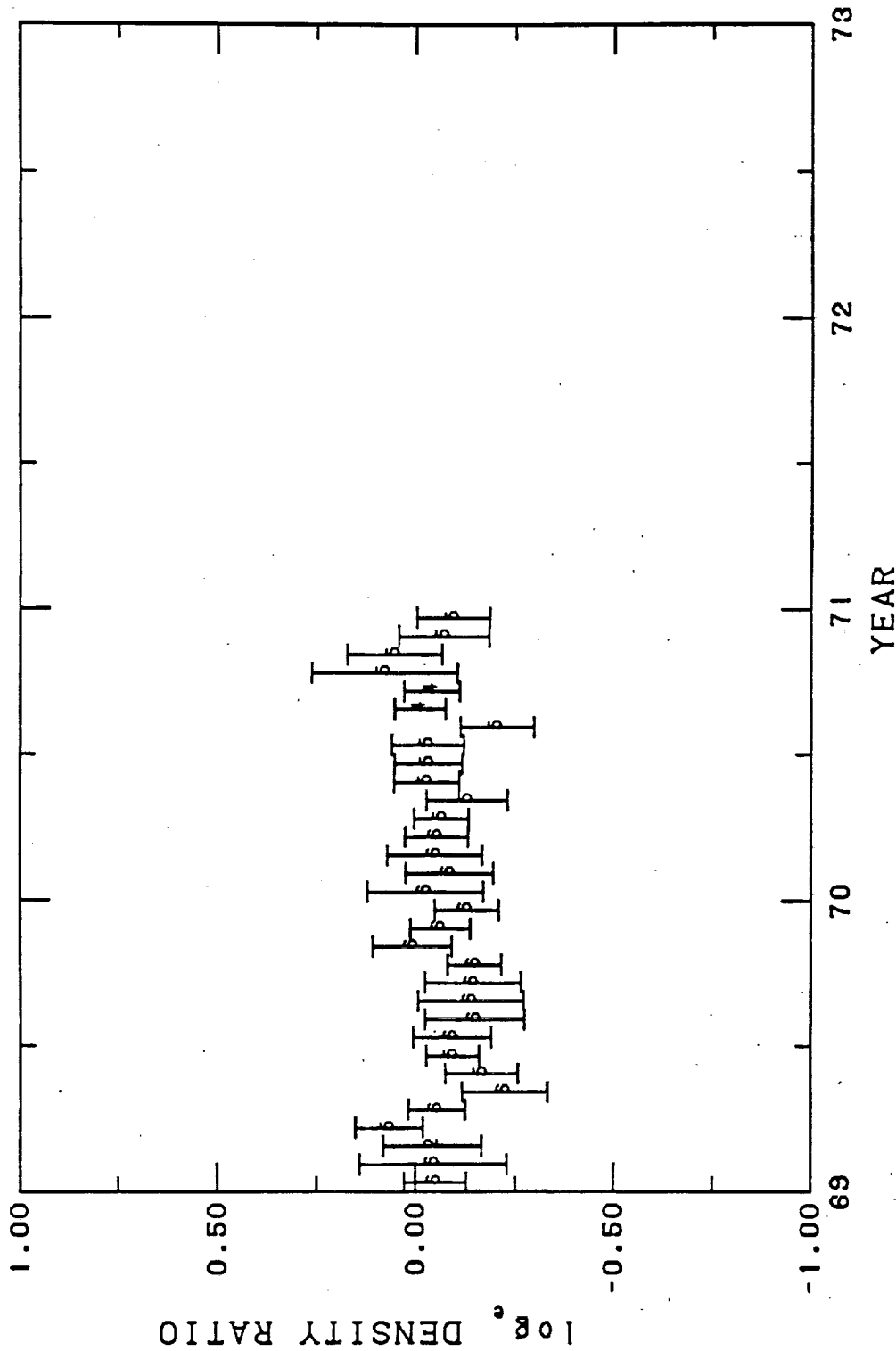
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JAC DRAG RHO - CIRA-86



GRP: 33. ALT LIM: 200.. 400.ISK: 2 SEL: 0 11.0 400.0 PTS PLT: 1833 AVG: -0.04 SD: 0.19 A: 0.063
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 61001 64365 ST,SX,SY 0 3828 0 SM 1.00 DATA-MODEL 3.
AVG.SD -0.0045 0.1081 AVXL,AVXH 0. 0. RMS 0.1928

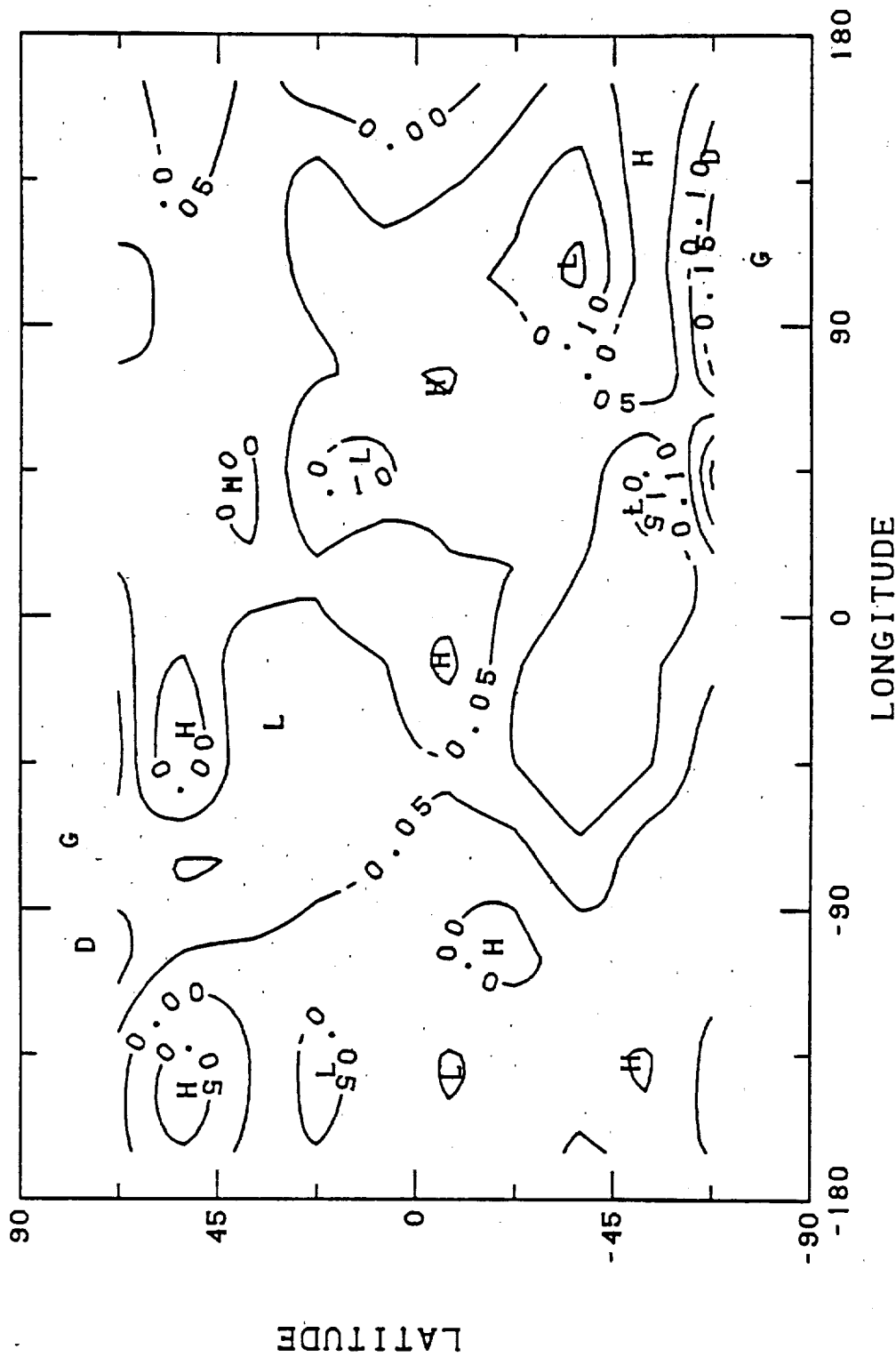
Fig. C10. Data residuals vs year averaged in .0625 year (about 23 day) bins.



```
GRP: 33. ALT LIM: 200., 400.ISK: 2 SEL: 0 11.0 400.0 PTS PLT: 1490 AVG: -0.07 SD: 0.13 A: 0.063  
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 68366 70365 ST,SX,SY 0 4171 0 SM 1.00 DATA-MODEL 3.  
AVG,SD -0.0703 0.0707 AVXL,AVXH 0. 0. RMS 0.1462
```

Fig. C12.. Data residuals vs year averaged in .0625 year (about 23 day) bins.

1.00 PLOTTED: 3/18/88
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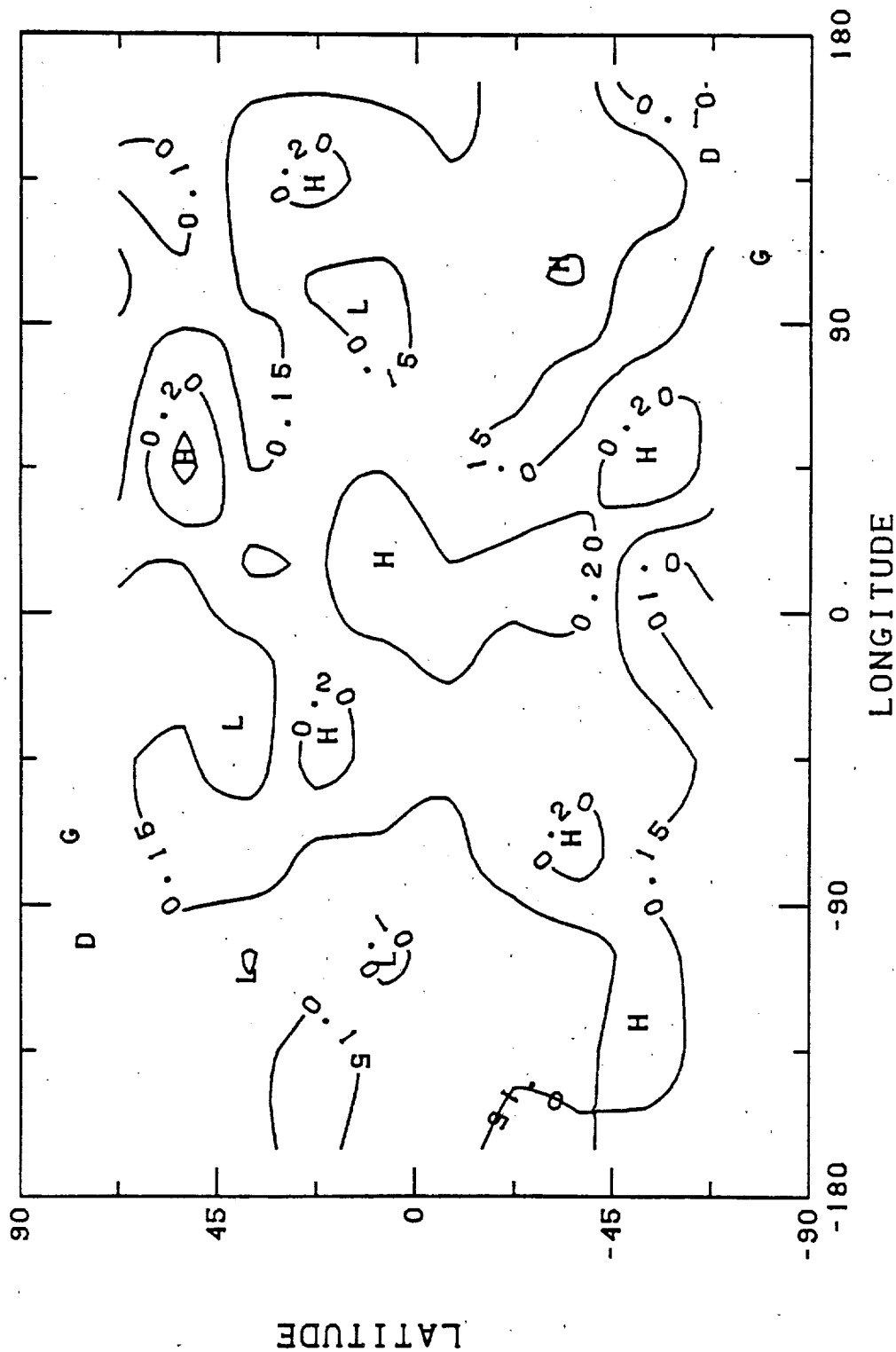
```
GRP: 0. ALT LIM.: 200., 400.ISK: 2 SEL: 0 -60.0 60.0 PTS PLT: 5661 AVG: -0.05 SD: 0.16 A: 30.000  
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 61001 70365 ST,SX,SY 0 0 0 SM 1.00 DATA-MODEL 3  
AVG.SD -0.0511 0.0452 AVXL,AVXH 0. RMS 0.1713 DSD,MSD,R 0.5480 0.5401 1.00
```

Fig. C13. Data residual contours on a latitude - longitude grid for data averaged in 15 degree latitude by 30 degree longitude bins.

