Determination of mean local time on the day of the anomaly on LEO spacecraft

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Abstract. Numerous spacecraft have been reported to experience failures or anomalies due to various sources such as solar and geomagnetic storms. One of the important keys to investigate anomalies on spacecraft is satellite local time (SLT) utilized to track satellite position in space. Since not every local time of anomaly was registered and recorded well especially for low Earth orbit (LEO) spacecraft, it is necessary to find a method to determine SLT. A Simplified General Perturbations-4 (SGP4) method has been applied to overcome the absence of SLT information in the satellite anomaly database. A series of DMSP satellites are employed for the case study. In addition, the AACGM model is also taken into account for mean local times (MLTs) calculation. The discrepancy of MLTs is found between the observation, calculation and AACGM model and supposedly comes from the TLE data, which seemingly gives rise to incorrect orbital parameters. The deviation of MLTs leads to different morphology of MLT distribution in which the observed MLTs scatter from dusk to midnight sector, whereas the others spread within the dusk and noon sectors of MLT.

1. Introduction

High-energy particles from the solar storm can be trapped by geomagnetic lines leading to magnetic reconnection in the form of a geomagnetic storm. Furthermore, a subsequent magnetic storm can occur while charged particles penetrate deeper into the magnetotail region forming substorms. Although geomagnetic storm does not always link to substorms, in most occasions fluctuation of charged particles from both phenomena are alike. Interestingly, the electric field generated at magnetotail plays a role in redirecting charged particles diffusion into the Earth.

It is commonly agreed that hot plasma from magnetotail is injected into nightside, high-altitude equatorial regions [1]. Should the magnetic activity becomes stronger leading to storm or substorms, the more injected high energy particles penetrate into ring current region. Abrupt changes of plasma property due to incoming energetic particles can endanger satellite missions through detrimental effects such as surface/internal charging.

Some studies found that failure or anomaly on spacecraft strongly linked to magnetic local time [2] [3]. For instance, [2] invented that a large number of satellite anomalies in their database corresponded to dusk to midnight sector of magnetic local time (MLT). A similar pattern of local time distribution found by [3] of which the majority of GEO anomalies scattered on the pre-midnight sector. However, another interesting feature with regard to local time distribution of anomalies invented by [4] in which GEO anomalies straggled from midnight to the dawn sector of MLT. On the contrary, [5] derived a contrast feature where most anomalies in their study stranded in the afternoon and evening sectors. This finding indicated the presence of time delay in anomaly occurrence.

Local time of anomaly plays an important role in diagnosing failure or loss of performance recurrences on satellites in space. Although classic features of anomalies showed anomaly occurrences in the midnight sector and related to substorms, another obvious indication presented the opposite
feature in which numerous anomalies occurred some times after the substorm onset [5]. Since a large number of energetic particles are injected during substorms, a particular portion of those particles are diffused earthward around local midnight and drifted eastward and then accelerated by ambipolar electric toward the down sector of MLT [5].

One plausible explanation regarding local time dependence of anomaly is surface charging attributed to substorms. For instance, a study by [1] showed that SCATHA satellite was exposed to high-voltage charging leading to anomaly around the midnight sector of MLT. Moreover, a study done by [6] invented that 133 out of 198 anomaly events subjected to surface as well as internal charging events. Thus, it can be roughly inferred that spacecraft charging becomes the major contributor to the anomaly on satellites in various orbits.

Important issues arise in accordance with the accessibility of local time of anomaly, meaning that local time of anomaly on satellite cannot always be obtained and provided by space anomaly database such as Satellite News Digest (SND) database (https://www.sat-nd.com/). Information about the time of anomaly is generally provided in UTC (Coordinated Universal Time) rather than Local Time (LT). In addition, some databases contain only information such as satellite orbit, a brief description of an anomaly and the day of anomaly without asserting the detailed information about UTC or LT of the anomaly. Hence, it is necessary to find a method to determine the detailed time of anomaly in the absence of the aforementioned issues. This paper aims to present an applicable method in celestial mechanic to determine the mean local time of satellite on the day of an anomaly using Two Line Element (TLE) data. This method can be utilized to overcome the absence of MLT on satellite anomaly database.

2. Data and Methodology
In this paper, the Defense Meteorological Satellite Program (DMSP) spacecraft placed in low Earth orbit (LEO) around 840 km altitude has been used as a case study. A previous study done by [2] employed some LEO satellites registered in the SND database. However, in order to further validate this method, another anomaly case in the LEO environment needs to be undertaken.

