Next-Generation Algorithms for Navigation, Geodesy and Earth Sciences Under Modernized Global Navigation Satellite Systems (GNSS)

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Abstract The project on "Next-generation algorithms for navigation, geodesy and earth sciences under modernized Global Navigation Satellite Systems (GNSS)" has been under development within the scope of the Geomatics for Informed Decisions (GEOIDE) Network. The GEOIDE Network is part of the Networks of Centres of Excellence program (NCE) of the government of Canada. Networks of Centres of Excellence are unique partnerships among universities, industries, government and non-profit organizations aimed at turning Canadian research and entrepreneurial talent into economic and social benefits for all Canadians. Among its objectives, the GEOIDE Network intends to drive the research and development of new geomatics technologies and methods via multidisciplinary collaboration in a fully networked environment. The GEOIDE Network, having started operations in 1998, is currently in its Phase III. In this paper the authors will present an overview of the activities which have taken place under this project. They include: (a) Processing and analysis of real modernized GNSS data (L2C) as well as simulated modernized GPS and Galileo data; (b) Performing constellation system performance and augmentation analyses of the modernized GNSS; (c) Designing algorithms for single point and relative positioning using combined signals; and (d) Integrating legacy and modernized GNSS signals.

Keywords Modernized GPS · L2C · PPP · Galileo

1 Introduction

Positioning from space, currently predominantly based on the Global Positioning System (GPS), has become

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nearly omnipresent in an ever growing variety of applications, both civilian and military. The global value of GPS device production is expected to increase to US$21.5 billion in 2008, up from $13 billion in 2003, according to the Taiwan-based Industrial Economics and Knowledge Center of the Industrial Technology Research Institute. Forecasts also indicate a strong annual growth and an expected market size of US $757 billion by 2017 (RNCOS, 2005). This tremendous commercial push has led to modernization plans of the GPS itself as well as the design of a European-based system known as Galileo – not to mention the revamp of the Russian GLONASS and development of for the Chinese Beidou/COMPASS system.

A project is underway within the scope of the Canadian Geomatics for Informed Decisions (GEOIDE) Network of Centres of Excellence to focus on the modernization of GNSS by the new GPS classes of satellites, Block IIR-M and Block IIF, and the Galileo system. Advantages coming from a modernized GNSS include improved positioning and navigation performance by means of doubling the availability of signals, impacting single point positioning accuracy, and faster and more reliable positioning techniques, including those based on carrier-phase ambiguity resolution.

The overall objective of this research endeavour is related to the modernization of GNSS and its implications for Canadian society, enhancing the current capabilities in applications related to positioning, navigation, environmental monitoring and atmospheric sciences. There are several objectives to be accomplished within this project, each one having a strong link with the other. They are:

1. Study of the availability, reliability, and accuracy of Galileo and GPS Block IIR-M and Block IIF measurements and their integration.
2. Development of carrier-phase ambiguity resolution techniques, involving combination of multi-frequency carrier-phase observations using GPS and Galileo signal designs in order to arrive at an optimal combination that allows fast, accurate and reliable ambiguity resolution for real-time kinematic (RTK) and post-processed data.
3. Analyze the impact of sources of error in the optimal combination and how to minimize them.
4. Design algorithms for single point and relative positioning using combined signals.
5. Integration of legacy and modernized GNSS signals.
6. Design increased capabilities of error modelling that are essential for RTK positioning and navigation, as well as for static positioning.
7. Development of robust quality control for integrity monitoring of observations from hybrid navigation systems.

The project entails various applications:

- Modernization of augmentation infrastructures, by testing the satellite-delivered Canada-wide Differential GPS (CDGPS) Service and other augmentation services, including how the Galileo signals will be integrated into these services.
- Determination of precise orbits for space geodetic missions.
- Exploring existing and investigating novel ways to use GNSS for environmental monitoring and atmospheric sciences.
- Testing newly developed algorithms for the analyses of continuous GPS network data for improved position accuracy (especially for sub-daily samples) and resolution of crustal motions in earthquake-prone regions.

This paper presents an overview of the activities that have been taking place under the scope of this project at several of the participating institutions.

