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PPP-RTK: Precise Point Positioning Using State-Space Representation in RTK Networks

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BIOGRAPHY

Dr. Gerhard Wübbena received his degrees in geodesy from the Universität Hannover. He has worked in the field of GNSS since 1983. In 1990 he founded the company Geo++®, which develops satellite navigation and positioning software and systems. Among these are the post-processing system GEONAP and the realtime system GNSMART.

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Andreas Bagge graduated in geodesy at the Universität Hannover. Since 1986 he is working in the field of GNSS, at first for several years at the Universität Hannover, and now at Geo++®.

All authors are currently employed at Geo++®. They are concerned with research and development in satellite positioning. Current projects focus on highly precise RTK phase positioning (GNSMART), absolute GNSS antenna field calibration, GNSS station calibration projects and realtime attitude systems.

ABSTRACT

The concept of precise point positioning (PPP) is currently associated with global networks. Precise orbit and clock solutions are used to enable absolute positioning of a single receiver. However, it is restricted in ambiguity resolution, in convergence time and in accuracy. Precise point positioning based on RTK networks (PPP-RTK) as presented overcomes these limitations and gives centimeter-accuracy in a few seconds.

The primary task in RTK networks using the Geo++ GNSMART software is the precise monitoring and representation of all individual GNSS error components using state-space modeling. The advantages of state-space modeling are well known for PPP applications. It is much closer to the physical error sources and can thus better represent the error characteristics. It allows to better separate the various error sources to improve performance and can lead to much less bandwidth for transmission.

With RTK networks based on GNSMART it is possible to apply the PPP concept with high accuracy. Ambiguity resolution within the RTK network is mandatory and allows the precise modeling of the system state. Since the integer nature of the carrier phase ambiguities is maintained, all error components can be consistently modeled and give full accuracy in an ambiguity fixing GNSS application.

For today's realtime applications, observations of a reference station together with network derived parameters to describe distance dependent errors or a virtual reference station are transmitted to GNSS users in the field using the RTCM standards. This can be termed as representation in observation space (Observation Space Representation: OSR). In contrast to this, also the actual state-space data

can be used for the representation of the complete GNSS state (State Space Representation: SSR). Hence, precise absolute positioning based on a RTK network (PPP-RTK) using state-space data is a practicable concept.

In principle, the concept can be applied to small, regional and global networks. A reference station separation of several 100 km to achieve ambiguity resolution and therefore the key-issue to PPP-RTK is already possible with GNSMART.

The complete transition from observation-space to state-space requires the definition of adequate formats and standardized models to provide the state-space data for GNSS application. A single receiver then can position itself with centimeter-accuracy within a few seconds in post-processing and realtime applications. In between, state-space data can still be used to generate data in observation-space, e.g. RTCM or RINEX format, through a conversion algorithm.

The state-space concept and pre-requisites are discussed. The benefits of state space representation of GNSS errors and their applications are pointed out.

INTRODUCTION

Global Navigation Satellite System (GNSS) applications serve different kinds of applications and accuracies in navigation and positioning. The number of applications is steadily increasing as well as the demand for precise navigation and positioning. GNSS applications generally provide

- absolute positioning
- differential positioning
- precise absolute (point) positioning

Absolute GNSS positioning is the basic mode of an GNSS and uses one single receiver for navigation and positioning. At least two simultaneously operating stations are required for differential GNSS positioning. It makes use of the spatial correlation of systematic errors between stations to estimate or reduce their effects in order to achieve much higher accuracy.

Precise absolute positioning is a quite new category, which is associated with the term precise point positioning (PPP) (Zumberge et al 1997). It is a combination of the original absolute positioning concept and differential positioning techniques. PPP also uses observation data of a single receiver and additionally state information on individual GNSS errors derived from a GNSS network.

In current applications, precise absolute positioning is applied in post-processing e.g. using IGS products, or using a global network in realtime (Mullerschoen et al 2001). IGS products like precise satellite orbits and clocks are actually state information on particular GNSS errors. The mathematical model of PPP uses undifferenced, dual-frequency observations and applies among other corrections the precise orbit and clock data. The receiver clock and tropospheric error are estimated, while the ionosphere is eliminated using the ionospheric free linear combination (L0).

PPP is limited in accuracy, because the ionospheric free linear combination is currently mandatory. Accurate ionospheric models are generally not available. Since the ionospheric free linear combination is not based on integer coefficients and the state information currently does not preserve the integer nature of ambiguities, it is not possible to resolve ambiguities adequately to access the full GNSS carrier phase accuracy levels. Therefore long integration or observation times are required for PPP.