A series of DMSP satellites were launched into Sun-synchronous, near-polar orbit with an inclination of 99° and an orbital period around 100 minutes. These satellites aimed to observe and monitor the weather as well as the near-Earth space environment (https://catalog.data.gov/dataset). DMSP spacecraft have been acclaimed to experience anomaly attributed to environmental-induced charging on many occasions as listed in table 1 [7].

| No | DMSP Sat | Anomaly Time | Voltage (volts) |
|----|----------|------------|----------------|
|    |          | Day        | UT  | MLT   |               |
| 1  | F7       | 12/4/86    | 190816 | 0100 | 100            |
| 2  | F7       | 12/6/86    | 031935 | 2318 | 462            |
| 3  | F7       | 12/7/86    | 062115 | 2211 | 215            |
| 4  | F7       | 12/11/86   | 064026 | 2205 | 147            |
| 5  | F7       | 12/12/86   | 043942 | 2239 | 314            |
| 6  | F6       | 12/13/86   | 120654 | 2042 | 462            |
| 7  | F6       | 12/14/86   | 215457 | 2210 | 145            |
| 8  | F6       | 12/16/86   | 110050 | 2053 | 213            |
| 9  | F6       | 12/17/86   | 172443 | 2309 | 100            |
| 10 | F6       | 12/23/86   | 001114 | 1929 | 145            |

It is important to note that DSMP satellites used as a case study in this paper are selected using the following criteria, i.e., high-voltage negative charging above 100 volts; distribute within dusk to dawn sector of MLT; TLE data are still accessible for LT calculation. Because TLE data on the day of the anomaly is not always applicable, it causes difficulty in determining the mean local time of satellite on the anomaly day. However, another solution is progressively opened using formulation applied by [8]. In this manner, in spite of calculating local time using equation (1), they also considered a rotation rate
of MLT per magnetic latitude in accordance with the location of a subsolar point. It is noted that calculation using the aforementioned method is not always resulting in good accuracy.

\[
MLT = UT + \left( \frac{\phi + \phi_N}{15} \right)
\]  

In equation (1) \(UT\) represents universal time in hour (1 hour \(\sim 15^\circ\) magnetic longitude), whereas \(\phi\) indicates longitude of magnetic frame of given point and \(\phi_N\) designates geographic longitude of the North center dipole frame which in the present study is computed with IGRF-1985 tabulated in http://wdc.kugi.kyoto-u.ac.jp/poles/polesexp.html.

![Figure 1. Schematic diagram of mean local times calculation on series DMSP F6 and F7 satellites.](image)

Another problematic calculation arises in which the rotation rate of MLT regarding subsolar point changes over time. Here, [8] estimated rotation rate ranges from 0.94 to 1.1 hours MLT per hour for the year 2015. Since in present study mostly used data in 1986, the rotation rate should be referred to as IGRF-1985. Thus, in this study, an assumption has been taken in which rotation rate approximately small around 0.5 hours MLT. The use of this assumption strongly affects the accuracy of the determination displayed in the present paper. The determination of MLT using this method can be seen through a schematic diagram in figure 1.

The schematic diagram in figure 1 depicts the calculation of local time on the day of an anomaly on a series of DMSP satellites. Note that only F6 and F7 satellites are considered a case study presented in table 1. Fortunately, records of the magnetic local time of anomaly are also available and useful for comparison. In this diagram, UT on the anomaly day has been used to sort DMSP orbital data in the form of TLE obtained from Space-Track. As previously mentioned that the obtained TLE data does not exactly portray satellite location on that UT, so it is necessary to propagate its trajectory using SGP4. In order to simplify propagate its TLE based on expected UT, a tracking software named Orbitron (http://www.stoff.pl/) has been applied to get satellite locations in the geographical frame. In order to get satellite locations in the geomagnetic frame, a conversion belongs to Kugi Kyoto University (http://wdc.kugi.kyoto-u.ac.jp) has been adopted. The converted longitude, together with geographic
longitude of North center dipole, is then used to determine the local time of satellite using equation (1). Lastly, the comparison between observed MLT and calculated MLT is presented to see its deviation.

3. Result and Discussion

The determination of satellite position earned from Orbitron software showed estimated locations, i.e., latitude and longitude, of DMSP satellites at a specified time. For instance, the location of the DMSP F7 satellite on 4 December 1986 at 19:08:16 UT can be seen in figure 2.

![Figure 2. Location of DMSP F7 satellite in the geographical frame on 12/4/1986 obtained from propagated TLE.](image)

Using transformation of coordinate, applicable through International Geomagnetic Reference Field (IGRF) model, the geographic latitude and longitude of DMSP satellite at a specified time (see table 1) can be converted into the geomagnetic frame summarized in table 2.

