

GNSS augmentation through Ku-band communication satellites with RTK realization

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Abstract: In this study, a method to broadcast real-time kinematics (RTK) corrections over a communication satellite is proposed. RTK corrections generated by the reference station are uplinked to the communication satellite within a multiplexed DVB-S carrier. Corrections are received by a satellite dish and the DVB-S satellite receiver. Better than 18 cm of accuracy is achieved for rover distances of up to 500 km in Turkey. The proposed method can be used as an alternative satellite-based augmentation system for Turkey and other countries.

Key words: Global Positioning System, real-time kinematics, satellite-based augmentation system, communications satellites

1. Introduction

The Global Positioning System (GPS) has 7.8 m or better accuracy for single frequency C/A code [1]. DGPS improves the positioning performance of the GPS by using one or more reference stations at known locations. DGPS systems can be categorized as using code-based and carrier-based techniques. Code-based DGPS systems rely on pseudorange error corrections, can provide decimeter-level position accuracies, and are not suitable for surveying applications. Carrier-based systems utilizing real-time kinematics (RTK) can provide centimeter-level accuracy by utilizing carrier-phase measurements [2].

Single reference station-based DGPS and RTK work well within a small geographical area, typically less than 50 km, due to distance-biased satellite orbit errors and ionosphere and tropospheric signal refractions. Wide-area DGPS systems with multiple reference stations provide meter-level accuracy, which does not depend on the proximity of the rover to the reference station. Differential GPS corrections and integrity data are transmitted through geostationary communication satellites in some wide-area DGPS systems, which are specifically known as satellite-based augmentation systems (SBASs). Wide-area augmentations systems (WAASs) in the United States and the European Geostationary Navigation Overlay System (EGNOS) in Europe are well-known SBAS systems. The primary use of WAASs is in air navigation with 1.6 m horizontal nominal accuracy [3].

Network RTK techniques are developed to overcome wide-area DGPS accuracy limitations for surveying applications using multiple reference stations [4]. Network RTK-implemented continuously operating reference stations (CORSs) are used in many countries, including Turkey. The Turkish RTK CORS network, TUSAGA-Aktif, provides centimeter-level accuracy with 146 reference stations installed in Turkey [5].

Data connection between reference and rover stations is commonly provided by UHF/VHF radio link

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or general packet radio service (GPRS). Turkey's CORS system, TUSAGA-Aktif, requires GPRS or Internet connection from rover stations. Some countries operate nationwide radio broadcasting stations for sending DGPS corrections (e.g., US Coast Guard NDGPS, Australian Maritime Safety Authority DGPS services).

Many countries need to deploy WAAS or EGNOS types of wide-area DGPS services. These systems require ground monitoring stations covering the whole country, control centers, and geostationary satellites with L-band transponders. Wide-area DGPS systems require high deployment and operating budgets. Frequency coordination of the L-band is becoming more difficult. On the other hand, Ku-band communication is widely used for TV broadcasting in almost all countries. The Ku-band, with lower satellite capacity and satellite receiver costs, is an alternative to L-band wide-area SBAS systems.

A very small aperture terminal (VSAT) over a communication satellite is used to provide a data link between rover station and network-RTK control center in Japan [6]. However, the VSAT is costly and tedious to deploy and operate compared to satellite TV receivers. This system and many other network RTK and CORS systems require two-way communication links, which are not suitable for military applications. Military applications have to use a broadcast communication link where the position of the rover station is not required. Two-way communication links are also not suitable for moving rover stations due to delays at the sending position of the rover station to the network RTK control center and receiving correction data.

Terrestrial TV broadcasting is used in network-RTK systems using FKP (Flächen-Korrektur-Parameter) [7]. Corrections are disseminated via TV audio subcarrier channel (ASC) at 9.6 kbps rate. The developed system uses a PC and special software developed by Geo++ to receive raw data from the rover station and FKP corrections from the ASC receiver to calculate corrected positions.

A baseline distance limitation of 50 km is typically assumed for most applications, as the accuracy of RTK greatly reduces after this limit. In this case, the data link provided by two radios at each station suffices. A novel RTK algorithm, flying RTK, is developed to achieve 5 cm + 1 ppm (steady state) horizontal positioning accuracy for baselines up to 1000 km from the reference station [8]. Flying RTK improves convergence time compared to conventional float RTK.

2. Differential GPS (DGPS) techniques

DGPS employs one or more reference stations with known locations to improve the positioning performance of GPS. The reference stations are linked to the rover using various terrestrial and space-based methods.