This paper has been structured in such a way that it summarizes these activities highlighting the most important accomplishments so far. References are made to papers that provide a more in-depth explanation of the various topics encapsulated in this paper. The activities have been divided by university just for organizational purposes even though there are activities that have taken place with the participation of more than one group as facilitated by the very nature of the network.

2 University of New Brunswick

During the past two years, within the framework of the GEOIDE project, the team at the University of New Brunswick (UNB) has concentrated most of its effort into assessing the quality of the GPS L2C signal, and developing the precise point positioning (PPP) software, GAPS (GPS Analysis and Positioning Software), (Leandro et al., 2007b), targeting the inclusion of L2C and future modernized signals. The development of GAPS allowed us to publish the first estimates of the P2-C2 bias reported in the literature (Leandro et al., 2007a).

L2C data has been collected by two Trimble receivers: first a Trimble R7 and a Trimble NetR5, both on loan from Cansel, a Canadian distributor of Trimble Navigation Ltd. products. We have also used NetRS and NetR5 data from the global IGS L2C Test Network. Among several distinct analyses, we want to showcase here the one involving C/A and L2C code multipath and noise levels based on the IGS L2C Test Network (Sükeová et al., 2007). For this analysis we chose four stations: FAIC, Fairbanks, Alaska; UNAC, Boulder, Colorado; UNB3, Fredericton, New Brunswick; and GANP, Gánovce, Slovakia. The first two stations use a Trimble NetRS receiver; while the other two stations use a Trimble NetR5 receiver. The standard deviations of multipath and noise values have been calculated for each of the 10-degree elevation angle bins, from 0 to 90° (9 bins); separately for the C/A and L2C pseudorange observations for a period of 24 days from December 1 through 24, 2006. The computation was carried out in two ways: (i) for each day separately; and (ii) for the 24-day periods as a whole. In Fig. 1, dots are used to show the mean standard deviation of multipath and noise, computed using the 24-day period, for each one of to the elevation angle bins. The spread of the standard deviations inside each bin is represented by an error bar superimposed on each mean standard deviation and expanded to twice its initial magnitude. The standard deviation is roughly inversely proportional to the sine of the elevation angle.

Precise point positioning (PPP) is one of the existing techniques to determine point coordinates using a GNSS receiver. In this technique, observations carried out by a single receiver are used in order to determine the three coordinate components, as well as other parameters, such as the receiver clock error and total neutral atmosphere delay. The technique is said to be "precise" because precise information, such as satellite orbit and satellite clock errors, is required in the data processing (because of this, one should have in mind that the usage of precise orbits, clocks and other precise products is an implicit procedure whenever the term "PPP" is used). More than that, PPP is "precise" also because the resulting parameter estimates are precise (and accurate). The idea behind UNB's present work is that PPP, and therefore precise products such as the ones provided by the International GNSS Service (IGS), can be used not only for positioning, but for a variety of other tasks, such as signal analysis. The

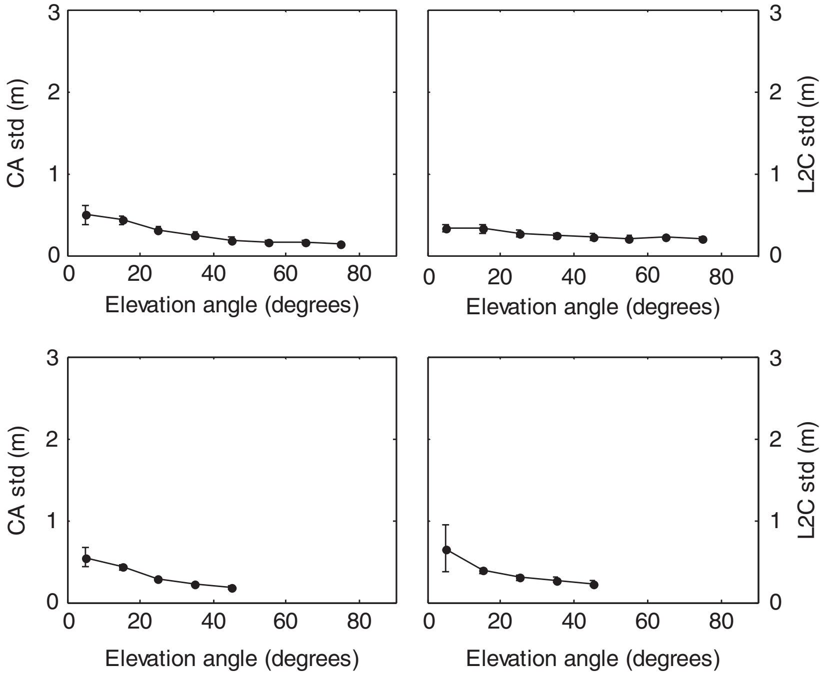

Fig. 1 C/A and L2C code multipath and noise standard deviation, PRN 31, stations UNB3 (*top*) and GANP (*bottom*)

