Long Term Behavior of the Thermosphere Determined from Satellite Drag Measurements

Stephen H. Knowles
Integrity Applications, Inc.
Chantilly, VA
sknowles@integrity-apps.com

Abstract – Archived satellite two-line element sets (TLEs) provide a unique source of comprehensive information about the state of the thermosphere since the start of the space age, due to the drag parameter estimation that results from each daily orbit determination. This information has been used to obtain estimates of the range of thermospheric variability over the entire space age from 1960 to 2013. Histograms of the mean atmospheric density at several altitudes are presented. Data from the latest solar cycle shows significantly decreased density at higher altitudes, which has implications for satellite and debris lifetimes.

Introduction - Much attention has been paid to the improvement of thermospheric models in order to reproduce the atmospheric density, and thus drag experienced by a satellite. However, there has been relatively little attention paid to the actual range of mean thermospheric density encountered by an object at various altitude regimes. This distribution is important to satellite designers and maintainers, to satellite catalog designers and to collision avoidance specialists, because it represents the range of parameters to design against. The mean drag retardation for all cataloged objects is easily available from the 'soak', or curvature parameter, attached to all JSpOC elsets in the form of $\dot{n}$, the rate of change of mean motion, or B*, a normalized ballistic coefficient. Although TLEs have inherent accuracy limitations, the drag retardation term is actually quite accurate, because it is derived from information over the entire fit span, typically three days for LEO objects. This information is available for $\dot{n}$ for the entire space age, and for B* from 1975 onwards, from the archive at spacetrack.org. We have used this information to extract satellite drag statistics.

These are several models for the density of the thermosphere that are commonly used to represent satellite drag. They include MSIS 2000 and Jacchia 71, which in some instances still provides the best representation of satellite drag. These models commonly use the solar proxies $_{10.7}$ and Ap, although improved indices are becoming available. The Ap index is a measure of the general level of geomagnetic activity over the globe for a given (UT) day. One model with the capability to use Mg II and Dtp is Bowman 1988, which has been shown to provide improved results under high solar activity conditions.

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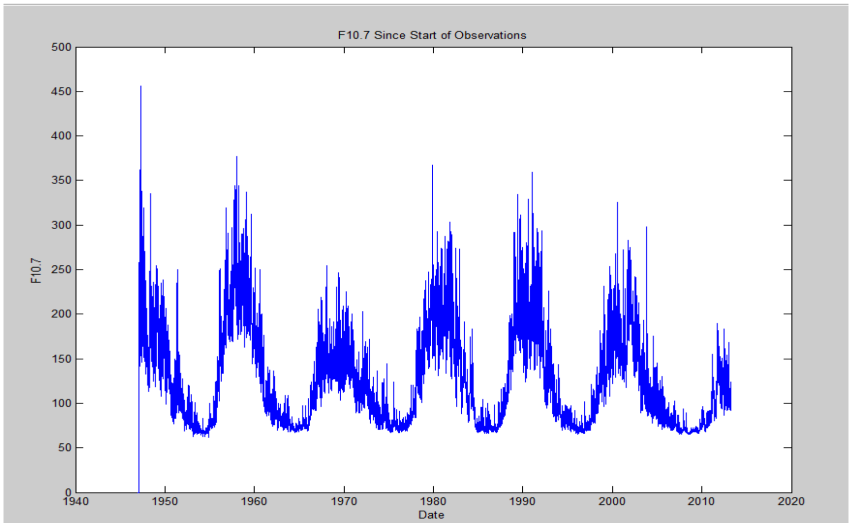


Figure 1 shows the value of the $F_{10.7}$ solar proxy from its inception in 1947 to the present. The effect of the 11-year solar cycle can be clearly seen.