The limitations of PPP can be overcome with RTK (Real Time Kinematic) networks using state space modeling. Such RTK networks can consistently derive all individual GNSS errors in realtime. The atmospheric GNSS effects are modeled and state information is also present for ionosphere and troposphere. The complete state information is ready for distribution to users in realtime. As a consequence, users are capable to resolve ambiguities and to achieve the known RTK accuracy level.

This concept of precise absolute positioning enabling ambiguity resolution is the synthesis of the known precise point positioning and network RTK. In the following it is termed as PPP-RTK: Precise Point Positioning-RTK. The main characteristics and differences of PPP and PPP-RTK are listed in Tab. 1.

	PPP	***PPP-RTK***
network size	global	local/regional/ global
primary state information		
satellite orbits	provided	provided
satellite clocks	provided	provided
ionosphere	corrected	provided
troposphere	estimated	provided
receiver clock	estimated	estimated
phase ambiguities & signal		
L1 / L2 / L0	- / - / +	+ / + / +
integration time	30 ... 1800 s	10 ... 50 s
accuracy		
static 3D	~ 5 cm	1 ... 3 cm
RTK 3D	15 ... 20 cm	1 ... 3 cm

Tab. 1 Characteristics of PPP and PPP-RTK

RTK NETWORKING

Precise positioning with GNSS requires the knowledge of (the sum of) all error components with a corresponding accuracy for the desired accuracy. The highest accuracy is demanded by RTK applications, which require the resolution of GNSS carrier phase ambiguities to gain accuracy at the centimeter-level. Hence, RTK positioning requires the knowledge of all error components with accuracy definitely better than 1 cm to enable a RTK service. The main error sources of GNSS are

- satellite and receiver clock
- satellite orbit
- ionosphere
- troposphere
- receiver antenna phase variations (PCV)
- multipath

The different GNSS error components do have different characteristics. Satellite orbit, ionosphere and troposphere are spatially correlated and it is therefore possible to determine the effects in differential GNSS processing. However, the effects decorrelate with distance and introduce a distance dependent error into processing results. The clock errors are estimated or eliminated in the modeling approach of the GNSS data processing. Antenna phase variations and multipath are station dependent errors and must either be corrected or be adequately accounted for.

The principle of RTK networking is depicted in Fig. 1. The GNSS errors ε may be determined based on a single reference station. However, the distance dependent error cannot be determined by a single reference station, and its correction data is not exactly valid for a user's position (rover).

The distance dependent GNSS errors are the main limiting factors in differential GNSS realtime applications. Therefore multiple reference stations are combined in an RTK network to determine primarily the distance dependent GNSS errors and provide correction information to enhance the positioning capabilities and accuracies for a user in the field. In Fig. 1 the RTK network is represented by two reference stations, which enables the determination of distance dependent errors (depicted as a simple linear interpolation between reference stations).

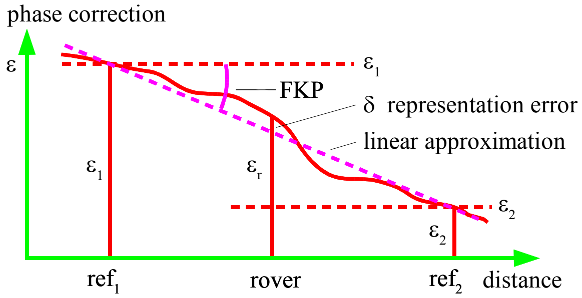

Fig. 1: RTK networking and OSR principle, representation error (FKP, VRS, PRS) for linear approximation

The modeling approach of GNSS is an important aspect for the different tasks in RTK networking. On the one hand, simplified models are easily implemented, but will show in the long run disadvantages in performance. On the other hand, a rigorous approach is more complex. However, the ideal approach is a complete state space modeling (SSM).

GNSS-SMART: STATE MONITORING AND REPRESENTATION TECHNIQUE

RTK networking is utilized in a rigorous and fundamental way in the Geo++® GNSMART software. GNSS-SMART stands for **S**tate **M**onitoring **A**nd **R**epresentation **T**echnique describing the essential concept, while GNSMART is the actual Geo++® software implementation of this technique. The GNSS errors must be precisely modeled and monitored to resolve ambiguities as a **primary task**. For any time and location within the covered network area sophisticated services must provide information on the GNSS errors based on the state monitoring. The methods for this **secondary task** are generally termed “representation technique”.

