Autonomous Ephemeris Prediction Using Navigation Receivers

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ABSTRACT

The prediction of ephemeris has been a long term problem being worked upon in the scientific community using the traditional methods of statistics and signal processing. In this paper, we present our machine learning-based approach for the autonomous prediction of ephemeris using navigation receivers. We have used the data provided by the Indian Space Research Organization (ISRO) for the duration of 30 days in the RINEX navigation file format and formalized the prediction of single day ephemerides using the previous 25 days' navigation data (ephemerides). This approach includes handling inconsistent timelines in the data. We have used the 'Forecasting at Scale - Prophet' model for time series prediction. Using this method we devised a solution to reduce the Time to First Fix (TTFF) effectively.

CCS CONCEPTS

• **Applied computing** → *Forecasting*; • **Computing methodologies** → *Machine learning*.

KEYWORDS

Ephemeris Prediction, Navigation Prediction, Time-Series Forecasting

ACM Reference Format:

Param Bhavsar, Ashish Kshirsagar, and Ashwin Samudre. 2020. Autonomous Ephemeris Prediction Using Navigation Receivers. In *MileTS '20: 6th KDD Workshop on Mining and Learning from Time Series, August 24th, 2020, San Diego, Claifornia, USA*. ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/1122445.1122456

1 INTRODUCTION

Ephemeris is a set of parameters used to provides information regarding the trajectory of an individual artificial satellite. A group of artificial satellites working together to achieve a single purpose is known as a 'constellation'. Satellite position data is in the form of Ephemerides, which is an aggregation of navigation information from a constellation.

Though ephemerides have worked reliably over the time providing location information consistently, procurement of ephemerides in advance for the upcoming days based on available data can be crucial to avoid any casualties as well as prepare the plan of action for future proceedings.

Different methods have been used to calculate orbit estimation such as the least mean square method, Kalman filtering technique and other analytical approaches but these required a large amount of data to predict future ephemeris.

In this work, we implemented a method to perform the automated prediction of satellite ephemeris using machine learning techniques. An important issue faced while processing the received data is the Time to First Fix (TTFF). TTFF is the time delay observed between switching on the navigation receiver and the provision of a navigation solution in the form of satellite position data. The general TTFF is considered to be 30 seconds under normal settings. Autonomous prediction of ephemeris can help in the procurement of the ephemeris and ultimately avoid the need for TTFF. We have focused on the prediction of ephemeris using the least amount of data possible. Ephemeris contains a total of 30 parameters which provide the complete information regarding the satellite. Our results show that with the use of specific parameters and a time series forecasting model, accurate ephemeris prediction can be obtained even with less amount of data. To our knowledge, this is the first attempt at using machine learning-based time-series forecasting for ephemeris prediction.

2 METHODOLOGY

2.1 LITERATURE

A variety of analytical approaches have been implemented for orbit and ephemeris prediction. In [1], the authors investigated machine learning algorithms for positioning error estimation. They computed the error estimation on a handpicked feature set and the data is collected from a camera on a vehicle testing platform. In [2], authors describe the forces responsible to determine the position of a satellite more accurately and the orbit data receiving mechanism for a satellite. It also explains the orbital perturbations and the physics laws that are responsible for the GPS satellite motion around the earth. [5] have used the Support Vector Machine technique for the improvement in the prediction of the orbit. Their results show that prediction of orbit over a short period can be improved with the SVM technique but it requires more data in case of long term prediction. [9] provided a completely analytical approach to estimate the satellite orbit and ephemeris. They have used methods like least squares batch estimation, Kalman filtering and computed the parameters of ephemeris individually which provided good performance in ephemeris and satellite orbit prediction. In [7] authors presented a way to predict satellite orbits in a GPS device without a network connection in order to reduce the time to first fix when assistance data is not available. This work provides a numerical approach for calculating satellite position based on their predicted orbit and the satellites initial position. However,

MileTS '20, August 24th, 2020, San Diego, California, USA

ACM ISBN 978-1-4503-9999-9/18/06…$15.00
https://doi.org/10.1145/1122445.1122456

authors could not find any predictive model to predict the earth's polar motion with sufficient accuracy within the lifetime of the device. [6] addresses the problem of predicting the orbit of a GNSS satellite with a combined force model that can be adjusted based on data. According to the study, the same model can be useful in prediction for different constellations if the satellites have equal orbital periods. However, the study only considered the accuracy of the orbit and not positioning accuracy.

