Improving the Two-Line Elements via assimilating Positioning Data of FORMOSAT-7/COSMIC-2

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ABSTRACT

Accurate prediction of the position and velocity of satellites is a critical task in satellite operation control. The increasing solar maximum activity has caused the density of neutral air to rise and fluctuate more rigorously over the past two years. This increasing variability complicates the precise prediction of satellites' two-line elements (TLE). For instance, a spike in radio emissions (F10.7) in late March 2022 led to downlink data loss for FORMOSAT-7/COSMIC-2 in early April 2022. The incident highlights the critical role of atmospheric drag in low Earth orbit satellite control. This presentation will outline the use of Extended Kalman Filter to assimilate FORMOSAT-7/COSMIC-2 position for TLE automation and rapid calculation, aiming to develop better operational strategies to prevent data loss.

OBJECTIVES

In the past, the Taiwan Space Agency (TASA) updated TLE twice a week to achieve satellite tracking. Due to the increase and significant variation in F10.7, the update frequency was adjusted to three times a week for better tracking. However, given the current manpower constraints, updating three times a week is already pushing the limits of the TASA's capabilities. In the future, with more satellites requiring tracking, it will be essential to find other solutions. To quickly grasp changes in space weather, it has become crucial to develop automated and fast calculations of TLE. Therefore, this study uses satellite payload-provided position and velocity data combined with EKF for rapid TLE computation. The process uses the satellite data from the previous day for TLE quality validation, assimilating data from two pass segments to compute TLE, with the TLE's timestamp taken from the nearest ascending time in the assimilated data.

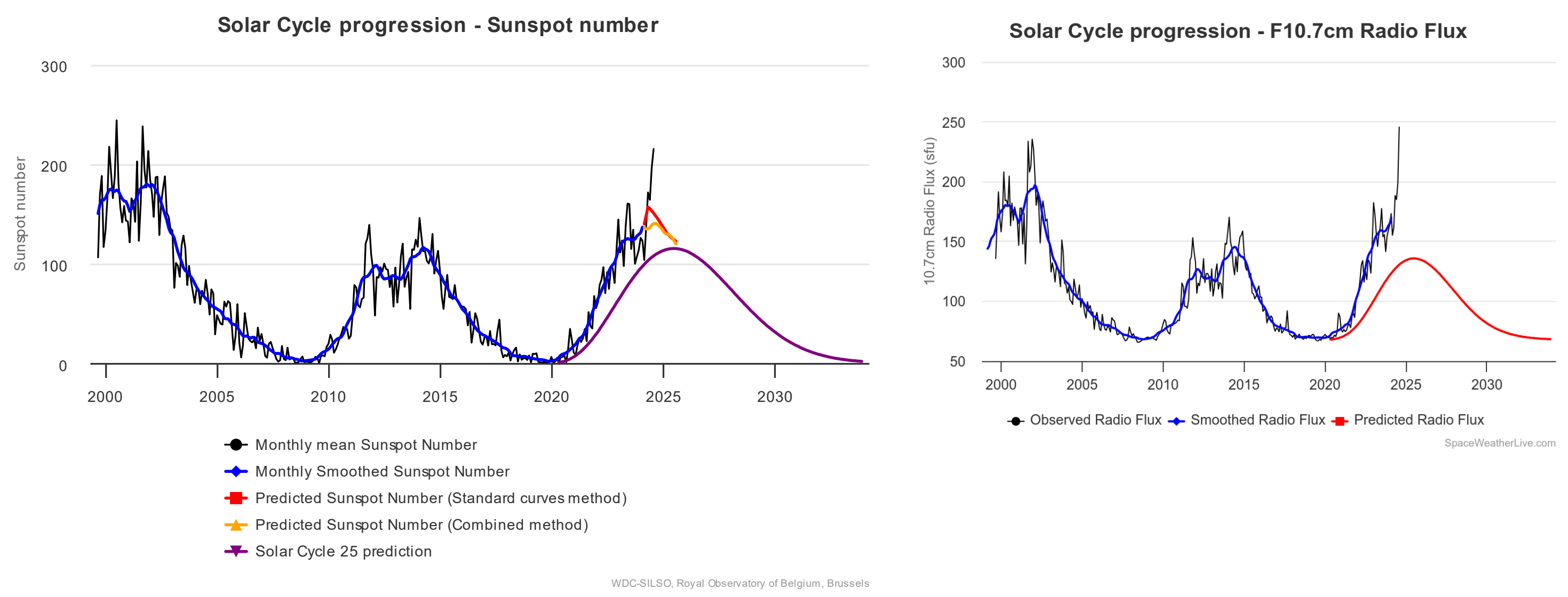

Figure 1. The progress of the solar cycle. The charts are updated by the SWPC with the latest ISES predictions.

