BASIC LIFETIME MODEL FOR REENTRY TIME PREDICTION OF ARTIFICIAL SPACE OBJECTS (MODEL DASAR KALA HIDUP UNTUK PREDIKSI WAKTU JATUH BENDA ANTARIKSA BUATAN)

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Diterima 15 Februari 2018; Direvisi 25 Juni 2018; Disetujui 3 Agustus 2018

ABSTRACT

The identification of space debris and the prediction of its orbital lifetime are two important things in the initial mitigation processes of threat from falling debris. As a part of the development of related decision support system, this study focuses on developing a basic lifetime model of artificial space object based on a well-known theory and prediction scheme in the field of satellite reentry research. Current implemented model has not accounted atmospheric oblateness or other correcting factors, but it has a reasonably good performance in predicting reentry time of several objects with various initial eccentricities. Among 30 predictions conducted to 10 objects that reentered the atmosphere from 1970 to 2012, there are 13 calculations that yield prediction time with accuracy of < 30% relative to the actual reentry time. In addition, 11 calculations yield prediction times which were more accurate compared to the outputs from SatEvo software that is currently used in the decision support system on the falling debris operated by Space Science Center LAPAN. These results were considered satisfying and can be developed further by adopting the updated atmospheric model and by calculating other relevant correcting factors.

Keywords: *space debris, reentry time prediction, atmospheric drag*

ABSTRAK

Identifikasi sampah antariksa dan prakiraan kala hidup orbitnya merupakan dua hal penting dalam proses awal mitigasi bahaya dari benda jatuh antariksa. Sebagai bagian dari pengembangan sistem pendukung keputusan terkait, studi ini berfokus pada pembuatan model dasar kala hidup objek antariksa buatan yang mengacu pada sebuah teori dan skema prediksi yang sudah sangat dikenal dalam riset benda jatuh antariksa buatan. Model yang telah diimplementasikan sejauh ini belum menyertakan faktor kepepatan atmosfer atau koreksi lainnya, tetapi sudah cukup baik dalam memprediksi waktu jatuh dari beberapa objek dengan beragam eksentrisitas. Dari 30 prediksi yang dilakukan terhadap 10 objek yang jatuh sejak tahun 1970 hingga 2012, 13 perhitungan menghasilkan prediksi waktu dengan akurasi < 30% dibandingkan waktu jatuh yang sebenarnya. Selain itu, 11 perhitungan menghasilkan prediksi yang lebih akurat dibandingkan keluaran perangkat lunak SatEvo yang kini digunakan dalam sistem pendukung keputusan benda jatuh antariksa di Pusat Sains Antariksa LAPAN. Hasil ini dinilai cukup memuaskan dan dapat dikembangkan lebih lanjut dengan mengadopsi model atmosfer terbaru dan dengan memperhitungkan faktor-faktor koreksi yang relevan.

Kata kunci: *sampah antariksa, prediksi waktu jatuh, hambatan atmosfer*

http://dx.doi.org/10.30536/j.jsd.2018.v0.a2902

1 INTRODUCTION

More than 22,500 of man-made space objects have fallen back to Earth, according to the United States Strategic Command (USSPACECOM). At least 7,000 of them are large enough that they were not completely burnt up during reentry and eventually struck the Earth's surface. Study by Opiela (2009) concluded that 30% of payload debris consists of medium to high-density and 10% of rocket bodies are high-density with higher endurance to atmospheric ablation. Most of the survive debris will fall on the ocean such that the threat of space debris reentry is generally considered to be less risky. However, any information about reentering objects is important to know because this event attracts public's attention and is related to multinational affairs. Moreover, there is a possibility that atmospheric reentries of artificial space objects will become a multiple daily occurrence in the future (Surratt *et al.*, 2015). Nowadays, several space faring countries already established national space debris mitigation standards that include reentry risk assessments (see Kato, 2001).

The Space Science Center LAPAN developed an automated monitoring system of reentry objects in 2010 (Rachman and Dani, 2010) as the backbone of decision support system related to space debris mitigation. Besides providing trajectory map of the objects that could potentially fall in Indonesia, this system also provides the prediction of reentry time calculated using SatEvo software by Alan Pickup. Since it is not developed in-house, full configuration and customization of the software could not be conducted. Consequently, calculating and updating processes are done manually, are prone to human error, and usually take much time. A system which runs automatically with as little human interference as possible is needed. This system should be based on software developed in-house which is fully controlled and tailored to specific requirements (e.g. taking into account the geographical condition of Indonesia). The underlying model should also be accessible for improvement.