A complete state space model with millimeter-accuracy is implemented for the rigorous and simultaneous adjustment of GNSS observables, which is essential for the **primary task**. The state space modeling follows the idea to model the actual error sources instead of handling the effects of the errors. The error effects belong to the observation space, while the error sources are associated with the state space. All error sources build up the state space model (SSM). The state space model consists of

- model algorithms
- model parameters

The state space models applied in GNSMART are often multiple step models. The models generally 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 enhancements are achieved by applying additional stochastic models with temporal and/or spatial characteristics to describe remaining effects not accounted for in the functional models. Tab. 2 lists the functional and stochastic models currently implemented and typically used in GNSMART. The actual applied models and model parameters are configurable in GNSMART.

The model parameters itself consist of

- state vector of unknown parameters
- complete variance/covariance matrix of unknown parameters

This already indicates, that an ideal representation should also contain stochastic properties. It is advantageous for any application to decide on the quality of service. But stochastic also express correlations between parameters.

To determine the (error) state of a GNSS system, GNSMART estimates the following state parameters:

- satellite clock synchronization error
- satellite signal delays (group delays)
- satellite orbit error (kinematic orbits)
- ionospheric signal propagation changes
- tropospheric signal delays

Error Component	*Functional and Stochastic Model*
satellite clock	dynamic 2nd order polynomial as the difference to broadcast clock plus white noise process
signal delay (sv)	constant plus integrated white noise with low variance
satellite orbit	difference to broadcast orbit as 3D cartesian (along-track, cross-track and normal) errors with Gauss-Markov process
ionosphere	3 step model: - dynamic single or multi layer functional model with 2D polynomial (geomagnetic latitude, local time) or spherical harmonics - satellite dependent dynamic functional biases - 3D Gauss-Markov process with 1 parameter per receiver-satellite combination to describe the remaining ionospheric effect
troposphere	correction with Niell troposphere model 3 step model for residual troposphere: - dynamic functional model with 3D polynomial (latitude, longitude, height) or spherical harmonics with height gradients for dry and wet components - dynamic mapping function improvement for low elevations - dynamic station dependent zenith delay parameters for dry and wet components
receiver clock offset	white noise process
signal delay (rcv)	constant with integrated white noise process
satellite PCV	correction
receiver PCV	correction
multipath (rcv)	elevation and/or signal to noise dependent weighting
measurement noise	white noise
ambiguity	constant
receiver coordinates	static or kinematic for unknown stations

Tab. 2: Functional and stochastic modeling of GNSS errors in GNSMART (standard settings)

- receiver multipath (optional)
- carrier phase ambiguities
- receiver coordinates (optional)
- receiver clock synchronization error
- receiver signal delays (group delays)

The state space modeling of GNSMART applies beforehand corrections to the GNSS observations. The SSM model is prepared for the following corrections:

- satellite-receiver phase wind-up effect (satellite attitude)
- (absolute) satellite antenna PCV correction
- site displacement effect (solid earth tide, pole tide, ocean loading, atmospheric loading, local displacement)
- relativistic corrections
- higher order ionospheric correction
- (absolute) receiver antenna PCV correction

The extension of the network defines the significance of the corrections and consequently the quality of the state space modeling. In smaller networks some corrections can be neglected. Therefore GNSMART currently does not correct for loading effects and higher order ionosphere in local or regional networks.

PPP-RTK in theory is capable to serve a global network, but is currently restricted by the models for physical displacements of the earth. In principle, if all relevant effects could be accurately modeled a priori and included in the processing, then only the measurement noise would remain (Ray et al 2004).

In addition, it is necessary to maintain the integer nature of carrier phase observations for all carrier frequencies in the SSM, despite all models and corrections applied. It is essential for the high accuracy.

The adjustment model is a Kalman filter for realtime applications. The Kalman filter is proofed to be well suited for state estimation and monitoring tasks (Wübbena, Willgalis 2001). The actual adjustment is a simultaneous adjustment of all L1 and L2 observations. Advantages of simultaneous L1/L2 adjustment are

- rigorous modeling of correlations between linear combinations
- rigorous modeling of common parameters like L1-L2 delays for satellite and receiver
- improvement of noise level for derived state parameters

The separation and modeling of individual GNSS error components is straight forward using undifferenced or also termed non-differenced observations. The use of non-differenced observations is a key issue in ambiguity resolution, optimized modeling and processing in

	Representation Technique	*Broadcast*	*Covered Area*	*Bandwidth*	*Representation Error*	*Kinematic Applications*	*International Standards*
SSR	SSR	++	unlimited	++	++	++	+ / -
OSR	RS+FKP	+	100 km	+	+	++	+ (SAPOS)
	PRS+FKP	+	100 km	+	+	++	-
	PRS	-	100 km	+	+	++	-
	VRS	-	local	+	-	-	-
	MAC	+	MA stations	-	+ / -	++	++

Tab. 3: Comparison of different state representation techniques (++ very good, + good, - fair to bad)

GNSMART. The advantages of non-differenced modeling and ambiguities are:

- network operates in absolute mode
- no mathematical correlation between observations
- robustness against failures of single reference stations
- optimal reliability

The use of differenced observations (i.e. double difference observable) and accordingly the use of baselines/triangles between reference stations is a limitation, and a loss of information compared to the non-differenced approach. Information on the GNSS errors can be best obtained from the rigorous adjustment of multiple reference stations with sufficient redundancy and network size.

