Relationship of FORMOSAT-7 Orbital Decay and Space Weather Conditions

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The orbit of an artificial satellite would be perturbed by various forces, especially affected by the aerodynamic drag which depends on the thermospheric density. The thermospheric density varies with solar activities and flux as well as geomagnetic activities. The enhancements of atmospheric drag under geomagnetic disturbed conditions and higher solar radio flux period might bring difficulties for predicting the trajectories of satellites and further cause communication anomalies between satellite and ground stations such as command failures, data missing, and/or contact losing. The Taiwan Space Agency (TASA) operates a constellation mission named FORMOSAT-7/COSMIC-2 (F7/C2) to provide the global navigation satellite system radio occultation data for meteorology, ionosphere, climatology, and space weather. F7/C2 consists of 6 identical small satellites which are orbiting with an inclination angle to acquire more observations at middle and lower latitudes. The precise F7/C2 spacecraft orbits are provided by the Taiwan Data Processing Center (TDPC) of the Taiwan Analysis Center for COSMIC (TACC). The daily mean semi-major axis indicates a day-to-day gradual descending, approximately 50 to 80 meters per day responding to solar activities. Under the geomagnetic disturbed conditions, the air drag would increase at higher latitude due to the particle precipitation and Joule heating. Therefore, the daily change of these six satellites also reveal a sudden decay simultaneously during the strong geomagnetic storm condition (Kp > 7). The orbital altitude decreased more than 100 meters per day during the geomagnetic storm which occurred on 10-12 May, 2024. In this study, the orbital data of all six FORMOSAT-7/COSMIC-2 satellites in 2024 are comprehensively analyzed to report the response of the satellite orbit to solar radio flux and geomagnetic conditions.

Orbital Information of the FORMOSAT-7/COSMIC-2

- The data centers (CWA/TACC and UCAR/CDAAC) publish orbital information of the F7/C2 that is specified in the Standard Product 3 (SP3) orbit format.
- During the particular period of orbit adjustment/maneuver, there is no record of orbit information due to the mission payload TGRS being turned off.
- Semi-major axis (SMA) values are additional resampled and interpolated with the temporal resolution of 1 minute.
- The artificial values caused by interpolation in the period of data gap should be removed to avoid the shift of daily mean value.

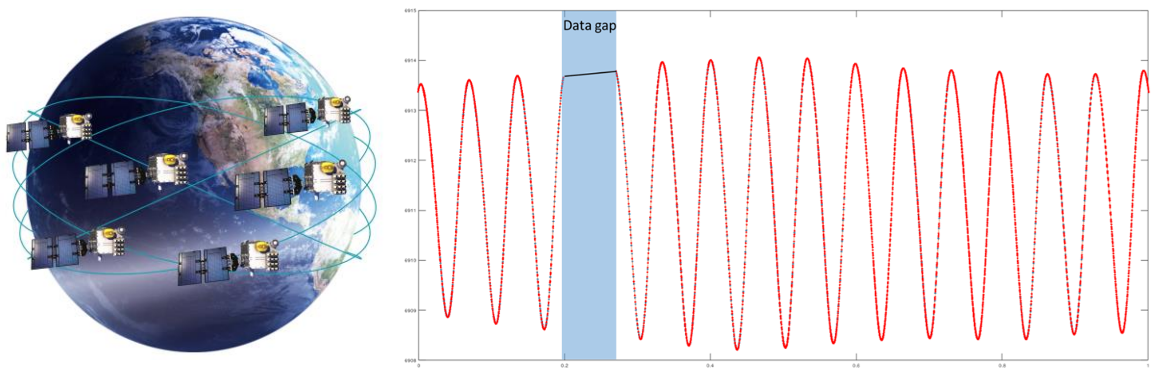

Fig. The six F7/C2 satellites orbiting at low-inclination orbits of 24 at 520-550 km shown on the left hand side. The example of F7/C2 semi-major axis function of time with a data gap due to the maneuver period.