Currently, the Space Science Center LAPAN is developing a model of space object reentry time. The model adopted the theory and prediction scheme described in the book Satellite Orbits in an Atmosphere: Theory and Applications by Desmond King-Hele (King-Hele, 1987). The scheme starts from a development of a basic model which takes into account the variation of density scale height, but not correction factors like atmospheric oblateness, etc. This paper aims to describe the LAPAN model which has been developed so far and to evaluate its performance. Until now we used the theory and prediction scheme as it was without any modification. Modifications and even corrections are possible in the future, especially considering the adopted theory and scheme developed more than 30 years ago.

2 METHODS

The model adopted for this study is well-known in the field of satellite reentry research, albeit with several simplifications. It is basically the model which was used by Royal Aircraft Establishment in Farnborough in 1973, when it correctly predicted the reentry time of the SkyLab 1 space station in 1979. It is also the model behind the successful SatEvo computer program, which has been used in LAPAN for more than 10 years. While it is true that both this study and SatEvo are based on the same theory and prediction scheme, it is difficult to compare them since as far as we know detailed implementation in SatEvo is not publicly available.

The basic model is made by assuming a few things: the atmosphere is spherically symmetrical; air density does not vary with time; only the drag tangential to orbit is considered; the atmosphere rotates with constant angular velocity; the unperturbed orbit is an exact ellipse; during one revolution, the action of air drag changes the orbit by only a small amount; and Lunisolar perturbations are ignored.

Basic lifetime for a space object L^* can be mathematically formulized as

$$L^* = \frac{e \times n}{\dot{n}} F(e), \quad (2\text{-}1)$$

where e is eccentricity, n is mean-motion, $\dot{n}$ is first derivative of mean motion with respect to time and $F(e)$ is lifetime function which depends on atmospheric density scale height H and its gradient μ.

To find the mathematical formulae for$F(e)$, we divide the orbital theory into four divisions: 1) orbit with normal eccentricity, e < 0.2; 2) circular orbit, $e = 0$; and 3) high eccentricity, $e \geq 0.2$. Orbit with normal eccentricity is further divided into two parts, which are **Phase 1** for $0.02 < e < 0.2$ and **Phase 2** for $0 < e \leq 0.02$. This is how we find the mathematical formulae for $F(e)$, which already accounts for the variation of H to height as follows:

For Phase 1,

$$F(e) = \frac{3}{4}\left\{1 + \frac{7e}{6} + \frac{1}{2z}\left(1 + \frac{3}{4z}\right) - \mu\left(\frac{1}{4} - \frac{1}{2z}\right)\right\}, \quad (2\text{-}2)$$

where $z = \frac{ae}{H}$ and a is semi major axis.

For Phase 2,

$$F(e) = \frac{3}{4}\frac{I_0(z)}{I_1(z)}\left[1 + 2e\frac{I_1(z)}{I_0(z)} - \frac{9ez}{40}\right] \times (1 - \mu J), \quad (2\text{-}3)$$

where $J = 2 + z - \frac{z^2}{20} - \left(z^2 + \frac{1}{2}z\right)\left(y_0 - \frac{1}{y_0}\right)$, $I_0(z)$ and $I_1(z)$ are modified Bessel function of first kind of order 0 and 1, respectively with argument z, $y_0 = \frac{I_0(z)}{I_1(z)}$.

For high eccentricity,

$$F(e) = \frac{3(1-e)^{\frac{1}{2}}(1+e)^2}{8e^2} f(e)\left\{1 - \frac{H(8e - 3e^2 - 1)}{8r_p e(1+e)}\right\}, \quad (2\text{-}4)$$

where

$$f(e) = \frac{3+e}{(1+e)\sqrt{1-e}} - 3 - \frac{1}{\sqrt{2}}\ln\frac{\sqrt{2}+\sqrt{1-e}}{(\sqrt{2}+1)\sqrt{1+e}},$$

while r_p is perigee height.

We obtained the values of a, e, n and $\dot{n}$ from TLE (two-line element) data provided by Space-Track (www.space-track.org). As for H and μ, we used CIRA 1972 by interpolating values from King-Hele (1987, Fig. 10.5) as depicted in Figure 2-1.

