SATELLITE LIFETIME AND SOLAR CYCLE PREDICTIONS

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ABSTRACT

Accurate lifetime estimates for satellites are an important aspect of satellite design and compliance with International debris guidelines. Many tools exist to estimate these times. Unfortunately, all tools rely on predictions of space weather (solar flux and geomagnetic indices). This paper explores various long-range solar flux predictions and their effect on satellite lifetime. A percentile approach is used to accurately simulate space weather conditions from observed values over the last 5 solar cycles. Both daily and smoothed values are possible. This should further our understanding of the variability in satellite lifetime predictions.

1 INTRODUCTION

Accurate satellite lifetime estimates are an important value to determine, especially when considering satellite design. Minimizing estimated post-mission lifetime below an internationally-established threshold is one of the central tenets to today's orbital debris mitigation guidelines.

Many tools exist for estimating the estimated decay time. While these tools vary in levels of fidelity, one of the most significant influencers on satellite lifetime is the impact of changing solar flux and geomagnetic predictions. For this reason, further research and comparisons of the various long-range space weather pre-dictions and their effect on satellite lifetime is warranted.

Note this topic intertwines both sunspot activity, and Extreme Ultraviolet (EUV) radiation and geomagnetic indices from the Sun. It's the EUV and geomagnetic values that drive atmospheric density changes, and thus changes to satellite lifetime. We can't measure the actual EUV radiation that causes the density changes, but F10.7 is a reliable proxy for the EUV values, and it's been measured for almost 100 years. The sunspot activity exhibits a similar cyclical motion over time, and has been measured for over 300 years. Figure 1 shows the relationship between the sunspot number and the solar flux proxy (F10.7). Note the different averaging times. 81 days is common for atmospheric density models that take three solar rotations into account. Sunspots use months, and years for averaging times. The daily sunspots vary more, but not as much as the daily F10.7 values.

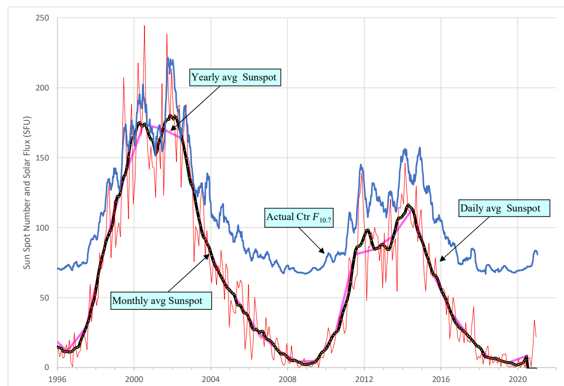

Figure 1. ***Solar Flux Proxy and Sunspot Numbers.*** *The last 2 solar cycles show remarkable similarity between solar flux and sunspot numbers, but there are differences. $F_{10.7}$ is averaged over 81 days while the sunspots are averaged over months and years. Sunspot data from WDC-SILSO, Royal Observatory of Belgium, Brussels, http://www.sidc.be/silso/datafiles January 28, 2021).*

Space weather varies greatly on both short-term (days to weeks) timescales, and long-term (approximately eleven year cycle). The timing (early/late) and the magnitude (high/low) are not consistent and predictable. There is also some variability in the accepted start and stop dates for each cycle

Prediction methods vary between physical models that try to understand the Solar processes, and heuristic curve matching approaches. The physical modeling is quite complex with the Schatten approach probably being the most well-known technique. Heuristic curve fitting is more common, but also lacks some realism in that the average values are often generated from a year or so of data. Thus, the granularity of any data spikes is lost. Longer range space weather predictions, those of 3-4 solar cycles or more, are even more difficult and

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less certain. However, their accuracy is needed to get reliable results for satellite lifetime.

A percentile approach to predict space weather from the existing observed values requires an accurate starting point so the solar cycle rise occurs at approximately the same relative point in each cycle. Vallado and Kelso (2015) extended the percentile approach (Oltrogge and Chao, 2007) to estimate space weather parameters for both the current solar cycle, plus additional future cycles, once a certain percentile was chosen. The advantage is that actual observed data is used to form any future cycle. This also includes the ability to take the daily values of each parameter (solar flux, geomagnetic indices, eight 3-hourly values, etc), and predict a future value. Because the data originates from correlated indices at points in time, the resulting predictions may better approximate the actual conditions on a date in the future.