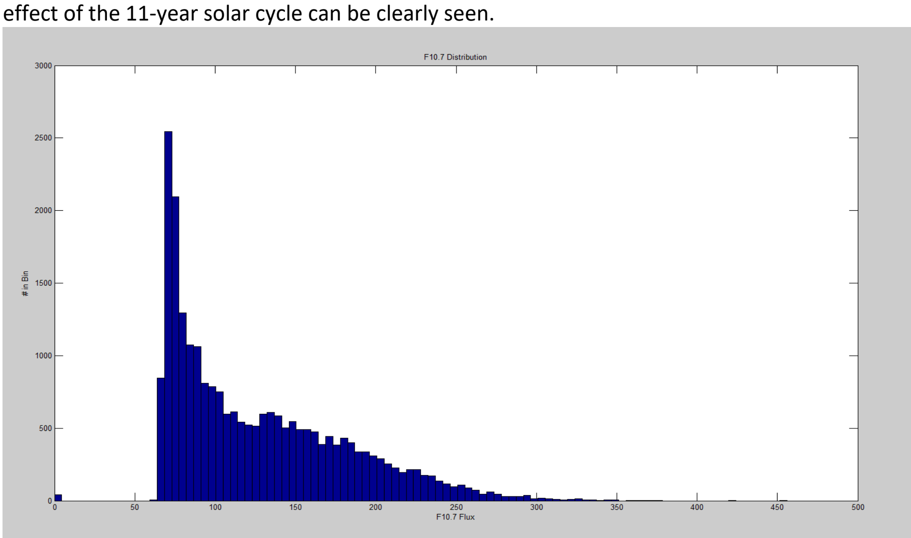


Figure 1A shows a histogram of the distribution of the daily F 10.7 index.

This is a base value for the undisturbed Sun which is always exceeded, while disturbed values appear to follow a Poisson-type distribution, with a highest recorded value of about 350 since 1947. It is unclear if higher values are possible.

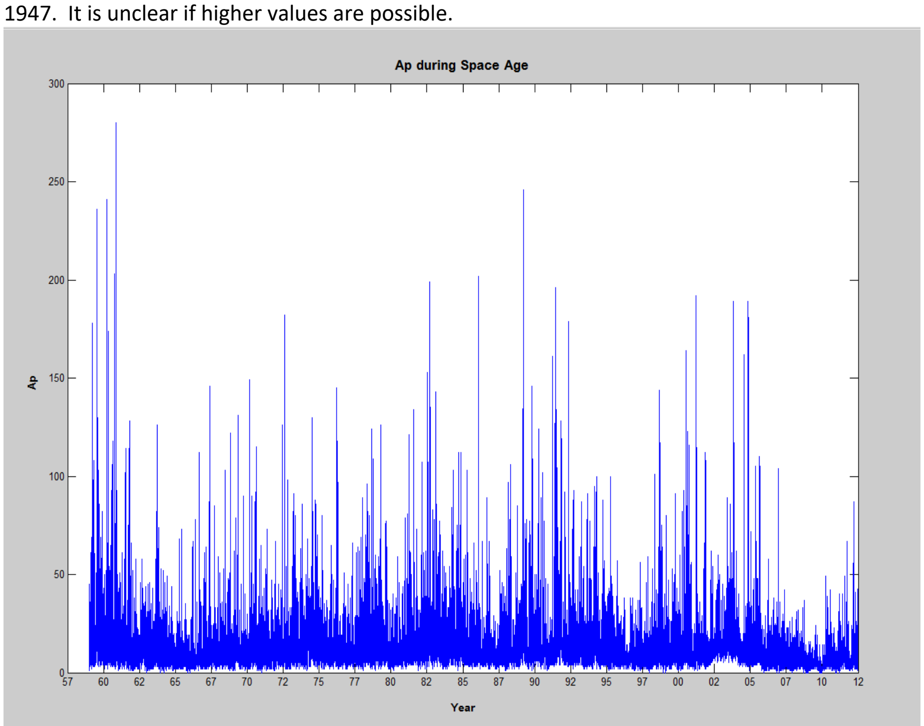


Figure 2 shows the value of Ap over the same period; the correlation with solar activity is much less obvious.