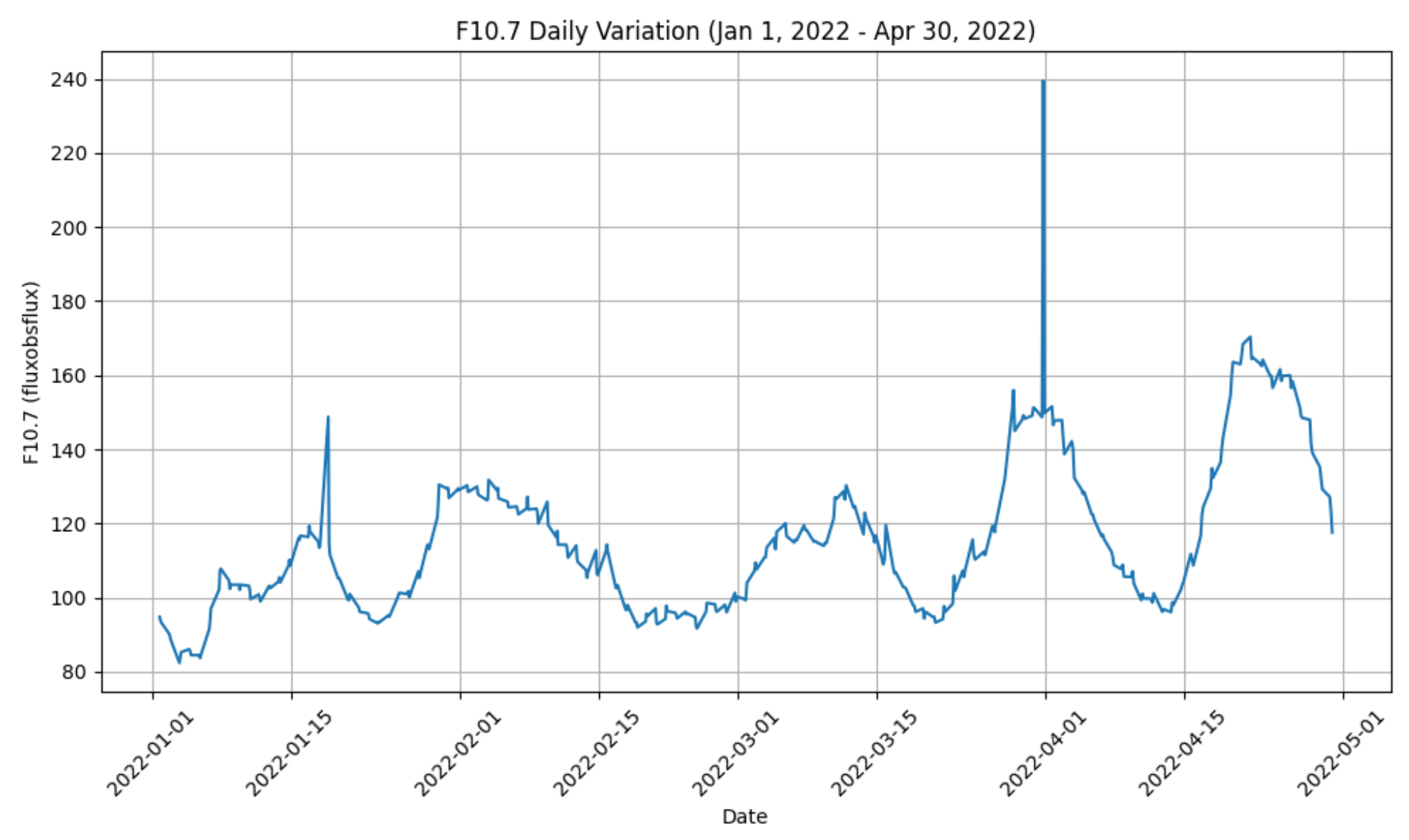

Figure 2. Observed 10.7-cm Solar Radio Flux (F10.7) from 2022 Jan 1 to 2022 Apr 30.

