Density Variations During the Entire Space Age as Determined From Satellite Drag Measurements

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Abstract – The principal source of error in predicting the position of LEO objects is the effect of atmospheric drag. We have used information derived from archived satellite two-line element sets to derive comprehensive information about this effect on a number of long-lasting satellites, and, thus, about the state of the thermosphere since the start of the space age. The drag retardation for typical payloads is from 0.25 to 75 km per day at an altitude of 450 km, and from 10 to 500 m per day at an altitude of 750 km. Importantly, this drag effect varies by a factor of at least 10 between solar minimum and solar maximum. The drag retardation between different objects is highly correlated, which affords an opportunity to improve the perceived accuracy of close approach predictions by taking advantage of this property. We present normalized values of the drag for a sample satellite, and histograms of the drag distribution. The density (drag) distribution is not uniform, but resembles a low-order Poisson distribution. Higher altitudes have larger variance. We have examined satellite drag information during several notorious solar storms, and find that drag does not increase extravagantly. There have been several noted solar storms during the space age that resulted in satellite drag increases. Our present expectation is that the storm frequency will continue at about the same level.

Introduction - Much attention has been paid to the improvement of thermospheric models 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 $\dot{\mathbf{n}}$, 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.

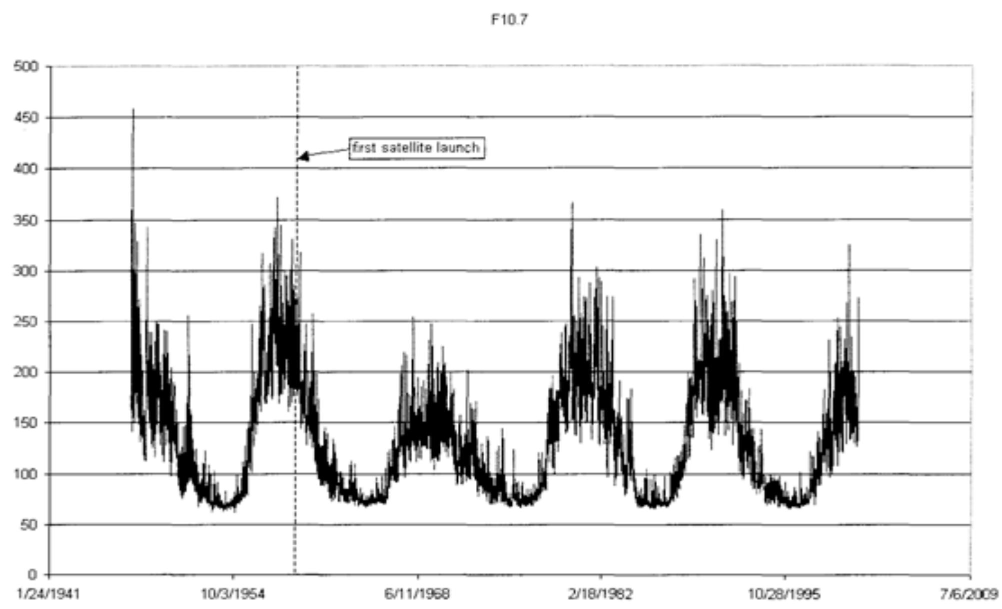
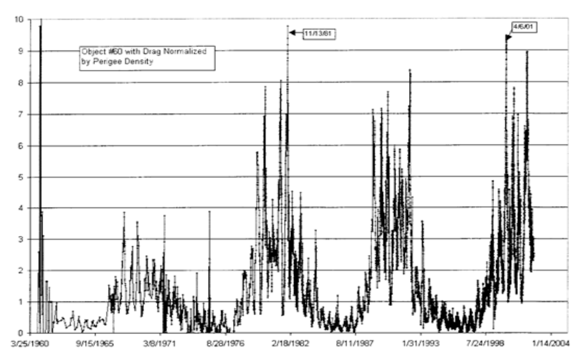


Figure 1

Figure 1 shows the value of the $F_{10.7}$ solar proxy from its inception in 1947 until 2002[1].