2.2 Ephemerides data

We have used the navigation data present in RINEX format (version 2.10). Each file in the data consists of daily ephemerides for 32 satellites. RINEX is data interchange *Receiver Independent Navigation Exchange* format for raw satellite navigation system data. It provides the standard format for the management and disposal of the measures generated by a receiver along with their off-line processing by a multitude of applications, irrespective of the manufacturer of both the receiver and the computer application. The ephemeris consists of 30 parameters for each satellite shown in Table 1.

The parameters depict the complete state of the satellite at a point of time concerning the previous position and the start position.
As the ephemeris contains a large number of parameters, we need to extract only the essential parameters which contribute significantly while removing the constant ones as their values do not affect the result (ephemeris estimation). According to the [2], the keplerian elements can be used as a way to represent the orbit of a satellite. Below are the six Keplerian elements -

- Eccentricity (e)
  Provides the shape of the ellipse, describing its elongation compared to a circle.
  - e=0, circular shaped orbit
  - e<1, elliptical orbit
  - e>1, hyperbolic trajectory
- Semi-major axis - Half the sum of the point of closest approach (periapsis) and point of farthest excursion (apoapsis) distances. Above two factors are used to determine the orientation of the orbital plane in which the ellipse is embedded.
- Inclination - The Vertical inclination of the ellipse with respect to the reference plane (equatorial plane), measured at the ascending node (where the orbit passes upward through the equatorial plane).
- Right Ascension of Ascending Node (RAAN) - The angle between the reference plane's vernal point and the ascending node, measured counterclockwise from vernal equinox.
- Argument of Periapsis/ perigee (omega) - The Angle measured from the ascending node to the periapsis, defining the orientation of the ellipse in the orbital plane.
- Mean anomaly - Position of the satellite along the ellipse at a precise epoch.

Table 1: Ephemeris parameters

Parameters	Description
`PRN`	GPS Satellite Number
`Epoch`	Time of satellite clock
`sv_clock_bias`	Satellite Clock bias
`sv_clock_drift`	Satellite Clock Drift
`sv_clock_drift_rate`	Satellite Clock Drift rate
`eccentricity`	Eccentricity
`inclination`	Inclination
`inclination_rate`	Inclination rate
`iodc`	Issue of Data - clock
`iode`	Issue of data & Ephemeris
`n`	Mean motion
`M0`	Mean anomaly
`omega`	Right Ascention of Ascending Node (RAAN)
`OMEGA_dot`	RAAN rate
`toe`	Time of Ephemeris
`sqrt_semi_major_axis`	Square root of Semi major Axis
`correction_inclination_cosine`	Correction factor for perturbation of inclination - cosine component
`correction_inclination_sine`	Correction factor for perturbation of inclination - sine component
`correction_latitude_cosine`	Correction factor for perturbation of argument of latitude - cosine component
`correction_latitude_sine`	Correction factor for perturbation of argument of latitude - sine component
`correction_radius_cosine`	Correction factor for perturbation of radius - cosine component
`correction_radius_sine`	Correction factor for perturbation of radius - sine component
`sv_accuracy`	User range accuracy
`sv_health`	The health of signal components
`tgd`	Satellite Group Delay
`t_tx`	Time of transmission of the current date
`GPS_Week`	GPS Week Number
`CODES`	Codes on L2 channel
`fit_interval`	Interval indicator flag
`L2_P_Data_flag`	Code modulation flag

