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☐ **9: Simulation & Modelling**

Modelling for Ground Track Shift Prediction of Indian Remote Sensing satellites

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Abstract

Almost all Indian Remote Sensing Satellites (IRS) have to maintain a path-row referencing scheme. To maintain this, the ground track of the spacecraft has to be within specific limits to provide flawless service to the user community, with minimum possible turnaround time interval and for other reasons, such as interferometry applications of payloads. The Ground Track Shift (GTS) management of Indian Remote Sensing Satellites (IRS) is always a challenging task for the mission management team. Continuously perturbing forces disturb the spacecraft orbit, resulting in drifting of the GTS from the specification. Once the GTS is near the limits, orbit maneuvers are done, resulting in the turning of the ground track towards the reference.In this paper, the problem of ground track shift for a specific Satellite is theoretically analysed and derived. Afterward, with actual satellite data, the variation of ground track shift is studied and analysed. The variation of the pattern is modelled using various model equations across many days, and then the final model is selected based on the performance over many cycles of actual spacecraft data. The selected model is implemented, and an utility software has been developed. Depending on the initial few days' data, the model tries to predict the requirements for doing the orbit maneuver before a specific date, and it also predicts how much the spacecraft is up or down from the reference height. The utility software also predicts, using rocket equation for the particular satellite configuration, how much thruster firing is required for bringing back the ground track to the reference track. This utility helps the mission management team to formulate the orbit maneuver plan efficiently and use the ground resource effectively. It also helps to reduce the number of orbit maneuver requirements by predicting the decay accurately.

Keywords: Ground Track Shift, Indian Remote Sensing Satellite, Batch Processing, Orbit Maneuver, Sub-system Modeling

Acronyms/Abbreviations

GTS: Ground Track Shift
IRS: Indian Remote Sensing Satellite
OM: Orbit Maneuver
ISRO: Indian Space Research Organization

1. Introduction

Maintaining a specified Ground Track Shift (GTS) for any mission for the whole mission life is one of the mission success criteria. Indian Remote Sensing Satellite Resourcesat-02 maintains a ground track within ±1 km from its nominal ground trace. To maintain the Ground Track Shift within mission specification, one needs to maneuver the satellite from time to time to change the altitude of the satellite. The orbital parameter semi-major axis is responsible for shifting the ground track. If the semi-major axis is nominal, then there will be no shift in the ground track. Generally, due to perturbations such as atmospheric drag, solar radiation pressure, gravity gradient of earth, etc., satellite altitude, or semi-major axis, decreases, resulting in a decrease in the orbital period. As the semi-major axis of the satellite decreases, the ground track shift will go eastward from the nominal path. It is called an eastward ground track shift. If the satellite's semi-major axis increases, the satellite ground track goes westward from the nominal. It is called a westward ground track shift. To arrest eastward drift and push it westward, -Ve IPC is carried out by increasing the semi-major axis from nominal, and to arrest westward drift and push it towards eastward, +Ve IPC is carried out to decrease the semi-major axis.

1.1 Ground Track and ground Track shift

The foot print of the satellite in the earth is called the ground track. The ground track where it crosses the equator it is called the reference point. A typical ground track of a satellite has been shown in the figure below.

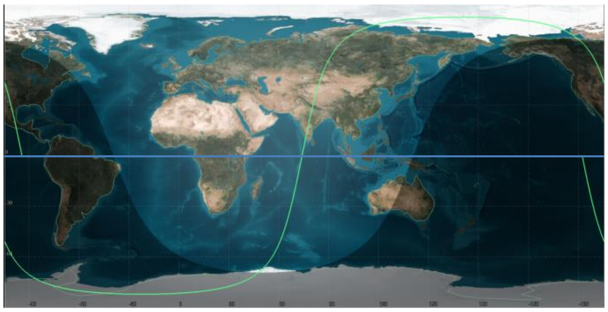

Fig. 1: Ground track of a satellite

If the orbital height is below the nominal then the ground track of the satellite will pass east direction of the reference point, it is called east ward shift and if the orbital height is above the nominal then the ground track of the satellite will pass in the west ward from the reference point , it is called west ward shift. It has been explained in the below figure.