Disturbance Period – 2024/05 Geomagnetic Storm

- Clearly to classify orbit decay associated with solar flux and geomagnetic disturbance due to there is no orbit adjustment/maneuver by TASA.
- One revolution is defined as perigee to perigee and to calculate the orbital decay per revolution.
- The SMA reveals daily variations might respond to other forcing as well as have a gradually decreasing trend over time.
- In general, the decay per revolution is bumpy but the daily decay points out negative values that agree with descent of the SMA.
- The orbit decay is roughly **50** meters per day, especially reaching to **-250** meters per day during the intense storm.

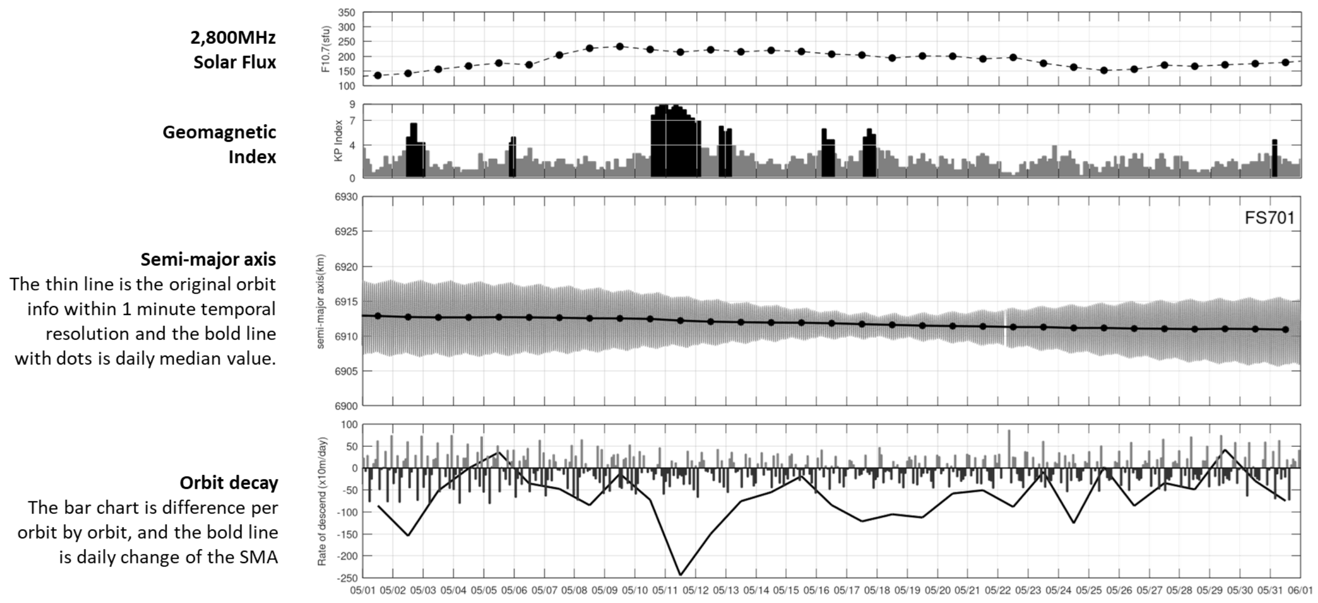

Fig. From top to bottom panels are solar 2,800MHz radio flux, Kp index, semi-major axis, and orbit decay in May 2024. The orbital information only illustrated data of one satellite named FS701.

Year 2024 Overview and Investigation

- Some sudden changes of orbital altitude for an individual satellite is due to adjustment/maneuver by TASA, and there are two major raises based on the mission requirement.
- The daily orbital decay obviously corresponds to the variation of solar flux with a correlation coefficient of **-0.642**, under the geomagnetic disturbance conditions based on the GFZ quiet day list.
- According to a higher solar flux condition after August, the daily decay is enhanced up to **100m**, but about 60m early 2024.
- It is clear to see that the SMA of six F7/C2 satellites suddenly decreased simultaneously during the severe (G4, Kp=8) to extreme (G5, Kp=9) geomagnetic storms that occurred on 10 May, 14 August, and 13 October.

