

EGNOS Based Virtual Reference Stations

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Abstract

We propose the use of the European Geostationary Navigation Overlay Service (EGNOS) data - real time on line data provided by SISNeT - to develop Virtual Reference Stations and, thus, increase the quality of the Position, Velocity and Time (PVT) solution of receivers unable to interface directly with EGNOS. A Virtual Reference Station (VRS) is a concept where the existence of a differential reference station located near a mobile rover is simulated by software in order to increase the accuracy of the PVT solution of the mobile GNSS receiver.

Keywords: *Navigation, DGNSS, SBAS, EGNOS, VRS.*

1 Introduction

Global Navigation Satellite Systems (GNSS) are global positioning systems that allow users to determine their location and time on Earth. Since these systems do not fully satisfy the requirements of certain navigation applications, several augmentation systems were designed to enhance further the quality of the stand alone GNSS service, namely, Ground Based Augmentation Systems (GBAS) and Satellite Based Augmentation Systems (SBAS).

Differential positioning is a well known technique to improve the positioning accuracy of a GNSS. A Differential GNSS (DGNSS) is a GBAS that uses a Reference Station (RS) located at a well known location to calculate the corrections that, once applied to the GNSS observations, result in a position solution equal to the RS location. These corrections are then transmitted and applied by mobile receivers located in the vicinity of the station. Differential DGNSS can be implemented with a single or multiple reference stations. Network-based systems grant higher quality service, which can be further enhanced by adopting the Virtual Reference Station (VRS) concept,

where the presence of a station near each rover is simulated. As a result, the first requirement of a VRS is to always have access to a network of RS.

The alternative to GBAS are Satellite Based Augmentation Systems (SBAS). SBAS cover large regions of the globe and broadcast via geostationary satellites wide-area corrections that SBAS enabled rovers are able to receive, decode, process and apply in real time. The SBAS that services our area is the European Geostationary Navigation Overlay Service (EGNOS). EGNOS delivers general error estimates generated for a large coverage area. In order to apply this data to a specific point in the EGNOS service area, there are two possibilities: *(i)* use an EGNOS enabled receiver that transparently applies the corrections to the receiver measurements or *(ii)* implement an application that receives and processes the EGNOS data according to a given location and then sends the results to the receiver. The latter case corresponds to the development of a dedicated VRS and is intended to address problems such as bad SBAS coverage due to high latitudes or urban canyons, legacy receivers that do not interface directly with a SBAS or the absence of a network of RS in the rover vicinity. To overcome these limitations, we propose the use of real time data from EGNOS to implement a VRS service.

1.1 Goal

The aim of this project is to develop an EGNOS based VRS service so that receivers unable to interface directly with EGNOS or without a network of RS in the vicinity can still improve their accuracy. The development of an EGNOS based VRS requires: *(i)* continuous access to real time EGNOS and satellite ephemeris data as well as to the approximate receiver location; *(ii)* decoding EGNOS data from RTCA D0-229; *(iii)* processing the EGNOS information according to the Minimum Operational Performance Standards (MOPS) document [10]; *(iv)* generating the differential correction data; *(v)* encoding the differential corrections into RTCM SC-104; and *(vi)* sending the RTCM SC-104 messages to the receiver.

This paper presents the EGNOS based VRS service developed so far and includes the contributions of two graduate students: Jelle Stuyvaert [13] and Tom Davidson [3].

1.2 Structure

This document is organised in six sections. The first Section provides a general introduction to the problem, goal and the structure of this document.

The second Section introduces differential GNSS. The third Section introduces SBAS and presents EGNOS. The fourth Section addresses VRS and the fifth Section describes the developed EGNOS VRS service application. The sixth and last Section presents the conclusions, limitations and includes also enhancement suggestions for future development.

2 Differential GNSS

Differential Global Navigation Satellite Systems (DGNSS) are complementary systems that rely on one or more reference stations (RS), installed at precisely known locations, to compute and broadcast the range errors of the GNSS satellites in view. There are two real time differential positioning methods - the code pseudorange and the carrier phase methodologies. Double frequency receivers use carrier phase measurements to provide Real Time Kinematics (RTK) accuracy (centimeter level) and single frequency receivers use code pseudorange measurements to provide standard differential accuracy (meter level).