The following parameters do not show any variance in their values - Codes, Fit interval, Gps week, L2p data flag, Sv accuracy, Sv clock drift rate, Sv clock drift, Sv health and tgd. The correction

inclination sine and correction inclination cosine values show a lot of variance over a period of time. The iodc curve does not provide any periodic pattern and is variable to a large extent.
Epoch time is the reference epoch of ephemerides within a week, across the interval of a month. The correction terms including correction radius sine, correction radius cosine, correction latitude sine, correction latitude cosine show periodic behavior with the curves being near sinusoidal for all these parameters. Remaining correction terms, correction inclination sine and correction inclination cosine do not follow any periodic pattern and show high variance. The eccentricity curve shows an increasing pattern. Inclination parameter shows non-uniform periodic behavior while the inclination rate shows near sinusoidal curve behavior which can similarly be observed in the mean motion parameter. The semi-major axis exhibits a non-uniform curve. (The variations of the parameters over time are provided in the Appendix.)

2.3 Prophet model

Prophet [8] is a framework to forecast time series data based on an additive model where non-linear trends are fit with seasonality. It fits the model in Stan so that the forecasts can be made in a few seconds. Stan is a probabilistic programming language that is used to create a statistical inference. It is robust to handle missing data, shifting trends and outliers in the data. It uses a decomposable time series model with trend, seasonality and outliers as it's main components.

$$y(t) = g(t) + s(t) + h(t) + e(t) \tag{1}$$

where *s(t)* represents periodic changes,
h(t) models the effects of outliers,
g(t) models non-periodic changes using linear or l logistic character
Prophet fits several linear and nonlinear functions of time as components using time as a regressor, similar to the generalized additive model. This formulation has an advantage that it decomposes easily and accommodates new components as required even when a new source of seasonality is identified.

3 EXPERIMENTS AND RESULTS

We have conducted forecasting experiments on an artificial satellite trajectory using the navigation data. We used the Prophet model to predict the ephemeris and used this to calculate the exact position of the artificial satellite in the form of earth-fixed geocentric satellite coordinates.
Parameters like epoch_time, gps_week, time_of_ephemeris and PRN are not used in the experiments. PRN is the identifier which is used to define the trajectory of the artificial satellite to forecast, epoch_time defines at what instance in time to forecast and gps_week and time_of_ephemeris is calculated using epoch_time. To avoid the effect of the scale of the parameter on the training of model the parameters are normalized using the Min-Max Scalar [4] method except for mean_anomly due to high impact generated by transformation and inverse transformation in and out of normalize form on trajectory prediction. There are slight variations in the way the prophet model uses changepoints for different parameters. The prophet changepoint decide the rate allowed to change. Table 2 shows the changepoint configuration of the features having a different configuration than that of default.
The ephemeris of the last 25 days has been considered for forecasting the next 24 hrs of trajectory for a given artificial satellite. The result of the forecasting model is evaluated into two stages. In the first stage of forecasting, each feature of ephemeris is evaluated using metric mean squared error (MSE) and mean absolute error (MAE). Table 3 shows the MSE and MAE on test data for each feature of ephemeris consider for a cluster of 31 artificial satellites.

Table 2: Prophet Changepoint Configuration

changepoint_prior_scale	Ephemeris features
0.5	iode, correction_radius_sine correction_latitude_cosine, t_tx correction_latitude_sine, correction_inclination_cosine, correction_radius_cosine, mean_motion correction_inclination_sine, omega
1.0	iodc

Table 3: MSE and MAE of Forcasted Ephemeris Features

Ephemeris features	MSE	MAE
OMEGA	2.757e-07	0.00045
OMEGA_dot	0.01281	0.09375
correction_inclination_cosine	0.00914	0.06328
correction_inclination_sine	0.00319	0.03885
correction_latitude_cosine	0.00419	0.05053
correction_latitude_sine	0.00486	0.05701
correction_radius_cosine	0.00493	0.05699
correction_radius_sine	0.00438	0.05141
eccentricity	6.157e-09	6.055e-05
inclination	1.781e-08	0.00011
inclination_rate	0.03588	0.16659
iodc	0.05016	0.16756
iode	0.04475	0.16238
mean_motion	0.00093	0.02522
omega	1.88083	0.00018
sqrt_semi_major_axis	0.00778	0.03004
sv_accuracy	0.07195	0.07195
sv_clock_bias	2.70638	2.70638
sv_clock_drift	0.00107	0.00107
t_tx	0.11540	0.11540