All space weather prediction models use some form/length of smoothing in the representation of the values. Admittedly, the prediction process has enough error in it to suggest some smoothing, yet, the effect of this smoothing on satellite position and lifetime is largely unquantified. One study [Woodburn, 2007] found via stochastic modeling that smoothing can have the effect of underestimating decay due to the non-linearities of drag forces as a function of space weather proxies. The smoothing is generally over about 13 months. Although the resulting data is convenient for transmission, does it accurately reflect the behavior a satellite will experience? Note that this smoothed solar activity is not to be confused with the 81-day aver-age. Positional differences are shown for various space weather conditions (high and low solar activity), as well as smoothed results.

Fraysse et al (2011) discuss an equivalent solar activity value they derive, predominantly for reentry calculations. It consists of statistically derived constant solar flux and geomagnetic values that assure a 50% probability of achieving a 25-year lifetime with various solar activity levels. Comparisons are also made to this approach as it is a variation of the smoothed methods used elsewhere. The approach uses these values.

$$a_{p50\%} = 15 \tag{1}$$

$$F_{10.7\_50\%} = 201 + 3.25\ln\left(\frac{c_D A}{m}\right) - 7\ln(a_a)$$

The satellite mass and area are input with a coefficient of drag (c_D = 2.2), and the altitude of apogee (a_a) is the mean value for the orbit under consideration.

Some existing studies have examined various aspects of this topic. An important paper is Niehuss et al. (1996) in which they detail the various prediction methods. Variations of the McNish-Lincoln approach are the most common forms in use today. They use a 13-month smoothing interval and produce only smoothed monthly estimates of solar activity. This complex technique uses quantiles and percentiles to arrive at sever-al percentile value estimates. Unfortunately, this approach does not produce the daily variations that we observe for solar activity and there are some caveats that seem to limit the length of time that the prediction is valid.

Woodburn and Lynch (2005) analyzed various aspects of satellite lifetime by developing “a stochastic sequence to generate realistic future solar flux trajectories”. They then used Monte Carlo results to show the variability of smooth vs varied space weather data, different atmospheric models, and numerical integration vs analytical propagation for lifetime calculations. They also examined short term proxy variations. Woodburn and Lynch showed that the effect of atmospheric drag is not linear with the proxies, and the smoothed result does not represent it linearly. We think the percentile approach better produces realistic solar cycles.

Oltrogge and Chao (2007) examined lifetime results, and included some detailed plots of bc vs lifetime.

Vallado and Finkleman (2014) examined many effects resulting from how the space weather data is implemented in various atmospheric models. They did not include details on the effects of an individual storm, nor on lifetime results from jagged or smoothed cycles.

This paper shows various lifetime predictions using several simulated space weather predictions for a variety of satellites that have reentered. We provide analysis of these satellites using the actual space weather data, smoothed approximations to the cycles, our percentile daily calculations, and the equivalent solar activity value of Fraysse et al. (2011). The effect on satellite lifetime is of interest. In particular, do the daily variations present in the actual data produce noticeably different results from the traditional smoothed, or constant predictions of solar flux?

2 SOLAR CYCLE START AND END DATES

For the percentile approach to work, the start and end dates of each solar cycle must be established so the rise and fall of each cycle is consistent. Because the cycles tend to rise rapidly after the start, the percentile approach requires a consistent/accurate estimate of the start times. The dates are generally extracted from sunspot activity which has a fair amount of variability (notably the early years in the 18^{th} and 19^{th} centuries, and the end of cycle 21 and beginning of cycle 22) depending on how researchers recorded sunspots. The values are periodically adjusted and a large adjustment took place in 2015 (http://www.sidc.be/silso/newdataset).

Table 1. Solar Cycle Dates. Solar cycles are usually found via sunspot numbers. There are some differences in dates between organizations. (Wikipedia/SIDC Jan 11, 2021) Future cycles are assigned arbitrary lengths. The 6 cycles refer to solar cycles 19 to 24.