The RS generates correction values (either for code pseudorange or carrier phase measurements) for each valid satellite in view. The computed corrections are to be applied, within a given time-window, to the corresponding measurements of rovers situated in the vicinity of the RS. By applying differential corrections, an user with a DGNSS enabled receiver expects to eliminate the error sources that affect in the same way both RS and rover. These so-called common errors include position-dependent error sources (*e.g.*, the variable propagation delays introduced in the GNSS signal when it crosses the ionosphere and the troposphere) and position-independent error sources (*e.g.*, the ephemeris and clock errors of the GNSS satellites). However, due to the spatially correlated error sources, as the distance between rover and RS (baseline) grows, the quality of the differential correction degrades. Single RS systems are also very sensitive to RS measurement errors (any RS error is automatically reproduced in all rover measurements).

One way to mitigate these problems is to implement a network of multiple RS and, instead of applying the corrections from just one RS, use the corrections from the group of RS surrounding the rover. This approach reduces not only distance-dependent errors but also minimizes the measurement errors of the receivers [9]. As a result, network based differential systems provide increased accuracy, integrity, availability and reliability when compared to single RS solutions.

Multiple RS networks use three main algorithms to generate network based differential corrections [1]:

- The measurement domain algorithms perform a weighted mean of the scalar correction data (*e.g.*, code pseudorange and range rate corrections) from several RS to create a DGNSS network solution [5]. These differential systems require a high density of RS since the quality of the corrections degrade as the users moves away from the various RS centroid. They are called local area augmentation systems.
- The position domain algorithms first compute the different DGNSS position solutions obtained from each of the available differential corrections and then calculate a weighted mean of the individual position solutions [1].
- The state-space domain algorithms use multiple RS equipped with dual frequency receivers and complex software to generate highly accurate corrections. These algorithms model separately the individual error sources that affect the differential positioning quality. This modelling includes not only the GNSS error sources (signal propagation errors and satellite-dependent errors), but also the receiver error sources. Users receive the satellite clock corrections, satellite ephemeris corrections and ionospheric corrections in separate components and are expected to integrate them with the locally measured data. These differential systems require a much lower density of RS and are called wide area augmentation systems.

The standard protocol used by most DGNSS to transmit differential corrections is the Radio Technical Commission for Maritime Services Special Committee N. 104 protocol [11] - referred in this paper as “RTCM SC-104”.

2.1 RTCM SC-104

Reference stations generate differential correction messages according to the RTCM SC-104 standard protocol. The overwhelming majority of GNSS receivers are able to receive and process RTCM SC-104 messages. The standard defines 33 of 64 possible message types.

The RTCM messages are made of standard International Reference Alphabet (IRA) bytes (8 b length) where the two most significant bits are set to space and mark (01) and the remaining 6 b constitute the so called RTCM byte. The messages are composed of 30 b (five RTCM bytes) blocks called RTCM words, holding 24 data bits and 6 parity bits.

The parity bits are used for two purposes: to encode the 24 data bits of the following word and to hold the parity value of the current word data bits. The algorithm used to compute/verify the parity value of the current word and to encode/decode the data bits of the following word is the algorithm

used in the NAVSTAR-GPS navigation messages [7].

An RTCM message is made of a mandatory header followed by a body of data of variable word length. The header is two RTCM words long and includes a fixed preamble and several other fields. The total length of a message contains always an integer value of RTCM words.

Message Type 1 (MT1) contains the standard differential GNSS corrections, *i.e.*, the pseudorange corrections for the healthy satellites visible by the *RS*. Equation 1 presents the pseudorange correction computed by *RS* for the pseudorange measurement of satellite *S* at reference epoch t_0 :

$$PRC_{RS}^S(t_0) = \rho_{RS}^S(t_0) - PR_{RS}^S(t_0) \quad (1)$$

where $PRC_{RS}^S(t_0)$, $\rho_{RS}^S(t_0)$ and $PR_{RS}^S(t_0)$ are the pseudorange correction for satellite *S*; the geometric range from station *RS* to satellite *S*, which is obtained from station *RS* known position and the broadcasted ephemeris of satellite *S*; and the pseudorange measurement of satellite *S* [6]. Additionally, the station also computes the range rate correction parameter $RRC^S(t_0)$ for satellite *S*, which models the rate of change of the pseudorange correction of satellite *S*.