B* is the acceleration or soak parameter in TLEs derived from the SGP4 theory. It is normalized by a crude atmospheric model which is basically proportional to altitude to the -4th power; the actual derivation is not transparent. It should be proportional to the area to mass ratio for a satellite, and also to the mean atmospheric density over the fit span.

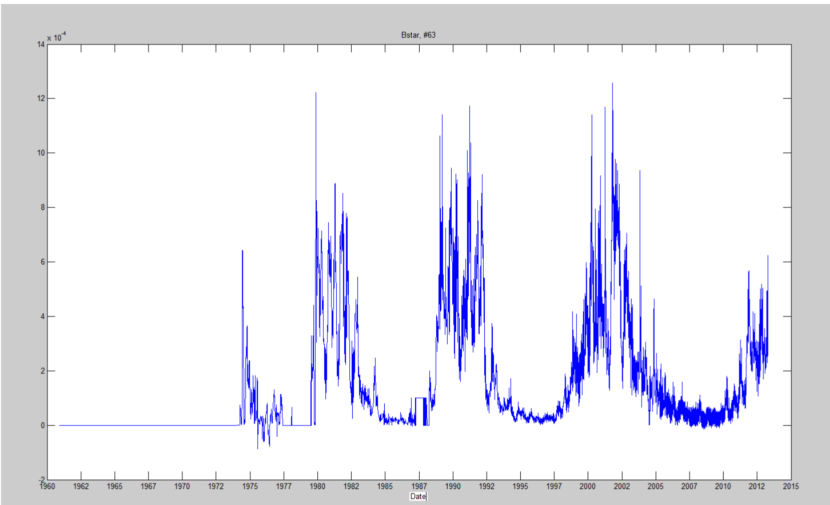


Figure 3 shows the value of B* for a typical LEO satellite over the period since its inception in 1975. Although orbital data has been maintained since 1957, the use of B* was not instituted until 1975, and the values for the first few years are less reliable than later. The general correlation with the F10.7 solar index is obvious.

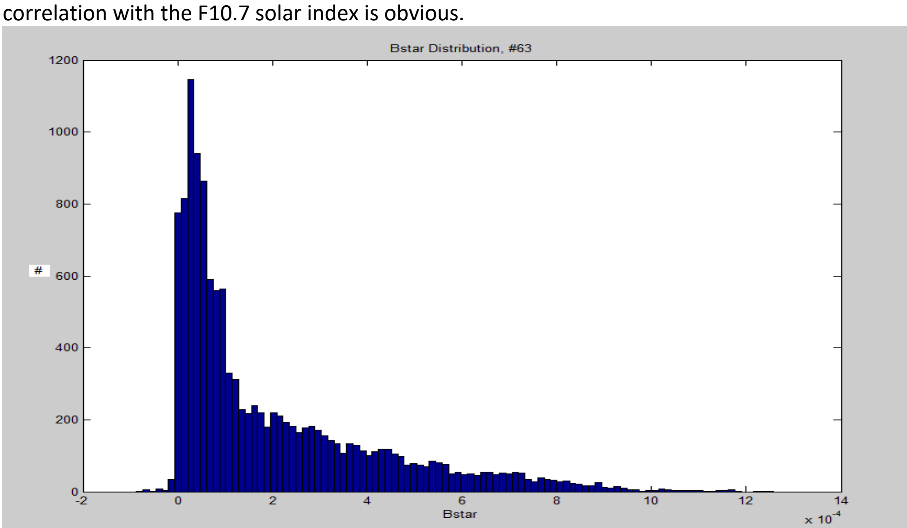


Figure 4 shows the distribution of the daily B* value for this object. A question of much interest is whether the maximum is a never-to-exceed value, or whether still greater values are to be expected from a 'super-storm'.