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JAC DRAG RHO - MSIS-86

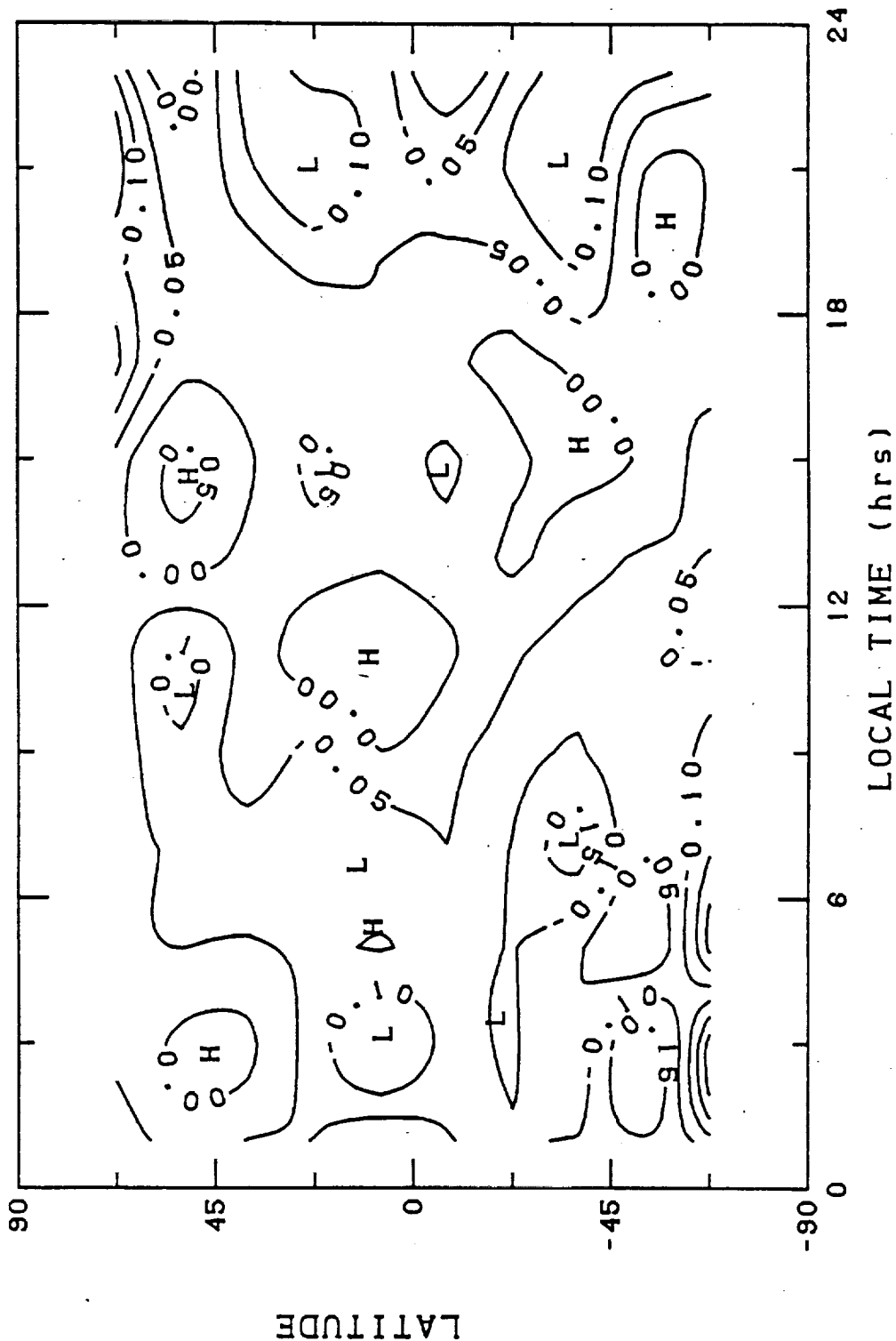


```
GRP: 0. ALT LIM: 200., 400.ISK: 2 SEL: 0 -60.0 60.0 PTS PLT: 5661 AVG: -0.05 SD: 0.16 A: 30.000 15.000
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 61001 70365 ST,SX,SY 0 0 0 SM 1.00 SD:DATA-MODEL 3
-0.0511 0.0452 AVXL,AVXH 0. 0. RMS 0.1713 DSD,MSD,R 0.5480 0.5401 1.00
AVG,SD
```

Fig. C14. Standard deviation contours on a latitude - longitude grid of data in 15 degree latitude by 30 degree longitude bins.

1.00 PLOTTED : 3/18/88
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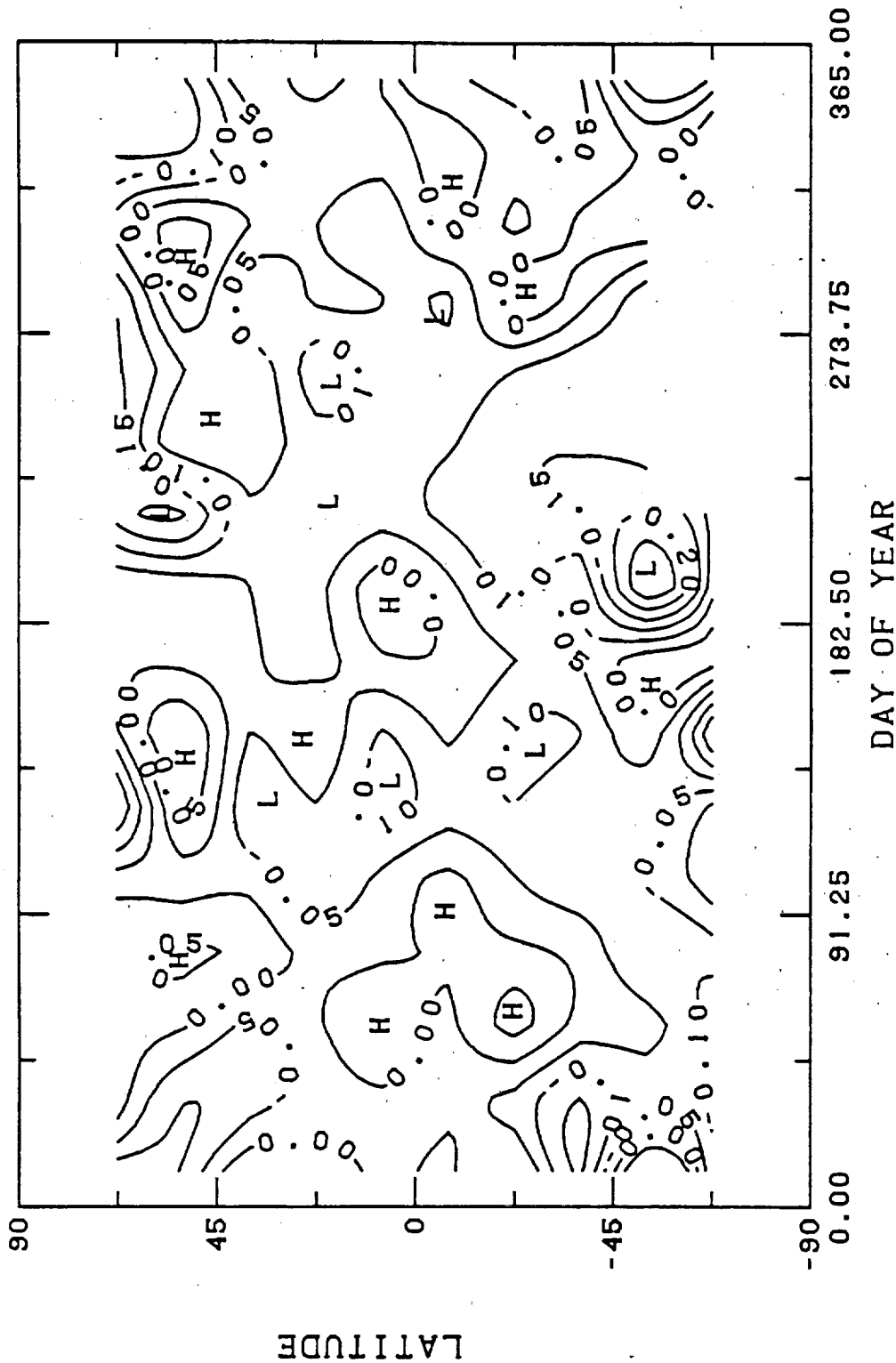
JAC DRAG RHO - MSIS-86



```
GRP: 0. ALT LIM: 200., 400.ISK: 2 SEL: 0 -60.0 60.0 PTS PLT: 5661 AVG: -0.05 SD: 0.16 A: 2.000  
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 61001 70365 ST,SX,SY 0 0 0 SM 1.00 DATA-MODEL 3  
AVG.SD -0.0533 0.0530 AVXL,AVXH 0. 0. RMS 0.1713 DSD,MSD,R 0.5947 0.5832 1.00
```

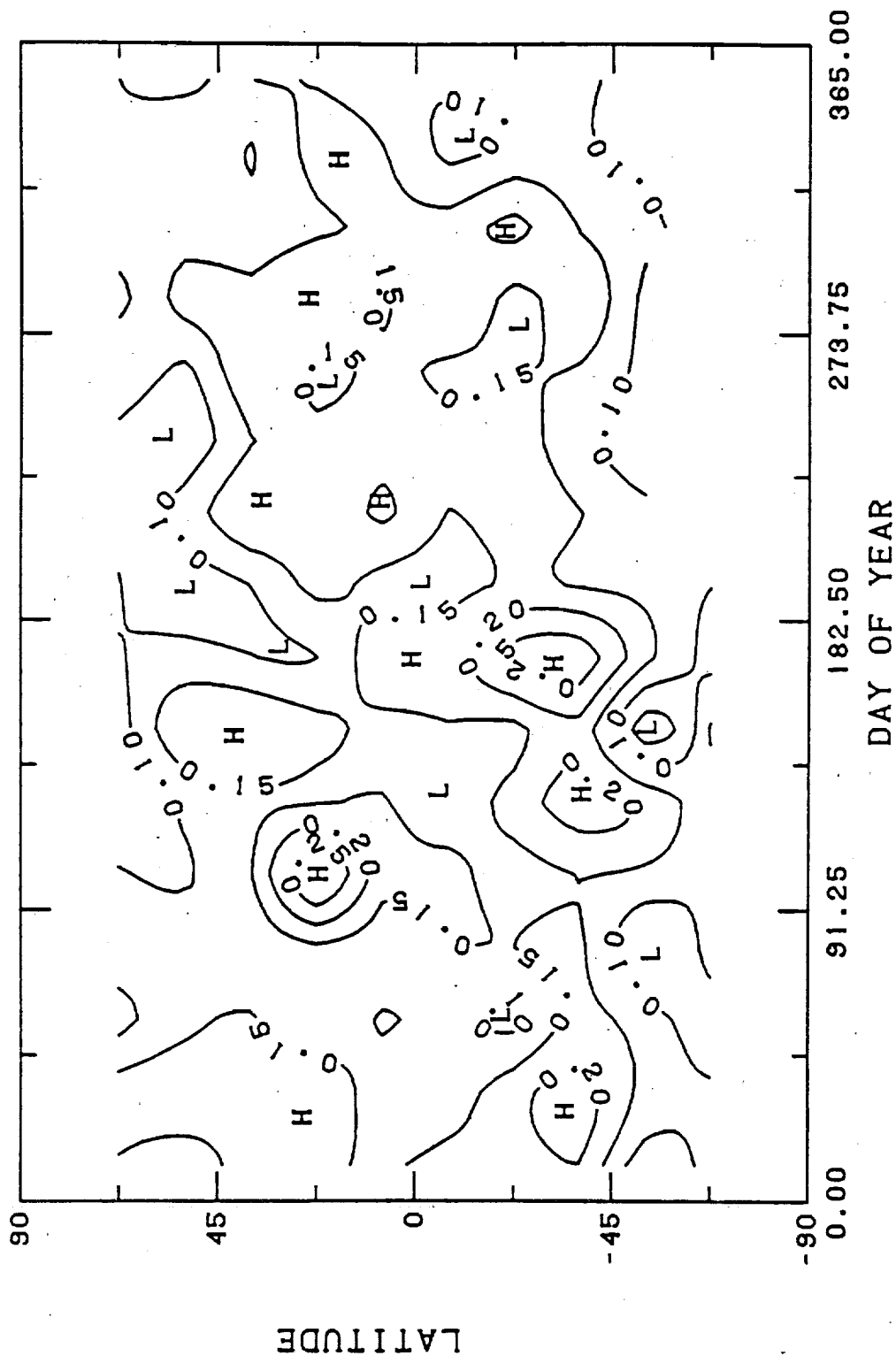
Fig. C15. Data residual contours on a latitude - local time grid for data averaged in 15 degree latitude by 2 hour local time bins.