The second stage of the model evaluates the mean displacement of an artificial satellite from the expected position. The result of the trajectory forecast is calculated for a single artificial satellite having PRN 2 the mean error is 4.964 km. The mean error of the forecasted trajectory is mainly affected by the mean_anomaly. Here, the percentage error of mean_anomaly is around 0.093 % error. The further analysis of ephemeris features shows that a slight reduction and increment in the error of mean_anomaly causes a drastic effect on trajectory prediction in the magnitude of multiple kilometers.

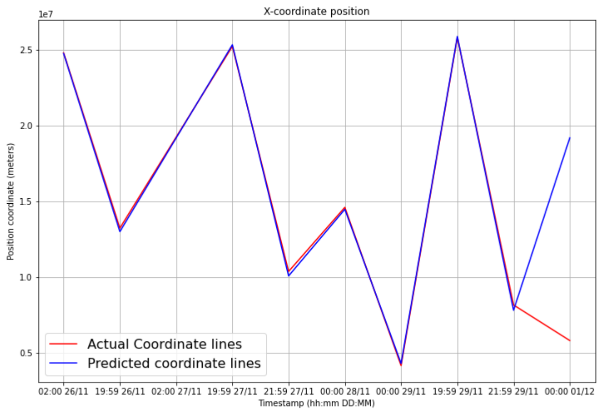

Figure 1: X-coordinate comparison

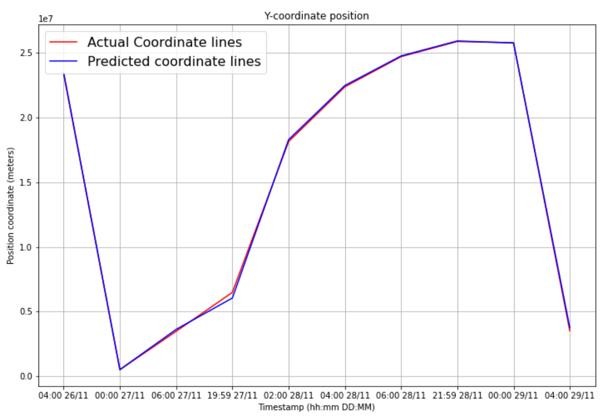

Figure 2: Y-coordinate comparison

The figures 1, 2 & 3 represent the comparison of forecasted and actual earth-fixed geocentric satellite coordinates for X, Y, Z respectively. The coordinates were calculated from the forecasted ephemeris based on [3].

4 CONCLUSION

In this work, we presented a novel approach for forecasting the navigation satellite ephemeris using a hybrid machine learning and statistical model that takes into account the trend, seasonality and outliers in the ephemeris parameters. Data, Experiments and models are provided at https://github.com/param087/Ephemeris-prediction. The forecasted ephemeris was used to estimate the earth-fixed geocentric satellite coordinates. Few parameters in the ephemeris do not provide a statistical trend over a short interval of time and thus we reckon, the performance can be improved with the use of the data in a longer time span. In the future, we plan to extend the results for GNSS based ephemerides data.