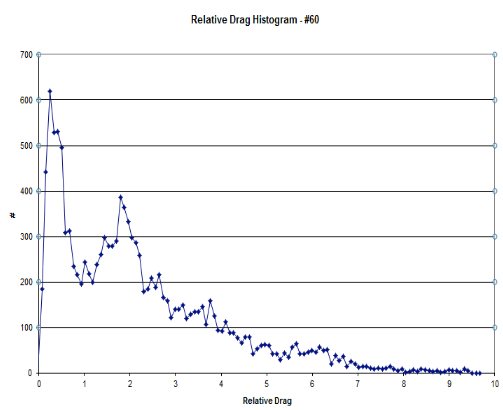


Figure 2

Figure 3

Figure 2 shows perigee-normalized drag for Explorer 8 over this period. The relationship between solar activity and drag can be clearly seen. Figure 3 shows a histogram of the distribution of drag for this object. The drag resembles a Poisson distribution of low order, with a minimum value and a long tail.

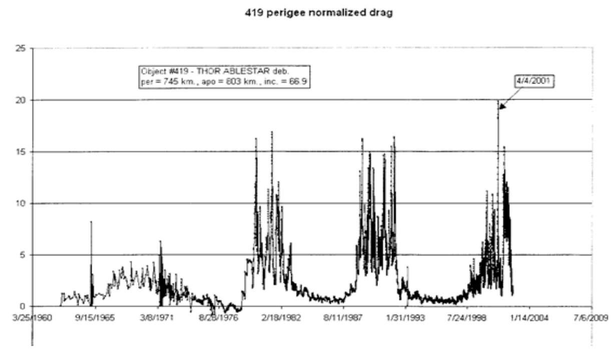


Figure 4

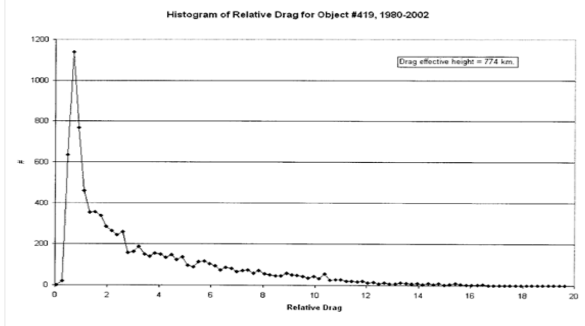


Figure 5

Figures 4 and 5 show these quantities for a satellite with an altitude of about 775 km. The variability is seen to be larger than that for the lower altitude 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'.

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 6 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 a much higher area-to-mass ratio, Figure 7 shows, for an object with typical B^*, the daily drag to be expected under typical solar minimum conditions, under typical solar maximum conditions, and under solar storm conditions. The greater variance at higher altitudes is clearly visible.

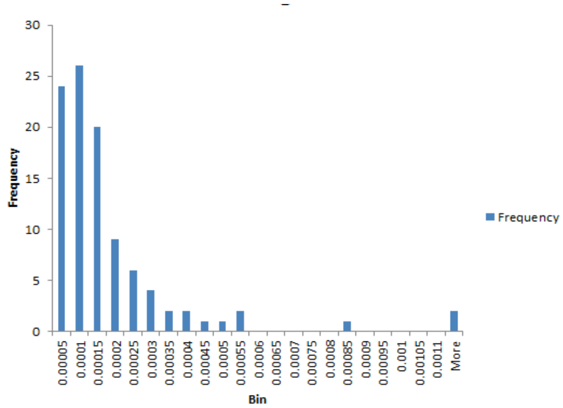


Figure 6

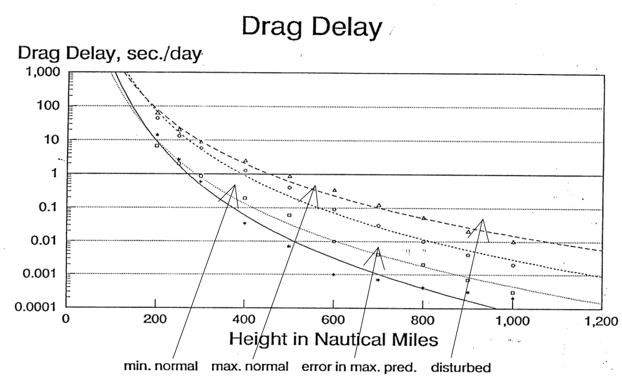


Figure 7

Cross-correlations – we have investigated the long-term correlation between satellite drag and geophysical parameters.