fact that the observation model used for accurate error modelling has to take into consideration the several effects present in GPS signals, and that observations are undifferenced (there are no differences between receivers nor between satellite measurements), makes PPP a powerful data analysis tool which is sensitive to a variety of parameters. The PPP software developed at UNB, known as GAPS, has been designed and developed in order to take advantage of precise products, resulting in a data analysis tool for determining parameters in addition to position, receiver clock error and neutral atmosphere delay. These other estimated parameters include ionospheric delays, code biases, satellite clock errors, and code multipath plus noise among others. In all cases the procedures were developed in order to be suitable for real-time as well as post-processing applications.

The ionospheric delay estimation uses a spherical ionospheric shell model, in which the vertical delays are described by means of a zenith delay at the station position and two horizontal gradients. This estimation makes use of carrier phase measurements only. The use of precise orbits and clocks is a key element for the quality control of the data which goes into the ionospheric estimation filter. The code multipath estimation is based on the assumption that the several effects present in code measurements are dealt with within PPP, but strongly based on carrier phase measurements. Based on this, these effects can be removed from pseudorange measurements, and the residual effect is essentially the code multipath plus receiver noise. The advantage of this technique is that it potentially can retrieve the mean multipath effect of a satellite arc, as opposed to other multipath retrieval techniques. This is possible only under the assumption that satellite orbit and clock errors are negligible for this application, which is achievable when using precise IGS products. Another effect which afflicts pseudorange measurements is the code bias. The code biases are important because satellite clock data products are computed using a certain arbitrary convention of observation type, such as P1 code measurements rather than C/A code. If the user's receiver employs a different observation type than the one which was used to generate the satellite clock error corrections, he (or she) has to apply an offset to the correction, equivalent to the bias between the observations, to be able to use these clock products. One of the analysis tools of GAPS produces values of the satellite code biases, based on a positioning observation model, as opposed to being based on a satellite clock estimation observation model as is usually the case when bias values are provided to users. This estimation is made possible by means of a pseudo-observable, which reflects the mismatch between the precise clock reference code (e.g. P1 and P2 for IGS products), and the code the receiver is actually using (e.g. C/A).

Regarding satellite clock error estimates, GAPS was enhanced in order to provide estimates of satellite clock offsets. This tool was created to provide a suitable approach for real-time carrier-phase-based satellite clock estimation. Once again, within the clock estimation filter; the assumption that precise orbit errors are reasonably small is made. It is worth mentioning that both code bias and clock error estimations can be improved by using data from several receivers. This is mainly due to multipath effects present in each individual receiver estimate, which is averaged out to a certain degree when combining uncorrelated (site-dependent) multipath effects from different stations, an obvious advantage of having data from a global network of receivers promptly available. However, even in a case where a combination of several stations is used, single-receiver data processing is still used as an initial step. This is an important aspect in terms of data processing performance, because solving receiver-dependent parameters in a single receiver step and solving network-dependent parameters (only) in a network processing step speeds up the data processing.

GAPS is available online via a web interface, (http://gaps.gge.unb.ca) through the UNB Research and Learning Resources website, which can be easily run from anywhere, producing all data analysis results mentioned in this paper. In addition to signal analysis outputs, GAPS provides state-of-the-art PPP results, including position, receiver clock errors, and neutral atmosphere delays, in static or kinematic mode. All aspects briefly mentioned above make GAPS a novel application, with innovations mainly in the field of GPS data analysis, available to the user community. One of the main accomplishments in GAPS development is that it takes advantage of precise satellite products made available by the IGS, coupled with a very complete observation error modelling to make possible a variety of analyses based on GPS data. Future enhancements to GAPS will include the ability to process modernized GPS observables as well as those from other GNSS constellations.