Generally, DGPS techniques are classified in pseudorange and carrier-phase measurements. Pseudorange measurement methods are composed of absolute or relative differential positionings as local area, regional area, or wide area. DGPS systems can be designed to service a very small geographic area where the distance between a user and a single reference station is less than 50 km. Several reference stations and different algorithms can be employed to effectively cover larger geographic regions.

Although carrier-phased systems include unknown integer wavelength components, which can be resolved by comparing multiple signals from multiple receivers, these measurements are much more precise than pseudorange ones. While code-phased differential systems offer decimeter-level position precision, carrier-phased systems provide centimeter-level performance.

2.1. GNSS correlation errors

GNSS error sources are deeply related to space and time characteristics. As a consequence of this relation, DGPS systems use these correlations to advance overall system performance. A DGPS system with a single reference

station has local errors in the reference station's pseudorange and carrier-phase measurements. Available GNSS satellites are expected to be similar to those seen by a nearby user. Once the reference station calculates the errors by leveraging its known surveyed position and provides this information in the form of corrections to the user, it is expected that the user's position accuracy can be enhanced as a consequence.

GNSS error sources can be grouped as atmospheric, ground, and satellite-based. Atmospheric degradations include tropospheric and ionospheric errors caused by the traveling of electromagnetic waves through these layers. The characteristics of electromagnetic radiation vary with temperature, pressure, and relative humidity of the medium it travels in. Satellite segment errors can be detailed as clock and ephemeris errors. Satellite clock errors increase with time, but not linearly [9].

2.2. Conventional DGPS Compensation

GPS requires range measurements to at least four satellites for positioning solutions. The set of basic equations for pseudorange and receiver clock offset is:

$$\begin{aligned} p_1 &= \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2} - c \times dT \\ p_2 &= \sqrt{(x - x_2)^2 + (y - y_2)^2 + (z - z_2)^2} - c \times dT, \\ p_3 &= \sqrt{(x - x_3)^2 + (y - y_3)^2 + (z - z_3)^2} - c \times dT, \\ p_4 &= \sqrt{(x - x_4)^2 + (y - y_4)^2 + (z - z_4)^2} - c \times dT, \end{aligned} \quad (1)$$

where p_i is pseudorange to the i th satellite; $x_i y_i z_i$ are coordinates of the i th satellite; dT is receiver clock offset; and c is the speed of light. There are different algorithms to solve this set of equations.

In the DGPS technique, the position of the reference station is known. The reference station continuously calculates the GPS position with the current field of view of GPS satellites and compares it to its known position. There will be a difference between the known position and calculated position due to selective availability, atmospheric errors (ionospheric and tropospheric), and satellite orbit errors. The reference station calculates these corrections for each satellite measured and sends them to the rover.

DGPS applications compensate the GNSS errors mentioned in the previous section. The distance of the k th reference station to the i th GNSS satellite is denoted as $D_{i,k}$ and can be calculated once the exact satellite position is known [10]. The reference station distance prediction can be calculated as:

$$r_{i,k} = D_{i,k} + h_k + c \times s_k, \quad (2)$$

where h_k and s_k denote the distance measurement error in meters and reference station clocking offset in seconds, respectively. The differential correction value ($\Delta d_{i,k}$) can be calculated using predicted distance and the exact value of the predetermined distance:

$$\Delta d_{i,k} = D_{i,k} - r_{i,k}. \quad (3)$$

The correction value calculated by the reference station is transmitted to the rover and added to the GNSS measurement done by the rover ($r_{i,rover}$) to calculate compensated position data:

$$R_{i,rover} = r_{i,rover} - \Delta d_{i,k}. \quad (4)$$

Since the instantaneous measurements of the reference station and rover are altering related with the time, the position of the rover can be defined as:

$$R_{i,rover}(t) = r_{i,rover}(t) - \Delta d_{i,k}(t). \quad (5)$$

2.3. Real-time kinematics realization

RTK is a DGPS technique developed in the mid-1990s to provide high positioning accuracy. RTK utilizes carrier-phase measurements in addition to pseudoranges. The phase of the GPS receiver and the phase of the GPS satellite signal are compared [11]. RTK requires a real-time communication link and works typically within 50 km of distance from the reference station.

Network RTK was developed in the late 1990s to overcome distance limitation problems of single reference station-based RTK. There are different types of network RTK methods such as MAC, FKP, VRS, PRS, and I-Max. The master auxiliary concept (MAC) sends the correction difference of auxiliary stations to the rover. Other methods can be realized from standardized MAC data [12]. All these network RTK solutions are implemented via GPRS or an Internet connection to the control center. The advantage of one-way broadcast communication is being realized for wider coverage and mass markets [13].