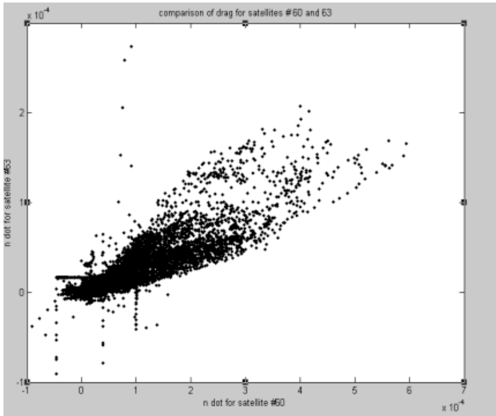


Figure 8

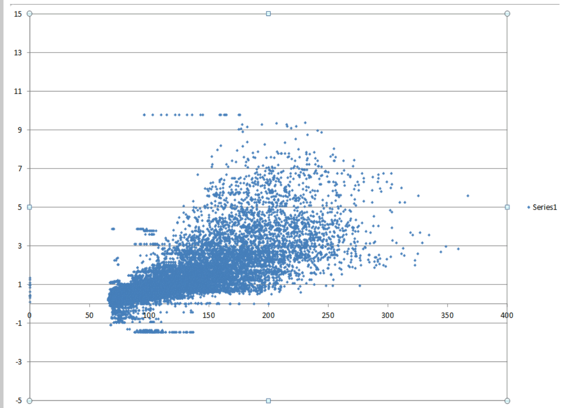


Figure 9

Figure 8 shows the cross-correlation between ndots for objects # 60 and 63. The correlation is generally excellent. This has large implications for collision avoidance predictions, as the cross-correlated part of the drag variance can be compensated for. Figure 9 shows the cross-correlation between $F_{10.7}$ and #60 drag. While good, it is not 100%. There is a particular tendency for discrepancies at the higher values of drag and/or $F_{10.7}$.

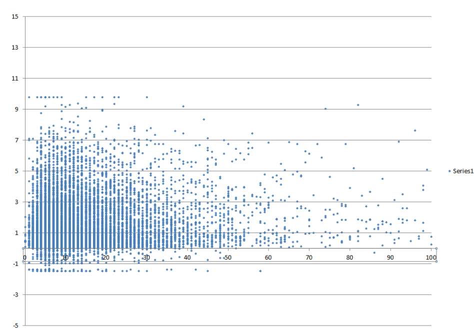


Figure 10

Figure 10 shows the correlation between the drag for object #60 and A_p. A_p is a standard geomagnetic index. The correlation is generally quite poor. This seems to be primarily because A_p is not an excellent measure of thermospheric geomagnetic disturbance.

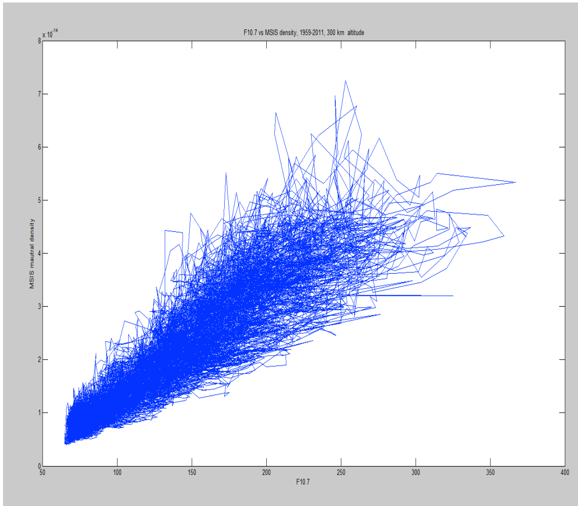


Figure 10

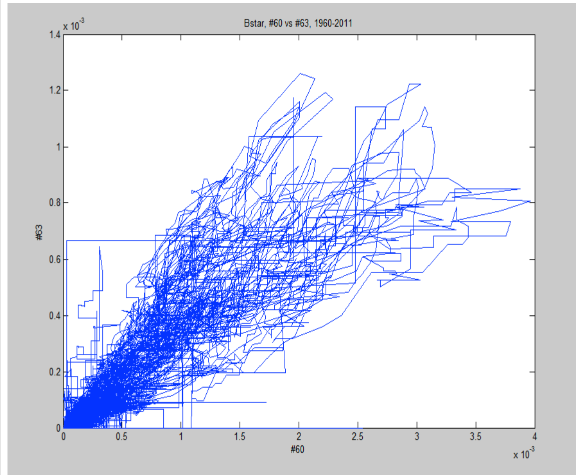


Figure 11

Figure 10 shows the correlation between the $F_{10.7}$ index and a mean MSIS density computed for object # 60, while Figure 11 shows the correlation between the B^*s for objects # 60 and # 63.