Cycle number	Adopted Date	Length (days)	# mons
14	1-Jan-1902	4199	140
15	1-Jul-1913	3683	123
16	1-Aug-1923	3684	123
17	1-Sep-1933	3805	127
18	1-Feb-1944	3712	124
19	1-Apr-1954	3836	128
20	1-Oct-1964	4169	139
21	1-Mar-1976	3836	128
22	1-Sep-1986	3622	121
23	1-Aug-1996	4505	150
24	1-Dec-2008	4017	134
25	1-Dec-2019	4139	138
26	1-Apr-2031	4413	147
27	1-May-2043	4475	149
28	1-Aug-2055	4322	144
29	1-Jun-2067	4413	147
30	1-Jul-2079		
	Avg 6 cycles	4018	
	Avg all cycles	3934	

3 EXISTING SMOOTHING APPROACHES

Smoothing is a characteristic of most, if not all, atmospheric prediction strategies. A very good description of some of the prominent smoothing and prediction approaches is from the Sunspot Index and Long-term Solar Observations, Royal Observatory of Belgium, Brussels. http://www.sidc.be/silso (descriptions of each method is in subdirectories such as silso/predisc).

Traditionally, smoothed results are given for future solar cycles, however the actual variability is considerably higher. Consider the following figure. Notice the large magnitude, timing, and other errors.

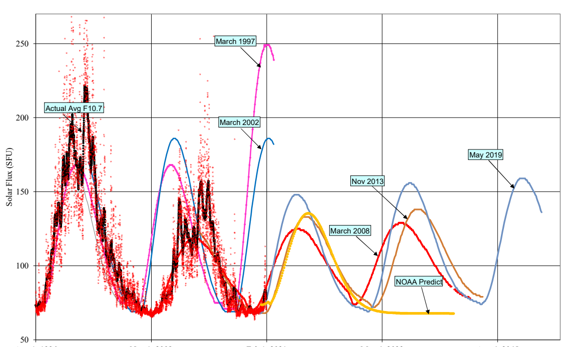

Figure 2. ***Predicted Schatten Solar Cycles.*** *A couple predictions about 10 years apart, are shown with actual daily and center 81 day values. Notice the magnitude and timing mis-matches. The March 1997 prediction missed the timing of Cycle 24, and really missed the magnitude of cycle 25. The March 2002 prediction got cycle 24 magnitude, but missed its timing, and really missed the cycle 25 magnitude and timing. The March 2008 matched cycle 24 pretty well, but was a bit low. While the Schatten predictions include variations to cover magnitude and timing, their accuracy seems to be limited to just about 1 solar cycle. Finally, the cycle 26 prediction from NOAA appears as a single value for the entire cycle!*

While we understand that precise predictions are impossible, the variability of the observed data suggests that "some" variability be placed in the future predictions. We wanted to find out what difference this variability will have on actual satellite lifetime predictions. Cases are presented for both solar flux and geomagnetic indices.

4 PERCENTILE PREDICTION SETUP

Using a percentile approach, Vallado and Kelso (2015) found that previous solar cycles could be modeled quite well. There were several options we used in creating the data.

1. Normalize the calculations to the length of a solar cycle (0.0 to 1.0), or use the number of days (1 to 4417, 3836, etc). The normalization seems to be a better approach as it should keep high and low points in the cycle at the same approximate times while an un-normalized approach, especially at the end of the cycle, could pair different portions of the cycles. The un-normalized approach also would draw from fewer existing data observations for longer cycles.
2. Report out all the daily percentile values. Although we could use the percentile approach with centered 81-day values, we felt this obscured too much variability in the data. We calculate the daily 81-day values once the daily values are found.
3. Average the monthly values for 13 months (that seems to be the common smoothing approach in the community) and report out the monthly values.

Using a normalized cycle approach, cycle 23 was best with a 48th order percentile, and cycle 24 looks like this using a 5th order percentile. Note that the 81-day average is simply taken from the daily estimated values, and is not smoothed for any additional time periods. The smoothed result is a centered average, otherwise, it would display a time lag from the rest of the data.