| No | Geographic | Geomagnetic |
|----|------------|-------------|
|    | Lat        | Long        | Lat   | Long  |
| 1  | 70.017S    | 23.945E     | 68.01S| 66.19E|
| 2  | 76.020S    | 143.426E    | 82.09S| 94.82W|
| 3  | 69.249S    | 84.042E     | 78.19S| 132.47E|
| 4  | 33.869S    | 61.463E     | 40.67S| 125.85E|
| 5  | 21.618S    | 89.246E     | 31.80S| 158.17E|
| 6  | 46.329S    | 90.654E     | 56.45S| 156.62E|
| 7  | 72.114S    | 75.268W     | 61.00S| 2.78W |
| 8  | 80.722S    | 47.962E     | 79.58S| 51.80E|
| 9  | 71.672S    | 132.343W    | 64.45S| 40.11W|
| 10 | 33.459N    | 93.007E     | 22.65N| 165.45E|

Notice that the transformation is done by applying the IGRF-12 model for the 1985 epoch magnetic coordinate. As previously mentioned that most anomaly data tabulated in table 1 were taken during 1986 events. Thus, the predicted locations of the North and South of geomagnetic pole longitudes are 70.8 W and 109.1 E, respectively (http://wdc.kugi.kyoto-u.ac.jp/POLES/polesexp.html). Those points are chosen as the standard reference point for MLT calculation in the present study. The obtained MLT calculation using this method (see figure 1) can be seen in table 3.
Table 3. MLT comparison between observed, calculated, and AACGM model.

| No | DMSP Sat | Observed MLT | Calculated MLT | AACGM MLT |
|----|----------|--------------|----------------|-----------|
| 1  | F7       | 0100         | 0417           | 1823      |
| 2  | F7       | 2318         | 1422           | 1917      |
| 3  | F7       | 2211         | 1955           | 0909      |
| 4  | F7       | 2205         | 1947           | 1034      |
| 5  | F7       | 2239         | 1956           | 1035      |
| 6  | F6       | 2042         | 0317           | 1750      |
| 7  | F6       | 2210         | 0249           | 1711      |
| 8  | F6       | 2053         | 1912           | 0954      |
| 9  | F6       | 2309         | 0048           | 1049      |
| 10 | F6       | 1929         | 1557           | 0607      |

A significant deviation arises not only from calculated MLT but also from AACGM (Altitude Adjusted Corrected Geomagnetic Coordinate) model [9]. For instance, in event #1 the observed MLT, as well as calculated MLT, distribute in the morning sector, whereas the MLT attained from AACGM model scatters in the dusk sector of magnetic local time. It is rarely found the MLT in the same sector as shown in figure 3. Some of the larger deviations of calculated MLT from the observed MLT occur at events #6, #7 and #9.

The deviation of calculated MLT from the observed one supposedly comes from the absence of a specific parameter called the equation of time in equation (1). It is evident that the equation of time is really important since it can represent the position of the Sun at a specified time. In addition, it can also indicate the difference between the right ascension of the apparent Sun and the right ascension of the fictitious mean Sun [10]. The right ascension parameter is known to play a role in Universal Time (UT) determination which is used in equation (1). It directly affects the variation of magnetic local time as found by [9].

![Figure 3](image-url)
The inclusion of the equation of time in MLT calculation does not always give a good agreement with the MLT attained from observation. It can be seen from figure 3 that even though the AACGM model has taken the equation of time into consideration, but the deviation is still obvious. The different results were also found by [8] as they compared their calculation involving the rotation rate of the Sun (similar to the equation of time) with the MLTs derived from other studies. Note that the determination of MLTs using the AACGM model is simply done by inputting some parameters needed in http://sdnet.thayer.dartmouth.edu/aacgm/aacgm_calc.php. Since the detailed calculation, as well as the method, are unknown, hence this paper only presents a rough calculation of MLTs. It supposedly affects the accuracy of the calculation as presented in this paper.

Another speculation of the difference comes from the determination of satellite position obtained from TLE data. As already mentioned that the present study employed TLE data on the day of the anomaly on the DMSP satellite. However, not all TLE data can be completely derived at the specified date. In order to overcome this issue, TLE data from the closest epoch should be propagated which in this study was done by using Orbitron software (e.g., see figure 1). It clearly affected the determination of the ‘true’ position of satellite as well as its right ascension parameter leading to precise time calculation (UT). Moreover, it further influenced the assessment of satellite position in the geomagnetic frame as shown in figure 4.

Figure 4 indicates local times distribution from observation (red), the calculation (blue), and the AACGM model (green). The numbers designate the nth events tabulated in table 2. According to observation, most DMSP anomalies distributed predominantly from dusk to midnight sector of magnetic local time. In contrast to observation, the calculation presented in this study found that most anomalies scattered at both sectors, pre-midnight and dawn, or dusk to dawn sectors. The different pattern is obtained from AACGM model where most local times spread in the Sunlight area or noon sector of magnetic local time.