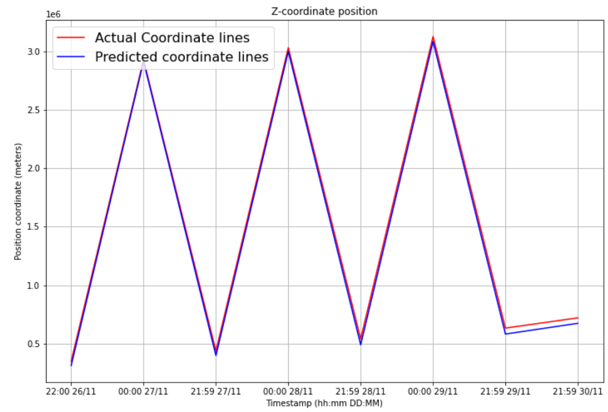

Figure 3: Z-coordinate comparison

5 ACKNOWLEDGMENTS

We would like to thank the Smart India Hackathon team for providing us a platform and Indian Space Research Organization (ISRO) team for the data to demonstrate this work. We would also like to thank Njoroge Wangosho for his guidance on RINEX, which provided us initial insights over the data.

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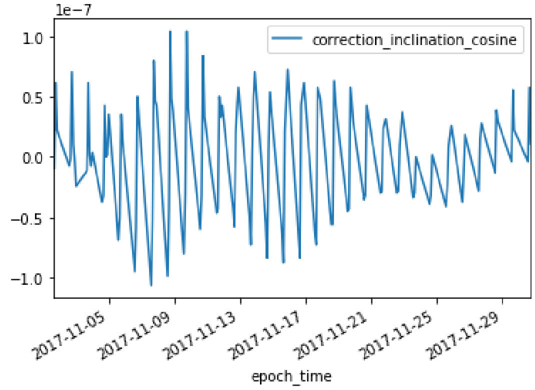
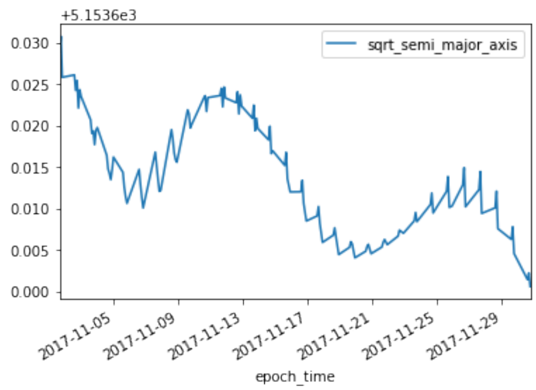
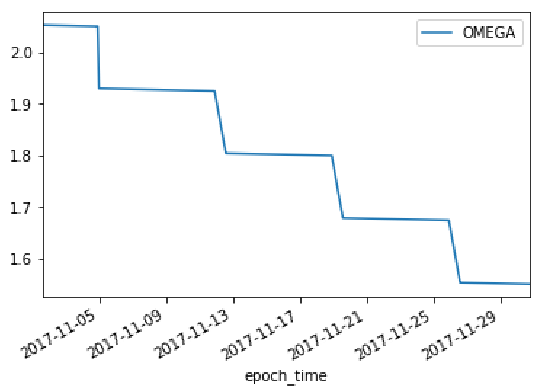
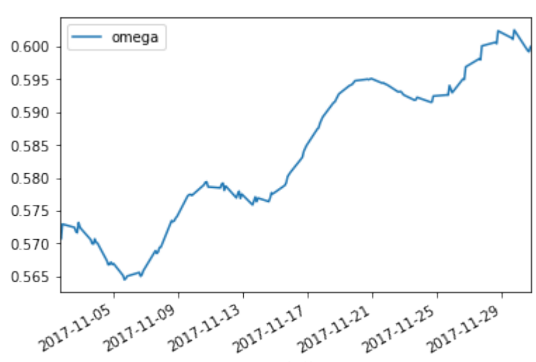
A DATA ANALYSIS AND VISUALIZATION