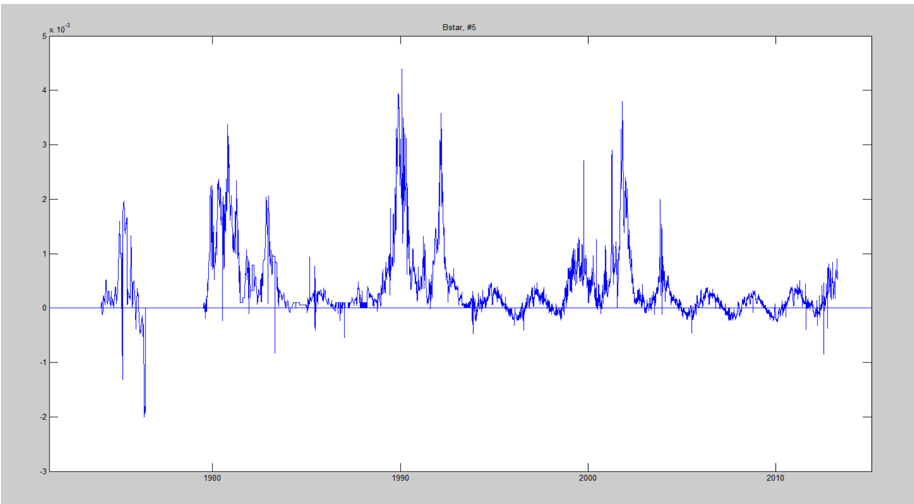


Figure 5 shows B* for a second satellite, the oldest object still orbiting. Because this is at a higher altitude in an eccentric orbit, the values are contaminated for drag purposes by a preiodic orbit term not accounted for in the SGP4 orbit theory.

To show the complex nature of the atmosphere over which an integration must be performed to find the total drag delay, we show figure 6,

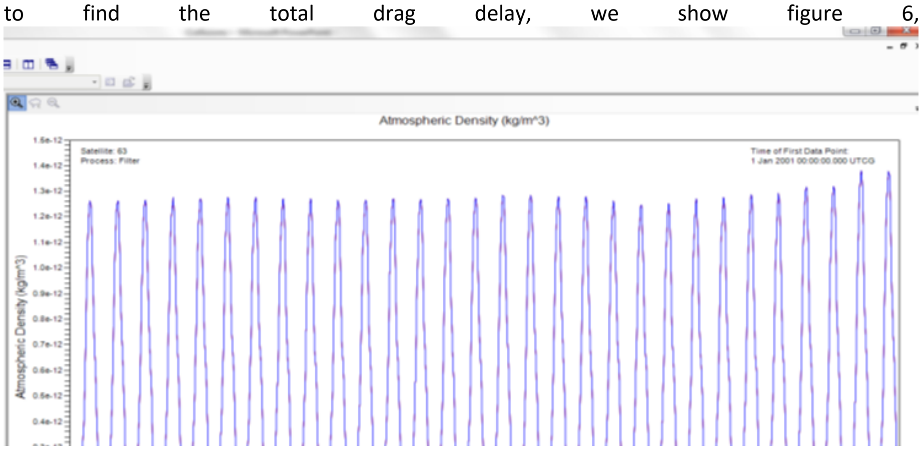


Figure 6 – MSIS-computed density for object #63 for a 2-day period

which shows the predicted atmospheric density over two days from the MSIS 2000 model for a typical satellite. The variation of density by more than an order of magnitude between the day side and night side of the orbit is evident.