1.00 PLOTTED : 3/18/88
TAPE: DRAG



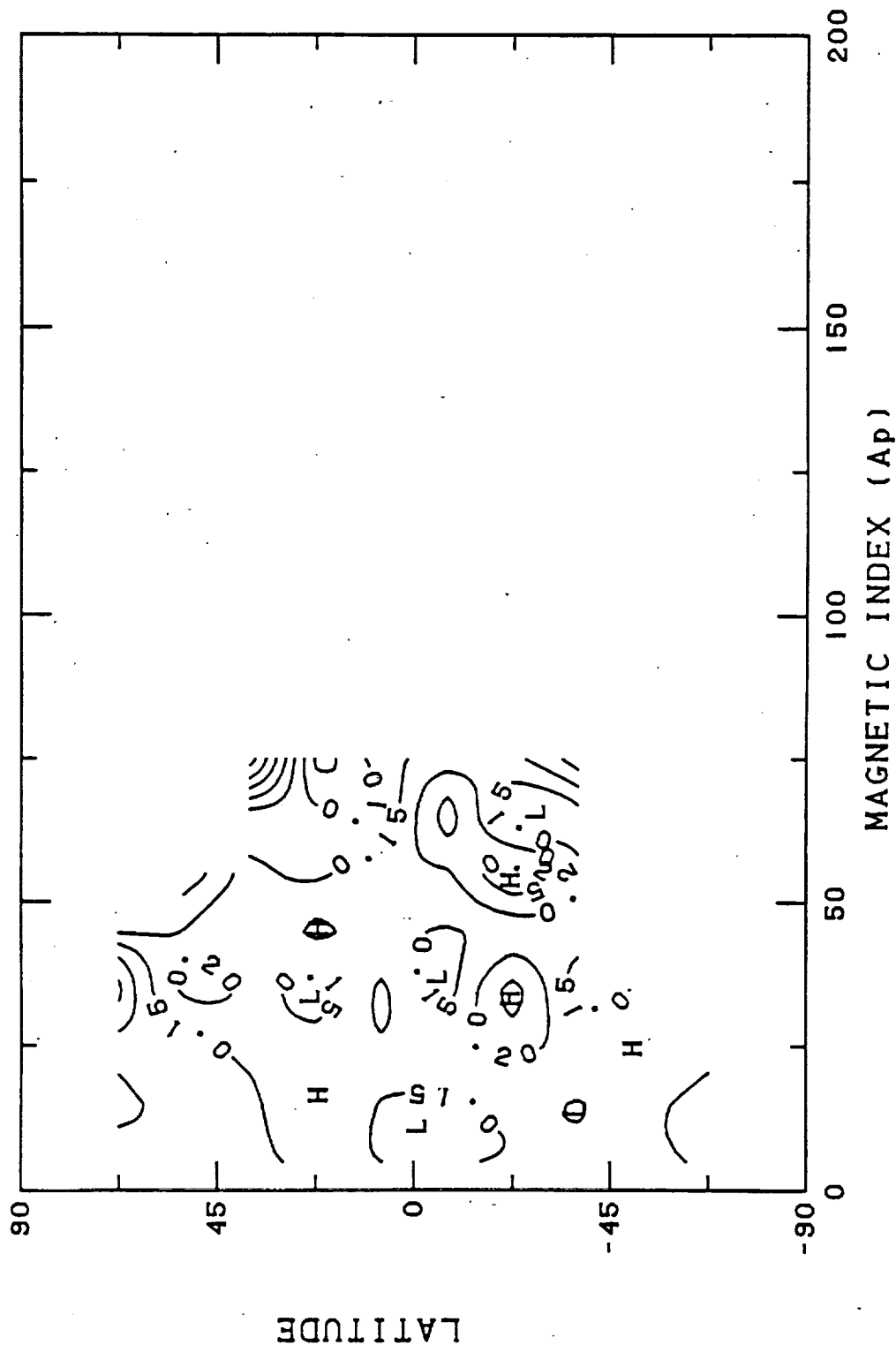
```
GRP: 0. ALT LIM: 200., 400.ISK: 2 SEL: 0 -60.0 60.0 PTS PLT: 5660 AVG: -0.05 SD: 0.16 A: 22.813 15.000
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 61001 70365 ST,SX,SY 0 1 0 SM 1.00 DATA-MODEL 3
AVG.SD -0.0514 0.0705 AVXL,AVXH 0. 0. RMS 0.1713 DSD,MSD,R 0.6349 0.6310 0.99
```

Fig. C17. Data residual contours on a latitude - day of year grid for data averaged in 15 degree latitude by 22.8125 day bins.



```
GRP: 0. ALT LIM: 200., 400.ISK: 2 SEL: 0 -60.0 60.0 PTS PLT: 5660 AVG: -0.05 SD: 0.16 A: 22.813 15.000
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 61001 70365 ST,SX,SY 0 1 0 SM 1.00 SD:DATA-MODEL 3
AVG.SD -0.0514 0.0705 AVXL,AVXH 0. 0. RMS 0.1713 DSD,MSD,R 0.6349 0.6310 0.99
```

Fig. C18. Standard deviation contours on a latitude - day of year grid of data in 15 degree latitude by 22.8125 day bins.

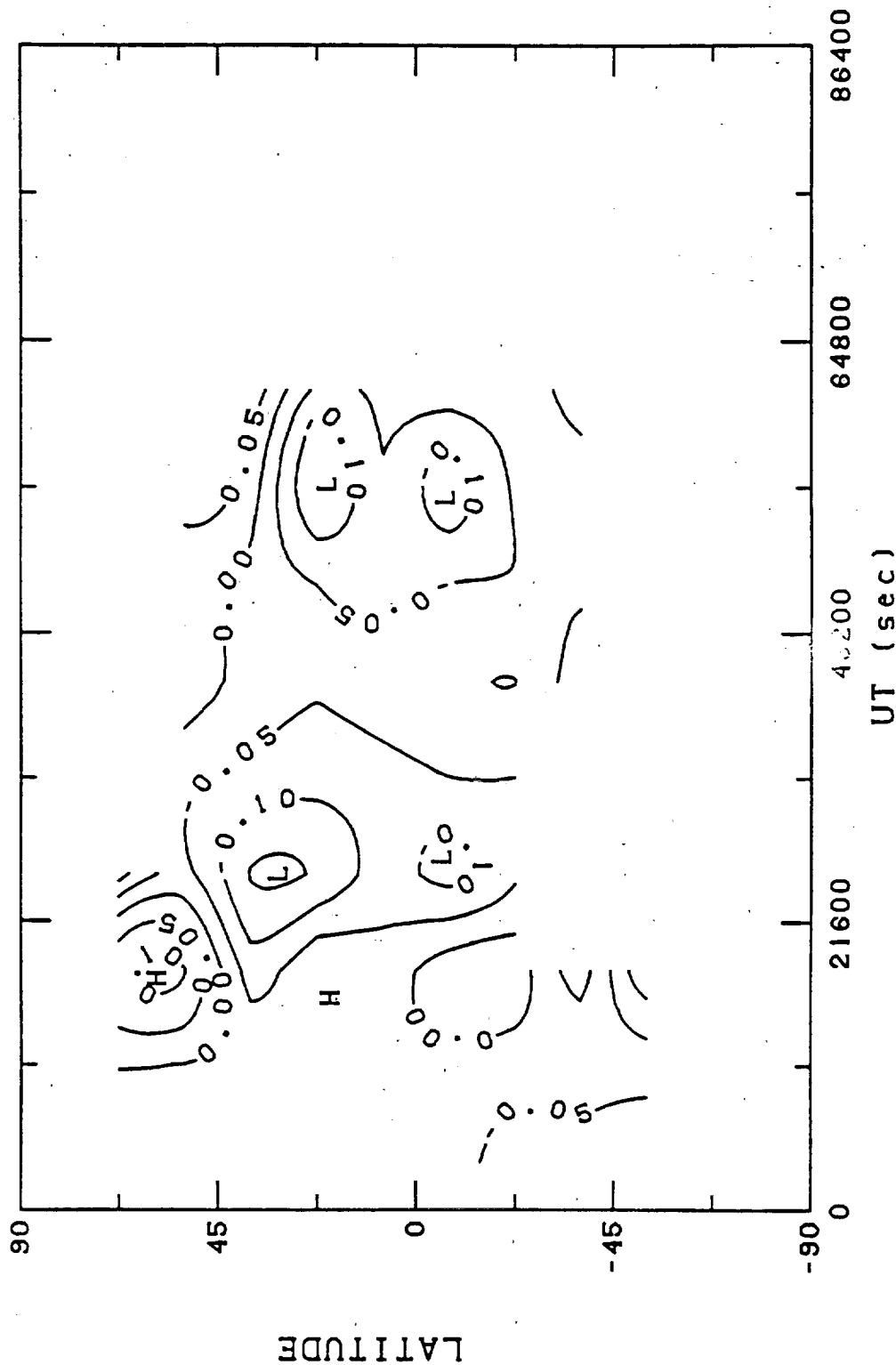


```
GRP: 0. ALT LIM: 200., 400.ISK: 2 SEL: 0 -60.0 60.0 PTS PLT: 5661 AVG: -0.05 SD: 0.16 A: 10.000 15.000
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 61001 70365 ST,SX,SY 0 0 0 SM 1.00 SD:DATA-MODEL 3
-AVG.SD -0.0088 0.0995 AVXL,AVXH 0. RMS 0.1713 DSD,MSD,R 0.5959 0.5976 0.99
```

Fig. C20. Standard deviation contours on a latitude - magnetic index grid of data in 15 degree latitude by 10 Ap unit bins.