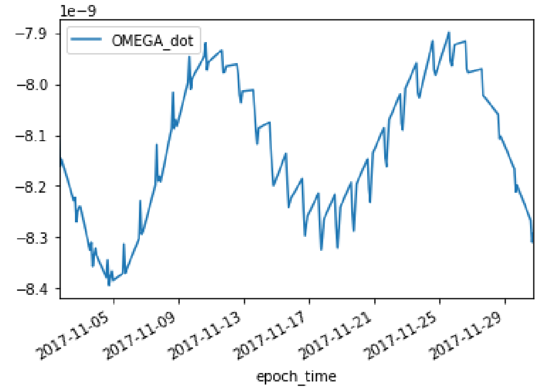
A.1 Parameter variation plots

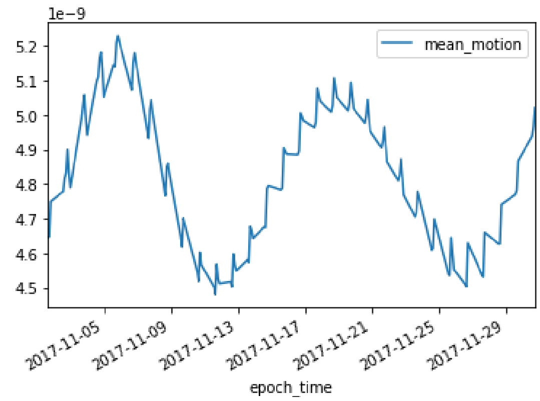


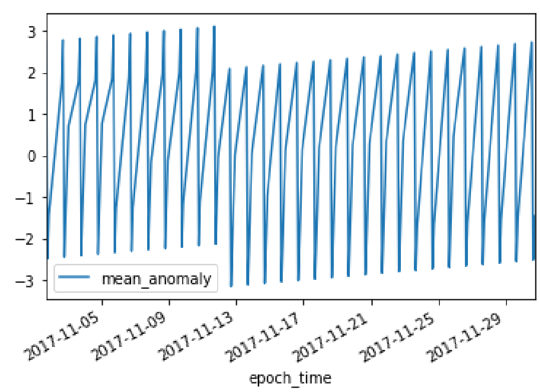


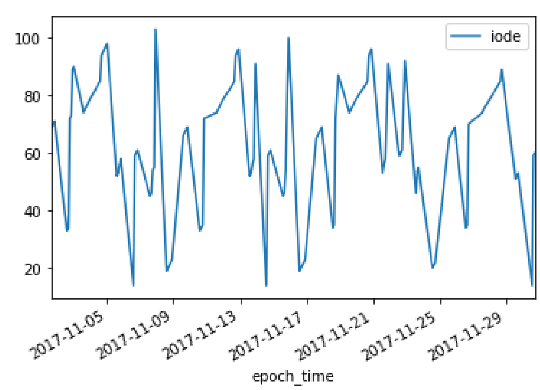


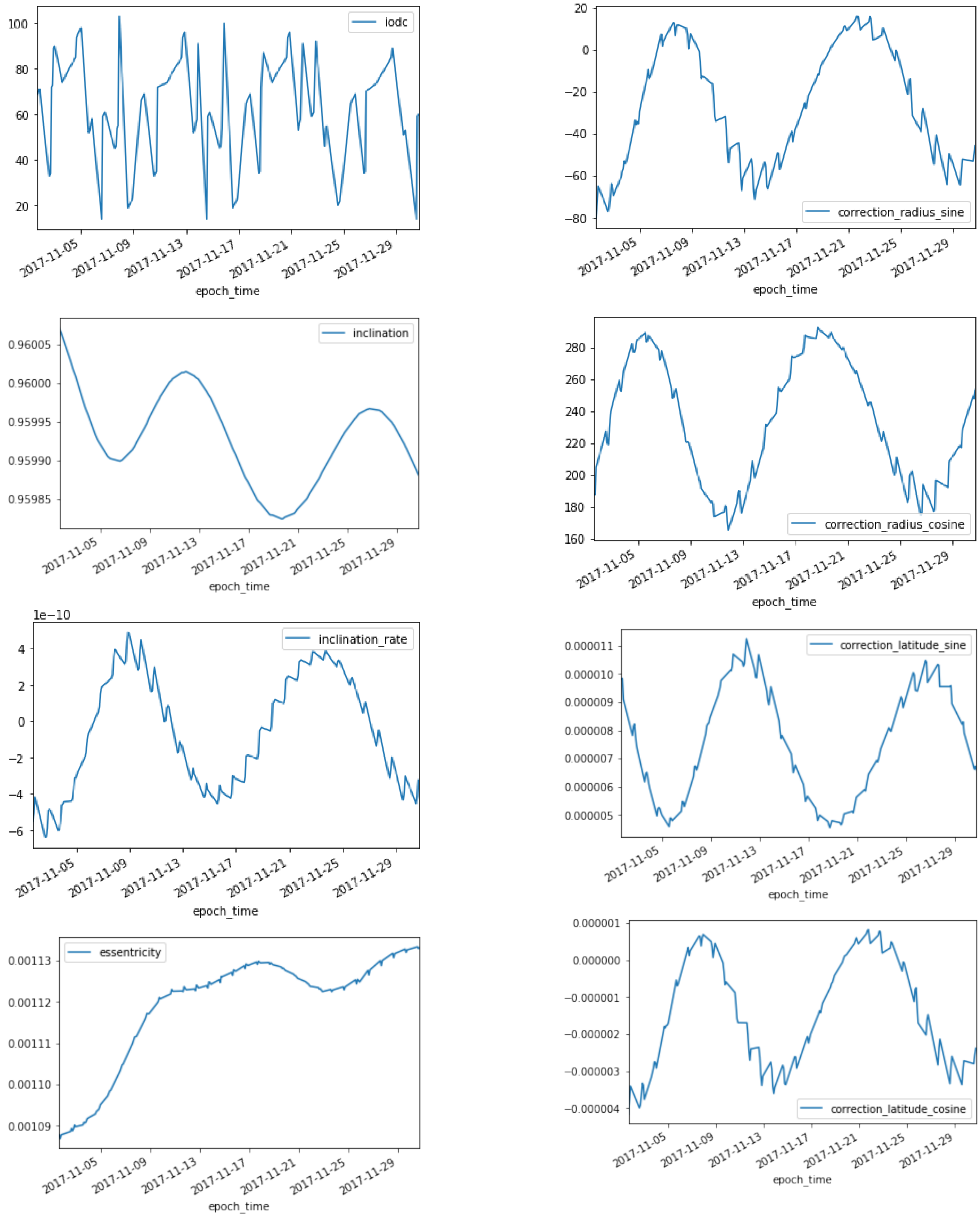