The **secondary task** of a RTK network is the computation of correction data from SSM, which represent the GNSS errors for an individual rover site within the network area.

The state representation techniques can be divided into two main approaches. These are for GNSMART the representation by transforming state parameters into observations or observation corrections, which is called Observation Space Representation (OSR) or using actual state parameters for direct use termed State Space Representation (SSR).

The use of OSR is the common technique in RTK applications and RTK networking. It will be discussed first to point out later the SSR concept and benefits.

OSR: OBSERVATION SPACE REPRESENTATION

The representation of RTK network corrections in the observation space always uses GNSS observations of an actual reference station, which are then applied by the conventional RTK rover algorithm. Fig. 1 depicts the principle of OSR. The GNSS error for the basic carrier phase observables in the figure is a lump sum of distance dependent GNSS errors. Either the phase correction for the rover position or a spatial model to describe the effect are currently used in RTK networking.

Depending on the RTK networking algorithm and also on network design parameters, the RTK network corrections have an uncertainty, which is generally called representation error. This error is caused by the irregular physical conditions between the actual reference stations and cannot be improved unless the distance between stations is decreased.

OSR is the currently used method in RTK network applications to provide correction or corrected data to a user. To transmit those, the following concepts can be distinguished:

- observation data + network correction
    - RS (Reference Station) + FKP
- network-corrected (individualized) observation data
    - PRS (Pseudo Reference Station)
    - VRS (Virtual Reference Station)
- observation data of multiple reference stations
    - MAC (Master-Auxiliary-Concept)

The different concepts are often summarized under the term FKP or VRS. One major difference between the two concepts is the computation of the RTK network correction for the user location. In the case of FKP this individualization is done at the rover site, while for VRS it is done at the service center.

The observations of a reference station are generally disseminated using the international standard RTCM 2.3 message types 18/19 (raw data) or 20/21 (correction data). Separate FKP corrections are transmitted using RTCM message type 59 (Wübbena, Bagge 2002). The Master-Auxiliary-Concept (MAC) (Euler et al 2001) is under discussion for a standardized RTK message in RTCM 3.0, but is is not yet operationally applied. The MAC will transmit observation data of a master station and correction differences between master and auxiliary stations. The rover can re-construct the observation data of the auxiliary stations (except a common clock term) and individually decide how to use master and auxiliary data for its location.

AREA CORRECTION PARAMETER: FKP

Area correction parameters are termed after the German acronym of “Flächenkorrekturparameter” FKP. Linear FKP represent the tilt angle of a plane which is centered at a reference station. The data of one single reference station and the FKP are transmitted to the user. The RTK algorithm at the rover site applies corrections derived from the FKP using its current approximate position. Fig. 1 shows the representation error in the case of the FKP-concept, which holds also for the VRS/PRS and multiple observation data. The state parameters are transformed to a simplified parameter model (plane or quadratic surfaces) representing the spatial variations of distance dependent state parameter.

Characteristics of the FKP concept are:

- broadcast possible
- kinematic application possible
- rover must be capable to work with FKP (since 2001 implemented in geodetic rovers using RTCM-59 FKP-AdV)
- limited range of FKP (approx. 100 km for linear FKP)

Especially notable compared to all other OSR concepts is the broadcast capability.

The RTCM-59 FKP-AdV is a special implementation of the FKP concept, which has been introduced by the German State Survey Authorities "Arbeitsgemeinschaft der deutschen Vermessungsverwaltungen" (AdV) for their satellite positioning service SAPOS (SAPOS 2004). The FKP-AdV are transmitted in the RTCM type 59 message, and all major GNSS manufacturers are capable to use these messages with their RTK rover systems.

VIRTUAL REFERENCE STATION: VRS, PRS

The Virtual Reference Station (VRS) does not separately provide observation data and network correction data. The reference station observations and the state parameters are transformed to (or individualized for) the user position. Hence, it is necessary for the rover to send an approximate position. The observations of the VRS are transmitted to the rover. The RTK rover receives the data of a VRS, which is recognized as a reference station in a very short distance away from the actual approximate user position.