1.00 PLOTTED: 3/18/88
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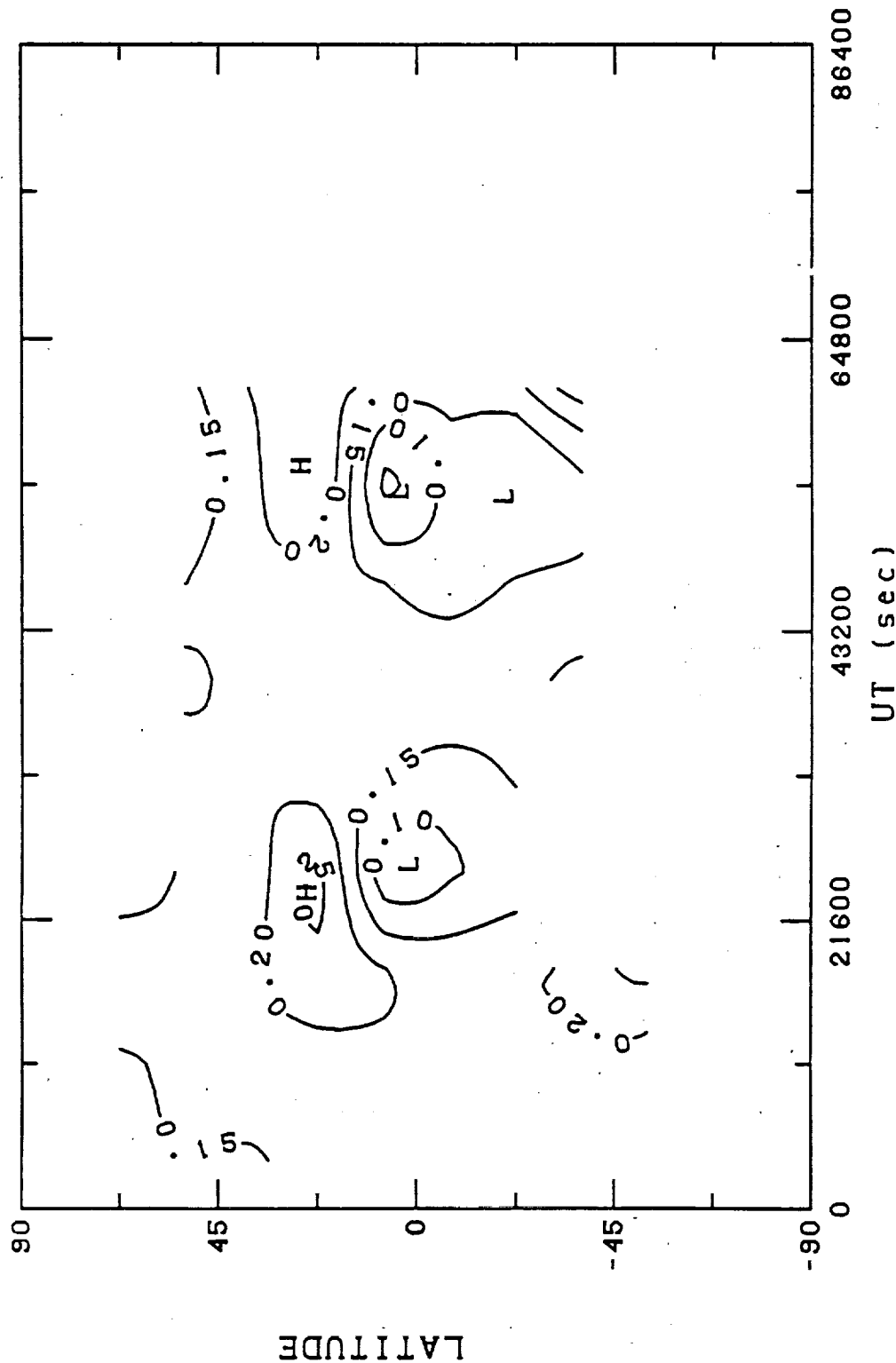
JAC DRAG RHO - MSIS-86



```
GRP: 0. ALT LIM: 200., 400.ISK: 2 SEL: 0 -60.0 60.0 PTS PLT: 5661 AVG: -0.05 SD: 0.16 A: 7200.000 15.000
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. D1.D2: 61001 70365 ST.SX.SY 0 0 0 SM 1.00 DATA-MODEL 3
AVG.SD -0.0312 0.0616 AVXL,AVXH 0. RMS 0.1713 DSD,MSD,R 0.4826 0.4752 0.99
```

Fig. C21. Data residual contours on a latitude - UT grid for data averaged in 15 degree latitude by 7200 sec bins.

JAC DRAG RHO - MSIS-86



GRP:	0.	ALT LIM:	200.	400.ISK:	2	SEL:	0	-60.0	60.0	PTS PLT:	5661	AVG:	-0.05	SD:	0.16	A:	7200.000	15.000	
SW:	1.	1.	1.	1.	1.	1.	1.	1.	1.	D1,D2:	61001	70365	ST,SX,SY	0	0	SM	1.00	SD:DATA-MODEL	3
AVG.SD	-0.0312	0.0616	AVXL,AVXH	0.	0.	RMS	0.1713	DSD,MSD,R	0.4826							0.4752	0.99		

Fig. C22. Standard deviations contours on a latitude - UT grid of data in 15 degree latitude by 7200 sec bins.

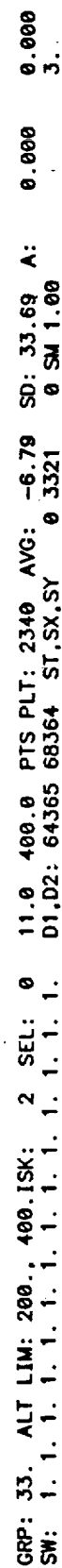


Fig. C24. Latitude vs year coverage plot with different plot symbols for different satellites.

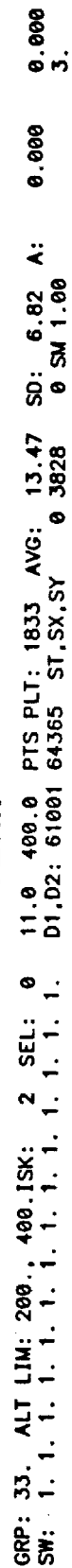
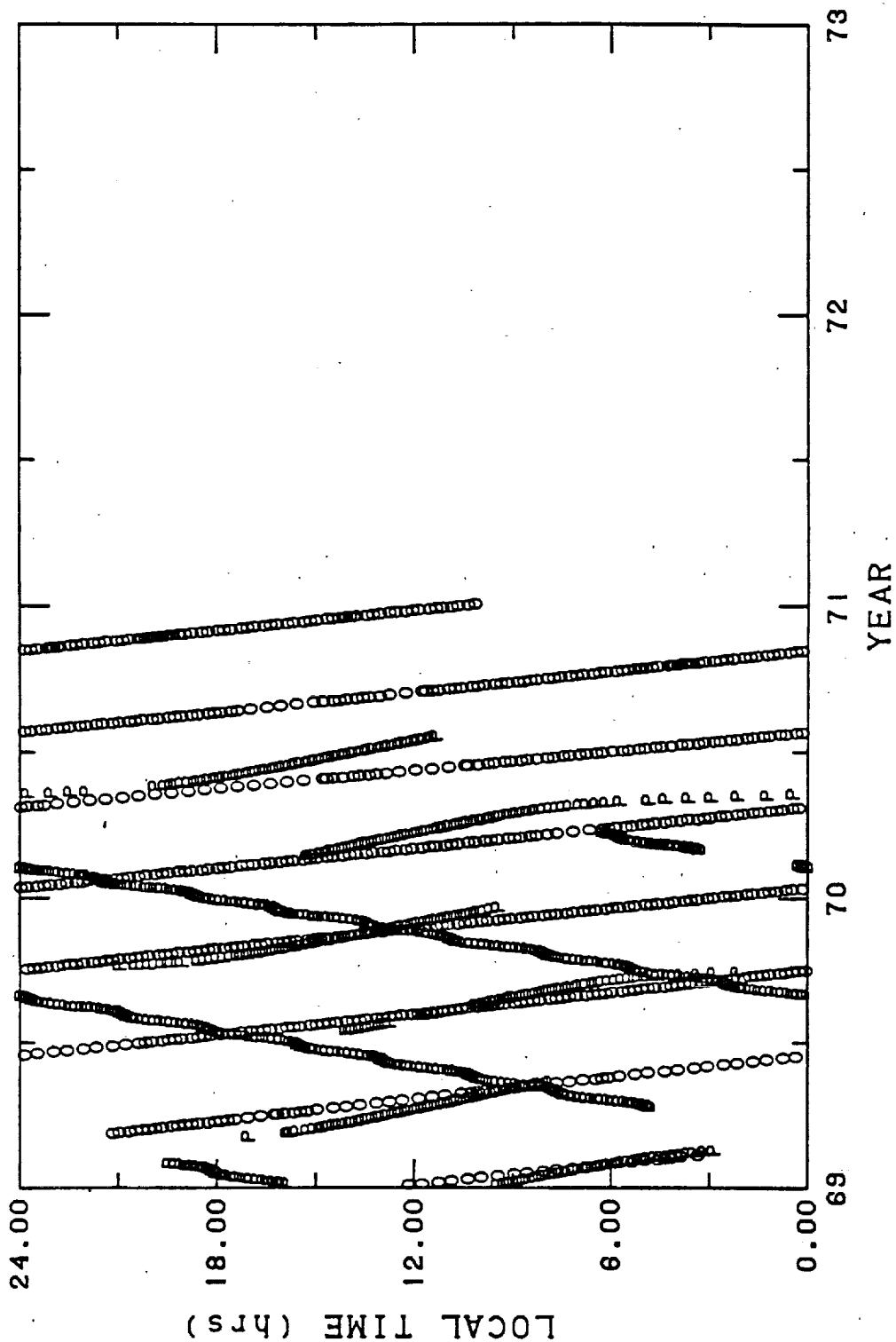


Fig. C26. Local time vs year coverage plot with different plot symbols for different satellites.

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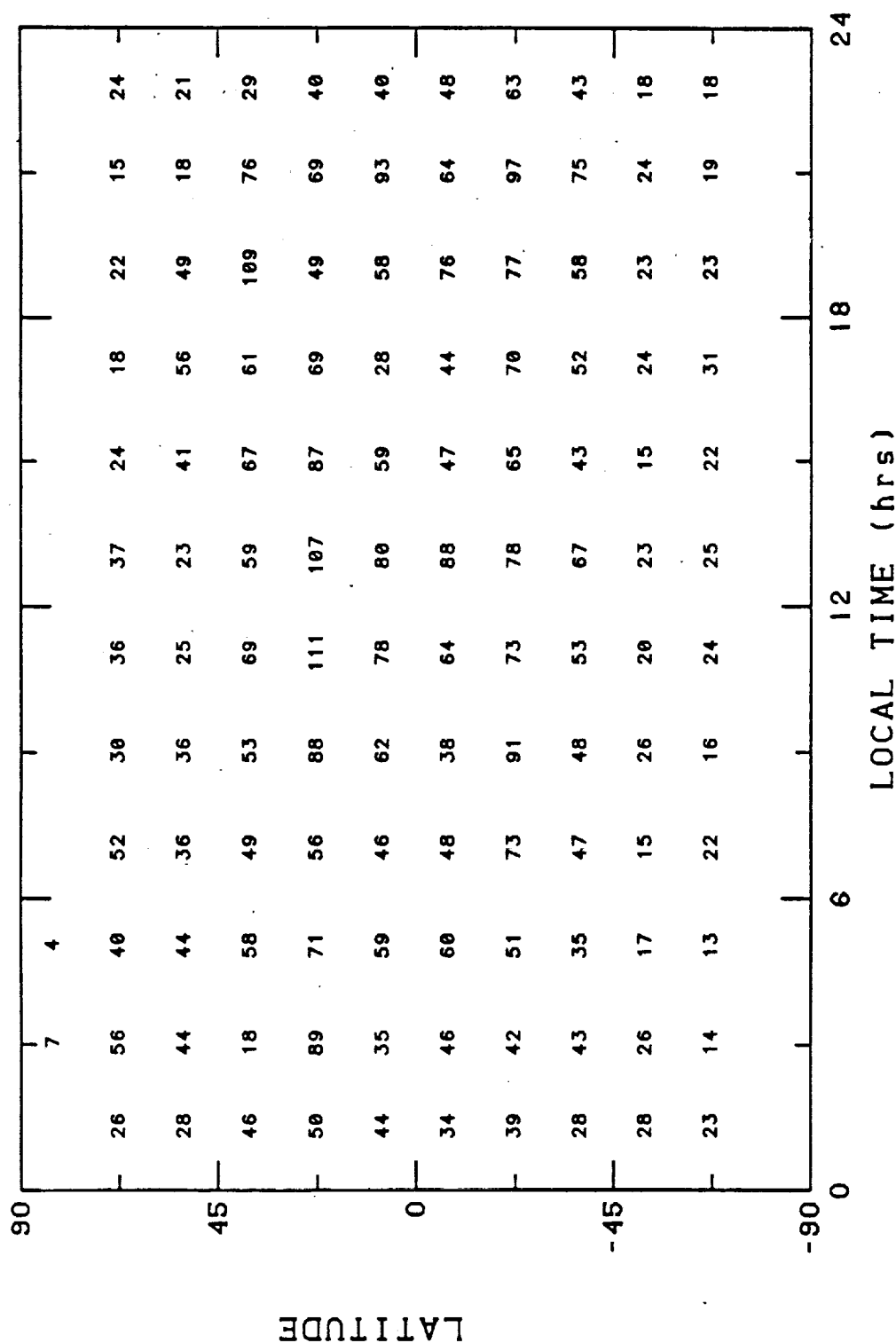
JAC DRAG, RHO - CIRA-86

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GRP: 33. ALT LIM: 200.. 400.ISK: 2 SEL: 0 11.0 400.0 PTS PLT: 1490 AVG: 11.98 SD: 6.28 A: 0.000
SW: 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. D1,D2: 68366 70365 ST,SX,SY 0 4171 0 SM 1.00 3.