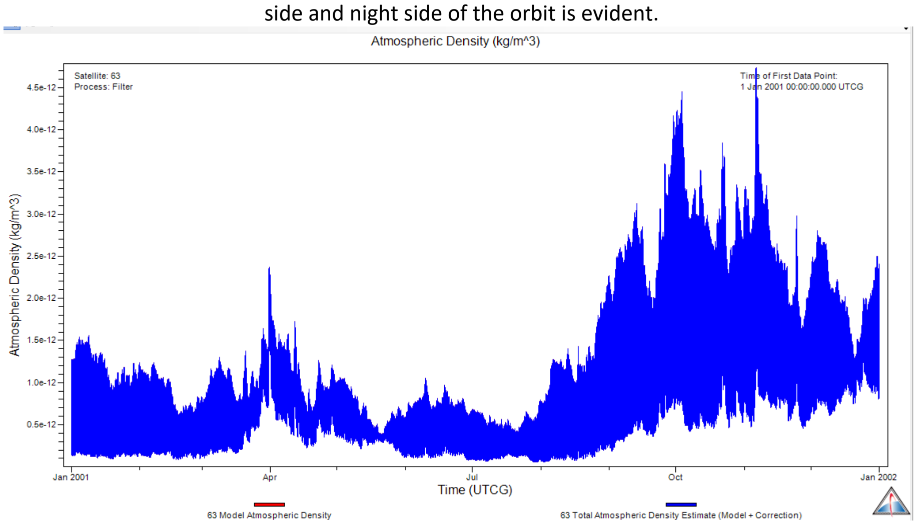


Figure 7 shows the variation for this object over a year. This includes both seasonal and solar activity related terms.

We can translate these numbers into expected daily drag retardation for typical space objects by examining the measured area-to-mass ratio as determined by B^*. Figure 8 shows the B^* for a sample of 100 active payloads. The typical B^* is seen to be about 0.001, although there are outliers with much higher area-to-mass ratio,

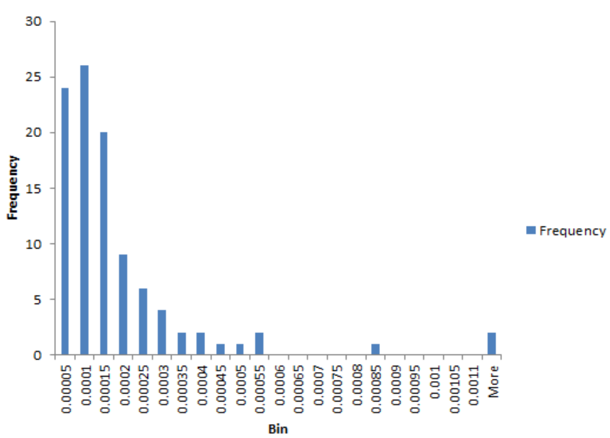


Figure 8 – Histogram of B* distribution for a sample of 100 payloads

Object Type	Average	Median	Sample Size
Payloads	0.00017	0.00008	389
Rocket Bodies	0.00074	0.00018	1054
Catalog	0.0018	0.00049	10742

Table 1 above shows the values for B* for the entire LEO catalog for a sample day, September 20, 2012. The median is a better representation than the average because it minimizes the effect of a few high area to mass ratio objects. On this day $_{F10.7}$ was 117 and Ap was 9. Figure 9 below shows the estimated median total drag retardation for the total catalog as a function of mean altitude for this day. This table was computed by computing a one-day in advance predicted position from each object's TLE, and from the same elset with B* set to zero. This was done with a Matlab script driving the STK engine. Also shown are the earlier prediction from Knowles 1984, which seem to be somewhat high. These are labeled 'max disturbed', 'max normal', 'error in normal' and 'min normal'.