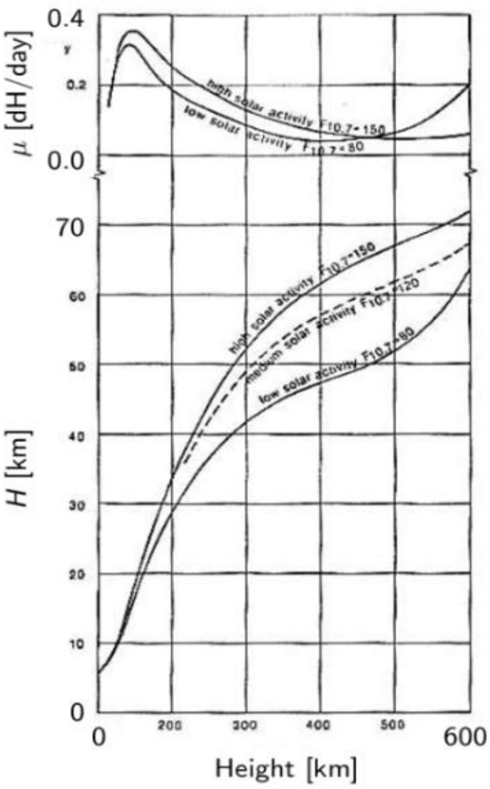

Figure 2-1: Variation of H and μ to height based on CIRA (1972).

The next step is implementing the model into a Matlab script which calculates the value of L^* by using a, e, n, $\dot{n}$, and solar activity level. We verified this implementation by reconstructing two reference graphs in King-Hele (1987) that relate $Q = e \times n \times F(e)$ with e. The first graph uses eccentricity range of $0 < e \leq 0.8$ (King-Hele, 1987, Fig. 12.1), while the second uses a range of $0 < e < 0.03$ (King-Hele, 1987, Fig. 12.2). The second graph is more constricted, but more detailed in revealing the variation of Q, although it is limited only for perigee height from 150 to 600 km. $F(e)$ is calculated by using Equation 2-2, Equation 2-3, or Equation 2-4 depending on the eccentricity value.

Table 2-1: LIST OF REENTERED OBJECTS FOR VALIDATION, ORDERED BY ECCENTRICITY VALUES.

No.	Object	Catalog number	Launch date [UTC]	Reentry date [UTC]	Eccentricity	Lifetime [years]
1	OSO-8	07970	21-Jun-1975	09-Jul-1986	0.0011–0.0002	11.05
2	BeppoSAX	23857	30-Apr-1996	29-Apr-2003	0.0014–0.0001	7.00
3	ROSAT	20638	01-Jun-1990	23-Oct-2011	0.0016–0.0002	21.39
4	YOHKOH	21694	30-Aug-1991	12-Sep-2005	0.0190–0.0002	14.04
5	SL-8 R/B	08745	12-Mar-1976	26-Jun-2005	0.1040–0.0030	29.29
6	EXPLORER 1	00004	01-Feb-1958	31-Mar-1970	0.1150–0.0030	12.16
7	INTELSAT 3-F5	04051	26-Jul-1969	14-Oct-1988	0.2780–0.0050	19.22
8	CZ-3A R/B	23416	29-Nov-1994	13-Oct-2003	0.7300–0.0150	8.87
9	DELTA 1 R/B(2)	10794	07-Apr-1978	04-Sep-1998	0.7300–0.0200	20.41
10	ARIANE 44L R/B	21654	14-Aug-1991	01-Jan-2012	0.7300–0.0500	20.39

For validation, we compared our result with real lifetime data of several space objects obtained from Space-Track and calculated the prediction error. In this regard, we carefully picked 10 objects (see Table 2-1) according to three criteria: 1) they are officially declared as already having reentered to the earth and the orbital data are available in Space-Track; 2) the set represents nearly the whole spectrum of eccentricities which ranges from 0 to 1; and 3) the set covers various lifetimes which range from several years to several solar cycles. For each object, the prediction was conducted three times. The first prediction was based on the object's TLE soon after the launch date, the next prediction was based on object's TLE at its mid-lifetime, while the last one was based on the TLE months before the recorded reentry date. The prediction duration is expected to influence the prediction accuracy. The duration itself can be categorized into short (less than 1 year), medium (1 to 12 years), and long (more than 12 years).