Fig. C28. Local time vs year coverage plot with different plot symbols for different satellites.

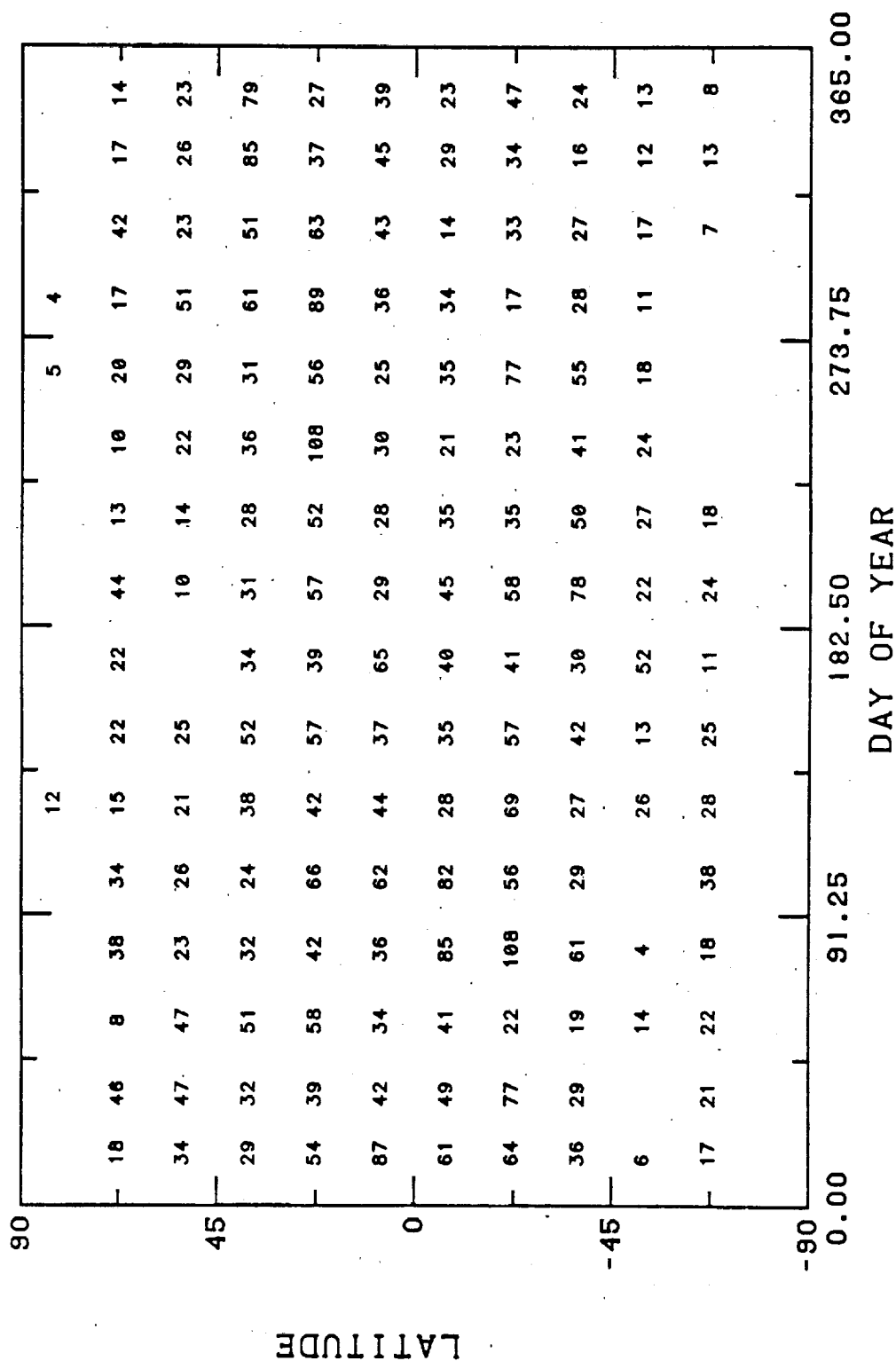


GRP:	0.	ALT LIM:	200.,	400.ISK:	2	SEL:	0	-60.0	PTS PLT:	5661	AVG:	-0.05	SD:	0.16	A:	2.000
SW:	1.	1.	1.	1.	1.	1.	1.	1.	D1,D2:	61001	70365	ST,SX,SY	0	0	SM	1.00 NUM POINTS
AVG.SD	-0.0533	0.0530	AVXL,AVXH	0.	0.	RMS	0.1713	DSD,MSD,R	0.5947	0.5832	1.00					3

Fig. C30. Latitude vs local time coverage plot with each integer indicating the number of data points in each 15 degree latitude by 2 hr local time bin.

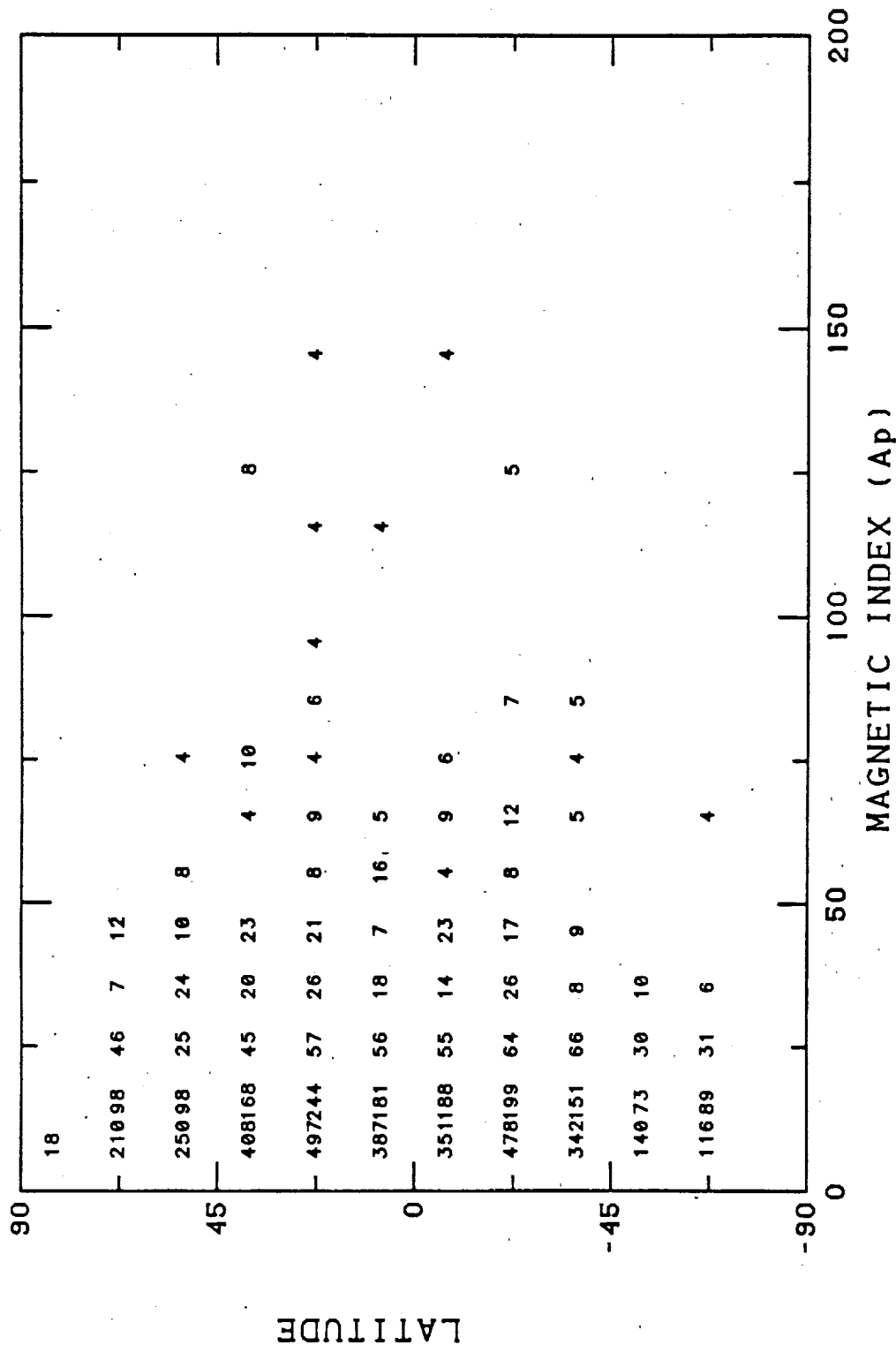
1.00 PLOTTED: 3/18/88
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JAC DRAG RHO - MSIS-86



GRP:	0.	ALT LIM:	200.	400.ISK:	2	SEL:	0	-60.0	60.0	PTS	PLI:	5660	AVG:	-0.05	SD:	0.16	A:	22.813	15.000		
SW:	1.	1.	1.	1.	1.	1.	1.	1.	1.	D1,D2:	61001	70365	ST,SX,SY	0	1	0	SM	1.00	NJM	POINTS	3
AVG.SD	-0.0514	0.0705	AVXL,AVXH	0.	0.	RMS	0.1713	DSD,MSD,R	0.6349							0.6310	0.99				

Fig. C31. Latitude vs day of year coverage plot with each integer indicating the number of data points in each 15 degree latitude by 22.8125 day bin.



GRP	ALT	LIM	200.	400	ISK	2	SEL	0	-60.0	60.0	PTS	PLT	5661	AVG	-0.05	SD	0.16	A	10.000		
SW	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	SM	1.00	NUM	POINTS
AVG	SD	-0.0088	0.0995	AVXL	AVXH	0	0	RMS	0.1713	DSD	MSD	R	0.5959	0.5976	0.99						

Fig. C32. Latitude vs magnetic index (Ap) coverage plot with each integer indicating the number of data points in each 15 degree latitude by 10 unit magnetic index bin.

Appendix D. Data set comparison summaries.

The following pages have a summary of the data subset comparisons with the models emphasizing observed trends for the different models.

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Altitude: 200-400 Parameter: Total Density Dates: 61001-70365
F10.7: 70-190 Source: Jacchia sat. trk. Data File: DRAG

Best quiet mean: -.03 (J77) Worst quiet mean: -.21 (MSIS-77)
Best quiet SD: .15 (MSIS-86,J77) Worst quiet SD: .18 (MSIS-77)
Best active mean: .02 (J77) Worst active mean: -.16 (MSIS-77)
Best active SD: .18 (MSIS-86,J70) Worst active SD: .21 (J77)

Altitude: All equivalent.
Residuals flat.

Latitude: MSIS-86 J70 least variance.
Residuals flat.

Local Time: MSIS-86 -77 least variance.
Residuals have terdiurnal variation for J77.

Mean F10.7: MSIS-83 least variance.
Residuals flat.

Delta F10.7: MSIS-77 least variance.
Residuals more positive with increasing activity for MSIS models and
more negative with increasing activity for J77 and J70.

Magnetic: MSIS-86 least variance.
Residuals near equator and poles flat except for MSIS-77 and J77.
Coverage to Ap 150 near equator and Ap 100 near pole.