3 Laval University and École de Technologie Supérieure

During the last two years, within the framework of the GEOIDE project, Laval University's team has been mainly working on two research themes. The first one was related to the contribution of modernized GPS signals and the addition of the future Galileo signals for the improvement of the instantaneous ambiguity resolution success rate (Boukhecha, 2006). Plans have been made to add GLONASS into this study. The second project dealt with the development of calibration methods for the receiver and satellite phase biases (Banville, 2007) – a key element for PPP ambiguity resolution.

The current GPS constellation limits RTK solutions to relatively short baselines. This limitation is mainly due to the disturbing influence of the ionosphere on the resolution of the initial phase ambiguities, which is indispensable to reach the centimetre accuracy level. In the near future, GPS will be modernized by the addition of a third frequency and the European Union will deploy its own satellite navigation system Galileo. The interoperability of both systems and the availability of hybrid receivers which are able to simultaneously track GPS and Galileo satellites on all three frequencies will lead to substantial improvements.

In order to investigate the performance of the future GNSS in terms of instantaneous ambiguity resolution, the upcoming constellations are simulated based on a Keplerian representation of the orbits. Through the Gauss-Markov model, the normal equation matrix for the unknowns containing the 3D-coordinates, the clock bias, the phase biases, the ambiguities, and zenith ionosphere biases is built. The latter are treated as an ionosphere-weighted model by applying constraints to these unknowns. Different values for the ionospheric constraint were adopted allowing for simulation of different levels of ionospheric disturbance present in the data. A modified search algorithm, adapted to the a priori case, is applied, leading to a theoretical discrimination factor used as a primary performance indicator.

Figure 2 is an example of results obtained. It presents the percentage of success of instantaneous ambiguity resolution for modern GNSS triple-frequency combinations as a function of the ionospheric noise. The results were obtained by simulation using standard deviations of 30 cm and 3 mm for code and phase measurements, respectively. The standard deviation of the assumed ionospheric noise refers to a nominal wavelength of 1 m (Boukhecha, 2006).

The simulation-based investigations showed that introducing Galileo and modernizing the GPS by adding a 3rd frequency will have a major impact on integer ambiguity resolution. In the mono-frequency case, a hybrid solution will guarantee a success of nearly 100 % in the absence of ionospheric noise. In the dual-frequency case, a hybrid solution will allow the resolution of the ambiguities even in the presence of moderate ionospheric noise. As expected, the best results were obtained for the hybrid triple-frequency case. One can reasonably expect that the future hybrid receivers which are able to measure on all 3 frequencies will become available. With such receivers, even over longer

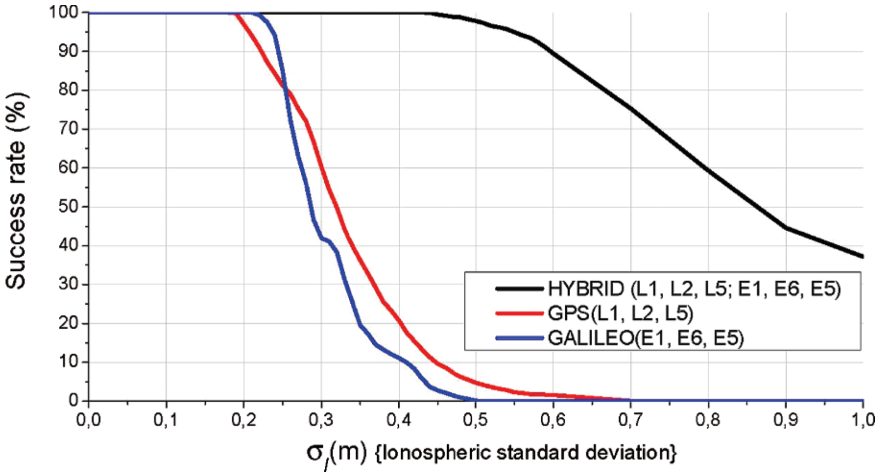

Fig. 2 Percentage of success of instantaneous ambiguity resolution for modern GNSS triple-frequency combinations as a function of the ionospheric noise