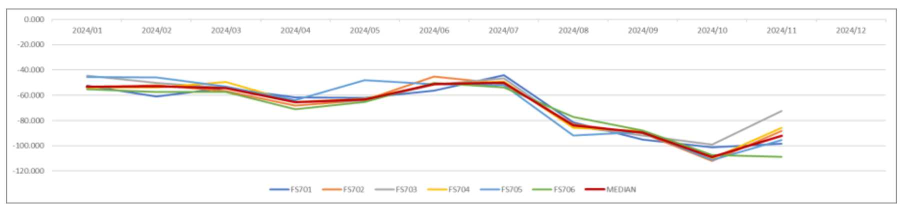

Fig. Mean value of monthly decay of F7/C2 based on GFZ quiet days.

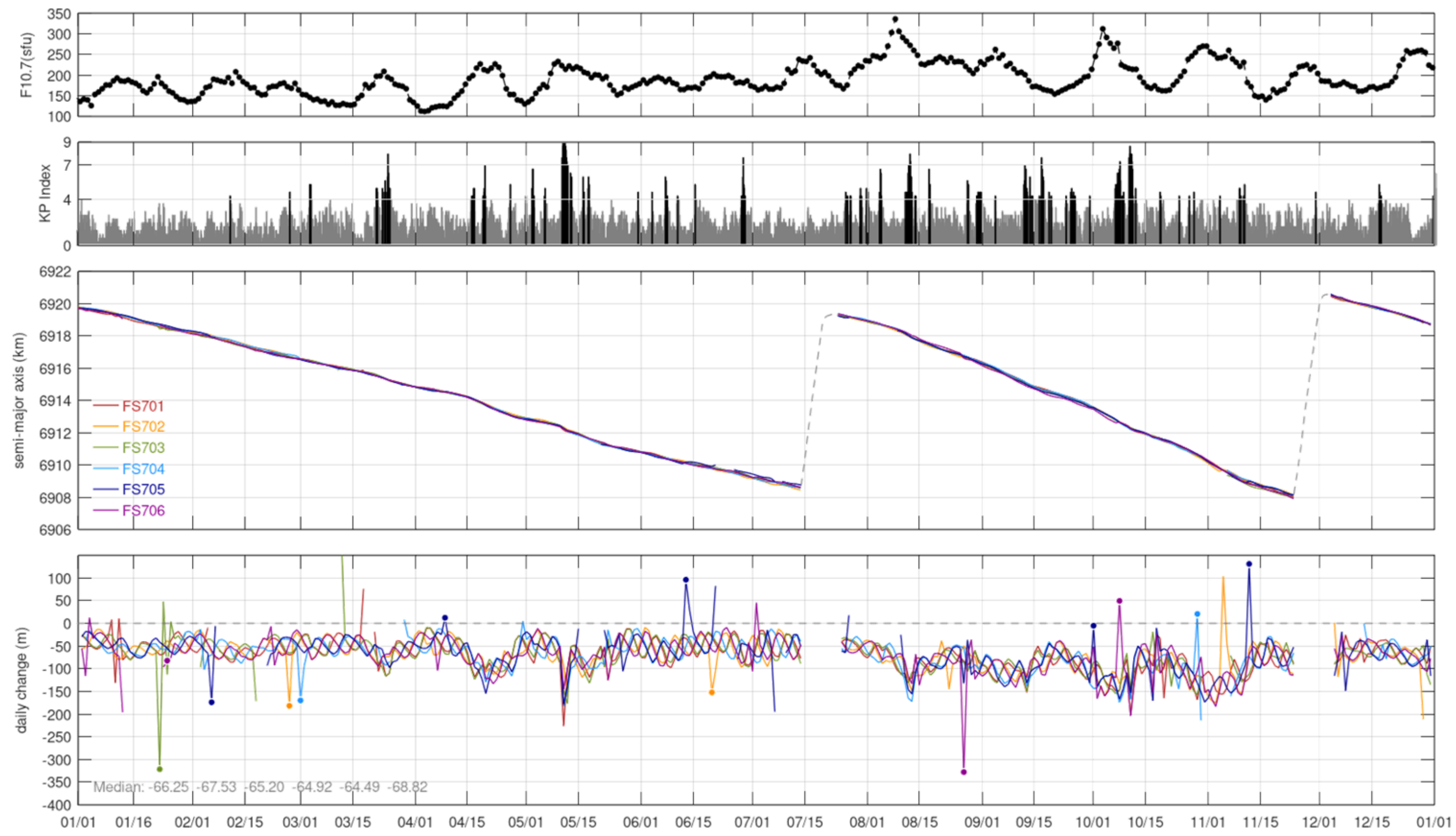

Fig. The 2024 overview of solar 2,800MHz radio flux, Kp index, daily mean of semi-major axis, and daily orbit decay, from top to bottom panel. The semi-major axis is between 6,920 and 6,908 km based on mission requirements. The grey dashed line indicates the two time periods under orbital adjustments.