A receiver, upon reception of a valid pseudorange correction message, extrapolates the correction values to the current epoch t and, then, adds the results to the correspondent current pseudorange measurements. Equation 2 holds the formula for the pseudorange correction of satellite *S* extrapolated to epoch t ,

$$PRC_{RS}^S(t) = PRC_{RS}^S(t_0) + RRC_{RS}^S(t_0) * (t - t_0) \quad (2)$$

where $PRC^S(t)$ is the correction value extrapolated to the current epoch t , $PRC^S(t_0)$ is the received pseudorange correction, $RRC^S(t_0)$ is the received range rate correction, to pseudorange correction reference epoch, t is the user receiver measurement time and $t - t_0$ is defined as the correction latency. The pseudorange correction $PRC^S(t_0)$ will diverge from the proper value as time elapses, *i.e.*, as messages grow old [11]. The pseudorange measured by the user, $PRM(t)$, is then corrected as follows:

$$PR^S(t) = PRM(t) + PRC_{RS}^S(t) \quad (3)$$

where $PR^S(t)$ is the differentially corrected pseudorange measurement.

3 Satellite Based Augmentation Systems

Satellite Based Augmentation Systems (SBAS) are wide-area systems supported by large terrestrial networks of reference stations (RS) deployed over

the coverage area that use geostationary satellites to broadcast the wide-area corrections. Currently, there are several SBAS: the Wide Area Augmentation System (WAAS) from the USA, the European Geostationary Navigation Overlay System (EGNOS) from the European Space Agency (ESA), the nation-wide Canadian DGPS Service (CDGPS), the Japanese MTSAT Satellite Augmentation System (MSAS) and GPS/GLONASS and Geostationary Augmentation Navigation (GAGAN) system from India. CDGPS, WAAS and MSAS are GPS augmentation systems; EGNOS and GAGAN augment both GPS and GLONASS signals. Whereas MSAS and GAGAN are at pre-operational stages, WAAS has been operating for aviation use since July 2003, EGNOS is currently under certification process for commissioning and CDGPS is operational. Tests conducted both with WAAS and EGNOS showed a positioning accuracy between 1 m and 2 m in the horizontal plane and 2 m and 4 m in the vertical plane 95 % of the time [2].

All SBAS signal formats and message contents conform to the Radio Technical Commission for Aeronautics RTCA DO-229 standard [10]. SBAS enabled receivers comply with the RTCA DO-229 standard.

3.1 RTCA DO-229

The RTCA DO-229 is described in the “Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment” (MOPS) document specified by the International Civil Aviation Organization (ICAO) [10]. The standard is applicable to SBAS and SBAS enabled equipment and defines a series of different message types, their format and how the data contained should be processed. From a total of 64 possible messages, only 18 are currently used - Table (1) .

RTCA DO-229 messages are 250 b long and are broadcasted at a 1 Hz frequency. Since 250 b/s is a very slow data rate, it is very manageable, either through the Internet or as a signal in space broadcast.

3.2 EGNOS

The European Geostationary Navigation Overlay Service (EGNOS) is a Satellite Based Augmentation System (SBAS) designed and operated by the European Space Agency, the European Commission and EUROCONTROL that augments the performance of the two existing GNSS: the NAVigation Timing and Ranging Global Positioning System (NAVSTAR-GPS) from the USA and the Russian GLobal Navigation Satellite System¹ (GLONASS).

¹Globanaya Navigatsionnaya Sputnikova Sistema

Table 1: RTCA messages

Content	Message Type
Test Mode/Fast Clock Corrections	0
PRN Mask Assignments	1
Fast Clock Corrections	2, 3, 4, 5 and 24
Integrity Information	6
Fast Corrections Degradation	7
GEO Navigation Message	9
Degradation Factors	10
WAAS Network Time Parameters	12
GEO Satellite Almanacs	17
Ionospheric Mask	18
Long-Term Corrections	24 and 25
Ionospheric Delay Corrections	26
WAAS Satellite Service Message	27
Clock Ephemeris Covariance Matrix	28

The EGNOS is designed to provide three services [4]:

EGNOS Open Service (OS) - The OS is a public, free service that is offered in Europe since early 2006. The OS performance accuracy is on the order of 1 m to 3 m in the horizontal plane and of 2 m to 4 m in the vertical plane, with 99 % availability.

EGNOS Commercial Data Distribution Service (CDDS) - The CDSS will be offered on a controlled access basis (*e.g.* through Internet, cellular phones, *etc.*) to customers who require enhanced performance for professional uses. This service will encompass the provision of corrections and integrity messages and of raw data from all Ranging and Integrity Monitoring Stations (RIMS), all provided in real time.

EGNOS Safety of Life (SoL) service - The SoL will be offered and guaranteed exclusively to the critical transport community, *e.g.* aviation, maritime, *etc.*, delivering enhanced performance that includes the provision of the integrity function, *i.e.* a warning of system malfunction that will reach the user in a given alarm time. This service will be certified against applicable standards and performance, *e.g.*, the SBAS standards of the ICAO, in 2009.