CORSs are combined to generate RTK correction solutions for precise positioning use within the area of reference station coverage. Observations taken from each CORS are flowed to a centralized network processing server continuously. The network RTK software (such as Trimble GPSNet or Leica GNSS Spider) generates RTK corrections from ambiguity-fixed double-difference phase measurements. Both corrections and observations are typically transmitted to the rover in the standard Radio Technical Commission for Maritime Services (RTCM) format using various mediums. The rover position is then computed using the received RTCM messages and the local observation for the same epoch to derive the precise user position [14].

Float RTK treats double-difference carrier-phase ambiguity as a float variable. If the ambiguity search is solved with an integer, a centimeter-level RTK fixed position is reached, but it may not be possible to fix carrier-phase ambiguity with integers for long distances within a reasonable time so that only float solutions may be available with decimeter-level accuracy. An alternative algorithm called flying RTK is proposed to improve the float RTK convergence performance. Flying RTK processes the ambiguity as float and never fixes it to an integer. Flying RTK generates some position correction to the standard float RTK and adds this correction to get the flying RTK solution. Fixed RTK tries to validate the reliability of the most probable integer candidate. Flying RTK tries to build some integer ambiguity field having found a number of most probable integer vectors. These vectors and associated chi-square statistics are used to generate flying RTK correction to be applied to the float position. As seen in Figure 1, flying RTK provides considerably better convergence patterns compared to float RTK.

3. Developed system and measurements

In this work, a method to broadcast RTK corrections through a Ku-band communication satellite is presented. Geostationary satellites are used in wide-area augmentation systems due to their advantage of providing communication within wide coverage areas. The WAAS space segment consists of Inmarsat 4F3, Galaxy 15, and Anik F1R satellites. The TÜRKSAT 4A satellite is used to transmit RTK corrections to Turkey as shown in Figure 2.

A Proflex 800 GNSS receiver is used as reference and rover stations in the system. Technical performance specifications of the Proflex 800 GNSS receiver are provided in Table 1 with horizontal and vertical accuracy

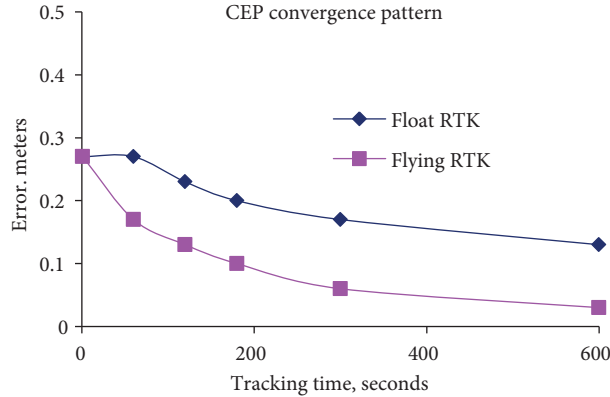


Figure 1. Comparison of float and flying RTK convergence.

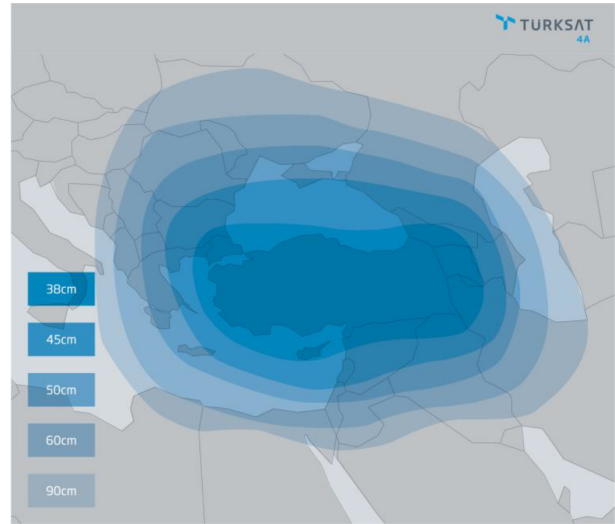


Figure 2. TÜRKSAT-4A satellite coverage area.

and parts per million (ppm) values for distance-related errors in single reference station operations [15]. While conventional RTK produces solution for reference stations less than 50 km away after sufficient convergence time, flying RTK guarantees a solution for distances up to 1000 km with better convergence time. Due to its superior specifications, flying RTK is found suitable for processing RTK corrections received from a geostationary satellite at distances more than 50 km from the reference station.

Table 1. Proflex 800 performance specifications.

