Geo++® White Paper

GNSMART Irregularity Readings for Distance Dependent Errors

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Introduction

Today, it is state-of-the-art technique to use multiple permanent reference stations to provide DGNSS and RTK services with homogeneous availability, reliability and accuracy. A sophisticated processing software is required for the many tasks involved in such services. The **G**lobal **N**avigation **S**atellite **S**ystem software using a **S**tate **M**onitoring **A**nd **R**epresentation **T**echnique is Geo++®-GNSMART. An implementation of GNSMART for a network of reference stations covering a service area is often termed RTK network.

The RTK network tasks are twofold. The primary task and pre-requisite is the GNSS state monitoring of all error sources, which comprises the carrier phase ambiguity resolution within the network through adequate modeling and includes the determination of distance (and site) dependent errors. The secondary task is to provides network state information to an RTK network user to correct errors, which are known from the redundant information within the network. This is generally termed as representation task.

One major error source is the ionospheric delay of GNSS observations in the atmosphere, which results into a dependency of a GNSS user from the separation to a reference station. In contrast to the other distance dependent errors like troposphere and orbits, the fast and large temporal changes of the ionosphere can make especially the ambiguity resolution difficult. In the following, modeling applied in GNSMART will be briefly summarized. The focus is placed on the ionospheric error component. The so-called irregularity readings of GNSMART will be discussed and compared with other indicators for the magnitude of ionospheric errors. The GNSMART irregularity is proposed as an indicator to decide on processing strategies on a RTK rover system in the field.

GNSMART State Space Modeling

GNNET, the processing kernel in GNSMART, uses a real-time Kalman Filter for the dynamic parameter estimation. A „complete" state space model with mm-accuracy is implemented for the rigorous and simultaneous adjustment of GNSS observables. It uses undifferenced observables, multiple stations, multiple signals and undifferenced ambiguity resolution to enable the RTK network tasks.

The state space models applied in GNSMART are often multiple step models. The models generally

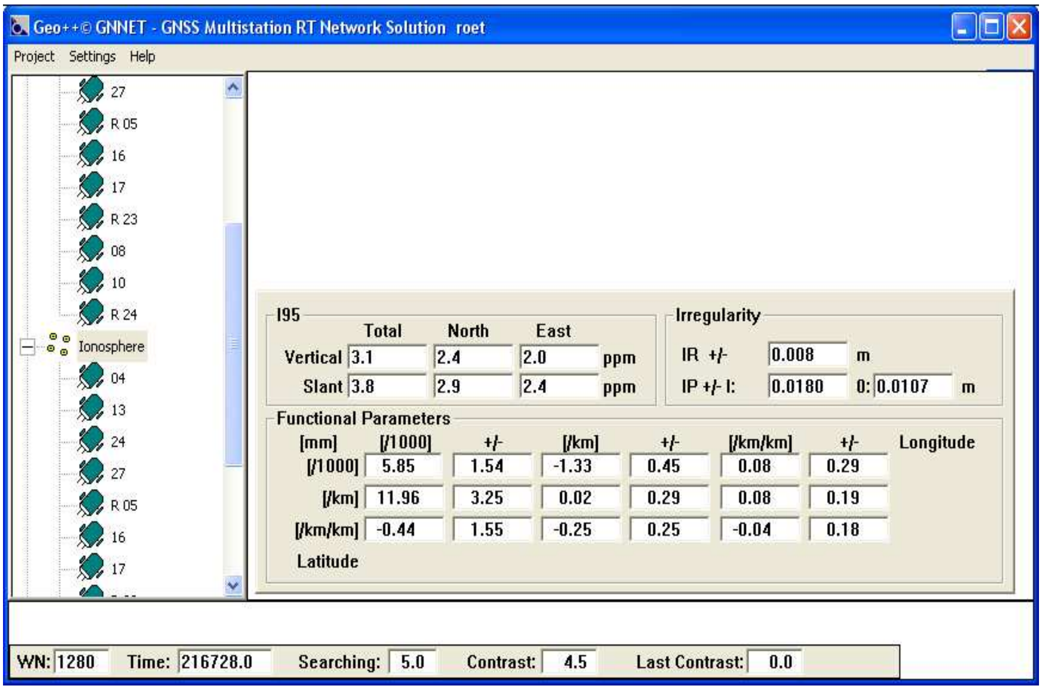

Fig. 1: GNSMART GNNET window with currently applied functional ionospheric model and currently computed ionospheric indicators (irregularities and I_{95} index)

consist of a functional model based on dynamic processes with temporal and/or spatial stochastic properties. Alternatively static parameters are used, when suited for the actual physical condition. Further enhancement is archived applying additional stochastic models with temporal and/or spatial characteristics to describe remaining effects not accounted for in the functional models.