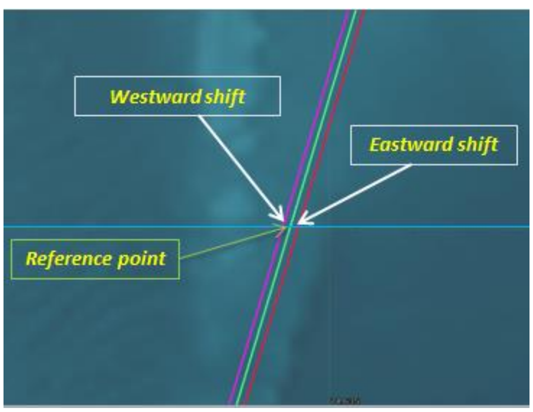

Fig. 2: East ward and west ward ground track

All most all the satellites have to maintain the ground track within some limits from the reference track point . Once the track is going to cross the defined limit, orbit Maneuver need to be performed.
In this paper effort has been put to predict when the orbit Maneuver need to be done and how much.

1.2 Problem Definition

The orbital period (T) of any spacecraft around the earth whose semi major axis is a can written as,

$$T^2 = (\frac{4\pi^2}{\mu})a^3$$

Where T is Orbit Period, a is semi major axis of the Orbit $\mu = GM$, where **G** is is universal gravitational constant and **M** is mass of the Earth.
As the Time period changes due to change in semi major axis change so for one orbit the time change will be as follows

$$dT = (\frac{3T}{2a})da$$

Ground Track Shift in (terms of ° per orbit) in dT Second = (dT)*(Rate of Earth Rotation).

$$= (\frac{3Tda}{2a})(\frac{360}{86400}) \text{ Degree/Orbit}$$

Ground Track Shift per Day (for the spacecraft which completes N orbits in a day

$$= (\frac{3Tda}{2a})(\frac{360}{86400})N \text{ Degree/Day}$$

as T*N=86400 sec,

$$= (\frac{540}{a})(da) \text{ Degree/Day}$$

Ground Track Shift Per Day (i.e GTS rate in terms of Km) : (as 1° separation in longitude at equator=111.32 Kms).

$$GTSRatePerDay = (\frac{540}{a})(111.32)(da) \quad \text{Km}$$

Let take any satellites's semi major axis like Indian remote sensing satellite Resourcesat-02 is having semi major axis as 7195.11 kms

$$da = \frac{GTSRatePerDay}{8.35467} \text{ in Km}$$

Ideally da should be zero but due to various external perturbation forces it is non-zero.

2. Ground Track Variation of A Satellite

The ground track maintenance is one of the mission management target for some satellites specially for those satellites which provides global imaging services based on the path row scheme [b6].It is also one of the requirements for interferometry imaging requirements. The below graph shows a typical ground track variation pattern for a Low Earth Orbiting satellite