It has been shown through some cases that the majority of LEO anomalies scattered from the dusk to the midnight sector of MLT [2]. The distribution of MLTs of LEO anomalies in this study has a good agreement with two transport mechanisms, i.e., electron scattering associated with whistler-mode chorus resonance as found by [5] and monoenergetic electrons accelerated by low-frequency Alfvén wave as invested by [11]. A similar morphology was found on DMSP satellite anomalies shown in figure 4. It appeared that those anomalies were also subjected to the aforementioned mechanisms especially during
precipitated auroral electrons events in which the fluxes dramatically increased after the substorm onset. However, the morphology of MLTs varies case by case. For instance, multiple anomalies related charging were experienced by SAMPEX satellites and occurred mostly from midnight to the dawn sector of MLT [12]. This morphology differs from the observed MLTs presented in this study. The precise cause of the morphological difference in MLT of anomalies is still unknown. Nonetheless, a geomagnetic storm/substorm onset plays a significant role in satellite anomaly occurrences.

4. Conclusion
Determination of mean local time for LEO objects such as a series of DMSP satellites is done by applying the right ascension parameter within the anomaly day given in UT. The anomaly time is necessary to track a satellite position through TLE data. Since we cannot always derive TLE data corresponding to the anomaly day, thus orbital propagation is needed through SGP4 available in Orbitron software. In this manner, the geographical location of the satellite is attained and then converted into the geomagnetic coordinate system. The converted longitude, as well as geographic longitude of the North center dipole, is employed to determine the mean local time of satellite.

A significant deviation of MLTs exists between observation, calculation and AACGM model as shown in table 2. Since the calculated MLTs are taken in the absence of the equation of time, it explains the source of deviation. The source of discrepancy also supposedly comes from the propagated TLE data, thus affecting the mean value of the right ascension parameter. In order to further examine the source of discrepancy, another comparison is done by adopting MLTs attained from the AACGM model. This model has already included the equation of time in its calculation. Nevertheless, the deviation is still obvious. This discrepancy supposedly comes from the incorrect input, e.g., latitude and longitude, needed for the calculation.

The distribution of MLTs on each category, i.e., observation, calculation, and model, results in different morphology. The observation has a good agreement with the most observed evidence where the majority of LEO anomalies scatter from dusk to the dawn sector of MLT and subject to acceleration of electron due to the electric field. On the other hand, the calculation presented in this study, together with the AACGM model, gives different morphology as the observed one in which MLTs spread within the dawn and noon sectors, respectively. It is important to note that this present study does not mean to acclaim one study is better than others rather than trying to determine MLTs by using some methods as presented in this paper.

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References
[1] Fennell J F, Koons H C, Roeder J L and Blake J B 2001 Spacecraft charging: observations and relationship to satellite anomalies Proc. of the Seventh Int. Conf. ed R A Harris (Noordwijk: European Space Agency) p 279
[2] Ahmad N, Herdiwijaya D, Djimaluddin T, Usui H and Miyake Y 2018 Diagnosing low Earth orbit satellite anomalies using NOAA-15 electron data associated with geomagnetic perturbations Earth Planet Space 70 91
[3] Choi H S, Lee J, Cho K S, Kwak Y S, Cho I H, Park Y D, Kim Y H, Baker D N, Reeves G D and Lee D K 2011 Analysis of GEO spacecraft anomalies: space weather relationship Space Weather 9(6) pp 1–12
[4] McPherson D A, Cauffman D P and Schober W R 1975 Spacecraft charging at high altitudes: SCATHA satellite program J. Spacecraft 12(10) pp 621–626
[5] Lam M M, Horne R B, Meredith N P, Glauert S A, Griffin T M and Green J C 2010 Origin of energetic electron precipitation >30 keV into the atmosphere J. Geophys. Res. 115(A4) A00F08

[6] Koons H C, Mazur J E, Selesnick R S, Blake J B, Fennell J F, Roeder J L and Anderson P C 1998 The impact of the space environment on space systems Proc. of the 6th Spacecraft Charging Conference (MA: AFRL Science Center) pp 7–11

[7] Frooninckx T B 1991 High-latitude spacecraft charging in low-Earth polar orbit Master science thesis (Utah: Utah State University)

[8] Landau K M and Richmond A D 2016 Magnetic coordinate systems Space Sci. Rev. 206(1–4) pp 27–59

[9] Baker K B and Wing S 1989 A new magnetic coordinate system for conjugate studies at high latitudes J. Geophys. Res. 94 pp 9139–43

[10] Vallado D A and McClain W D 1997 Fundamentals of astrodynamics and applications (New York: McGraw-Hill)

[11] Wing S, Gkioulidou M, Johnson J R, Newell P T, Wang C-P 2013 Auroral particle precipitation characterized by the substorm cycle J. Geophys. Res. 118 pp 1022–39

[12] Mazur J E, Fennell J F, Roeder J L, O’Brien P T, Guild T B, Likar J J 2012 The time scale of surface-charging events IEEE T Plasma Sci. 40(2) pp 237–45