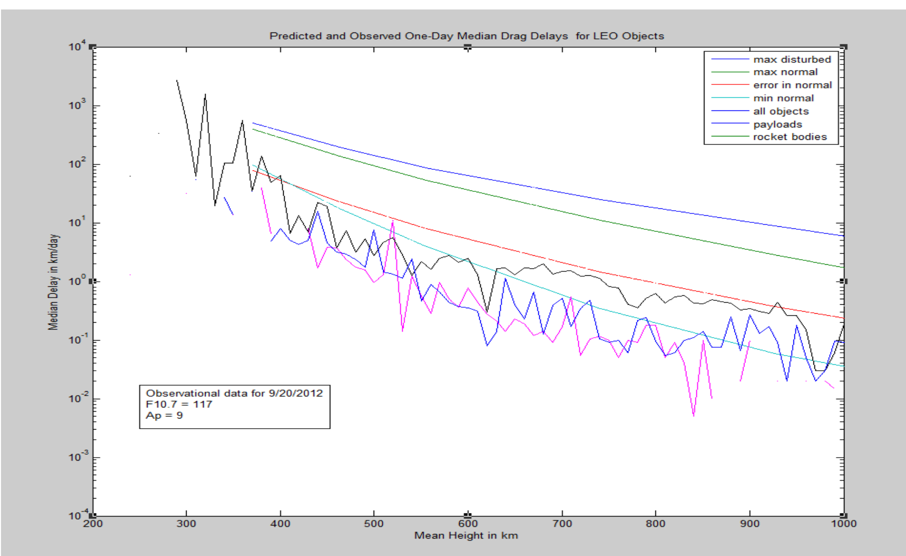


Figure 9 – One-day median drag delays for LEO objects

How correlated are the B* parameters and thus the mean atmospheric drag for different objects? Figure 10 shows regression graphs of 3 pairs of objects with very similar orbits, as well as a close approach of a debris piece to the ISS. Different colors are used to represent high, medium and low phases of the solar cycle. The B*s of the close objects are highly correlated, while the B*s of the ISS and the PSLV object are less so, but still significantly. It is unclear whether the outliers are due to different mean atmospheric density, or peculiarities in the observations for the relevant elset.