GNSMART Ionospheric State Model

The ionosphere is modeled by GNSMART as

- dynamic single layer or multi-layer model
  - using 2D polynomial in latitude and longitude/local time, or
  - using spherical harmonic expansion
- dynamic satellite dependent vertical delay bias
- stochastic 3D Gauss-Markov process
  - one parameter per receiver-satellite pair

The multiple levels of the ionospheric modeling are depicted in Fig. 1 to Fig. 3. The spatial, second order polynomial model and its currently estimated parameters in latitude and longitude as well as the standard deviations are summarized in a table. The additional indicator shown will be discussed later. Fig. 2 shows the satellite dependent functional models as displayed in GNNET. Beside general information on the satellite, orbit and clock state information, the satellite dependent functional vertical ionospheric delay and standard deviation of the stochastic 3D Gauss-Markov process are displayed. In Fig. 3 a map containing the remaining vertical ionospheric delay in meter for every receiver-satellite pair as estimated in the adaptive stochastic 3D Gauss-Markov process is given for one satellite.

The different modeling levels all together describe the actual state of an error component. Hence, the main part of the ionospheric errors is modeled by the spatial functional model. Individual deviations from that model are furthermore accounted for using the individual satellite dependent stochastic processes. Finally, a stochastic model absorbs all remaining effects.

These applied models enable mm accuracy to describe the actual ionospheric state in the rigorous GNSMART adjustment. To provide the estimated state to a RTK network service user not the

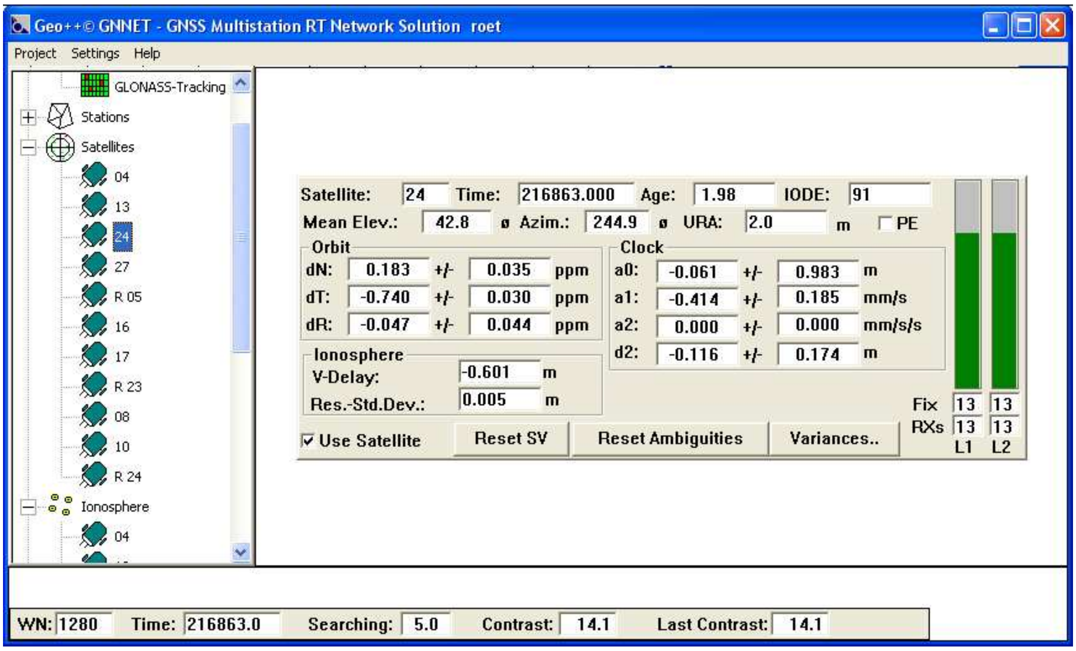

Fig. 2: GNSMART GNNET window with current estimate of satellite dependent functional models

actual modeling capabilities are relevant. Instead, infrastructure, communication link properties (e.g. band width), application requirements and international formats define limits, which make an adequate representation of error components necessary.