The EGNOS Open Service (OS) is available through two interfaces:

- Signal-In-Space (SIS) - the standard EGNOS interface, *i.e.*, the EGNOS satellites IOR-W (PRN 126), AOR-E (PRN120) and the EGNOS ESA ARTEMIS satellite (PRN 124);

- Signal-In-Space (SIS) through the Internet (SISNeT) - the EGNOS web interface [14].

Additionally, there is also the EGNOS Message Server (EMS) that keeps the archive of the EGNOS broadcasted messages.

4 Virtual Reference Station

The implementation of the Virtual Reference Station (VRS) concept requires a network of DGNSS reference stations connected via data links to a control center. This central node gathers the information from all RS and creates a living database of regional corrections [8]. There are two possible implementations [12]:

Virtual Reference Network Station (VRS) that uses a bi-directional data link between the rover and the control center. The rover sends its position, with an accuracy of 100 m, to the control center. The control center then creates and sends back customized differential correction messages (RTCM SC-104) based on the current regional corrections and the approximate rover location. Since the VRS follows the rover, the position-dependent errors are better modelled and, thus, the PVT solution quality does not depend on the rover-RS distance;

Virtual Reference Cell (VRC) that divides the coverage area in cells. The control station creates a virtual reference station per cell. The rover is assigned to a cell and the virtual reference station does not follow the rover. When the rover leaves a cell, it is assigned to a new one. The advantage is that there is no limitation of the number of users and no need for bi-directional communication. The disadvantage is a lower accuracy when compared to the VRS approach.

Our proposal is to substitute the regional corrections generated by the central node by the wide-area EGNOS corrections. These EGNOS real time corrections result already from processing the data gathered by the EGNOS network of DGNSS RS, which is continuously monitored and conveniently scattered through out the coverage area. As a result, our efforts are concentrated on developing an EGNOS based VRS service from the real time EGNOS corrections and the approximate location of the rover.

A similar approach was proposed and implemented by [2] for the Finnish Geodetic Institute. The main difference is that the authors use EGNOS data to generate static virtual differential GPS stations, *i.e.*, VRC instead of VRS. Their goal is to solve the problem of receiving EGNOS data at the high latitudes of Finland as well as in city canyons.

5 EGNOS VRS Service

The EGNOS VRS service interacts simultaneously with SISNeT - to obtain the real time RTCA DO-229 messages - and with the GNSS client receivers - to generate and apply customized pseudorange corrections (PRC). As a result, the application has two main modules: (i) the input module which interacts with the SISNeT server and decodes the SISNeT messages in RTCA DO-229 to obtain the EGNOS wide-area corrections; and (ii) the VRS module that estimates, for each rover client, the PRC and encodes them into RTCM SC-104 messages. The architecture of this application is presented in Figure (1).

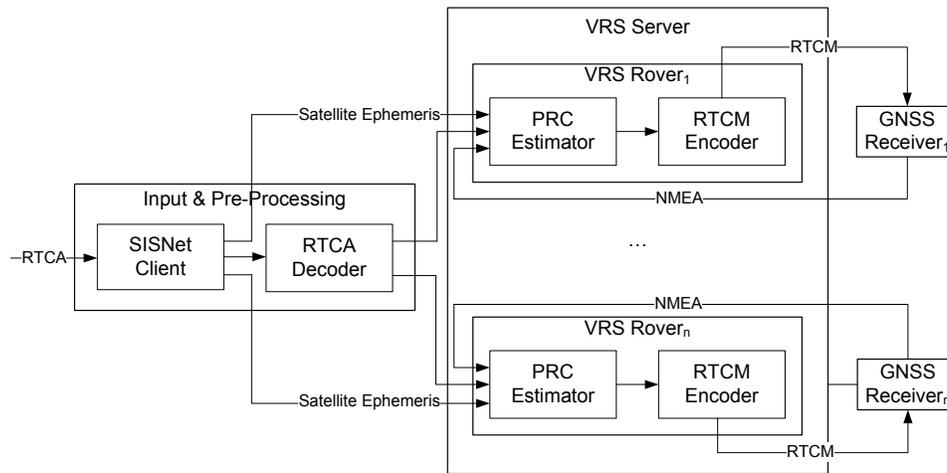


Figure 1: Architecture of the EGNOS VRS Service

The “Input and Pre-processing” module includes the SISNeT Client, which interacts with the ESA SISNeT Server, and the RTCA Decoder, which processes and decodes the RTCA messages.