For the VRS concept some aspects must be considered:

- the rover RTK algorithm does not expect distance dependent errors, and is not capable of modeling any remaining representation errors
- kinematic users "see" distance dependent errors while moving away from the VRS (VRS position must be kept fixed because of limitations in rover algorithms)
- no broadcast possible; one bi-directional communication link required per user

The Pseudo Reference Station (PRS) is a modified VRS approach introduced by Geo++® and implemented in GNSMART. The reference station observations and state parameters are transformed to the approximate user's position (like VRS), giving an optimal OSR representation for the user. However, the actual position used and transmitted for the PRS is in a certain distance (for instance 5 km) from the approximate user position. Furthermore, the transformed RTK network corrections are always individualized for the current (last known) rover position. This avoids, that the representation error increases with distance for a moving rover and enables kinematic applications.

The PRS approach has some advantages compared to VRS:

- rover RTK algorithm will expect some distance dependent errors and is therefore capable of modeling remaining representation errors
- PRS shows in practice much better positioning performance than VRS
- kinematic applications possible, because OSR always optimal for rover position

Instead of using the individual positions of users, predefined fixed positions can be used for the computation of the correction data. This can be done for a couple of predefined positions arranged in a grid. This is equivalent to the VRS approach. It can be further enhanced using the PRS approach combined with the FKP method.

The enhanced characteristics of a PRS + FKP approach are:

- broadcast possible
- kinematic applications possible

SSR: STATE SPACE REPRESENTATION

The modeling in GNSMART estimates the individual GNSS error components within SSM as state parameters. Therefore it is a straight forward concept to use actual state parameters for the representation of all the GNSS errors in RTK applications.

The state space representation is a functional and optional stochastic description of the state, i. e. the individual GNSS error components. Actual state parameters are transmitted to the rover. The user corrects his own observations of a single GNSS receiver with SSR corrections computed from the state parameters for his individual position, and performs RTK positioning with corrected observations. An optimized solution is possible with SSR with the following properties:

- not dependent on single reference stations
  - station dependent errors like multipath and noise practically removed in redundant networks
  - no missing satellites
- mixed GNSS support (e.g. GPS/Glonass) for complete network even with partially Glonass equipped stations
- low bandwidth required for large areas
  - update rate for most parameters is low
  - highest update rate for satellite clocks (10 s), update rate for all other parameters is generally lower
  - different services with different accuracies possible
  - single and dual frequency application

In contrast to the above discussed OSR techniques, the state space representation (SSR) offers some prominent advantages.

BENEFITS OF SSR

The SSR bandwidth can be significantly reduced compared to OSR, because the dynamics of different parameters can be utilized to optimize the bandwidth. SSR also makes use of properties such as the satellite independence of the tropospheric modeling or station independence of satellite clock errors.

For OSR, generally one common update rate is necessary due to the transformation of the lump sum distance dependent GNSS errors into observation space. Exceptions are the FKP concept and MAC, which make use of the dispersive effect of the signal. The ionospheric signal LI (difference of the basic observables L1-L2) and non-dispersive (or geometric) GNSS errors vary at different rates, which can be used to enable different transmission rates. Nevertheless, the bandwidth using OSR cannot be optimized as much as SSR, because the individual error components are not individually accessible.

The individual dynamics of state parameters are:

- satellite clocks
  very high (max. 10 s validity for millimeter-accuracy)
- satellite orbits
  low (3 h correlation length)
- ionosphere
  low (10 min) to high (10 s)
- troposphere
  low (2 h correlation length)

As a consequence, common update rates for OSR are less than 10 s (typically 1 s), while for SSR different update rates for different state parameters can be utilized, minimizing the bandwidth. However, the update rates must accomplish other requirements like a cold start-up of an RTK rover, which suggests rates not higher than 30 s or 60 s.

Another factor for bandwidth reduction is the possibility to optimize the necessary parameter ranges. For SSR the parameter ranges can be chosen with respect to the expected range for the individual physical error components. For OSR the parameter ranges have to be chosen to cover the sum of the individual components, which results in much higher values.

As an example, the bandwidth requirements for a service area of 1000 km x 1000 km, are listed in Tab. 4 for the different representation concepts. A broadcast mode of the area and 12 GPS satellites are assumed.

The FKP concept requires at least an actual reference station every 100 km, which in theory increases the amount of data by a factor of about 100 (number of reference stations). In case of VRS and PRS, the dynamic number of users define the required bandwidth compared to a single reference station. The MAC allows the transmission of 32 auxiliary station in addition to the master station data. Thus approximately three sub-networks are needed to cover the complete area.