In addition, we also compared our result with that from SatEvo v0.51 (summarized in Table 3-1). This is interesting since SatEvo is also based on the theory we have adopted. For this purpose, we calculated the difference between our results and real lifetime data, in days, and we did the same by using SatEvo's results. Whichever had smaller discrepancy or relative error was regarded as better calculation.

3 RESULT AND DISCUSSION

The verification we have performed indicates that our basic model is generally satisfying. First, we notice a similarity between our result and the reference for the value of Q, with $0 < e \leq 0.8$ as Figure 3-1 shows. Despite this general conformity, we have a discontinuity in our result at $e = 0.2$ when the formula changes from Equation 2-2 to Equation 2-4. The gap does not appear in the reference graph. In addition, the construction is better when using normal eccentricity ($e < 0.2$) as calculated by Equation 2-2 and Equation 2.3. Second, we also see a similarity between our result and the reference in the range of $0 < e < 0.03$ as Figure 3-2 shows. Differences only appear in two cases which are for $n \sim 16.0$ if $e > 0.015$ and for $n \sim 16.2$ if $e > 0.01$. Same as the previous figure, there is also a discontinuity which is now located at $e = 0.02$ as the formula changes from Equation 2-2 to Equation 2-3.

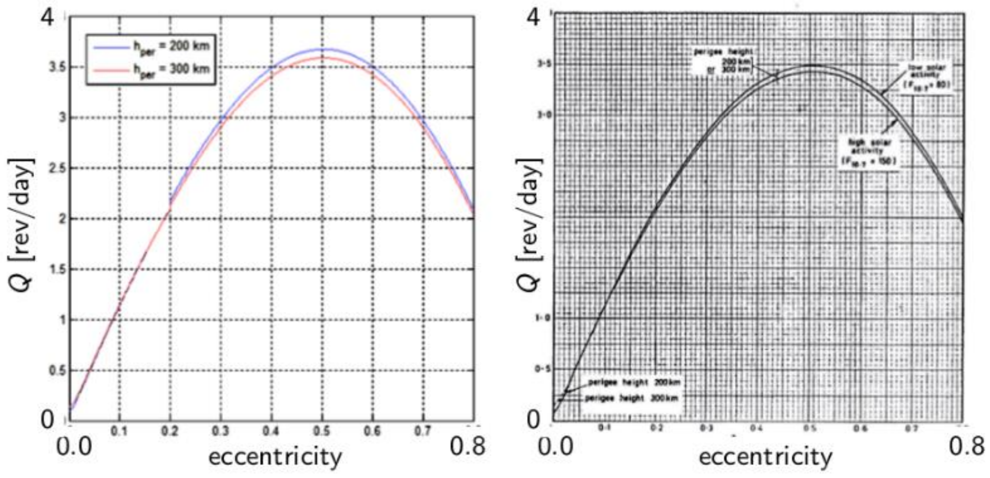

Figure 3-1: Variation of Q with e ≤ 0.8 from this study (left) and from the reference King-Hele (right).