The “VRS Server” module implements for each rover client a dedicated PRC Estimator and RTCM Encoder.

5.1 Input and Pre-processing

The “Input and Pre-processing” module includes the SISNeT Client and the RTCA Decoder units which are responsible for gathering all necessary real time data from EGNOS or other on-line sources. It includes also a graphical user interface (GUI) where the decoded data is displayed.

5.1.1 SISNeT Client

The SISNeT Client module is intended to continuously interact with SISNeT to request and obtain the necessary real time data: ephemeris data and EGNOS wide-area corrections. Alternatively, and for test purposes, the user can choose to decode the contents of an EMS file - a file downloaded from the EGNOS Message Server (EMS). It is important to realize that when the selected EGNOS data source is a file, the application still needs to obtain the correct ephemeris parameters from some other alternative source, *e.g.*, the International GNSS Service (IGS)². This module implements, according to the SISNeT User Interface Document [15], the necessary client authentication as well as the continuous message request.

5.1.2 RTCA Decoder

The RTCA Decoder is prepared to decompress, parse and process RTCA messages conforming with the RTCA DO-229C “Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment” [10]. All SISNeT messages are compressed according to the SISNeT Compression Algorithm (SINCA) described in [15], and, thus, have first to be decompressed. The RTCA Decoder can process real time RTCA data directly from the ESA SISNeT Server or archived RTCA messages, *e.g.*, from the EMS Server. Additionally, it also decompresses and parses non-RTCA SISNeT messages such as satellite ephemeris and ionospheric corrections messages.

5.2 VRS Server

The “VRS Server” module is a multi-threaded application based on the client/server model. Every time a client rover establishes connection with the EGNOS VRS module, it launches a new thread that includes a PRC Estimator and a RTCM Encoder.

5.2.1 PRC Estimator

The PseudoRange Corrections (PRC) Estimator is the main processing unit. For each satellite, it estimates: (*i*) the current satellite position using the corresponding satellite ephemeris data; (*ii*) the user to satellite elevation and azimuth angles using the approximate rover location; (*iii*) the user’s Ionospheric Pierce Point (IPP) and obliquity angle; (*iv*) the range correction

²<http://igsceb.jpl.nasa.gov/index.html>

due to the ionospheric delay based on the user's IPP and on the ionospheric delay corrections; (*v*) the tropospheric range correction, which depends on the relative user to satellite position; (*vi*) the fast range correction; (*vii*) the satellite clock error range correction based on the long-term correctional data; and (*viii*) the total pseudorange correction, which is the sum of all estimated range corrections.

5.2.2 RTCM Encoder

This module creates and encodes only two RTCM message types: Message Type 1 (MT1) and Message Type 3 (MT3). MT1 contains pseudorange corrections (PRC) and the rate of change of the pseudorange corrections (RRC) for the visible healthy satellites. MT3 holds the Earth-Centered-Earth-Fixed (ECEF) coordinates of the VRS.

A MT1 includes the PRC values of all visible satellites that are in good health. The decoded header of a MT1 includes the preamble - "01100110"; the message type - "1"; the reference station identification - the client rover identification; the Modified Z-Count (MZC) parameter - the message epoch in seconds, starting from the last hour; the sequence number - a number that increments from "0" to "7" and restarts; the message length - the number of RTCM words that compose the message; and the station health. Then, it creates the decoded body of the message, holding the PRC of the selected satellites. The total length of a message depends on the number of satellites being corrected, but it contains always an integer value of RTCM words.

A MT3 header is identical - only the message type, the sequence number and the message length need to be updated. The body contains the ECEF coordinates of the approximate location of the rover client.

Finally, the decoded message is encoded according to the RTCM SC-104 sequential encoding algorithm. It is a sequential coding method, that uses the last two bits of the previous word to encode the next RTCM word.

6 Conclusions

This paper presents the EGNOS based Virtual Reference Station service created to increase the quality of the PVT solution of receivers that, although located within the EGNOS coverage area, are unable to interface directly with it. The developed service interacts with the on-line data sources (*e.g.*, SISNeT, IGS, *etc.*) as well as with client rovers and implements, for each client rover, the VRS concept. Since this approach is generic, it is applicable to any SBAS with a real time web interface.

The implementation of the described modules is practically finished. Currently, we are concentrated on: *(i)* verifying message time-outs periods; *(ii)* checking the interrelations and dependencies between messages; *(iii)* creating additional data buffering; and *(iv)* working at latitudes higher than 75° . As a result, the future work will be focussed on tackling these issues, field testing and on the subsequent debugging.

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