Thermospheric Neutral Density Variations Along Orbit

1. NCAR/HAO TIEGCM GPI Run
   - Using real geophysical parameter index (F10.7 & Kp) to drive model simulation.
2. CWA DART-TIEGCM Data Assimilation System Prediction
   - Using NOAA/SWPC daily 3-day forecast F10.7 & Kp for prediction period.
   - Hourly assimilating F7/C2 RO electron density profiles and ground GNSS-TEC.
   - Take every first hour prediction for this investigation.
3. Estimation via orbital decay
   - The drag force F_D on a body acts in the opposite direction of the velocity vector and is given by the equation： $F_D = \frac{1}{2} C_D \rho v^2 A$.
     - C_D ≡ Coefficient of drag, set to **1.06** in this presentation.
     - ρ ≡ the air density; v ≡ the satellite's velocity; A ≡ Spacecraft drag area about **2.512** m².
   - For circular orbits, the approximate changes in semi-major axis per revolution could be estimated by the equations： $\Delta a_{rev} = \frac{-2\pi C_D A \rho a^2}{m}$, around 15.09 revolutions per day.
     - a ≡ the semi-major axis; m ≡ satellite's mass, about **249.0167** kg.

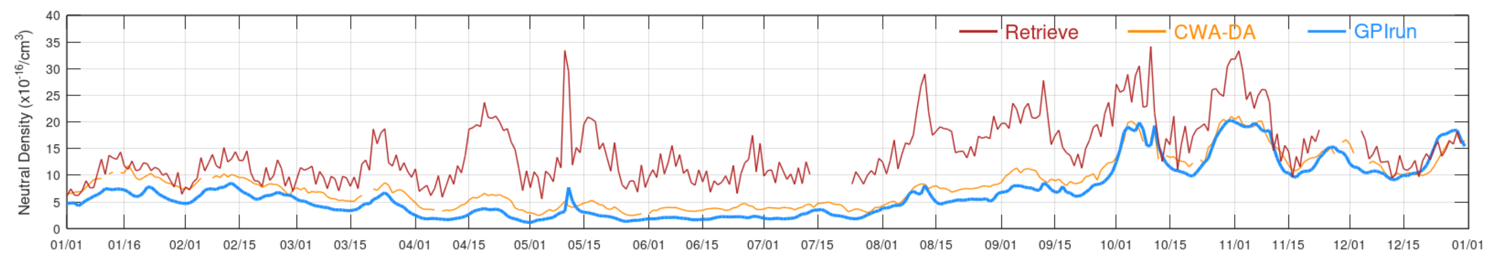

Fig. The thermospheric neutral density from GPI Run, CWA data assimilation, and estimation via orbit decay which was taken out along the orbits of six F7/C2 satellites. Beside the solar flux, changes also respond to geomagnetic disturbance.

- This F7/C2 orbit information is converted to semi-major axis, and resampled to 1 minute resolution for this study. During the orbit adjustment/maneuver period, no orbit record due to the TGRS being turned off. Therefore, the interpolated values in these periods are artificial and should be removed.
- By the analysis of satellite orbit information, it can be clearly pointed out that the satellite orbit decay more obviously due to higher solar flux and more geomagnetic storms in recent years. In particular, the severe geomagnetic storm that occurred in May this year caused the orbital decay rate of six F7/C2 satellites to exceed 200 meters in one day.
- Through the investigation of the output of the data assimilation system and simulation of the numerical model with actual geophysical parameters, it can be seen that the orbital descent rate of F7/C2 is similar to the change trend of thermospheric neutral density.
- The thermospheric density fluctuation of DA results is lower than that of pure GPI run might result from the forecasted values of Kp and F10.7 are underestimated. Meanwhile, the retrieved density from orbital decay reveals more obvious variation but still under investigation.