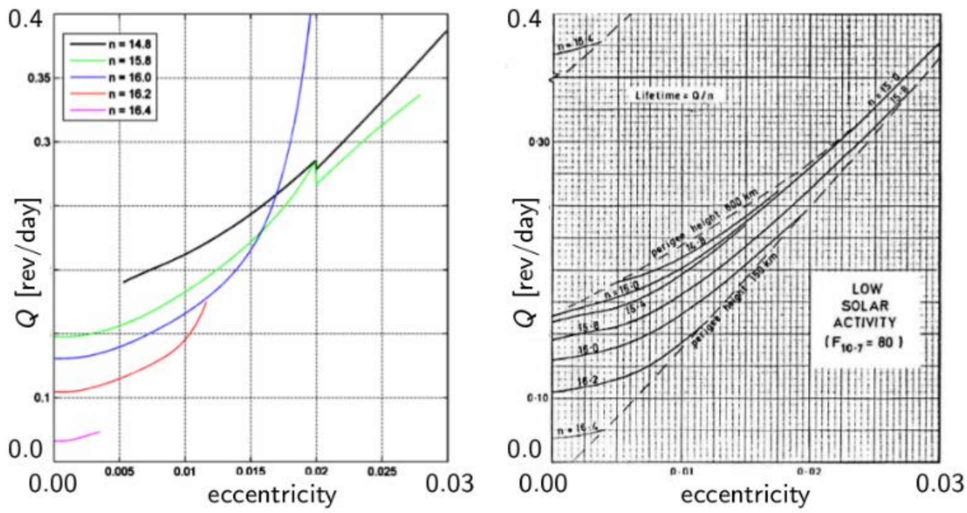

Figure 3-2: Variation of Q with e ≤ 0.03 from this study (left) and from the reference King-Hele (right). Perigee height is limited from 150 to 600 km.

Out of the 30 cases we studied, 13 of them have less than 30% error, as Table 3-1 shows. We even have 4 cases with less than 10% error (cases no. 12, 14, 24 and 27). In contrast, we have 6 cases with more than 100% error (cases no. 1, 4, 17, 23, 25 and 30). The last column of the table also reveals 11 cases where our study results are better than SatEvo (cases no. 4, 5, 14, 16, 18, 19, 20, 21, 22, 24 and 28). Therefore, we consider our result is quite remarkable given the simplicity of the model which has not taken into account various correcting factors.

While it is true that this study gives satisfying results, there are several limitations that should be noted. As Figure 3-1 reveals, the bigger Q values for $e \geq 0.2$ in this study will affect the predicted lifetime for objects with high eccentricity. For example, in the case where perigee height equals 200 km with high solar activity, our result can be 380 days longer than the reference model with an eccentricity of 0.5. Also, one should always be careful when making predictions for objects near their reentry time. Generally, these objects have mean motion values of more than 16 rev/day. Based on our result, that will tend to give Q values that are much higher than they should be (as Figure 3-2 shows). The higher Q values, the longer lifetime predictions.

Table 3-1: COMPARISON OF THE RESULT FROM THIS STUDY WITH THE REAL (RESIDUAL) LIFETIME OF THE OBJECTS IN ORBIT AND WITH THE RESULT FROM SATEVO. SOLAR ACTIVITY IS CONSIDERED LOW WHEN IT IS LESS THAN 100 SFU AND HIGH WHEN IT IS HIGHER THAN 140 SFU. P1, P2 AND HE STAND FOR PHASE 1, PHASE 2 AND HIGH ECCENTRICITY, RESPECTIVELY. $\boldsymbol{\Delta L = L_{\mathrm{real}} - L^*}$. PLUS SIGN IN THE LAST COLUMN MEANS THAT THIS STUDY RESULTS BETTER THAN SATEVO FOR THAT CASE, WHILE MINUS MEANS THE OTHER WAY.