GNSMART Representation Concepts

The transmission of the complete state space would be the best choice for the representation of the error components. However, the RTK network users currently can only handle observation based data (observation or correction). Therefore it is required to transfer state space information into observation space. The user will work with corrected observation data. Today, spatial models (FKP, areal correction parameters) are used to transport the state space information and finally apply the state at observation data or an actual observation space representation is used (termed VRS, virtual reference station or PRS, pseudo reference station).

Ionospheric Indicators in GNSMART

For a RTK network provider and also for the RTK rover system in the field it is important to have information on the remaining effect coming from the ionosphere or other distance dependent error components for a RTK network user.

Fig. 1 displays beside the functional spatial ionospheric model some ionospheric indicators. These are the GNSMART irregularities and the so-called I_{95} index of the ionosphere.

In the upper left corner the current I_{95} index is displayed in ppm. The index has been defined as a statistical parameter derived from FKP describing the ionospheric errors (Wanninger 2002). It is a measure for the gradient, hence, the relative ionosphere influence. The elevation dependency of the ionospheric delay is maintained in the index (therefore slant I_{95}). The index also changes with inter-station distances in the network, applied elevation mask and integration time. GNNET computes the I_{95} for every epoch.

In contrast to the original definition of I_{95}, there are two improvements. The index is computed separately for the north and east component and in addition for the vertical ionospheric delay. The I_{95} is not an isotropic number and will have direction dependent properties, which are of interest and now accessible. The slant ionospheric delay depends on elevation and therefore in general on the

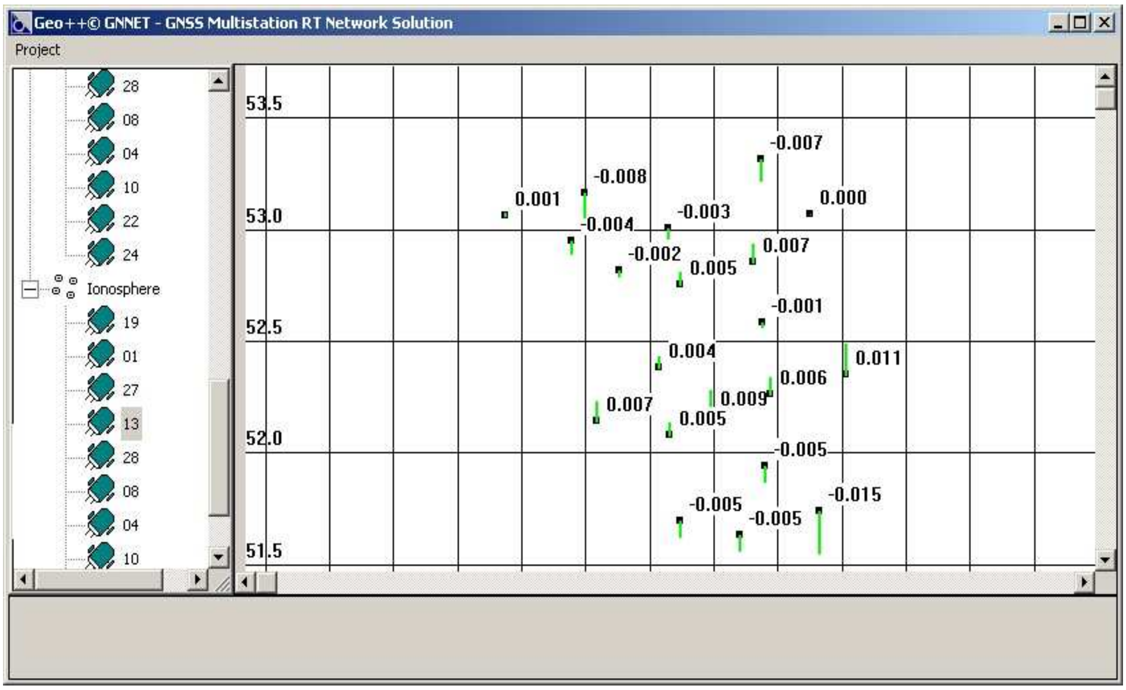

Fig. 3: GNSMART GNNET window with current estimate of stochastic ionospheric model of PRN 13

satellite constellation. There will be slant I_{95} changes for rising or setting satellites, which are not actually caused by the ionosphere, but by elevation changes. Although the same ionospheric conditions are present, a large I_{95} index number is obtained from satellites only visible at low elevation and a small number from only high-elevation satellites. The vertical delay removes the elevation dependent effects and maps the slanted ionospheric delay with an adequate mapping function into the zenith. Hence, the vertical I_{95} index is free of such effects.