RESULTS

This case study focuses on the communication anomaly of FORMOSAT-7 on April 5, 2022 (DOY 095). The TLE used at that time was generated four days earlier on April 1, 2022 (DOY 091) by the TASA. The F10.7 data indicates that there was a magnetic storm on DOY 91, and the starred ballistic (BSTAR), which is highly correlated with F10.7, also showed significant changes (CelesTrak / TASA).

In practice, when the tracking error of FORMOSAT-7 exceeds 45 kilometers, there is a risk of data loss. On April 5, all six satellites exceeded this threshold, resulting in insufficient signal strength and even signal loss. Figure 3 clearly shows that the position prediction errors of the six satellites' TLEs under the SGP4 model exceeded the threshold by the end of April 4. After this point, operators continuously reported insufficient signal strength, leading to data loss.

The results show that the TLE calculated using the EKF data assimilation with the data from March 30 significantly reduces the orbit prediction error. Here, we used data from CelesTrak as a reference, which also indicated that the performance of the EKF-TLE is comparable.

This study demonstrates that using only the direct downlink data from the satellites for data assimilation can achieve significant improvements in orbit prediction. The TLE results can be obtained in a very short time, greatly saving manpower and enabling rapid TLE updates to maintain the accuracy of orbit predictions.

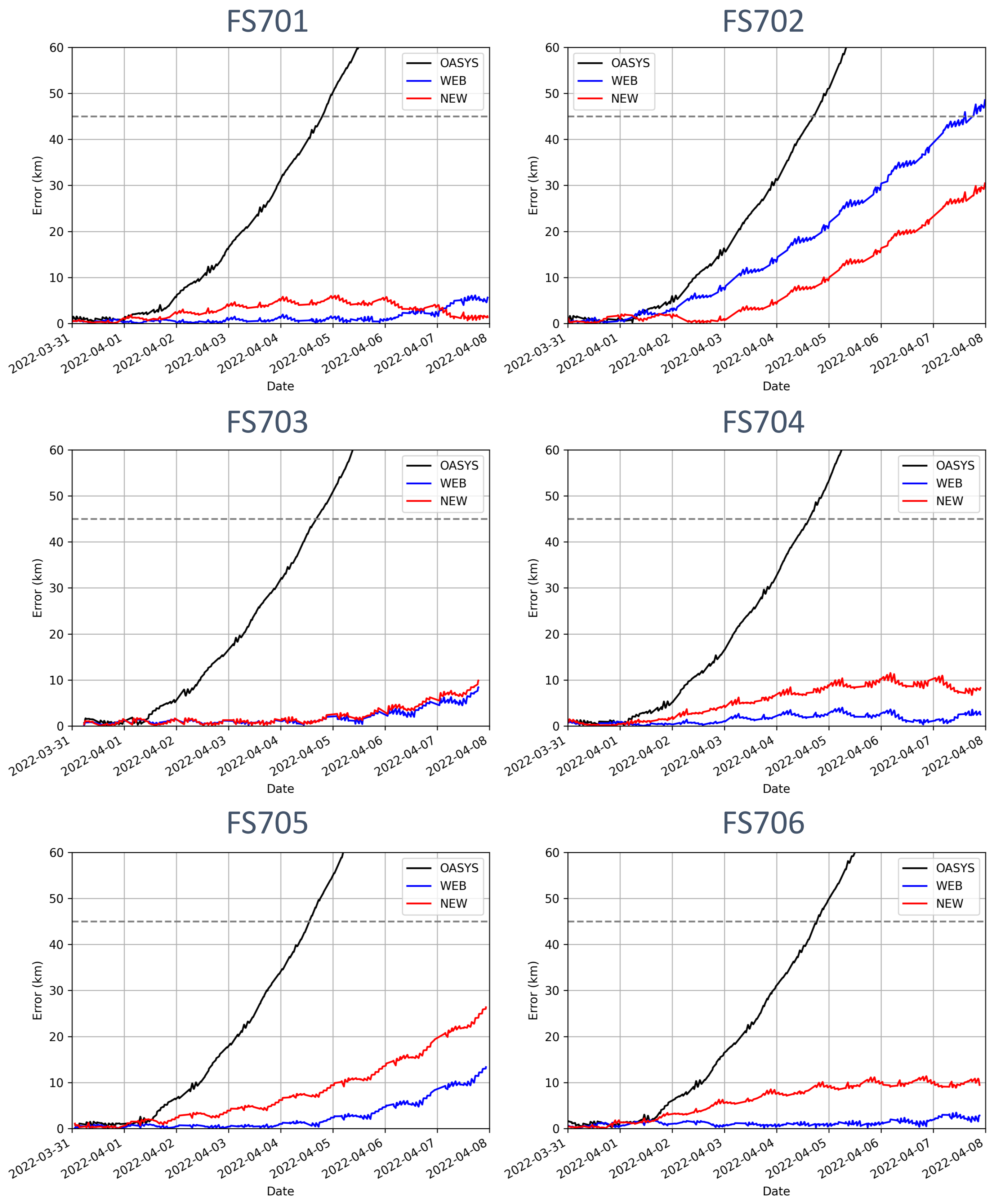

Figure 2. Satellites tracking error estimate by TLE from TASA (black), CeleTrak (Blue) and EKF-TLE (red).

METHODOLOGY

The simplified perturbation model (SGP4) which uses the TLE for orbit propagation is a highly nonlinear. The estimation algorithms (EKF) method cannot be directly applied.

The state estimate vector x which consists of the six orbit elements and satellite ballistic coefficient be defined as

$$x = [n\ e\ i\ \omega\ \Omega\ \theta\ B^*]^\mathrm{T}$$

KALMAN FILTER ALGORITHM