Day/year: J70 least variance.
Residuals have annual, semiannual and longer trends.

Longitude/UT: Variances similar for all models.

Comments: Little overall difference between models except worse
for MSIS-77.

MSIS-86 trends: delta F10.7 and annual.

Altitude: 400-800 Parameter: Total Density Dates: 61134-70364
F10.7: 70-190 Source: Jacchia sat. trk. Data File: DRAG

Best quiet mean: $-.05$ (MSIS-86,J77) Worst quiet mean: $-.23$ (MSIS-77)
Best quiet SD: $.25$ (J77) Worst quiet SD: $.29$ (MSIS-77)
Best active mean: $-.04$ (MSIS-86,-83) Worst active mean: $-.16$ (MSIS-77,J77)
Best active SD: $.28$ (J70) Worst active SD: $.31$ (MSIS-77)

Altitude: J77 least variance.
Residuals flat but irregular for all models.

Latitude: J77 J70 least variance.
Residuals more negative at midlatitudes for MSIS-86 -83.

Local Time: J70 least variance.
Residuals have diurnal and semidiurnal for all models.

Mean F10.7: J77 least variance.
Residuals irregularly more positive with increasing activity for MSIS models.

Delta F10.7: J77 least variance.
Residuals more positive with increasing activity for MSIS models and more negative with increasing activity for J70.

Magnetic: MSIS-86 least variance.
Residuals flat but irregular. Coverage to Ap 150.

Day/year: J77 least variance.
Residuals have annual, semiannual and longer trends.

Longitude/UT: MSIS-86, J77, J70 least variance.
Residuals may have second harmonic at lower latitudes for all models.

Comments: Little overall difference between models except worse for MSIS-77.

MSIS-86 trends: latitude, local time, mean and delta F10.7 and annual.

Altitude: 800-1200 Parameter: Total Density Dates: 61134-70364
F10.7: 70-190 Source: Jacchia sat. trk. Data File: DRAG

Best quiet mean: -.03 (J77)	Worst quiet mean: -.05 (J70)
Best quiet SD: .22 (J70)	Worst quiet SD: .30 (MSIS-77)
Best active mean: .02 (MSIS-77)	Worst active mean: -.12 (J70)
Best active SD: .23 (J70)	Worst active SD: .33 (MSIS-77)

Altitude: MSIS-86 least variance.
Residuals irregular but flat for all models except more negative at higher altitudes for J70.

Latitude: J70 has least variance.
Residuals more negative at midlatitudes for MSIS-86 -83.

Local Time: J70 least variance.
Residuals have diurnal and semidiurnal for all models.

Mean F10.7: J70 least variance.
Residuals flat except more positive with increasing activity for MSIS-77.

Delta F10.7: MSIS-86 , -83 least variance.
Residuals more negative at low and high activity for MSIS models and more negative with increasing activity for J77 and J70.

Magnetic: J70 least variance.
Residuals near equator and pole irregularly more negative with increasing activity for all but J70. Coverage to Ap 150.

Day/year: J70 least variance.
Residuals have annual, semiannual and longer trends.

Longitude/UT: J70 has least variance.

Comments: J70 best at this altitude.

MSIS-86 trends: latitude, local time, delta F10.7 and annual.

Altitude: 120-200 Parameter: Total Density Dates: 66362-73057
F10.7: 90-190 Source: Barlier sat. trk. Data File: DRAG

Best quiet mean: .02 (MSIS-86)	Worst quiet mean: -.07 (J77)
Best quiet SD: .22 (MSIS-86,J77)	Worst quiet SD: .23 (MSIS-83,-77)
Best active mean: .00 (MSIS-86)	Worst active mean: .13 (J77)
Best active SD: .21 (J70)	Worst active SD: .23 (J77)

Altitude: J77 J70 least variance.
Residuals more positive at lowest altitudes for MSIS models.

Latitude: MSIS-77 has least variance.
Residuals flat.

Local Time: MSIS-86 -77 least variance.
Residuals have diurnal and semidiurnal variation for MSIS-83, J77,
and J70.

Mean F10.7: J77 J70 least variance.
Residuals flat.

Delta F10.7: Variances similar for all models.
Residuals flat for all models.

Magnetic: Variances similar for all models.
Residuals near equator more negative with increasing activity for all
models and no clear trend near poles. Coverage to Ap 200 near
equator and Ap 50 near poles.

Day/year: J70 least variance.
Residuals have annual, semiannual and longer trends.

Longitude/UT: Variances similar for all models.

Comments: Little overall difference between models but local time
and latitude variations somewhat worse for Jacchia models.

MSIS-86 trends: altitude, annual, and magnetic activity.

Altitude: 200-400 Parameter: Total Density Dates: 64033-73058
F10.7: 70-190 Source: Barlier sat. trk. Data File: DRAG

Best quiet mean: .02 (MSIS-83) Worst quiet mean: -.06 (MSIS-77)
Best quiet SD: .20 (MSIS-86,-83) Worst quiet SD: .21 (MSIS-77,J70,J77)
Best active mean: .00 (J77) Worst active mean: -.09 (MSIS-77)
Best active SD: .20 (MSIS-86) Worst active SD: .23 (J77)

Altitude: MSIS-77 least variance.

Residuals more positive with increasing altitude except for MSIS-77.

Latitude: Variances similar for all models.

Residuals flat.

Local Time: MSIS-86 -77 least variance.

Residuals have terdiurnal variation for J77.

Mean F10.7: MSIS-83 J77 least variance.

Residuals flat.

Delta F10.7: MSIS-86 least variance.

Residuals more negative with increasing activity for J77 and J70.

Magnetic: MSIS-86 least variance.

Residuals near equator and poles more negative decreasing with
increasing activity for all models. Coverage to Ap 200 near
equator and Ap 150 near poles.

Day/year: MSIS-86 least variance.

No obvious trends.

Longitude/UT: Variances similar for all models.

Comments: Little overall difference between models.

MSIS-86 trends: altitude and magnetic activity.

Altitude: 400-800 Parameter: Total Density Dates: 66011-73058
F10.7: 70-190 Source: Barlier sat. trk. Data File: DRAG

Best quiet mean: -.04 (J77)	Worst quiet mean: .15 (J70)
Best quiet SD: .31 (MSIS-86,J70)	Worst quiet SD: .33 (MSIS-77)
Best active mean: .00 (J70)	Worst active mean: .11 (J77)
Best active SD: .29 (MSIS-83)	Worst active SD: .32 (MSIS-77)

Altitude: J77 J70 least variance.
Residuals flat but irregular for all models.

Latitude: Variances similar for all models.
Residuals flat for all models.

Local Time: MSIS-86, -83, J70 least variance.
Residuals have diurnal and semidiurnal for MSIS-77 and J77.

Mean F10.7: Variances similar for all models except MSIS-77 worse.
Residuals flat for all models except MSIS-77.

Delta F10.7: MSIS-77 least variance.
Residuals more negative with increasing activity for all models.

Magnetic: MSIS models least variance.
Residuals near equator and pole more negative with increasing activity
for all models. Coverage to Ap 150 near equator and Ap 100 near
pole.

Day/year: Variances similar for all models except MSIS-77 worse.
Residuals have annual, semiannual and longer trends.

Longitude/UT: Variances similar for all models.
Residuals may have second harmonic at lower latitudes for all models.

Comments: Little overall difference between models.

MSIS-86 trends: delta F10.7, annual, and magnetic activity.

Altitude: 200-400 Parameter: Total Density Dates: 69187-71177
F10.7: 100-170 Source: OGO-6 MS Data File: OGORHOFIFTH

Best quiet mean: -.04 (MSIS-77) Worst quiet mean: .15 (J70)
Best quiet SD: .14 (MSIS) Worst quiet SD: .17 (J70)
Best active mean: .00 (MSIS-86) Worst active mean: .17 (MSIS-77)
Best active SD: .19 (MSIS-86,-83) Worst active SD: .21 (J77,J70)

Altitude: Insufficient coverage.

Latitude: MSIS-86 least variance.

Residuals more positive toward north pole for all models.

Local Time: Variances similar for all models.

Residuals flat but irregular.

Mean F10.7: MSIS-86 least variance.

Residuals flat for all models.

Delta F10.7: MSIS least variance.

Residuals more negative with increasing activity except flat for MSIS-77.

Magnetic: MSIS-86 least variance.

Residuals more negative with increasing activity for all but MSIS-86.
Coverage to 160 Ap.

Day/year: Variances similar for all models.

Residuals more negative at beginning of 1971 for all models, but less pronounced for Jacchia models.

Longitude/UT: Variances similar for all models.

No obvious trends.

Comments: MSIS models best for standard deviations and overall.

MSIS-86 trends: delta F10.7 and annual.

Altitude: 400-800 Parameter: Total Density Dates: 69179-71177
F10.7: 100-170 Source: OGO-6 MS Data File: OGORHOFIFTH

Best quiet mean: .04 (MSIS-77) Worst quiet mean: .25 (J70)
Best quiet SD: .17 (MSIS-86) Worst quiet SD: .21 (J77)
Best active mean: .02 (MSIS-77) Worst active mean: .23 (J77)
Best active SD: .20 (MSIS-86,-77) Worst active SD: .22 (J77)

Altitude: Variances similar for all models.
Residuals more positive at higher altitudes for all models.

Latitude: MSIS least variance.
Residuals more positive at midlatitudes for J77 and J70.

Local Time: MSIS least variance.
Residuals have semidiurnal or terdiurnal variation for J77 and J70.

Mean F10.7: MSIS-77 least variance.
Residuals flat but irregular.

Delta F10.7: MSIS-86 least variance.
Residuals more negative at higher activity for J77 and J70.

Magnetic: MSIS-86 least variance.
Residuals more negative with increasing activity near equator for all
but MSIS-86 and more positive with increasing activity near poles
for MSIS-77, J77, J70. Coverage to Ap 160.

Day/year: MSIS-77 least variance.
Residuals have no clear trend.

Longitude/UT: MSIS least variance.
Residuals more positive near magnetic poles for J70.

Comments: Little overall difference between models except Jacchia
models slightly worse in latitude variations.

MSIS-86 trends: altitude.

Altitude: 130-200 Parameter: Total Density Dates: 73353-75100
F10.7: 70-110 Source: AE-C MESA Accel. Data File: MESA-C

Best quiet mean: .00 (J70)	Worst quiet mean: .11 (MSIS-86,-83)
Best quiet SD: .15 (MSIS-77)	Worst quiet SD: .18 (J77,J70)
Best active mean: .07 (J70)	Worst active mean: .14 (MSIS-86)
Best active SD: .15 (MSIS-77)	Worst active SD: .21 (J77)

Altitude: MSIS-83 J70 least variance.
Residuals more positive with decreasing altitude for MSIS models.

Latitude: MSIS least variance.
Residuals more positive toward north for MSIS models and more positive toward both poles for J77 and J70.

Local Time: MSIS least variance.
Residuals have diurnal variation for J77 and J70.

Mean F10.7: MSIS least variance.
Residuals more positive with increasing activity for J70.

Delta F10.7: MSIS-83 MSIS-77 least variance.
Residuals more positive with increasing activity for all models.
Coverage small.

Magnetic: MSIS least variance.
Residuals near equator are irregular and near poles more positive with higher activity for all models. Coverage to Ap 100 near equator and Ap 130 near pole.

Day/year: MSIS-77 least variance.

Longitude/UT: Variances similar for all models except worse for J77.

Comments: Jacchia models better than MSIS in absolute values but slightly worse in standard deviations. Jacchia models worse for latitude and daily variations.

MSIS-86 trends: latitude, delta F10.7.

Altitude: 200-250 Parameter: Total Density Dates: 73353-76110
F10.7: 70-110 Source: AE-C MESA Accel. Data File: MESA-C

Best quiet mean: .02 (MSIS-86)	Worst quiet mean: -.08 (MSIS-77)
Best quiet SD: .21 (all)	Worst quiet SD: .21
Best active mean: .02 (MSIS-86)	Worst active mean: .07 (J77)
Best active SD: .20 (MSIS-77)	Worst active SD: .23 (J77)

Altitude: All models have low variance.
Residuals flat for all models.

Latitude: MSIS-86 least variance.
Residuals flat but irregular for all models.