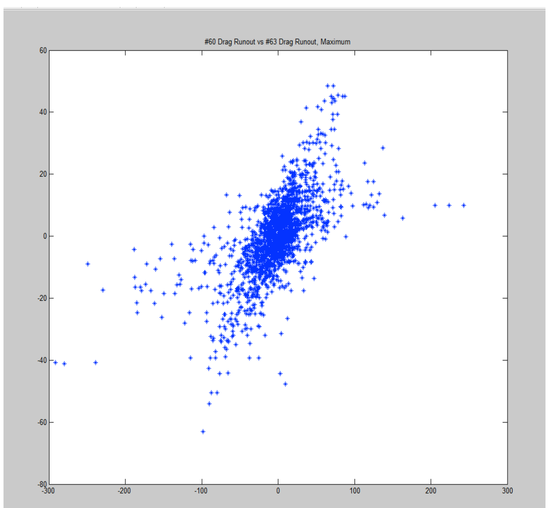


Figure 12

Figure 12 compares drag runout for objects #60 and #63 for the times of solar maximum. The runout is computed by comparing the predicted position from elset #n at the time of elset #n+1 to the actual value from elset n+1 at that time. It may be seen that the differences generally track quite well. The long-term computed correlations are shown in the table below. The best correlation is that between the drag coefficients for objects with similar orbits.

Indices	**Long-Term Correlation**

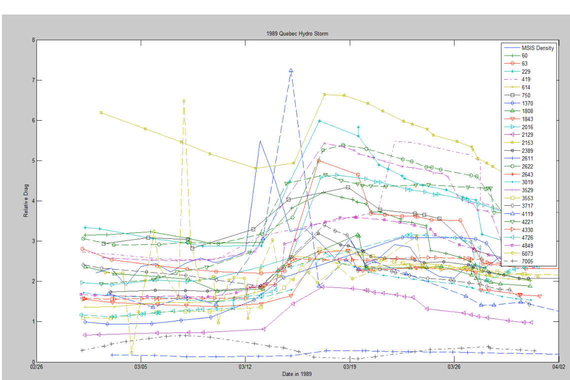
$F_{10.7}$, B^* for #60	0.62
MSIS density, B^* for #60	0.66
A_p, B^*	0.11
B^* for #60, #63	0.85

What about implications for future satellite drag? Some authors have found a decrease in mean density during the recent solar minimum[2]. If this decrease continues, it will mean longer satellite lifetimes, and aggravate the space debris problem. However, it is very important to verify this during the active portion of the solar cycle, as this is when the major part of drag retardation takes place.

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, supervolcano 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 1959 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[3]. The next two figures show changes in satellite drag for a number of objects for the Quebec Blackout Storm and the Halloween Storm. This effect is clearly visible.



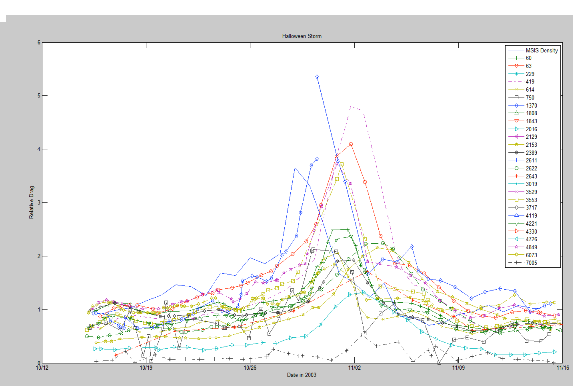


Figure 13 Figure 14

Conclusion - The database of space object B^*s is a unique resource. This paper describes a very preliminary investigation of this database. Extending it would yield much information about thermospheric density, satellite drag, collision likelihood, and environmental dangers to the Earth.

References

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

2 - J.T. Emmert, J.M. Picone, J.L. Lean, and S.H. Knowles, "Global Change in the Thermosphere: Compelling Evidence of a Secular Decrease in Density," with J.T. Emmert, J.M. Picone, J.L. Lean, J. Geophys. Res. 109(A02301), doi:10.1029/2003JA010176 (2004).

3 - "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 SpaceFlight Mechanics Meeting, Big Sky, Montana, 4-7 August 2003