No.	Object	Prediction date (DD-MM-YYYY) [UTC]	Prediction duration	Solar activity	Orbit type	L^* [day]	ΔL [year]	Prediction error [%]	L_{SatEvo} [day]	L^* vs L_{SatEvo} [day]
1	OSO-8	01-01-1976	medium	low	P2	12048	-22.47	214	11843	-205
2	OSO-8	01-01-1980	medium	high	P2	1849	1.46	22	2257	-408
3	OSO-8	01-01-1986	short	low	P2	230	-0.11	22	221	-9
4	BeppoSAX	06-01-1997	medium	low	P2	5933	-9.93	157	6149	+216
5	BeppoSAX	01-01-2000	medium	high	P2	1609	-1.08	33	1644	+35
6	BeppoSAX	01-01-2003	short	high	P2	138	-0.06	17	131	-7
7	ROSAT	01-01-1992	long	high	P2	2292	13.53	68	2818	-526
8	ROSAT	01-01-2000	medium	high	P2	3714	1.64	14	3814	-100
9	ROSAT	01-01-2011	short	low	P2	431	-0.37	46	425	-6
10	YOHKOH	01-01-1992	long	high	P2	3103	5.20	38	3374	-271
11	YOHKOH	01-01-2001	medium	high	P2	1138	1.58	34	1168	-30
12	YOHKOH	01-04-2005	short	low	P2	158	0.02	3	159	-1
13	SL-8 R/B	02-01-1980	long	high	P1	7371	5.30	21	7450	-79
14	SL-8 R/B	01-01-2000	medium	high	P1	1824	0.49	9	1821	+3
15	SL-8 R/B	01-12-2004	short	low	P2	175	0.09	15	178	-3
16	EXPLORER 1	07-02-1960	medium	high	P1	850	7.82	77	849	+1
17	EXPLORER 1	01-01-1964	medium	low	P1	8958	-18.28	293	8953	-5
18	EXPLORER 1	01-10-1969	short	high	P1	252	-0.19	39	252	0
19	INTELSAT 3-F5	03-01-1970	long	high	HE	5774	2.97	16	5537	237
20	INTELSAT 3-F5	01-01-1980	medium	high	P1	2171	2.84	32	2170	+2
21	INTELSAT 3-F5	01-07-1988	short	high	P1	137	-0.09	31	138	0
22	CZ-3A R/B	03-02-1995	medium	low	HE	2739	1.19	14	2257	+482
23	CZ-3A R/B	01-01-1997	medium	low	HE	9456	-19.11	282	7929	-1527
24	CZ-3A R/B	01-12-2002	short	high	HE	295	0.06	7	270	+25
25	DELTA 1 R/B(2)	19-02-1979	long	high	HE	19826	-34.74	178	16593	-3233
26	DELTA 1 R/B(2)	03-01-1990	medium	high	HE	3692	-1.44	17	3370	-322
27	DELTA 1 R/B(2)	01-02-1998	short	low	P1	230	-0.04	7	230	-1
28	ARIANE 44L R/B	30-03-1992	long	high	HE	4410	7.68	39	3638	+772
29	ARIANE 44L R/B	01-01-2002	medium	high	HE	6898	-8.89	89	5860	-1037
30	ARIANE 44L R/B	01-05-2011	short	low	HE	597	-0.96	144	527	-70

We have some indications that our accuracy does not depend on specific values of prediction duration, solar activity level, and orbital type. This is based on evaluation of the six cases with more than 100% error, which show no preferences for those three factors. Considering the discrepancy we got in reconstructing the two figures in the references, we assumed that it was the main factor that affected the accuracy. However, we could not confirm this assumption yet. Out of the six cases, three of them have eccentricities larger than 0.2 (cases no. 23, 25 and 30), two of them (cases no. 1 and 4) have eccentricities around 0.001, and the other one (case no. 17) around 0.1. While the first three are indeed consistent with the discrepancy we found while reconstructing the first reference graphs (see Figure 3-1), the last three are inconsistent with the discrepancy we found while reconstructing the second reference graph (see Figure 3-2).

In comparison with SatEvo, we are surprised with the eleven cases which favor our model. From the beginning, we assumed that SatEvo had been created by incorporating most of the necessary correcting factors as explained by King-Hele (1987). Therefore, we thought there was no chance that our simple model will offer better results in any case. The fact is the software also suffers from the error of more than 100%, just as our model does. However, SatEvo also shares the same number of cases which have less than 30% error with our model. The 30% threshold is approximately the median value of relative errors.

It is also important to discuss the quality of TLE data as the source for inputs in our model. Basically, it is impossible to thoroughly know the accuracy of TLE data since it depends on many factors, such as the particular sensors used, the amount of data collected for the type of orbit, and the space environment which are all different with each element set (Kelso, 1998). According to Kelso, it is possible to check the consistency of calculated element set with those from its predecessor or successor element set. By doing this over time for a particular satellite, it is then "possible to gauge the general accuracy of the data and get a sense for how long an element set is valid" (Kelso, 1998).

Whatever the real accuracy of TLE data may be, we should always be careful when using the data. King-Hele warned us that TLE is actually created for prediction purposes instead of scientific purposes, which usually require higher data accuracy (King-Hele, 1987). He also mentioned in his book that mean motion n values derived from TLEs are usually reliable until six-figure accuracy for "normal satellites". By that he means that "the eccentricity is not greater than 0.3; that the satellites have not just been launched; is not just about to decay; has not been 'lost' (and is not just about to be lost); does not maneuver; and does not have any other extreme or awkward features" (King-Hele, 1987: 198). However, we should not use the first time derivative of mean motion $\dot{n}$. King-Hele suggests using $\Delta n/\Delta t$ instead for successive TLEs, with a minimum time interval of 12 hours. The reason for this is due to the highly fluctuating values of $\dot{n}$ compared with n. We can see this in Figure 3-3, which we chose as an example.