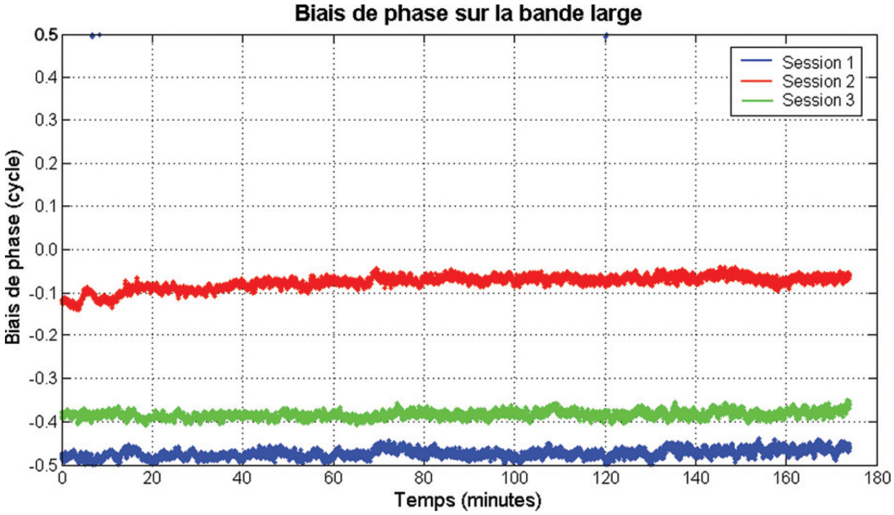

Fig. 3 Receiver widelane phase biases for three calibration sessions using a Spirent STR4760 GPS simulator (Banville, 2007)

baselines, instantaneous integer ambiguity resolution will become feasible. This work was done in collaboration with Prof. René Landry from Department of Electrical Engineering at École de Technologie Supérieure de Montreal.

In PPP one currently refrains from integer ambiguity resolution. Real-valued biases are estimated instead. This allows the use of the ionosphere-free combination as input data. In addition, these biases absorb unmodelled errors such as receiver and satellite phase biases. The drawback, however, is a long convergence time of several hours before reaching cm-level accuracy. In order to solve for integer ambiguities in the absolute mode explicit modelling of different error sources becomes mandatory. This research concentrated on the calibration of the receiver and satellite phases biases.

Methods to calibrate the satellite phase bias have been proposed during the last few years. A modified method has been suggested by Banville (2007) to improve the compatibility with PPP's functional model. This part of the research will be reported in a future paper. Next, a method to calibrate the receiver phase bias will be discussed.

For the calibration of the receiver phase biases, a simulator was used to generate errorless code and phase signals. Data from three 3-h calibration sessions have been gathered on two consecutive days using the Spirent STR4760 simulator at UNB and a NovAtel ProPack V3 dual-frequency receiver connected to the hardware simulator, collecting phase and code observations on L1 and L2. Between each calibration session the simulator and the receiver were turned off.

Figure 3 presents the estimated receiver widelane phase biases for the three sessions. The L1 and L2 receiver phase bias values can also be found in Banville (2007).

The results show that the receiver phase biases were similar for each satellite over one session, but were different from session to session. As already mentioned, the simulated signals did not contain satellite phase biases.

The results also indicated the presence of unmodelled, absolute receiver code biases affecting the estimated values of the receiver phase biases. In addition, clear evidence for a thermal sensitivity of the phase biases was found. Further work needs to be done to control the potential sources of electronic bias delays in the hardware simulator.

Other investigations and tests for the calibration of the receiver phase biases will be conducted in collaboration with colleagues from the Department of Electrical Engineering at École de Technologie Supérieure de Montréal.

4 Ryerson University

The Ryerson group has been working on high-rate precise orbital prediction and stochastic modelling of residual tropospheric delay.

Precise real-time GPS orbit information is required for a number of applications, including real-time PPP, long range RTK and GPS weather forecasting. At present, users may take advantage of the predicted part of the IGS ultra-rapid orbit for real-time applications. Unfortunately, however, the accuracy of the predicted part of the ultra-rapid orbit is limited to about 10 cm (the 24-h predicted part), which is not sufficient for the above applications. In this research, a 6-h predicted orbit is generated by extrapolating a concatenated group of previous precise ephemerides for 5 days. RINEX observation files corresponding to the same period of precise ephemeris are collected from 32 globally distributed tracking stations. Using the Bernese GPS data processing software those observation files were utilized to make further improvements of the prediction. The resulting prediction is finally refined by implementing a modular, three-layer feed-forward back-propagation artificial neural network (ANN). It is shown that the obtained precision of ANN-based prediction is less than 3 cm, which is superior to that of the IGS ultrarapid orbit (Yousif and El-Rabbany, 2007). Future research will enhance the orbital prediction through the use of 35 well-distributed IGS tracking stations (Yousif, 2007).