The proposed finite element based EKF is an iterative algorithm. It is noted that the state vector, $\tilde{x}$ is a time invariant vector. Thus the propagation models for both $\tilde{x}$ and state error covariance P^- are not required.

$$K = P_j^- H^T (H P_j^- H^T + R)^{-1}$$
$$\hat{x}_j^* = \hat{x}_j + \alpha \Delta x$$
$$P_j^+ = (I - KH) P_j^- + Q$$
$$\hat{x}_{j+1} = \hat{x}_j^*$$
$$P_{j+1}^- = P_j^+$$

α is a simple weightage parameter method to ensure each element of $\hat{x}_j^*$ does not violate the boundary constraint.

Q is the process noise matrix to avoid P_j^- matrix becomes semi-positive definite matrix (or eigenvalue near zero), which causes $HP_j^- H^T + R$ to become singular matrix.

After both the state vector and covariance matrix have been successfully updated, the information is carried into the next iteration.

FINITE DIFFERENCE METHOD

The finite difference method is a numerical method to approximate the partial differential equations without any derivation. The finite difference method is used to compute the Jacobian matrix of the SGP4 model.

$$H = \begin{bmatrix} \frac{\partial h_1}{\partial x_1} & \frac{\partial h_1}{\partial x_2} & \cdots & \frac{\partial h_1}{\partial x_n} \\ \frac{\partial h_2}{\partial x_1} & \frac{\partial h_2}{\partial x_2} & \ddots & \frac{\partial h_2}{\partial x_n} \\ \vdots & \ddots & \ddots & \vdots \\ \frac{\partial h_m}{\partial x_1} & \cdots & \cdots & \frac{\partial h_m}{\partial x_n} \end{bmatrix}$$

$$\frac{\partial h}{\partial x_i} = \frac{-h_{i,2} + 8h_{i,1} - 8h_{i,-1} + h_{i,-2}}{12\Delta x_i} + O\left[(\Delta x_i)^4\right]$$

CONCLUSIONS

1. Using EKF assimilation technology to calculate TLE can provide reliable orbit prediction.
2. The EKF-TLE, being fast and accurate in calculation, can continuously provide TLE updates, reducing manpower and maintaining the threshold requirements for satellite tracking.
3. The future work is using the data provided by TACC for data assimilation to further improve the accuracy of orbit prediction.

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