Representation	***Aux Rate***	***bps***
SSR		1500
RS+FKP		*100* * 4800
VRS / PRS		*users* * 4800
MAC 3 sub-networks, each 32 auxiliary stations	1s	93160
	10 s	13700

Tab. 4: Estimated bandwidth for a 1000 km x 1000 km service area, 12 GPS satellites

The SSR is valid for the complete area covered and can be made independent from the number of reference stations. The RTK network, however, has some restrictions on the reference station spacing (with respect to the irregular behavior of physical conditions between reference station, see Fig. 1). Nevertheless, the disseminated SSR corrections are not related to the reference stations. The position dependent atmospheric influence can be described with functional and/or gridded parameters.

The dissemination of SSR is ideally suited for broadcasting services for an unlimited area (only restricted by the RTK network size). The communication link is therefore a uni-directional one, which broadens the number of suitable communication links in general. Communications channels generally considered not suited for RTK become now practicable again (e.g. radio and TV). SSR is also completely compliant with kinematic applications within the service area.

Debates on bandwidth are often faced with the argument, that communication links like Internet or mobile phone provide sufficient capacities. Considering increasing number of users, the demand for higher accuracy and costs for data transmission bandwidth issues are of interest.

Space based augmentation systems are ideal communication links for SSR. Besides SBAS systems, Galileo will offer free or fee based augmentation services as well as the Japanese Quasi-Zenith Satellite System (QZSS) (Tsujino 2005) will provide augmentation with GPS compatible signals. In these cases, the user requires no additional communication links to access the SSR network corrections, because the rover receives the augmentation data via its build in capabilities.

The SSR performance is also considered better concerning the associated representation error. The temporal and spatial prediction of the parameters is more precise in the state space, compared to the correction data in observation space. The interpolation of the different physical parameters can use different and optimized mathematical models as well as the stochastic properties of the parameters. For OSR the interpolation has to be done for the lump sum of all effects, thus not allowing different interpolation models.

As an example, the tropospheric propagation delay may be considered. The tropospheric delay is generally modeled independently from the satellites. For OSR the tropospheric effect is included in any observation and the interpolation (or prediction) for the rover position is independently performed for each observation. With SSR the interpolation (or prediction) is done for the tropospheric effect itself. Together with stochastic state information this prediction can be optimized and a representation error may be modeled as a residual tropospheric effect.

SSR allows to minimize site dependent GNSS errors, while OSR always uses data of a reference station with e.g. multipath. SSR corrections are generally derived from all redundant reference stations, which leads to a significant reduction of station dependent errors. Therefore a major improvement in the representation error of SSR corrections is anticipated.

The benefits of SSR correction are not limited to dual frequency users. L1 only users can apply the SSR corrections without any restriction. However, L1 only rover are more sensitive to ionospheric residual errors and cannot apply sophisticated ambiguity resolution techniques. Therefore, the overall performance will be different to dual frequency receivers.

The different concepts of state representation techniques are summarized in Tab. 3. It is obvious, that the application of SSR is best suited for an unlimited number of static or kinematic users (broadcast mode) and for an unlimited service area covered by reference stations.

SSR CORRECTIONS AND STANDARDIZATION

An important issue in the use of any representation technique is standardization. It is indispensable, that the models and corrections are identical in the RTK network processing and in the algorithms used by the RTK rover systems.

Standardization covers the actuals formats used to disseminate the correction data, but also the consistency of corrections/parameters and models applied.

The current situation for OSR is generally settled, but OSR techniques transmitting RTK network corrected observation data (FKP, VRS, PRS) are not internationally defined. Only the FKP-mode has been implemented by all major manufactures due to the efforts of SAPOS in Germany.

For SSR we are currently facing a similar situation. SSR techniques are already in use, but standardization of parameters and models for the state space modeling with millimeter-accuracy for precise applications is urgently required.

Several additional corrections must be applied to the processing of SSR correction data, because it is an absolute positioning technique. The observation data of one single GNSS RTK rover system are combined with the SSR data.

In differential GNSS techniques these additional corrections can generally be neglected. Effects like e.g. solid earth tides are in conventional RTK applications absorbed through the use of a nearby reference station with known coordinates. Nevertheless, these additional corrections are in most cases well investigated and standardized formulas are at hand.

One simple example is the computation of satellite coordinates for code and carrier phase corrections for RTCM 20/21, which has been standardized with reference to the interface control document for GPS (ICD-GPS-200 1993).

Standards that could be used for SSR are available for most issues in the IERS/IGS conventions (McCarthy, Petit 2003). In addition, the interface control documents for GPS (ICD-GPS-200 1993) and GLONASS (ICD GLO 2002) can be used. The general demand for standardization has already been addressed by other groups for PPP applications (Ray et al 2004).