The I_{95} index is not a suitable indicator for RTK network users to judge the network correction quality. Of more interest for the user and for the provider is, however, the deviation from the actual representation. Therefore the GNSMART irregularity parameters have been developed.

In the upper right corner the irregularity readings IR and IP are numerically displayed. The value IR is a standard deviation of the stochastic 3D Gauss-Markov process for one satellite. The IR number is the maximum standard deviation currently present in the system from one particular satellite. The IR irregularity is also not suited for an service user indicator, but give the RTK network provider information on the maximum ionospheric process standard deviation.

The IP values are a measure of the interpolation quality of the state information. It is the standard deviation of a second order FKP representation of the current state space using the standard deviation computed from all stations and satellites with a distance dependent weighting. It is separately displayed for the ionospheric (IP_I) and the geometric (IP_0) part of the error components. The IP readings correspond to the remaining third or higher order effects, which a RTK network user equipment has to expect and must account for in the field. The numbers are derived from the non-describable residual errors in meter with the assumption of a quadratic FKP model, which must not exactly correspond to the models used in the actual RTK network.

The IP numbers require a large redundancy in the network, while the IR numbers already allow an interpretation even for low redundancies. In case of low redundancy, a first order FKP representation is used for the computation of the irregularities.

The IP readings are a good indicator for the RTK network user, but require further standardization and general acceptance to be adequately used by a RTK rover system in an automatic procedure.

Magnitude of Ionospheric Indicators

First Order Effect of Ionosphere/Distance Dependency	*I_{95} [ppm]*
less	0 ... 2
small	2 ... 4
large	4 ... 8
severe	8 ...

Tab. 1: Interpretation of I_{95} index numbers

It is obviously, that the I_{95} index represents the first order ionospheric error, because it is derived from the FKP. Consequently, these effects are already corrected through the RTK network corrections and the index only reflects the relative changes of the ionosphere or the eleven year solar cycles.

The ionosphere has small gradients (temporal and/or spatial) for an I_{95} index in the range of 0 ... 2, while large distance dependency will give an index in the range of 4 ... 8. Tab. 1 summarizes the different magnitude classes and their interpretation for the ionospheric activity and distance dependency.

The GNSMART irregularities do have already metric properties. The IR irregularity shows the maximum currently occurring ionospheric vertical delay variations. The IP_I irregularity is an average measure for the complete RTK network and represents a mean magnitude of remaining ionospheric errors in the provided RTK network corrections. The IP reading is an absolute measure representative for the mean distance of neighboring reference stations. A distance dependent value is obtained, while scaling the absolute IP numbers by the mean distance.

The irregularity is also computed for the geometric part of the RTK correction IP_0, which also have metric properties. The IP_0 reading can be used accordingly.

Consequences for RTK network user

The GNSMART irregularity measures represent the residual errors, which should be considered appropriately by a rover system operating in a RTK network. The absolute ionospheric part can be eliminated by dual frequency receivers, if the rover can resolve successfully ambiguities. The geometric part is mainly caused by tropospheric irregularities, because satellite orbits do not show significant irregularities today. Generally both remaining effects can be accounted for at a rover site using an additional stochastic model for the ionosphere and/or the troposphere. The rover system, however, require some indication to decide on the processing options. The GNSMART irregularity readings are such an indicator, but no standard data format nor procedures are currently available to communicate remaining residuals to the rover. It is practice to use the distance of the reference station to give to the rover an indirect indication, what magnitude of residuals might be possible. This approach is termed Pseudo Reference Station in GNSMART. Nevertheless, the irregularity parameters displayed in GNSMART can already today give a good indication for the RTK network operator,whether possible problems may occur at a rover site.

Conclusion

GNSMART provides some basic indicators for the current irregularities of the ionosphere, but also on the other distant dependent errors (geometric part). There is some demand from RTK network users and providers to incorporate such indicators into the RTK network concepts. The GNSMART irregularity readings are generally well suited, because they actually represent a measure of the remaining errors in the provided RTK network corrections. The irregularities can easily transfered to the rover with a new message type in the international RTCM format, the existing RTCM message type 16 ASCII or in proprietary formats within the RTCM message type 59. A transition of the absolute numbers of the irregularity readings into relative, distance dependent variances are feasible and need only additional normalization. Currently an implementation of a type 59 message is done in GNSMART and a proposal for a RTCM message type 16 is under preparation at Geo++.

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Most of the references are available for download at http://www.geopp.com/publications.