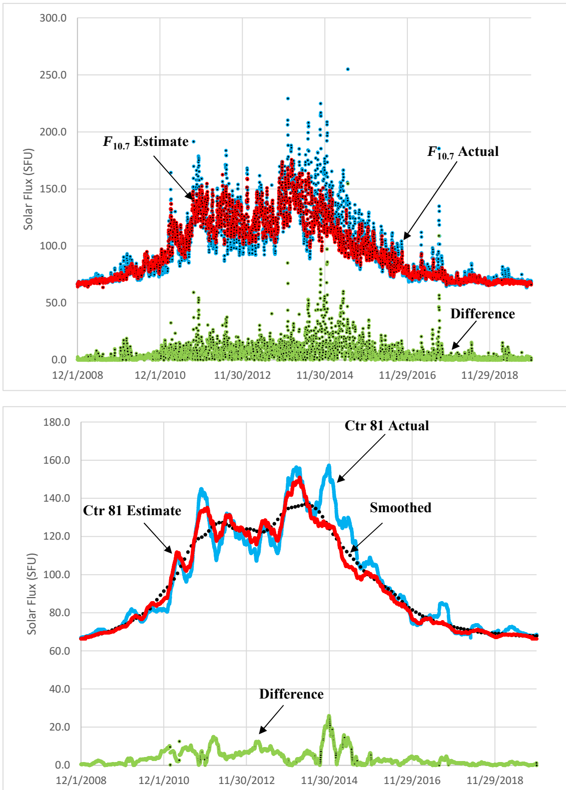

Figure 3. **Solar Cycle 24 Daily and Center 81-day Solar Flux.** The daily solar flux (top) and center 81-day average (bottom) are derived from the percentile approach. A 5th percentile seems to approximate the actual data very closely. The cycle lasted 4017 days which is a little longer than the average 3934 days.

5 LONG RANGE PREDICTIONS

Generally, the next solar cycle or two into the future is as far as predictions cover. Lifetime calculations can often exceed this time interval. The solar cycle generally is determined by counting the number of sunspots. This process has some variability in approaches, and the values are periodically re-estimated. Values are often smoothed over 13 months, thus they will immediately not represent that actual behavior we would see over time. We note that most current predictions seem to follow the previous known cycle. But the cycles do not show that same behavior from cycle to cycle except in only a couple cases over the last several hundred years. It would therefore be unrealistic to assume that the next 3-4 cycles would match the previous cycle. An April 2018 Schatten prediction showed 4 cycles into the future, however, these cycles all followed the previous cycle – something we don't observe since records began being kept in about 1700.

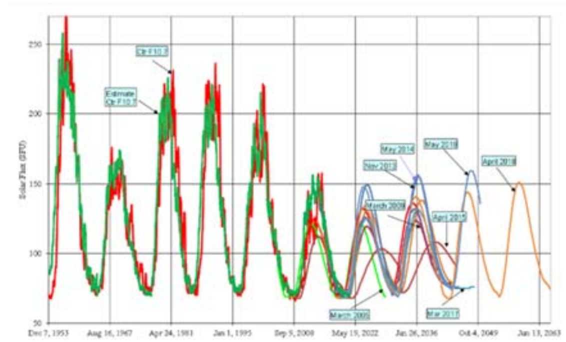

Figure 4. **Future Space Weather Predictions.** Future predictions show a conformity to the previous cycle.

6 SATELLITES CONSIDERED

We searched for some satellites that had reentered, but also that had sufficient TLE information with which to perform lifetime analyses. Several important notes apply. Specific satellite parameters (c_D, c_{SR}, m, A, etc) are sometimes difficult to obtain. The mass and area are from the DISCOS database. The primary information is from entries in the US Space Force (USSF) situation catalog. However, these are usually the last known or recorded values. Thus, the apogee and perigee values would represent end-of-life values from the TLE's. For predicting the reentries of these objects, we required the standard mission operational orbit "before" decay had taken place. In some cases, de-orbiting burns are performed as when UARS performed a maneuver in 2006 to adjust the operational orbit (575 × 575 km altitude), to a 518 × 381 km altitude orbit. An epoch is included to indicate the TLE date used for the analysis. The decay date is from the USSF situation report. While some objects have confirmed sightings or other information detailing the precise reentry time, others do not and can have some variability (days?) in the actual reentry time. For the rocket bodies and debris, TLEs were taken about a month after orbit insertion/debris generation to allow time for the satellite to be in its operational altitude and properly picked up by the TLE orbit determination processing.