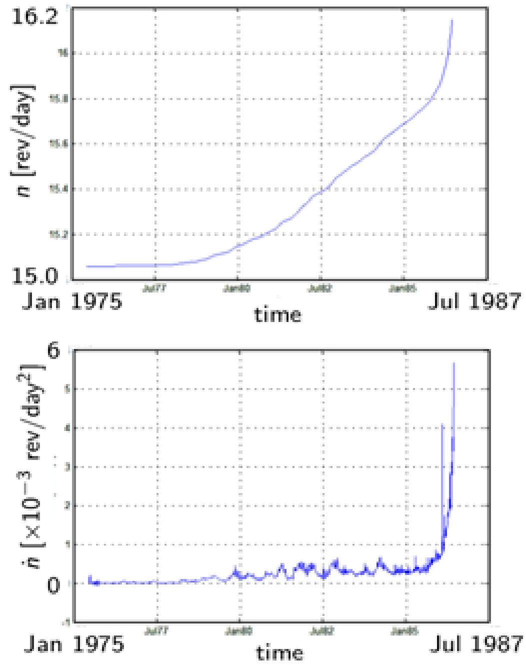

Figure 3-3: Variation of $\boldsymbol{n}$ with respect to time (top) and that of $\dot{\boldsymbol{n}}$ (bottom) for OSO-8 satellite.

Therefore, one can improve this study by replacing $\dot{n}$ as one of the inputs. Two successive n can be used instead to calculate the $\Delta n/\Delta t$ as suggested by King-Hele (1987). One can easily create an algorithm to find the suitable pair of n from historical TLE data to allow for an automatic process. Furthermore, one can also try to select only good TLEs to be used in the model. This is important since several satellites show erratic variation in their time series of mean motion due to interference from the tracking result of other satellites (Doornbos, 2012). For this purpose, one can use a selection method as described in Emmert (2009) to identify outliers in the mean motion.

The method described in King-Hele (1987) is remarkable on predicting the reentry times of space objects. However, since the book was written more than 30 years ago, we believe that it is very likely to improve the method. For example, we can use NRLMSISE-00 atmospheric model (Picone *et al.*, 2002) or the new series of CIRA (Rees, 2006) instead of the CIRA 1972 model. By using an up-to-date and more sophisticated model in calculating the value of H and μ, we could predict the lifetime more accurately. It will be better if we can directly get the two values from the model, rather than having to do the interpolation, and without being limited by only three values of solar activity, i.e. low, medium, and high.

We feel that this study has uncovered an important finding which could benefit the reentry objects monitoring program in Indonesia. The implementation of the model which is given in this study could serve as a base for future automatic system of reentry prediction in the country.

4 CONCLUSION

We have developed a basic model to predict the orbital lifetime of space objects based on theory and prediction scheme described in the book *Satellite Orbits in an Atmosphere: Theory and Applications* by Desmond King-Hele (King-Hele, 1987). The results can be used in the reentry space objects monitoring program in Indonesia by LAPAN. The model has been implemented into a script which gives the space object's predicted lifetime by using inputs derived from TLE data and solar activity level. Although it is in an early phase of development, the model has taken into account the varying atmospheric density scale height.

Even though many correcting factors have not yet taken into account, and while there are probably mistakes in the implementation, we nevertheless believe that the result is quite satisfactory. This is because in the 30 cases we looked at, 13 of them have errors of less than 30%. The result also indicates that the accuracy does not depend on specific values of prediction duration, solar activity level, and orbital type. In comparison with SatEvo, the LAPAN model is also quite satisfactory. It may even be surprising due to the 11 cases which favor the model. This finding has prompted the author to question the extent of SatEvo implementation for correcting factors described in King-Hele (1987).

One can improve the study by replacing the first derivative of mean motion $\dot{n}$ (which is used as one of the inputs) with a pair of successive mean motion to get $\Delta n/\Delta t$. Particular selection methods can be applied to detect outliers which sometimes exist in the mean motion prior to analysis. In addition, the 1972 CIRA atmospheric model should be replaced with an up-to-date and more sophisticated model, such as NRLMSISE-00, to make better lifetime predictions.

ACKNOWLEDGEMENT

The authors would like to thank the Journal Aerospace Sciences' Editorial Team and the Peer Reviewers for all their constructive comments and supports.

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