Measurement method	Accuracy
RTK	H: 1 cm + 1 ppm V: 2 cm + 1 ppm
Flying RTK	H: 5 cm + 1 ppm

The Ku-band augmentation signal can easily be received by using a 45-cm antenna within Turkey as shown in Figure 2. The frequency of the satellite signal is 12,379 MHz with horizontal polarization, 30,000 symbol rate, and 3/4 forward error correction (FEC) parameters. The reference station is located at the TÜRKSAT Headquarters in Gölbaşı, Ankara, where more than 200 TV channels are uplinked to TÜRKSAT satellites from this facility.

RTK corrections are generated by the Proflex 800 reference station. The Maindata DVB-S encapsulator receives these corrections from the reference station serial port, encapsulates them into a DVB-S transport stream, and outputs them to its asynchronous serial interface (ASI) interface. These data are combined with other TV channels using a Cisco DCM 9900 multiplexer with program ID (PID) number 6708. The multiplexed signal is then modulated, amplified with a high power amplifier (HPA), and transmitted to the satellite through a parabolic antenna as shown in Figure 3.

RTK corrections are received using a 45-cm satellite dish and a DVB-S receiver. The receiver forwards RTK corrections that are addressed with specific PID to its RS-232 port. Another Proflex 800 is used as the rover. The rover station has an RS-232 port connected to the DVB-S satellite receiver to receive RTK corrections.

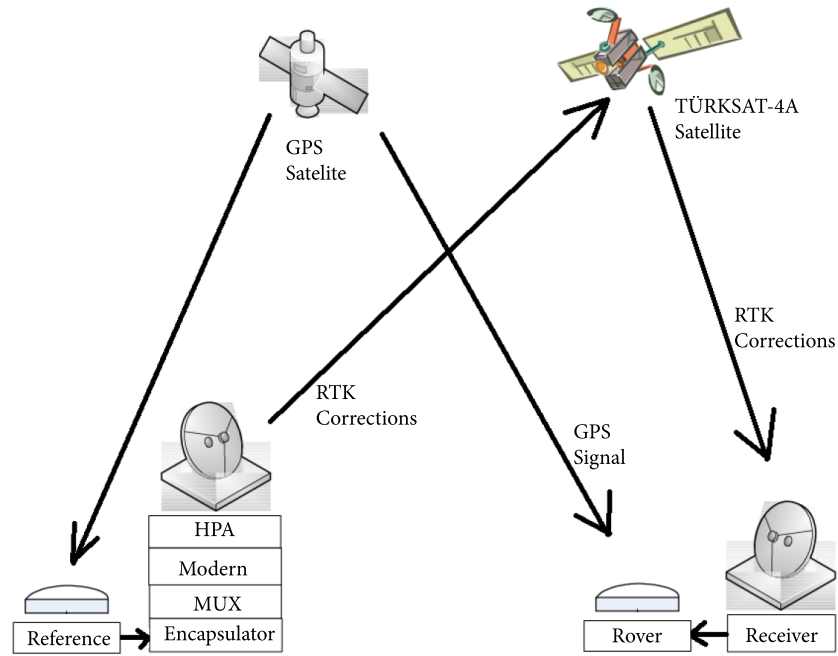


Figure 3. Uplink and receiver block diagram of the developed system.

The developed method does not need any special hardware or software. There are many DVB-S satellite receivers that can transmit received data with defined PID to their RS-232 ports. On the other hand, many rover stations have RS-232 ports for external radio modem connections. Although these RS-232 ports are built for external radio modem connection, they can be utilized to receive RTK corrections from communication satellites using DVB-S satellite receivers.

Field measurements are performed in Turkey at four different location, distances of 15 to 505 km from the reference station, as presented in Table 2. As shown from the measurement results, the accuracy is enormously enhanced with RTK corrections provided over the satellite. In these measurement results, HRMS stands for the horizontal root mean square of the rover location. As expected, RTK fixed solutions could not obtained for İstanbul and İzmir where the distance to the reference station is too far to resolve the carrier-phase ambiguity. Flying RTK yields better than 18 cm of accuracy at distances up to 500 km. Accuracy of measurements without RTK corrections (GPS only) is independent from the distance to the reference station. Both L1 and L2 frequencies are used for GPS-only measurements.

The visibility of GPS satellites is generally good, as shown in Figure 4, but SBAS signal reception is poor in Turkey and SBAS satellites with PRN 120, 126 (EGNOS over Inmarsat) and 127, 128 (GAGAN) provide

Table 2. Measurement results.