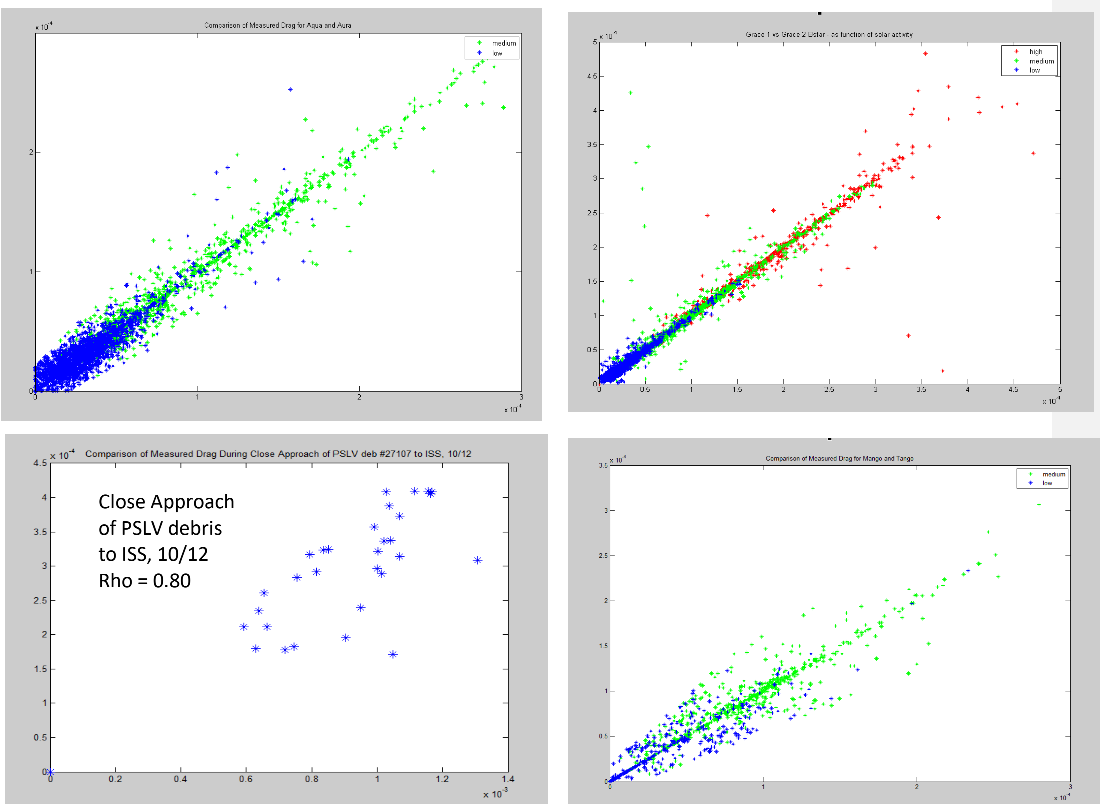


Figure 10 – Regression graphs of B* values for pairs of close satellites

Solar storms – In the past decade, much evidence has come to light of 'extraordinary' events in the history of the Earth that are not easily seen on the time scale of a few years or a century. These events include asteroid impacts, super volcano eruptions, earthquakes, long-term temperature and weather changes, etc. What about the behavior of the Sun? While it seems likely that the mean solar flux has stayed quite constant for some time, we only have quantitative evidence of the impact of solar storms since the middle of the 19th century. The Carrington Event of late August – early September 1859 resulted from the largest sunspot recorded and caused notable perturbations in the telegraph lines of the era, as well as aurorae visible into the tropics. Since the beginning of the Space Age in 1959, several notable storms of lesser intensity have occurred. A brief list includes:

The Space Age Storm	8/2/1972
The Quebec Blackout Storm	3/13/1989
The Bastille Day Storm	7/15/2001
The Halloween Storm	10/29/2003
The Boxing Day Storm	12/26/2011

Each one these produced a large increase in satellite drag. Figure 11 below shows changes in satellite drag for a number of objects for the Halloween Storm. The increase in drag during this event is evident.

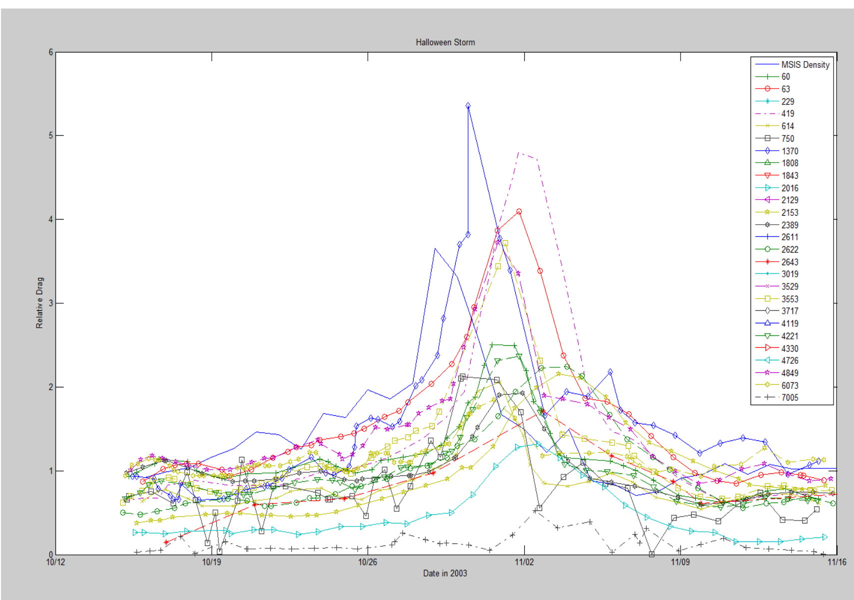


Figure 11- Variation of drag computed from B* during the Halloween Storm

What about the future? Contrary to various alarmist predictions, the current solar activity has actually been somewhat less active than the last .Figure 12 shows the latest monthly means for F10.7