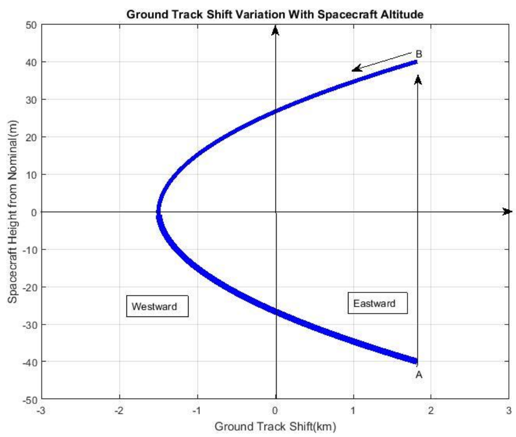

Fig. 3: Typical GTS Variation Pattern

In the graph x axis represents the Ground track shift. It is known as C curve. Once the spacecraft track is passing through eastward longitude from the reference it is called eastward shift and if it passes westward longitude from the reference then it is called westward shift. Generally, at point A, orbit maneuver is resulting shifting of operating point from A to B. At this point the height of the spacecraft is more than the nominal resulting longer orbit period which Result in drifting the ground track westward direction. The atmospheric drag and various perturbing forces act on the spacecraft and the spacecraft height start reducing and finally it follows the path as shown in the figure and reaches at point A. The goal of the paper is to predict the A point well in advance for efficient mission management.

3. *Modelling Equation Formulations For GTS Data*

The GTS data is taken for fitting the various model equations to derive the best fitted curves by principle of least square. One of the second order general model equations has been shown below.

$$y = a + bx + cx^2$$

There are n observations pair like

$(x_1, y_1), (x_2, y_2), \ldots (x_n, y_n)$.

The expected value is $n_i = a + bx + cx_i^2$

The error, $e_i = y_i - n_i$,The sum of squares of all of these errors areas shown below.

$$E = e_1^2 + e_2^2 + e_3^2 + \ldots + e_n^2$$

To get minimum E the below equations should satisfy [2],

$$\frac{\delta E}{\delta a} = \frac{\delta E}{\delta b} = \frac{\delta E}{\delta c} = 0$$

From the above three equations one gets the below equations

$$\left\{ \begin{array}{l} \sum_{i=1}^{n} y_i = na + b\sum_{i=1}^{n} x_i + c\sum_{i=1}^{n} x_i^2 \\ \sum_{i=1}^{n} x_i y_i = a\sum_{i=1}^{n} x_i + b\sum_{i=1}^{n} x_i^2 + c\sum_{i=1}^{n} x_i^3 \\ \sum_{i=1}^{n} x_i^2 y_i = a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i^3 + c\sum_{i=1}^{n} x_i^4 \end{array} \right\}$$

The above equations can be arranged to get the value of the coefficient a , b and c by solving the below equations provided the inverse exist for the mentioned matrix.

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} n & \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} x_i^2 \\ \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} x_i^2 & \sum_{i=1}^{n} x_i^3 \\ \sum_{i=1}^{n} x_i^2 & \sum_{i=1}^{n} x_i^3 & \sum_{i=1}^{n} x_i^4 \end{bmatrix}^{-1} \begin{bmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_i y_i \\ \sum_{i=1}^{n} x_i^2 y_i \end{bmatrix}$$

The various model equations are derived by using the above mentioned principle and by taking observed data. Here two data sets have been considered and for each set, three fourth amounts of data is taken for deriving the best fitted model equations. Once after deriving the model equations it is used for predicting the future values. As the actual values are already available so the predicted and actual values are compared to formulate the best predictable model equation. The results have been shown in the below sections

3.1 ***Analysis of First Data Set***

The actual raw GTS data of a spacecraft has been taken as the first data set and been shown in the figure below. The 1st grid shows the full cycle data and the 2nd grid shows the data taken for deriving the model equations. The graph shows the GTS variations in Km with the day number of the Starting of the cycle.

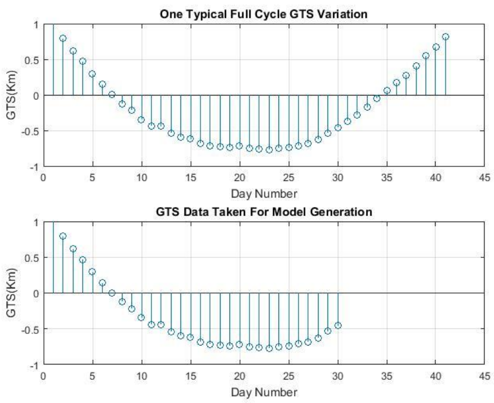

Fig. 4: Raw Data of Spacecraft GTS

The three quarter data set was fitted with the various curves. Once the curves are fitted it was extended for the full cycle for predicting. The results are shown in the below figure.