The additional corrections and standardizations of modeling can be divided into satellite dependent effects, relativistic effects, ambiguities, atmosphere, datum and site displacement.

The SSR requires standardization for consistent modeling of the following parameters:

- **satellite parameters**
  - orbit error: expressed as difference to broadcast orbits
  - antenna reference point at satellite (ARP)
    - for GPS: ICD-GPS-200
    - for GLONASS: ICD-GLONASS 1998
  - satellite clock error: expressed as difference to broadcast polynomial
  - L1/L2 group delays for codes and phases
  - procedure for satellite antenna PCV
  - procedure for phase wind-up effects
    - orientation of satellites in space (attitude model)
- **procedure for relativistic effects**
- **ambiguities**
  - procedure for identical ambiguity levels
  - integer nature of carrier phase measurements must be maintained for RTK applications
- **atmospheric parameters**
  - ionosphere modeling
    - higher order effects
    - functional and stochastic models
  - troposphere modeling
    - zenith delay models (dry and wet component)
    - meteorological parameters
    - mapping functions
    - elevation and azimuth dependent mapping of zenith delays into direction to the satellite
- **datum and site displacements**
  - reference datum for state parameters (ITRF2000, ETRS89/ETRF2000, WGS84)

- reference datum for different Satellite Systems (GPS, GLONASS, Galileo)
- procedure for site displacements
  - solid earth tides
  - pole tides
  - ocean loading
  - atmospheric loading

The previous list contains already some initial proposals.

PPP-RTK: APPLICATION MODES OF SSR

The basic idea of PPP-RTK and SSR method is to give a RTK rover system sufficient information to compute its position eliminating or at least reducing the influence of all relevant error sources. Since the errors are changing with time, and the effects are depending on the location of the rover, it makes sense to describe the various error sources (and their changes) in a way that each rover equipment can determine the influence on its positioning itself. The SSR correction data contain all this information.

A network of reference stations, distributed regularly over the area of interest, collects all available satellite observation data (mainly code and carrier phase measurements). In practice, each measurement is affected by the error sources similar to a rover receiver. Thus each measurement contains information about the error sources.

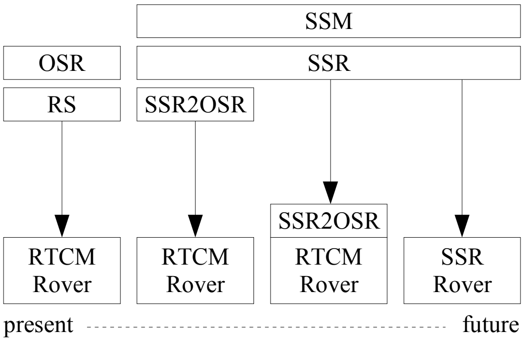

Fig. 2: Present GNSS error representation in GNSMART using observation (OSR) or state space (SSR) up to a future SSR rover

Depending on the desired accuracy and on the quality of the processing software, the density of the network has to be chosen carefully. All observation data from the reference stations is collected in a network computation center in (near)realtime.

A networking software, based on theoretical models for the various error sources, computes the error sources from the measurement data of all reference stations. The networking software has to separate the various error sources, although only the lump sum of the influence of all error sources is included in each measurement. The networking software uses some knowledge about the typical functional and statistical behavior in space and time of the error sources to separate the errors (SSM).

The error sources are changing continuously, and the measurement data from the reference stations are updated regularly. For each new epoch (typically 1 second) new estimates for the error sources can be derived.

Finally the networking software provides state information (SSR) on the current error sources as SSR correction data, and updates this information regularly. Depending on accuracy, bandwidth and other restrictions, different sets of SSR correction data can be derived (e.g. a decimeter-accuracy service).

The transmission of the state space corrections is the best choice for the representation of GNSS errors, which leads to a SSR rover. But it is also possible to generate GNSS observations from SSR data.

The different application scenarios of SSR taking also the currently mostly applied OSR method into account are shown in Fig. 2.

The SSR data are state parameters, which are related to standardized models. While knowing the standardized models and the current state parameters, conventional GNSS observation can be re-constructed from the SSR data (e.g. RINEX, RTCM data). For the time being, the conversion of SSR to OSR can be executed either at the service center or at the rover site.

The use of the SSR data directly in the processing of the RTK system requires some reconsideration of the rover algorithm (SSR rover). Using standardized models and the current SSR correction parameters it is possible to compute the influence of each error source onto each single satellite observation and to correct the observations accordingly. Depending on the quality of the SSR correction data, the influence can be reduced or eliminated. With such quasi error free observations, the position can be computed with high accuracy.