Measurement location	Distance to reference (km)	GPS only HRMS (m)	Flying RTK	RTK Fixed
Ankara	15.44	0.64	0.06	0.005
Eskişehir	196.93	0.56	0.09	0.023
İstanbul	359.30	0.75	0.11	NA*
İzmir	505.67	1.07	0.18	NA*

*RTK fixed solution is not reached.

weak signals, as shown in Table 3. SBAS satellite statuses are either “unhealthy” or “no ephemeris”. This situation clearly shows the need for a national SBAS system. SBAS systems typically provide 50 cm or less accuracy. Measurement results show that RTK over a communication satellite can provide better results for countries like Turkey and can be used as an alternative SBAS system.

Table 3. SBAS satellite visibility in Ankara.

SBAS ID	Status	Az.	El.	SNR	Smooth
				(dBHz)	count (s)
				L1C	L1C
120		240	23		
124		196	43		
126	Unhealthy	192	43	42	31
127		148	39		
128	No ephemeris	118	21	37	31

The time of the corrections is around 9 s due to processing and satellite path delays. The compact measurement record (CMR+) developed by Trimble is used for RTK correction data format. Total data rate in the satellite is 5.5 kbps.

RTK corrections provide centimeter-level accuracy within a few seconds of convergence time. Flying RTK has worse accuracy compared to RTK fixed as expected. HRMS and VRMS convergence with time is shown in Figure 5 for measurements in Ankara.

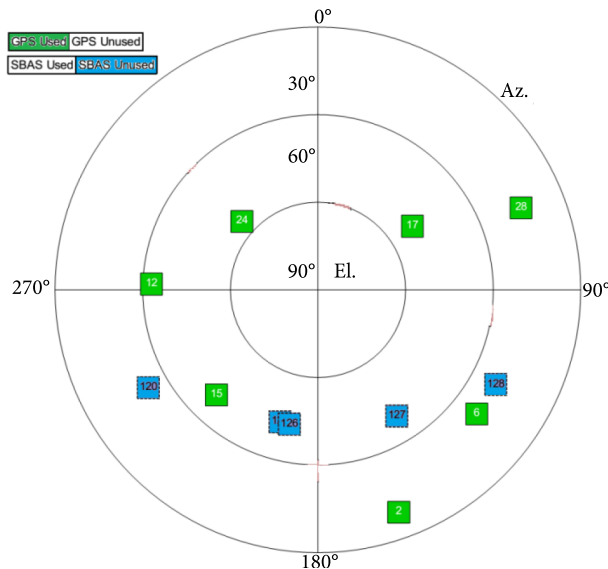


Figure 4. Polar view of GPS and SBAS satellites on Ankara.

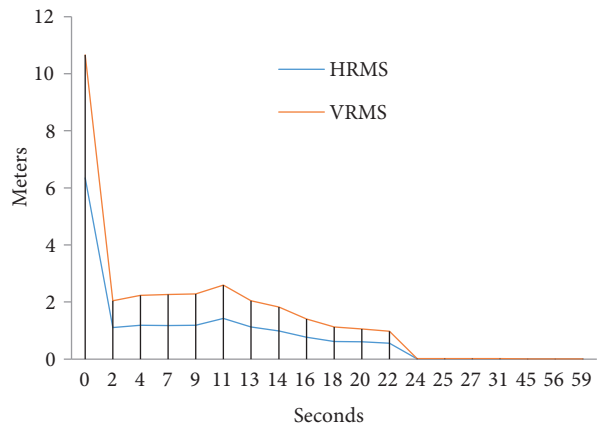


Figure 5. Convergence of RMS values.

4. Conclusion

Many commercial and military applications require submeter and even centimeter-level position accuracy. There are a few wide-area augmentation systems serving geostationary communication satellites, such as WAAS,

EGNOS, and GAGAN. These systems have high infrastructure and operating budget requirements. Besides, frequency coordination of the L-band is becoming more difficult for new satellite operators. Many countries have their own CORSs developed for surveying needs. CORSs use bidirectional communication links, radio modems, or GPRS, which are not suitable for mass markets, moving rovers, and military applications. This situation motivates us to develop a nationwide augmentation system based on Ku-band geostationary satellites.

In this study, a wide-area augmentation system developed by using the TÜRKSAT-4A Ku-band communication satellite is presented. The proposed system is operable with existing rover stations and does not need special hardware or software installed on GNSS receivers. The system provides better than 18 cm of accuracy within Turkey. The developed method can be used as an alternative solution for Turkey and many other countries to develop their national independent satellite-based wide area augmentation systems.

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