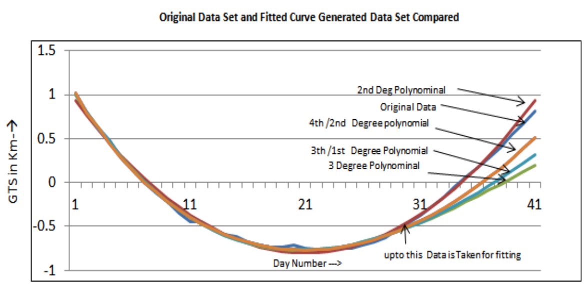

Fig. 5: Original Data Filled with Various Curves

Actual data were used to generate the model equations by best fit principle, it was used to predict for the future GTS values. As the actual observed values are already available, model generated predicted values are used to compare the results. The difference between the original data set and the data derived from the various model curves was predicted. The quality of the fit for various curves is shown in the

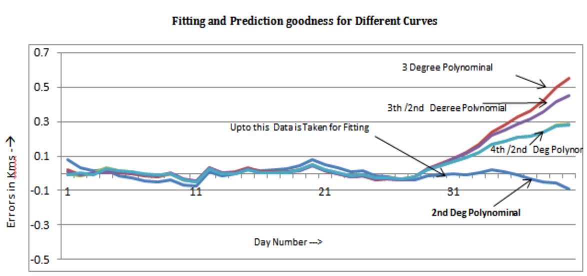

Fig. 6: Curves showing The Goodness of predicting future GTS

3.2 *Analysis of Second Data Set*

Similar analysis was carried out for the 2nd cycle data set. The raw satellite data and the data taken for model equation derivation for analysis has been shown in the figure below

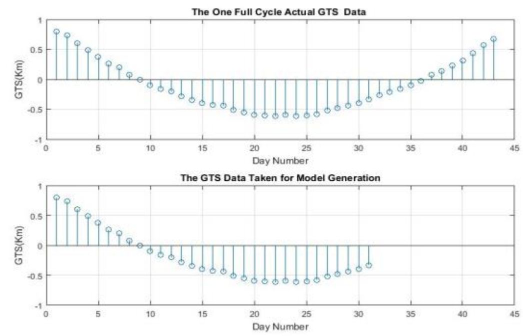

Fig. 7: Raw Data of Spacecraft GTS Variation

The initial three quarter data of the set was fitted with the various model equations. Once the model curves are ready it was extended for the full cycle for prediction. The results have been shown in the below figure.

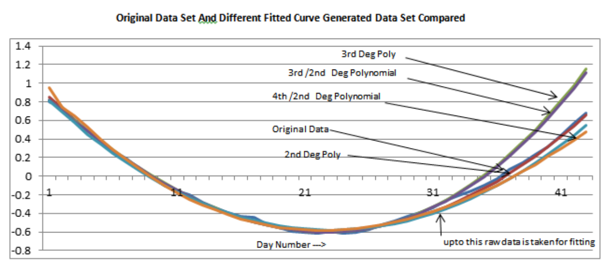

Fig. 8: Original Data Filled with Various Curves

Once the data set was generated with each of the model curves, it was compare with the actual one. The difference between the original data set and the data predicted from the various curves was derived. The quality of the fit for various model curves has been shown in the figure below.