Old or legacy rovers may not be designed to use SSR correction data directly. For those legacy rovers the option to convert the SSR correction data into other standardized observation data types must be used. A software module located in the terminal can do the conversion from SSR to e.g. RTCM corrections.

The SSR concept in post-processing applications is in operational use with GNSMART e.g. in Israel, Japan, Italy, Czech Republic and Bulgaria.

PPP-RTK: SYNTHESIS OF PPP AND RTK NETWORKING

A concept of state space representation with some restrictions and limitations is PPP (precise point positioning). The PPP applications are typically all based on a global network of reference stations. RTK networking use networks of smaller size, but allow precise and fast positioning for RTK rovers. The proposed PPP-RTK is the synthesis of the positive characteristics of both, PPP and RTK networking, concepts (Fig. 3). The individual strategies have already shown to work well.

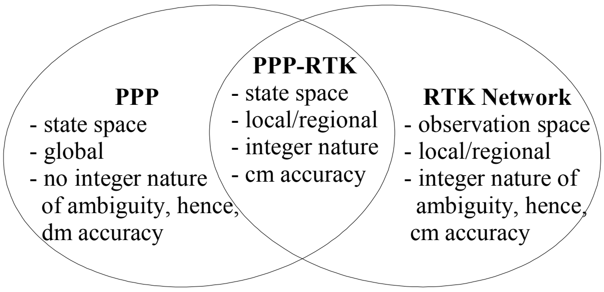

Fig. 3: Synthesis of PPP and RTK Networking

The main characteristics of the conventional PPP and the PPP-RTK approach as realized with GNSMART are pointed out in the following using a comparison.

- PPP provides only a subset of the relevant state parameters; state space information is provided only for satellite orbit and for satellite clocks, but not for ionosphere and troposphere.
  PPP-RTK provides all state parameters that are relevant for centimeter accuracy, including for ionosphere and troposphere.
- in PPP, ionospheric delay has to be corrected by dual frequency observations; thus dual frequency receivers are always required, even for decimeter class accuracy.
  In PPP-RTK as with GNSMART, the state space representation includes information about the ionosphere, thus the ionosphere can be reduced or eliminated. This allows the use of single frequency receivers in PPP-RTK applications.
- in PPP, the troposphere has to be estimated on the rover system as additional unknown in the adjustment algorithm.
  In PPP-RTK, the troposphere is provided as part of the state space representation, thus for the rover the troposphere can be reduced or eliminated.
- large inter station distances between reference stations in the network inhibit resolution of integer ambiguities in the network. This limits the accuracy to decimeter for realtime applications.
  In PPP-RTK the distances are chosen so that the integer ambiguities can be resolved in the network. With GNSMART for example inter station distances of several hundred kilometers are possible. This allows centimeter applications in realtime.
- in PPP, the state parameters from the network do not maintain integer nature of carrier phase observables. Thus even with sophisticated rover algorithms it is not possible to solve the ambiguities for the rover's carrier phase measurements.
  With PPP-RTK, all state parameters maintain the integer nature of carrier phase observables. Thus a rover can solve its integer ambiguities and can get RTK (centimeter) accuracy.
- in PPP, the rover needs long integration time (up to 30 min) to get decimeter-accuracy. Centimeter accuracy would only be possible with very long (many hours) integration time.
  In PPP-RTK, the initialization time at the rover is typically in the order of a few (10 ... 50) seconds.

The PPP-RTK concept in GNSMART avoids the disadvantages limiting the use of the conventional PPP concept. In practice, PPP-RTK will provide

- cheaper rover equipment
- better accuracy
- faster work in the field

than conventional PPP and RTK networking.

DISCUSSION AND CONCLUSION

Differential GNSS RTK networks are ideally suited to serve as an augmentation system to derive complete state information on all GNSS errors, which are then distributed to an unlimited number of users using ground based or satellite based broadcast communication links.

The concepts of precise point positioning (PPP) and RTK networking can be combined to a concept, which we call PPP-RTK. It is the use of state space representation in RTK networks, which give centimeter-accuracy for an unlimited number of static or kinematic users (broadcast mode) and for an unlimited service area covered by reference stations.

The ideal solution is the dissemination of SSR correction data with a GNSS compatible signal to avoid any additional telecommunication on user side. This is also a challenge considering Galileo or the Japanese Quasi-Zenith Satellite System (QZSS).

An improvement in quality, accuracy and time-to-fix in RTK networking using state space monitoring is already obvious while using the currently applied OSR techniques. A furthermore transition to SSR will also improve the general performance.

The goal of PPP-RTK is ubiquitous accurate positioning at the few centimeter-level using a single GNSS receiver while providing information on all relevant GNSS errors using a state space representation.

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