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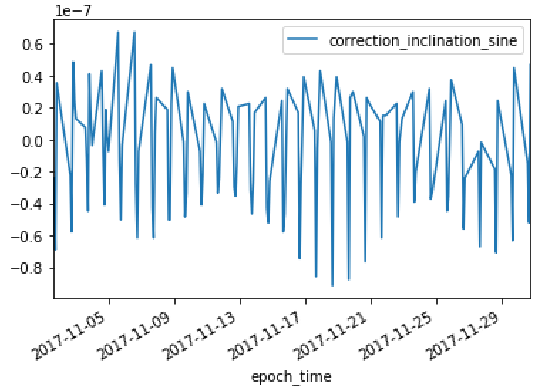
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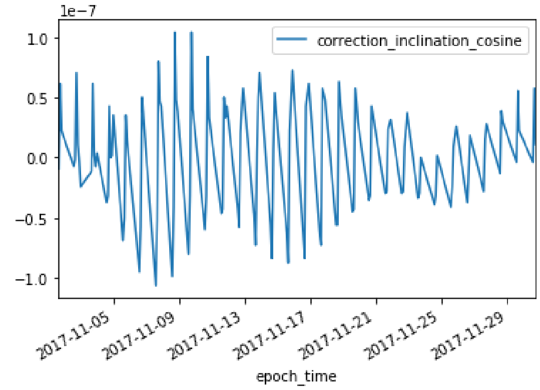
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