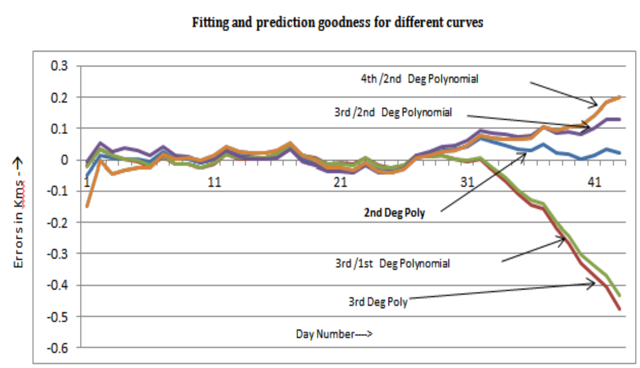

Fig. 9: Curves showing The Goodness of predicting future GTS

The above analysis results of two data sets have been summarized numerically in the below table

Table 1: Table Showing the Results of 1^{st} Data Sets

Polynomial	Average prediction Error for next 5 days(Km)	Average Prediction error in next 10 days(Km)
2^{nd} degree	0.00322	-0.00934
3^{rd} Degree	0.1793	0.05529
3^{rd} /1^{st} Deg	0.12692	0.02862
3^{rd}/2^{nd} Deg	0.16542	0.04481
4^{th}/2^{nd} Deg.	0.12654	0.02826

Table 2: Table Showing the Results of 2^{nd} Data Sets

Polynomial	Average prediction Error for next 5 days(Km)	Average Prediction error in next 10 days(Km)
2^{nd} degree	0.04882	0.03647
3^{rd} Degree	-0.04204	-0.13313
3^{rd} /1^{st} Deg	-0.03488	-0.11927
3^{rd}/2^{nd} Deg	0.07856	0.08284
4^{th}/2^{nd} Deg.	0.06422	0.08009

The result revels that for the 2nd degree polynomial, the average five days prediction error as well as for next ten days prediction errors are better.

4. *Implementation*

4.1 Flow Chart

The outcome of the analysis was implemented and an utility software was developed. The involved steps have been mentioned below.

The flow chart of implementation process has been shown below.

- Take the data from the remote terminal and show the variation of last few cycle data in the form of graph like C curve as shown in the figure-1
- Take the current cycle data and check if sufficient data is available or not. If data is not available, then show the current cycle data up to the current data and exit.
- If sufficient data is available then generate the model and predict for next 5 days.
- In next 5 days prediction, if it is crossing the limit then specifies how much decay has happened and calculate the required OM firing duration.
- If not crossing in five days then predict for next 10 days and check if the GTS is crossing the limit or not. If crossing the limits then calculate the firing duration.
- If it is not crossing the GTS limit then wait for the next day and run next day with new data point. The flowchart has been shown in the below figure

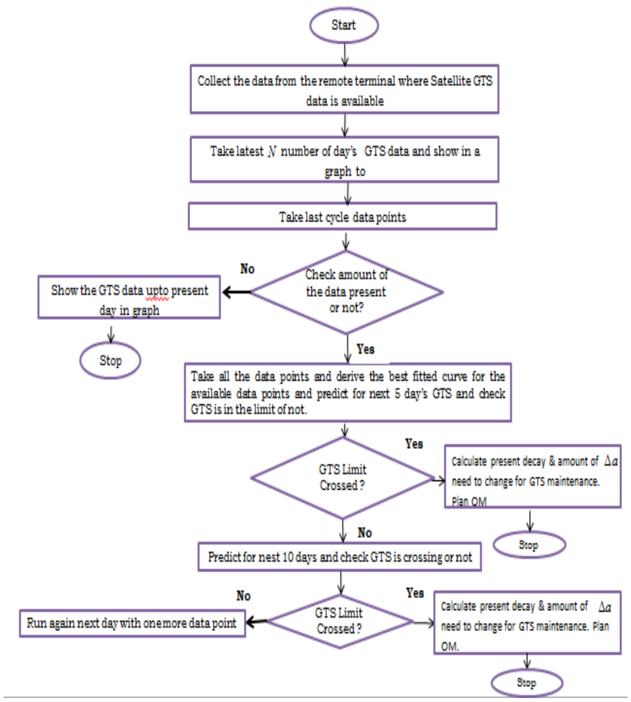

Fig. 10: Flow Chart Indicating Implementation Process of GTS Control

In the utility software, from present day to back N numbers of days GTS data from the data base are taken and plots to show the last N day's variations.