Table 2. Analysis Satellites. This list shows several satellites we used as tests for lifetime calculations. Some of the satellites had maneuvering capability, but most did not. The mass and area are from the DISCOS database that lists most satellite information derived from various sources. The Titan 34B and COBE debris satellites had no DISCOS entry, so we assumed values for these. The epoch date represents a time where the satellite was no longer maneuvering and was simply orbiting until reentry.

Name	NORAD #	Apogee Alt (km)	Perigee Alt (km)	*e*	*i* (°)	Mass (kg)	Area (m^2)	Launch Date	Epoch Date	Decay Date
TITAN 34B AGENA D R/B	6792	340	95	0.018573	62.800	600.0	8.3056	1973-08-21	1991-01	2020-02-25
COBE DEB	23073	884.05	820.25	0.004412	98.974	15.0	0.5000	1989-11-18	1994-01	1996-05-12
ROSAT	20638	545.34	530.87	0.001046	52.990	2468.8	5.8669	1990-06-01	1999-03	2011-10-23
UARS	21701	511.61	370.72	0.010330	56.981	6757.2	43.2734	1991-09-12	2006-01	2011-09-24
ARIANE 44L+ R/B	21941	32963.68	246.48	0.711763	3.969	1764.1	25.9747	1992-04-15	1996-11	2020-10-02
DM-F3	26476	20552.25	200.40	0.607356	27.527	4348.0	4.2412	2000-08-23	2000-09	2019-12-31
IRIDIUM 96	27376	738.38	287.48	0.032717	86.383	655.0	6.5552	2002-02-11	2018-01	2020-05-30
ATLAS 2A CENTAUR R/B	27567	30484.89	182.13	0.697846	26.778	2095.0	28.3647	2002-12-05	2003-01	2018-11-04
MONITOR-E 1	28822	534.34	523.64	0.000775	97.466	750.0	7.0840	2005-08-26	2008-02	2020-09-22
PSLV R/B	32477	585.64	469.13	0.008436	41.050	920.0	6.1850	2008-01-21	2008-02	2020-01-23
TIANGONG-1	37820	394.50	375.57	0.001399	42.763	8500.0	25.2522	2011-09-29	2016-04	2018-04-02
PHOBOS-GRUNT & YINGH	37872	333.58	207.72	0.009465	51.433	13505.0	11.6940	2011-11-08	2011-11	2012-01-15
SL-24 DEB	40048	613.94	552.16	0.004437	97.992	50.0	3.9713	2014-06-19	2014-07	2020-12-21
ARIANE 5 DEB [SYLDA]	41796	35588.90	253.60	0.727082	6.071	440.0	27.3908	2016-10-05	2016-11	2021-01-06
SHENZHOU 11 MODULE	41868	387.60	373.68	0.001030	42.798	1842.0	9.2767	2016-10-16	2016-11	2020-10-06

7 CREATING THE SPACE WEATHER FILES

To test the various analysis satellites, we required several space weather files. The actual observed files are readily available (http://www.celestrak.com/SpaceData/). Files were constructed to achieve the various smoothed configurations. Recognize that all the approximations are formed to a known cycle where the magnitude and length would not be fully known. Thus, the variations likely have less magnitude and timing uncertainty than they would in actual operations.

Several options existed to create the solar cycles.

1. A baseline for all the cases was to create a full solar cycle for each day using a single percentile value. This creates the variability observed in all the previous data, but results in the largest data file (depending on how many future solar cycles are included).
2. Average the daily data over the three-solar rotation 81-day period used in most atmospheric models.
3. Average the results over a longer period of time. Most techniques seem to average the values over 13 months. While making the cycles appear to vary smoothly, it misses important dynamic characteristics of the actual data.