Local Time: MSIS-77 least variance.
Residuals have semidiurnal variation for all but MSIS-77.

Mean F10.7: J77 least variance.
No obvious trends.

Delta F10.7: MSIS-77 J77 least variance.
Residuals more positive with increasing activity for all models.

Magnetic: MSIS-77 least variance.
Residuals irregular. Coverage to Ap 130.

Day/year: J70 least variance.
No obvious trends.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models but Jacchia models
worse for daily variation and J77 worse for latitude variation.

MSIS-86 trends: delta F10.7.

Altitude: 130-200 Parameter: Total Density Dates: 74001-75100
F10.7: 70-110 Source: AE-C OSS MS Data File: OSSC48

Best quiet mean: -.01 (MSIS-86,-83) Worst quiet mean: -.07 (J70)
Best quiet SD: .10 (MSIS-77) Worst quiet SD: .13 (J77,J70)
Best active mean: .00 (MSIS-77) Worst active mean: -.02 (J70)
Best active SD: .11 (MSIS-77) Worst active SD: .16 (J77)

Altitude: MSIS-77 least variance.

Residuals more positive with increasing altitude for J77.

Latitude: MSIS least variance.

Residuals more positive toward north for MSIS models and more positive toward both poles for J77 and J70.

Local Time: MSIS least variance.

Residuals have diurnal variation for J77 and J70.

Mean F10.7: MSIS-77 least variance.

No obvious trend.

Delta F10.7: MSIS-77 J77 least variance.

Residuals more positive with increasing activity for all models.
Coverage small.

Magnetic: MSIS-77 least variance.

Residuals near equator are more negative with higher activity for J77 and J70. Coverage to Ap 130.

Day/year: MSIS-77 least variance.

Longitude/UT: MSIS least variance.

Comments: Little overall difference between models but Jacchia models worse for latitude and daily variations.

MSIS-86 trends: latitude, delta F10.7.

Altitude: 200-390 Parameter: Total Density Dates: 74001-76161
F10.7: 70-110 Source: AE-C OSS MS Data File: OSSC200S20

Best quiet mean: .01 (J70)	Worst quiet mean: .09 (J77)
Best quiet SD: .14 (MSIS)	Worst quiet SD: .16 (J70)
Best active mean: .00 (J70)	Worst active mean: .10 (MSIS-83)
Best active SD: .15 (MSIS-86)	Worst active SD: .19 (J77)

Altitude: MSIS-86, -83 least variance.
Residuals more negative at higher altitudes for all models.

Latitude: MSIS-83 least variance.
Residuals more positive near the equator for all models.

Local Time: MSIS least variance.
Residuals have terdiurnal variation for J77.

Mean F10.7: MSIS-86 least variance.
No obvious trends.

Delta F10.7: MSIS-77 J70 least variance.
Residuals more positive with increasing activity for MSIS-86, -83,
and J70.

Magnetic: MSIS-83 least variance.
Residuals irregular. Coverage to Ap 130.

Day/year: MSIS-83 least variance.
No obvious trends.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models but Jacchia models
worse for daily variation J77 worse for latitude variation.

MSIS-86 trends: altitude, latitude, and delta F10.7.

Altitude: 130-200 Parameter: Total Density Dates: 75284-76029
F10.7: 70-80 Source: AE-D MESA Accel. Data File: MESA-D

Best quiet mean: .00 (MSIS-83,-77) Worst quiet mean: -.03 (MSIS-86)
Best quiet SD: .14 (MSIS-77,J70) Worst quiet SD: .15 (MSIS-86,-83,J77)
Best active mean: .00 (MSIS-83) Worst active mean: .04 (MSIS-77)
Best active SD: .15 (all but J77) Worst active SD: .17 (J77)

Altitude: Jacchia least variance.
Residuals more negative with decreasing altitude for MSIS models.

Latitude: J70 least variance.
Residuals flat except more positive toward south for J77.

Local Time: MSIS-86 J70 least variance.
Residuals flat but irregular.

Mean F10.7: Insufficient coverage.

Delta F10.7: J77 J70 least variance.
Residuals more positive with increasing activity for all models.
Coverage small.

Magnetic: MSIS least variance.
Residuals flat near equator and more positive with higher activity for
all models. Coverage to Ap 50 near equator and Ap 70 near pole.

Day/year: Insufficient coverage.

Longitude/UT: Variances similar for all models except worse for J77.
Residuals negative near south magnetic pole.

Comments: Little overall difference between models.

MSIS-86 trends: altitude, and magnetic activity.

Altitude: 200-250 Parameter: Total Density Dates: 75284-76029
F10.7: 70-80 Source: AE-D MESA Accel. Data File: MESA-E

Best quiet mean: .01 (J77) Worst quiet mean: -.11 (MSIS-77)
Best quiet SD: .18 (not MSIS-83) Worst quiet SD: .19 (MSIS-83)
Best active mean: .03 (MSIS-83) Worst active mean: -.08 (MSIS-86)
Best active SD: .19 (not J77) Worst active SD: .20 (J77)

Altitude: All models have low variance.
Residuals flat for all models.

Latitude: Variances similar for all models.
Residuals flat but irregular for all models.

Local Time: Variances similar for all models.
Residuals flat but irregular for all models.

Mean F10.7: Insufficient coverage.

Delta F10.7: J77 J70 least variance.
Residuals more positive with increasing activity for all models.

Magnetic: Variances similar for all models.
Residuals irregular. Coverage to Ap 50 near equator and Ap 70 near poles.

Day/year: Insufficient coverage.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models.

MSIS-86 trends: delta F10.7.

Altitude: 130-200 Parameter: Total Density Dates: 75291-76029
F10.7: 70-80 Source: AE-D OSS MS Data File: OSSD48

Best quiet mean: -.01 (MSIS,J70)	Worst quiet mean: .04 (J77)
Best quiet SD: .11 (MSIS,J70)	Worst quiet SD: .13 (J77)
Best active mean: .00 (J70)	Worst active mean: .06 (MSIS-77,J77)
Best active SD: .13 (MSIS)	Worst active SD: .15 (J77)

Altitude: Variances similar for all models.
Residuals flat for all models.

Latitude: MSIS-77 least variance.
Residuals flat except more positive toward south for J77.

Local Time: Variances similar for all models.
Residuals flat but irregular.

Mean F10.7: Insufficient coverage.

Delta F10.7: All models have low variance.
Residuals flat for all models. Coverage small.

Magnetic: Variances similar for all models.
Residuals flat near equator and more positive with higher activity for all models. Coverage to Ap 50 near equator and Ap 70 near pole.

Day/year: Insufficient coverage.

Longitude/UT: Variances similar for all models except worse for J77.
Residuals more negative near magnetic poles for all models.

Comments: Little overall difference between models.

MSIS-86 trends: magnetic activity and longitude.

Altitude: 200-390 Parameter: Total Density Dates: 75291-76029
F10.7: 70-80 Source: AE-D OSS MS Data File: OSSD48

Best quiet mean: -.02 (MSIS-83) Worst quiet mean: -.20 (MSIS-77)
Best quiet SD: .17 (MSIS-86,Jac) Worst quiet SD: .18 (MSIS-83,-77)
Best active mean: .00 (MSIS-83) Worst active mean: -.12 (MSIS-77)
Best active SD: .21 (MSIS-86,J70) Worst active SD: .23 (J77)

Altitude: MSIS-83 J70 least variance.
Residuals flat for all models.

Latitude: MSIS-77 least variance.
Residuals more positive near equator for all models.

Local Time: MSIS-77 least variance.
Residuals flat but irregular for all models.

Mean F10.7: Insufficient coverage.

Delta F10.7: MSIS-77, J77 J70 least variance.
Residuals more positive with increasing activity for all models.

Magnetic: MSIS-83, -77 least variance.
Residuals irregular. Coverage to Ap 50 near equator and Ap 70 near poles.

Day/year: Insufficient coverage.

Longitude/UT: MSIS-77 least variance.
Residuals more negative near magnetic poles.

Comments: Little overall difference between models except MSIS-77 worse.

MSIS-86 trends: delta F10.7 and longitude.

Altitude: 200-400 Parameter: Total Density Dates: 75178-79021
F10.7: 70-200 Source: Cactus Accel. Data File: CACTUSTENTH

Best quiet mean: -.03 (J77)	Worst quiet mean: -.26 (MSIS-77)
Best quiet SD: .14 (MSIS-86)	Worst quiet SD: .18 (MSIS-77)
Best active mean: -.02 (MSIS-86)	Worst active mean: -.15 (MSIS-77)
Best active SD: .17 (MSIS-86)	Worst active SD: .21 (J77)

Altitude: J77 J70 least variance.

Residuals sharply negative below 270 km for MSIS-86 -83, more negative with increasing altitude for MSIS-77, and rather flat for J70 and J77.

Latitude: MSIS-86, -77, J70 least variance.

Residuals more positive near equator for MSIS-83 and more negative near equator for J77. Coverage 30S to 30N.

Local Time: MSIS-86 least variance.

Residuals have diurnal variation for all models.

Mean F10.7: J77 J70 least variance.

Residuals irregular.

Delta F10.7: J77 J70 least variance.

Residuals more positive with increasing activity for MSIS models.

Magnetic: MSIS-83 least variance.

Residuals irregularly more positive with increasing activity for all models.

Day/year: MSIS-86 -83 least variance.

Residuals have semiannual variation with equinox minimum for all models.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models except MSIS-77 (significantly worse) and Jacchia models significantly worse for local time variations.

MSIS-86 trends: altitude, mean and delta F10.7, and magnetic activity.

Altitude: 400-600 Parameter: Total Density Dates: 75178-79021
F10.7: 70-200 Source: Cactus Accel. Data File: CACTUSTENTH

Best quiet mean: -.01 (MSIS-83,J77) Worst quiet mean: -.36 (MSIS-77)
Best quiet SD: .24 (MSIS-86) Worst quiet SD: .28 (MSIS-77)
Best active mean: .00 (MSIS-86) Worst active mean: -.23 (MSIS-77)
Best active SD: .28 (MSIS-86) Worst active SD: .31 (J77)

Altitude: J70 least variance.

Residuals more positive with increasing altitude for all models.

Latitude: MSIS-77, J70 least variance.

Residuals more positive near equator for MSIS-86, -83, flat for MSIS-77 J77, S shaped for J70. Coverage 30S to 30N.

Local Time: MSIS-86 least variance.

Residuals have semidiurnal variation for all models.

Mean F10.7: J77 least variance.

Residuals irregular.

Delta F10.7: MSIS-83 least variance.

Residuals irregularly more positive with increasing activity for MSIS models.

Magnetic: MSIS-83 least variance.

Residuals irregularly more positive with increasing activity for all models.

Day/year: MSIS-86 -83 least variance.

Residuals have semiannual variation with equinox minimum for all models.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models except MSIS-77 (significantly worse) and Jacchia models significantly worse for local time variations.

MSIS-86 trends: altitude, delta F10.7, and magnetic activity.

Altitude: 130-200 Parameter: Total Density Dates: 75335-76320
F10.7: 70-80 Source: AE-E MESA Accel. Data File: MESA-E

Best quiet mean: -.01 (MSIS-77,J77) Worst quiet mean: -.03 (J70)
Best quiet SD: .12 (MSIS) Worst quiet SD: .14 (J77,J70)
Best active mean: -.02 (J70) Worst active mean: .07 (MSIS-83)
Best active SD: .14 (MSIS-77) Worst active SD: .16 (J77)

Altitude: J77 least variance.
Residuals more positive with decreasing altitude for all models.

Latitude: All models have low variance.
Coverage 20S to 20N.

Local Time: MSIS-86 least variance.
Residuals have semidiurnal variation for all but MSIS-86.

Mean F10.7: Insufficient coverage.

Delta F10.7: MSIS least variance.
Residuals more negative with increasing activity for J77 and J70 models.

Magnetic: MSIS least variance.
Residuals more positive at highest activity for all models. Coverage to Ap 110.

Day/year: MSIS-86 -83 least variance.
Residuals more negative in middle of year for all models.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models although J70 and J77 significantly worse for diurnal, delta F10.7 and magnetic activity variations.

MSIS-86 trends: altitude.