The software detects the last orbit manoeuvre point from the GTS data and if the number of data point is sufficient then the data point is passed to fit a 2nd order polynomial. The equation is derived based on the minimum error root square method. The fitted curve equation holds all the character of the pattern of GTS variation for the present cycles so equation is extended further to predict the GTS for future 5 days. If the predicted GTS is crossing the limits it will show the predicted day number and the predicted GTS value for that day.

It will also calculate the present decay value and to maintain the GTS how much height should increase. If it is not crossing the limits in next five days it will predict and check for the next ten days. If GTS is crossed the limit then it will do the same things as mentioned above. If it is not crossing in next 10 days also then it will wait for next day to have one data point to predict the same. The software can predict for any days but for weekly operation planning 10 days limit has been considered.

*4.2 **Output of the Software***

The figure-9 shows a typical output. The first greed shows the GTS variation for last 150 days.
The 2nd grid shows the present cycle GTS variation with 5 days prediction.
The 3rd grid shows the present cycle GTS variation with next 10 days GTS predictions.
The fourth grid shows the present orbit is decay by how much amount. It will also inform to maintain the GTS, how much thruster firing is required. It will also inform when GTS will cross the limit and in that day what will be GTS value.

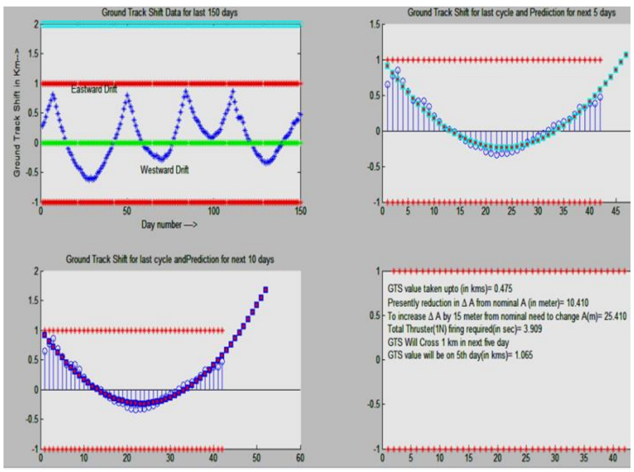

Fig. 11: Front end Output of the implemented Software

5. Conclusions

The input raw data contains all the characteristic of solar flux effect up to current date therefore no need to take solar flux data separately. The result shows very good match .The software has been implemented in many satellites and prediction has closely matched. This utility software or the technique can be used for monitoring and controlling the GTS for any satellites.

Discussion

The results can be further refined if the solar flux prediction model is used in process of predicting the maneuver dates. Analysis can be done on quantifying the effects on solar flux, magnetic flux, atmospheric
Drag etc. in the individual satellites for more accurate prediction of GTS. To take care sudden big variation of Solar flux and magnetic flux, methods can be explored.

Application

Maneuver has to be carried out before GTS crosses the specified Limits mentioned in the mission documents for a particular mission. For that mission team has to plan for the maneuver in advance. This paper will help the mission team to plan the orbit maneuver in advance to use the resources (station visibility and payload clash) optimally for orbit maneuver. This is already being used by the mission team to plan the Maneuver and to maintain the Ground Track Shifts. Apart from planning the maneuver it can also help the following, Any time visually see the pattern which provide better representation of the GTS data. The output will show the relative performance of the past OMs. As a result, directly the feedback from last OMs can be taken for generating current OM Plans. It helps to avoid frequent Orbit maneuver as it can predict accurate GTS crossing data as a result last OM to next OM day span will be maximum. Daily basis, looking into the pattern it will help to determine the accuracy of Orbit Determination as it has a specific pattern and if solar flux variation is not there then day to day much change is not expected. If some unexpected jump is observed it can indirectly reflect the Orbit determination quality.

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