Consider the following figure.

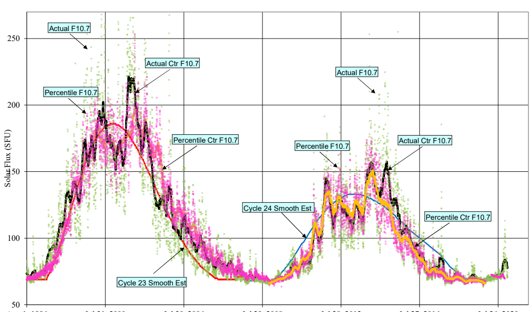

Figure 5. **Study Space Weather Values.** The actual F10.7 and centered values are shown with the percentile approximations, and the smoothed cycles. The percentile approach has slightly less variability than the actual data. All the approximations are fit after the fact and are likely better correlated than true predicted cycles would be.

This let us construct several files to use in the analyses. First was the actual space weather data for cycle 23, 24, and part of 25. We then created a daily and a smoothed file for the best percentile to match cycle 23 and 24, and an estimate for cycle 25. Finally, we created files for a 5th percentile above, 10th, above, and 20th percentile above. The last test files were intended to understand the variability of the percentile and its proximity to the best value for a solar cycle.

8 LIFETIME RESULTS

Using the actual space weather data, we find the following estimated reentry times using numerical (HPOP) and SGP4 techniques. Note that the approaches are not always better or worse than the other. The estimates are all from the epoch time of the TLE chosen (see Table 2 values) and the differences are for the estimated dates from the actual date of reentry. There doesn't appear to be too much correlation in the data other than perhaps the TLEs from 20 years ago seemed to perform a little better than the numerical counterpart.

Table 3. Lifetime Results – Actual Space Weather Data. The numerical and SGP4 lifetime estimates are shown for the analysis satellites. The closest predictions are highlighted. The estimates are all from the epoch for each satellite, while the difference is from the actual decay date for both approaches. Remember that Phobos-Grunt, Tiangong, and UARS have large masses.

Name	NORAD #	Actual Decay	HPOP Est from epoch			SGP4 Est from epoch			from actual (days)	
TITAN 34B AGENA D R/B	6792	2020-02-25								
COBE DEB	23073	1996-05-12								
ROSAT	20638	2011-10-23	2021-08-09	22.4	yrs	2010-12-10	11.7	yrs	-3578	317
UARS	21701	2011-09-24	2010-04-01	4.2	yrs	2009-07-02	3.5	yrs	541	814
ARIANE 44L+ R/B	21941	2020-10-02	2000-04-22	3.4	yrs	2017-01-28	20.1	yrs	7468	1343
DM-F3	26476	2019-12-31	2150-12-16	150	yrs	2014-03-30	13.3	yrs	-47832	2102
IRIDIUM 96	27376	2020-05-30	2020-04-15	2.3	yrs	2019-04-12	1.3	yrs	45	414
ATLAS 2A CENTAUR R/B	27567	2018-11-04	2004-09-20	1.6	yrs	2003-06-25	150.0	dys	5158	5611
MONITOR-E 1	28822	2020-09-22	2022-01-09	13.9	yrs	2107-09-05	99.6	yrs	-474	-31758
PSLV R/B	32477	2020-01-23	2015-08-08	7.4	yrs	2063-12-07	55.7	yrs	1629	-16024
TIANGONG-1	37820	2018-04-02	2018-09-06	2.4	yrs	2017-10-07	1.5	yrs	-157	177
PHOBOS-GRUNT & YINGHOU-1	37872	2012-01-15	2012-01-31	79	dys	2011-12-22	38.0	dys	-16	24
SL-24 DEB	40048	2020-12-21	2016-03-17	1.7	yrs	2029-05-12	14.8	yrs	1740	-3064
ARIANE 5 DEB [SYLDA]	41796	2021-01-06								
SHENZHOU 11 MODULE	41868	2020-10-06								

Next we took daily, smoothed, and equivalent versions of the space weather data and ran the same lifetime analyses.