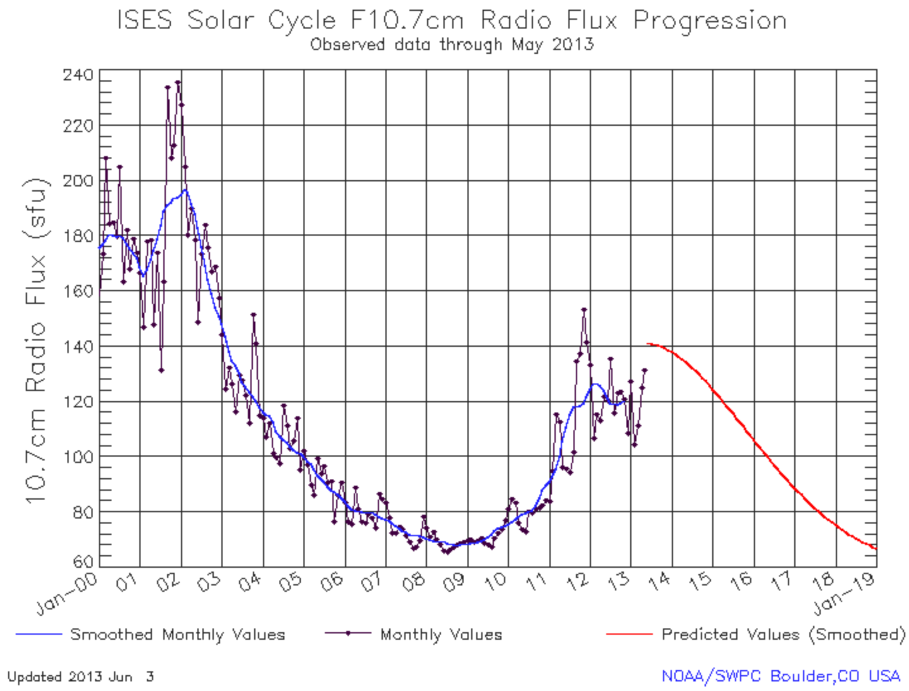
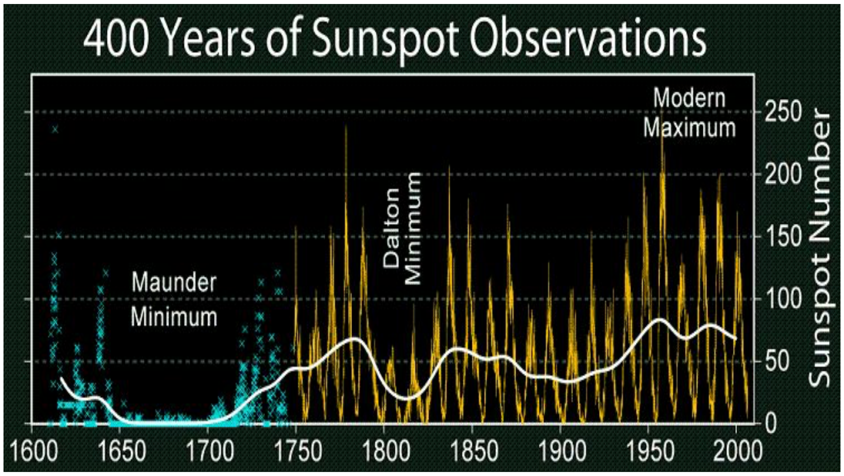


Figure 12 ISES Solar Cycle

Figure 13 below shows sunspot numbers over the 400 year period of quantitative measurement.



There is definitely a possibility of considerably less solar activity in the future; this seems more likely than increased activity.

Conclusion - The database of space object B^* is a unique resource. While not perfect, it can serve as a very useful measure of the thermosphere when properly calibrated. Mean values from B* are quite consistent even with the tremendous day-night variation. It varies by a factor of at least 10 over the solar cycle. Mean densities and thus B*s for objects with similar orbits are highly correlated. This can be used to reduce close approach prediction error. This solar cycle seems to be less active than the previous three.

References

"Density Variations in the Upper Atmosphere During Several Solar Cycles Determined from Satellite Drag Measurements", S. Knowles, Proceedings of/presented at Sixth US/Russian Space Surveillance Workshop, 8/22-26/2005, St. Petersburg, Russia

"The Behavior of the Upper Atmosphere During Solar/Geophysical Storm Conditions As Measured By Satellite Drag During The Entire Space Age," S.H. Knowles, A.C. Nicholas and S.E. -Thonnard, E.O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, DC 20375, presented at 14th AAS/AIAA Space Flight Mechanics Meeting, Big Sky, Montana, 4-7 August 2003

"Density Variations During the Entire Space Age as Determined From Satellite Drag Measurements",S. Knowles Proceedings of/presented at Ninth US/Russian Space Surveillance Workshop, August 2012, Listvyanka, Russia