Altitude: 200-250 Parameter: Total Density Dates: 75335-77278
F10.7: 70-110 Source: AE-E MESA Accel. Data File: MESA-E

Best quiet mean: .00 (MSIS-83)	Worst quiet mean: -.06 (MSIS-77)
Best quiet SD: .18 (MSIS-86)	Worst quiet SD: .20 (J77, J70)
Best active mean: .01 (MSIS-77)	Worst active mean: .05 (MSIS-83)
Best active SD: .17 (MSIS-86)	Worst active SD: .20 (J77)

Altitude: MSIS-77 least variance.

Residuals more positive with increasing altitude for all models.

Latitude: All models have low variance.

Coverage 20S to 20N.

Local Time: MSIS least variance.

Residuals have semidiurnal variation for all models.

Mean F10.7: J70 least variance.

Residuals irregular for all models.

Delta F10.7: MSIS least variance.

Residuals more negative with increasing activity for J77 and J70.

Magnetic: Variances similar for all models.

Residuals irregular. Coverage to Ap 110.

Day/year: MSIS-86 -83 least variance.

Residuals have no clear trend.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models although J70
and J77 significantly worse for diurnal, and delta F10.7 variations.

MSIS-86 trends: altitude, local time.

Altitude: 130-200 Parameter: Total Density Dates: 75343-76319
F10.7: 70-80 Source: AE-E OSS MS Data File: OSS-E

Best quiet mean: .00 (MSIS-83) Worst quiet mean: -.07 (MSIS-77, J70)
Best quiet SD: .13 (MSIS-77) Worst quiet SD: .17 (J70)
Best active mean: .02 (MSIS-86, -83) Worst active mean: -.11 (J77)
Best active SD: .15 (MSIS-83, -77) Worst active SD: .19 (J77)

Altitude: J77 least variance.
Residuals more positive with decreasing altitude for all models.

Latitude: All models have low variance.
Coverage 20S to 20N.

Local Time: MSIS-86 least variance.
Residuals have semidiurnal variation for MSIS-77, J77, and J70.

Mean F10.7: Insufficient coverage.

Delta F10.7: MSIS least variance.
Residuals more negative with increasing activity for MSIS-77, J77 and J70 models.

Magnetic: MSIS-77 J77 least variance.
Residuals more positive with increasing activity for all models. Coverage to Ap 110.

Day/year: MSIS-77 least variance.
Residuals have no clear trend.

Longitude/UT: All models have low variance.

Comments: MSIS models slightly better overall than the Jacchia models,
but Jacchia models significantly worse for local time variations.

MSIS-86 trends: altitude and magnetic activity.

Altitude: 200-400 Parameter: Total Density Dates: 75343-78336
F10.7: 70-170 Source: AE-E OSS MS Data File: OSS-E

Best quiet mean: -.01 (J77) Worst quiet mean: -.15 (MSIS-77)
Best quiet SD: .18 (MSIS-83) Worst quiet SD: .21 (MSIS-77, J70)
Best active mean: -.03 (MSIS-86, -83) Worst active mean: -.12 (MSIS-77)
Best active SD: .19 (MSIS-86) Worst active SD: .23 (J77)

Altitude: MSIS-83 least variance.
Residuals more negative with increasing altitude for MSIS-77
J70.

Latitude: All models have low variance.
Coverage 20S to 20N.

Local Time: MSIS-86 least variance.
Residuals have semidiurnal variation for all models and diurnal
for J77 and J70.

Mean F10.7: All models same variance.
Residuals flat for all models.

Delta F10.7: MSIS least variance.
Residuals more negative with increasing activity for J77 and J70.

Magnetic: J77 MSIS-77 least variance.
Residuals more positive at highest activity for all models. Coverage
to Ap 110.

Day/year: MSIS-83 J70 least variance.
Residuals have no clear trend.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models except
MSIS-77 (worse), but Jacchia models significantly worse for
local time and delta F10.7 variations.

MSIS-86 trends: altitude, local time, and magnetic activity.

Altitude: 130-200 Parameter: Total Density Dates: 75341-76307
F10.7: 70-80 Source: AE-E NACE MS Data File: NACE-E

Best quiet mean: -.05 (all but J70) Worst quiet mean: -.07 (J70)
Best quiet SD: .11 (MSIS-86) Worst quiet SD: .17 (J77)
Best active mean: -.04 (MSIS-86,-83) Worst active mean: -.15 (J77)
Best active SD: .13 (MSIS-86,-83) Worst active SD: .19 (J77)

Altitude: MSIS-86,-83 least variance.
Residuals more negative with decreasing altitude for all models.

Latitude: MSIS-86 least variance.
Residuals more positive in northern hemisphere for J70.
Coverage 20S to 20N.

Local Time: MSIS-86 least variance.
Residuals have semidiurnal variation for MSIS-77, J77, J70.

Mean F10.7: Insufficient coverage.

Delta F10.7: MSIS-86,-83 least variance.
Residuals more negative with increasing activity for MSIS-77 and J77 models.

Magnetic: MSIS-86, -83 least variance.
Residuals flat but irregular for all models except more negative with increasing activity for J77. Coverage to Ap 150.

Day/year: MSIS-86 -83 least variance.
Residuals have annual variation with June minimum for MSIS-77, J77, and J70 models.

Longitude/UT: All models have low variance.

Comments: MSIS models better than Jacchia models overall. Jacchia models significantly worse for local time variations and annual.

MSIS-86 trends: altitude.

Altitude: 200-400 Parameter: Total Density Dates: 75341-81155
F10.7: 70-230 Source: AE-E NACE MS Data File: NACE-E

Best quiet mean: -.07 (J70)	Worst quiet mean: -.22 (MSIS-77)
Best quiet SD: .19 (MSIS-83)	Worst quiet SD: .23 (MSIS-77)
Best active mean: -.07 (MSIS-83)	Worst active mean: -.18 (MSIS-77)
Best active SD: .22 (MSIS-83)	Worst active SD: .24 (MSIS-77)

Altitude: J70 least variance.

Residuals more negative with increasing altitude for MSIS.

Latitude: All models have low variance.

Coverage 20S to 20N.

Local Time: MSIS-86 least variance.

Residuals have semidiurnal variation for all models and diurnal for J77 and J70.

Mean F10.7: MSIS-86 least variance.

Residuals irregularly more negative with increasing activity for MSIS models and flat for J70 and J77.

Delta F10.7: J70 least variance.

Residuals flat but irregular for all models.

Magnetic: J77 MSIS-77 least variance.

Residuals irregularly more positive for all models. Coverage to Ap 150.

Day/year: J77 J70 least variance.

Residuals have semiannual variation with equinox minimum for all models.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models except

MSIS-77 (worse) but Jacchia models worse for local time variations.

MSIS-86 trends: altitude, local time, mean F10.7, annual, and magnetic activity.

Altitude: 400-480 Parameter: Total Density Dates: 78336-80281
F10.7: 160-230 Source: AE-E NACE MS Data File: NACE-E

Best quiet mean: -.08 (J70) Worst quiet mean: -.32 (MSIS-77)
Best quiet SD: .18 (J77) Worst quiet SD: .22 (MSIS-77)
Best active mean: -.14 (J77, J70) Worst active mean: -.29 (MSIS-77)
Best active SD: .23 (not MSIS-77) Worst active SD: .27 (MSIS-77)

Altitude: J70 least variance.

Residuals flat except more positive with increasing altitude for MSIS-77 models.

Latitude: All models have low variance.

Coverage 20S to 20N.

Local Time: MSIS-86, -83, J77 least variance.

Residuals have semidiurnal variation for all models except terdiurnal for J77.

Mean F10.7: MSIS-86, -83 least variance.

Residuals more negative with increasing activity except for MSIS-83.

Delta F10.7: MSIS-86, -83 least variance.

Residuals flat but irregular for all models.

Magnetic: J77 least variance.

Residuals flat but irregular for all models. Coverage to Ap 150.

Day/year: All models the same except MSIS-77 worse.

Residuals irregular for all models.

Longitude/UT: All models have low variance.

Comments: Little overall difference between models except MSIS-77 (worse).

MSIS-86 trends: local time mean F10.7.

Altitude: 200-400 Parameter: Total Density Dates: 81220-83047
F10.7: 125-230 Source: DE-B NACS MS Data File: NACSB RHOFIFTH

Best quiet mean: -.15 (J77)	Worst quiet mean: -.33 (MSIS-77)
Best quiet SD: .14 (MSIS-86)	Worst quiet SD: .23 (MSIS-77)
Best active mean: -.15 (MSIS-83)	Worst active mean: -.35 (MSIS-77)
Best active SD: .16 (MSIS-86)	Worst active SD: .21 (MSIS-77)

Altitude: MSIS least variance.

Residuals more negative at lowest altitude for all models.

Latitude: MSIS-86 least variance.

Residuals more negative near poles for MSIS-83 and J70, and more positive for J77. MSIS-77 more negative at south pole and positive at north pole.

Local Time: MSIS-86 -83 least variance.

Residuals have semidiurnal or terdiurnal variation for MSIS-77, J77 and J70.

Mean F10.7: MSIS-86 -83 least variance.

Residuals more negative at higher activity for MSIS-77.

Delta F10.7: MSIS-86 -83 least variance.

Residuals more negative at lowest activity for all models.

Magnetic: MSIS-86 least variance.

Residuals more negative with increasing activity for MSIS-83 and -77 near pole. Coverage to Ap 200.

Day/year: MSIS-86 -83 least variance.

Residuals have semiannual variation for all models.

Longitude/UT: MSIS-86 -83 least variance.

Residuals more negative near magnetic poles for MSIS-77, J77, and J70.

Comments: MSIS-86 model best for standard deviations and J77 best for absolute values. Instrument calibration may be inaccurate.

MSIS-86 trends: altitude, delta F10.7 and annual.

Altitude: 400-800 Parameter: Total Density Dates: 81228-83014
F10.7: 150-230 Source: DE-B NACS MS Data File: NACSB RHOFIFTH

Best quiet mean: -.09 (J77)	Worst quiet mean: -.38 (MSIS-77)
Best quiet SD: .17 (MSIS-86)	Worst quiet SD: .22 (MSIS-77)
Best active mean: -.03 (J77)	Worst active mean: -.31 (MSIS-77)
Best active SD: .24 (MSIS-86)	Worst active SD: .28 (MSIS-77)

Altitude: MSIS-86 least variance.

Residuals more positive at higher altitudes for all models.

Latitude: MSIS-86 J70 least variance.

Residuals more positive at midlatitudes for J77.

Local Time: Variances similar for all models.

Residuals have semidiurnal or terdiurnal variation for all models.

Mean F10.7: MSIS-86 least variance.

Residuals more positive at higher activity for all models.

Delta F10.7: MSIS-86 least variance.

Residuals more negative at lowest activity for all models.

Magnetic: MSIS-86 least variance.

Residuals flat but irregular for all models. Coverage to Ap 200.

Day/year: MSIS-86 least variance.

Residuals have no clear trend. Coverage inadequate.

Longitude/UT: MSIS-86 J70 least variance.

Residuals more negative near magnetic poles for all but MSIS-86.

Comments: MSIS and Jacchia models equivalent except MSIS-77 worse.
Instrument calibration may be inaccurate.

MSIS-86 trends: altitude, mean and delta F10.7.



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16. Abstract Five empirical models were compared with 13 data sets, including both atmospheric drag-based data and mass spectrometer data. The most recently published model, MSIS-86, was found to be the best model overall with an accuracy around 15 percent. The excellent overall agreement of the mass spectrometer-based MSIS models with the drag data, including both the older data from orbital decay and the newer accelerometer data, suggests that the absolute calibration of the (ensemble of) mass spectrometers and the assumed drag coefficient in the atomic oxygen regime are consistent to 5 percent. This study illustrates a number of the reasons for the current accuracy limit such as calibration accuracy and unmodeled trends. Nevertheless, the largest variations in total density in the thermosphere are accounted for, to a very high degree, by existing models. The greatest potential for improvements is in areas where we still have insufficient data (like the lower thermosphere or exosphere), where there are disagreements in technique (such as the exosphere) which can be resolved, or wherever generally more accurate measurements become available.			
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