Table 4. Lifetime Results – Percentile Data. Smoothed and percentile space weather data is used in varying configurations with the test satellites. The highlighted cells indicate predictions that were closest to the actual reentry date for each satellite.

					Daily Percentiles							
Name	**NORAD #**	**Actual Decay**	Actual SPW		Baseline		5		10		20	
TITAN 34B AC	6792	2020-02-25										
COBE DEB	23073	1996-05-12										
ROSAT	20638	2011-10-23	2021-08-09	22.4	2009-05-23	10.2	2009-06-21	10.3	2008-10-05	9.6	2006-10-20	7.6
UARS	21701	2011-09-24	2010-04-01	4.2	2006-11-14	0.9	2006-11-27	0.9	2006-11-15	0.9	2006-09-28	0.7
ARIANE 44L+	21941	2020-10-02	2000-04-22	3.4	2000-10-28	3.9	2001-02-11	4.2	2001-07-15	4.6	2003-12-11	7.0
DM-F3	26476	2019-12-31	2150-12-16	150.0	2082-11-08	81.9	2092-01-31	91.2	2069-11-06	68.9	2047-12-14	47.0
IRIDIUM 96	27376	2020-05-30	2020-04-15	2.3	2018-10-21	0.8	2018-11-09	0.8	2018-10-30	0.8	2018-09-28	0.7
ATLAS 2A CE	27567	2018-11-04	2004-09-20	1.6	2004-07-13	1.5	2004-07-15	1.5	2004-07-13	1.5	2004-07-07	1.4
MONITOR-E 1	28822	2020-09-22	2022-01-09	13.9	2011-09-27	3.6	2012-01-17	3.9	2011-10-23	3.7	2010-11-21	2.8
PSLV R/B	32477	2020-01-23	2015-08-08	7.4	2011-09-05	3.5	2011-12-02	3.7	2011-09-28	3.5	2011-01-04	2.8
TIANGONG-1	37820	2018-04-02	2018-09-06	2.4	2017-05-04	1.1	2017-05-29	1.1	2017-05-15	1.1	2017-03-28	1.0
PHOBOS-GRU	37872	2012-01-15	2012-01-31	0.2	2012-01-23	0.2	2012-01-24	0.2	2012-01-23	0.2	2012-01-19	0.2
SL-24 DEB	40048	2020-12-21	2016-03-17	1.7	2015-11-06	1.3	2015-12-25	1.4	2015-11-25	1.3	2015-08-02	1.0
ARIANE 5 DEI	41796	2021-01-06										
SHENZHOU 11	41868	2020-10-06										

					Smoothed Percentiles							
Name	**NORAD #**	**Actual Decay**	Fraysse		Baseline		5		10		20	
TITAN 34B AC	6792	2020-02-25										
COBE DEB	23073	1996-05-12										
ROSAT	20638	2011-10-23	2014-08-08	15.4	2018-06-21	19.3	2015-12-06	16.7	2014-08-13	15.4	2012-06-04	13.2
UARS	21701	2011-09-24	2007-02-19	1.1	2008-11-21	2.9	2008-10-07	2.8	2008-08-19	2.6	2008-04-23	2.3
ARIANE 44L+	21941	2020-10-02	2046-12-20	50.0	1999-11-10	2.9	1999-12-11	3.0	2002-04-13	5.3	2000-06-29	3.6
DM-F3	26476	2019-12-31	2169-01-24	168.2	2078-07-13	77.6	2068-06-05	67.5	2057-08-21	56.7	2063-08-27	62.7
IRIDIUM 96	27376	2020-05-30	2018-09-09	0.7	2020-01-22	2.1	2020-01-03	2.0	2019-12-10	1.9	2019-11-01	1.8
ATLAS 2A CE	27567	2018-11-04	2004-10-06	1.7	2004-08-01	1.5	2004-07-28	1.5	2004-07-24	1.5	2004-07-18	1.5
MONITOR-E 1	28822	2020-09-22	2012-07-12	4.4	2022-03-27	14.1	2019-03-03	11.1	2016-11-15	8.8	2015-02-20	7.0
PSLV R/B	32477	2020-01-23	2012-05-14	4.2	2015-09-03	7.5	2015-02-13	6.9	2014-10-07	6.6	2014-03-18	6.0
TIANGONG-1	37820	2018-04-02	2017-03-27	1.0	2018-07-10	2.2	2018-05-31	2.1	2018-04-27	2.0	2018-02-19	1.9
PHOBOS-GRU	37872	2012-01-15	2012-01-26	0.2	2012-02-05	0.2	2012-02-02	0.2	2012-01-30	0.2	2012-01-25	0.2
SL-24 DEB	40048	2020-12-21	2015-07-28	1.0	2017-05-04	2.8	2016-11-02	2.3	2016-06-10	1.9	2015-12-13	1.4
ARIANE 5 DEI	41796	2021-01-06										
SHENZHOU 11	41868	2020-10-06										