Real-time and near-real-time precise GPS positioning requires shorter GPS solution convergence time. Residual tropospheric delay, which exists as a result of the limitations of tropospheric correction models, represents a limiting factor for rapid GPS solution convergence. In this research a stochastic modelling of the residual tropospheric delay is proposed. The NOAA tropospheric delay model is used to generate daily time series of zenith total tropospheric delays (ZTD) at ten IGS stations spanning North America for many days in 2006. The NOAA-based ZTD is then compared with the new IGS tropospheric delay product to obtain daily residual tropospheric delay time series at 5 min intervals. Estimates of a set of autocovariance functions of the unmodelled residuals are obtained, which are used to develop the empirical covariance functions, in the least-squares sense. Several empirical covariance functions are examined, including first- and second-order Gauss-Markov processes, and exponential cosine function.

Fitting results show that the exponential cosine function gives the best fit most of the time, while the second-order Gauss-Markov model gives the worst fit. The first-order Gauss-Markov fits are close to those of the exponential cosine. Additionally, the model coefficients seem to be season independent, but change with geographical location (Ibrahim and El-Rabbany, 2007). In future research, the developed covariance model will be used to stochastically model the residual tropospheric error through a modification of the observations' covariance matrix. The effect of implementing the stochastic model on the solution convergence and accuracy estimation will then be examined.

5 York University

The York team has been working on improving the measurement accuracy of atmospheric constituents as derived from GPS satellites and occultation measurements. The ultimate goal is to obtain 3D maps of refractivity and eventually vertical profiles of atmospheric parameters locally and/or globally. This can be achieved through: (1) improving the ionospheric calibration (i.e. accounting for higher order ionospheric effects), and (2) extracting atmospheric refractivity from bending angle profiles.

As far as the refractivity profile determination is concerned, the basic software code has been written and tested to estimate bending angle profiles, through measurements of the atmospheric Doppler shift observed at a LEO satellite. Solution of a non-linear system of equations provides an estimate of the bending angle as a function of impact parameter, which is inverted with the Abel inversion algorithm (with spherical symmetry) to give refractivity profiles. The position and velocity vectors of both the transmitter (GNSS) and receiver (LEO) need to be obtained with high accuracy. The Bernese GPS software v5.0 is employed for the precise orbit determination of both satellites.

For the ionospheric calibration we use the Bernese software for the estimation of the ionospheric total electron content (TEC) along the GPS-LEO raypath. This is required because higher order ionospheric effects need accurate estimates of the TEC. We have also been making progress on the modification of the Bernese software to account for higher order ionospheric corrections in order to examine their impact on the retrieved refractivity profiles. The leading role of York University in this project transpires through the modelling of the ionosphere and its impact on the retrieved atmospheric constituents, as well as the improvement of the 3D mapping of the atmospheric refractivity locally and/or globally by accounting for the ellipsoidal shape of the atmospheric layers.

York's contributions for the coming two years includes the development of a multi-GNSS constellation blended performance software covariance propagation simulator, designed to simulate the performance of various combinations of systems when particular processing methodologies are employed.

6 Concluding Remarks

In this paper we have presented an abridged description of activities taking place under Project 31 of the GEOIDE Network Phase III. These activities involve research on L2C noise assessment, development of new tools for data analysis, development of PPP software packages, performance analysis of future GNSS with respect to ambiguity resolution, calibration methods for receiver and satellite biases, experiments pushing the limits of solution convergence time in real-time and near-real-time positioning, enhancing the quality of real-time orbits, improving the modelling of the atmosphere, and covariance analysis of various system combinations. The interested reader may find details of project activities on its website: gge.unb.ca/Research/GRL/GNSS/index.htm.

As major contributions so far we can call attention to calibration of receiver phase biases with a simulator, the first determination of P2-C2 bias and the development of an artificial neural network-based orbit prediction model.

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