We had hoped for more conclusive results. However, all the techniques seemed to perform well at times. The highlighted cells indicate predictions that were closest to the actual reentry date for each satellite. It was interesting that the actual space weather data performed well, but that the percentile daily approximation did not perform as well. The daily percentile seems to underestimate the reentry times because all the best performing cases were at significantly higher levels than the percentile that best matched the observed data. The smoothed data seemed to perform well in some cases, but also for percentiles above what best matched the observed data.

The smoothed data and Frasse et al. (2011) approaches are essentially both mean values, and they performed well in several cases. It makes sense that the averaging techniques employed in satellite lifetime calculations would perform well with average space weather values, but we expected a more definitive performance among all cases.

9 CONCLUSIONS

We have explored the various space weather predictions processes and investigated a percentile approach that permits a statistically valid representation of daily values for a solar cycle prediction. Comparing this process to actual data suggests a strong correlation between the two. We then analyzed several satellites that had already reentered and compared various smoothed, and non-smooth space weather predictions to satellite lifetime predictions. We found that the results were sometimes closer to the actual reentry date when using the percentile approach that simulated each daily variation, and sometimes closer with the smoothed solar cycle results. Although not conclusive at this point, the certainty of lifetime analyses for IADC compliance and other planning studies seem less reliable depending on the satellite, and the use of daily or smoothed data.

10 FUTURE WORK

Additional runs need to be made for various combinations of smoothed and time-varying space weather data.

11 REFERENCES

1. Fraysse, Hubert, et al. 2011. Long Term Orbit Propagation Techniques Developed in the Frame of the French Space Act. Paper 55 presented at the ISSFD.
2. Oltrogge, Daniel L. and Chia-Chun Chao. 2007. Standardized Approaches for Estimating Orbit Lifetime after End-of-Life. Paper AAS 07-261 presented at the AAS/AIAA Astrodynamics Specialist Conference. Mackinac Island, MI.
3. Niehuss, K.O., and H.C. Euler, Jr., W.W. Vaughan. 1996. Statistical Technique for Intermediate and Long-Range Estimation of 13-Month Smoothed Solar Flux and Geomagnetic Index. NASA Technical Memorandum 4759.
4. Vallado, David A., and David Finkleman. 2014. A Critical Assessment of Satellite Drag and Atmospheric Density Modeling. 95:141-165, Acta Astronautica.
5. Vallado, David A., and T.S. Kelso. 2015. “AAS 15-500 New Consolidated Files for EOP and Space Weather Data Final”. Paper AAS 13-373 presented at the AAS/AIAA Space Flight Mechanics Conference, February 10-14. Ka-uai, HI.
6. Vallado, David A., and T.S. Kelso. 2013. Earth Orientation Parameter and Space Weather Data for Flight Operations. Paper AAS 13-373 presented at the AAS/AIAA Space Flight Mechanics Conference, February 10-14. Kauai, HI.
7. Vallado, David A., and T. S. Kelso. 2005. Using EOP and Solar Weather Data for Real-time Operations. Paper USR 05-S7.3 presented at the US/Russian Space Surveillance Workshop, August 22-26. St Petersburg, Russia.
8. Woodburn, James, and Shannon Lynch. 2005. A Numerical study of Orbit Lifetime. Paper AAS 05-297 presented at the AAS/AIAA Spaceflight Mechanics Conference, January 23-27. Copper Mountain, CO