Off-Board Positioning Using an Efficient GNSS SNAP Processing Algorithm

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BIOGRAPHIES

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ABSTRACT

A method is described for off-board positioning using an efficient algorithm for processing GNSS snapshots. Snapshot data (SNAP) is generated using a digital baseband snapshot receiver. The described method is advantageous for emerging applications such as geotagging, data logging and tracking, and results in lower power consumption, better time-to-first-fix (TTFF) and higher accuracy than traditional real-time navigation receivers.

The described method separates data capture, which must be performed in real-time, from processing, which may be performed in a distributed manner. Distributed processing is conducted using an efficient GNSS signal processing algorithm. This reduces processing time for the off-board solution while enabling high sensitivity measurements.

The method also enables dynamic selection between an off-board GNSS solution and an on-board GNSS solution. This is achieved by utilizing a host-based solution architecture that enables a host-selectable mode of operation. Operating mode may either be automatically selected by the system to fit operating conditions, or may be manually selected by the user.

There are various applications in which there is an advantage to using the off-board method or a hybrid on/off-board solution. The main advantages of the off-board method are lower power consumption required on the capture device and very short TTFF. The applications that may benefit the most from using the off-board method are those that do not require real-time position output such as tracking devices and multimedia geotagging applications.

A prototype system, in which the off-board positioning method is utilized, has been built and verified. Initial testing of the system demonstrates accurate and consistent positioning results in various environments and conditions.

INTRODUCTION

Traditionally, satellite navigation receivers operate in real-time, and provide positioning, velocity and timing information on-board the platform on which the receiver is installed. This implementation is suitable for many applications, such as turn-by-turn navigation, real-time tracking and automated machine control. These traditional receivers are inherently limited by the minimal time required to obtain the first-fix after being turned off for more than a few hours. This limitation is due to the fact the receiver is required to download the satellite navigation message and obtain ephemeris information after being turned off for a few hours. Typical time-to-first-fix with these receivers under open-sky conditions is usually 30 seconds or more.

Developments in cellular communication networks and receiver technology resulted in the implementation of assisted GPS (AGPS) receivers. These receivers offer improved performance over legacy receivers as they are designed to use assistance data that is transmitted over a wireless link. Assistance data includes reference time, reference position and satellite navigation models. AGPS receivers offer shorter time-to-first-fix and higher sensitivity over their counterpart non-AGPS receivers. The typical time-to-first-fix with these receivers under open-sky conditions is usually a few seconds.

However, there are numerous applications in which fast acquisition time is essential, but real-time output is not required. Examples of such applications are geotagging of digital images, location reporting for social networking and animal tracking. Devices implementing these applications usually impose additional requirements such as low weight, low power and low solution cost. The off-board positioning approach provides a superior solution for these applications over traditional GPS or AGPS receivers.

The off-board positioning solution separates GNSS data capture performed on a mobile device from GNSS processing and positioning which is performed off-board the mobile device on a processing platform. The processing platform may be, for example, a personal computer or a network resource. A positioning solution based on the off-board approach requires significantly fewer resources from the mobile device compared to traditional GPS or AGPS receivers. The off-board positioning solution requires less power and offers significantly lower acquisition times when compared to traditional solutions. Furthermore, the off-board positioning solution does not require the mobile device to have any kind of network connectivity, reducing the cost and complexity of the target platform.

Short acquisition times and lower power requirements enable applications that were not possible with traditional receivers. One example is a digital camera geotagging application. Digital camera users often turn on their camera for short periods of time - sometimes only a few seconds - before turning it off and returning the device to their pocket or pouch. Traditional receivers are unable to successfully obtain a position in such a short time, and are not useful or efficient in such scenarios. A camera using an off-board positioning system requires an acquisition time of less than one second to capture GNSS data and enable off-board positioning. GNSS data may be captured at the same time or after a picture image is taken, while the camera is still hand-held by the user and has a good view of the sky.

A second example of an application in which the off-board solution is advantageous is animal tracking. In this application, platform weight is a highly limiting factor. A widely acceptable figure is that equipment used for animal tracking should not weigh more than 10% of the weight of the animal itself. This is especially limiting for tracking smaller animals that weigh less than 100 grams. It should be noted that smaller animals are of particular interest to scientists, due to the difficulty in conducting tracking experiments with them. Maximum logging times are also of great importance in this application. Logging time is mostly dependant on the capacity of the battery on the mobile device. Higher battery capacity requires heavier batteries, resulting in a trade-off between maximum logging time and equipment weight. Using the off-board positioning approach, it is possible to reduce the required battery capacity due to lower power requirements. Significantly reduced power requirements enable the use of lighter receivers that can log position data for longer with a given platform weight.

ON-BOARD GNSS OPERATION

GNSS navigation receivers typically perform on-board processing of received satellite transmission data. On-board processing usually comprises signal detection, tracking, data-bit detection and measurement generation. Measured data includes pseudo-range, Doppler frequency and phase measurements. The majority of navigation receivers for consumer applications additionally conduct real-time processing of measurement data and output position information in real-time.

On-board, real-time processing is suitable for many applications such as navigation, telematics and location-based services. However, there are numerous applications in which real-time data output is not required or critical. Such applications include tracking devices, data logging and geotagging (adding location data to digital images and multimedia files). For such applications, it is usually a disadvantage to use conventional consumer navigation receivers with real-time position output. The time-to-first-fix (TTFF) of conventional GNSS receivers is typically more than 30 seconds in warm-start conditions. This is due to the fact that the receiver needs to download the satellite navigation message in order to obtain satellite ephemeris and clock data.

The common denominator for tracking, data logging and geotagging applications is that position data is usually required for short, specified instances and not continuously. Furthermore, position data is not required to be available in real-time on the receiving platform, as data is usually transferred to a personal computer or server at the end of the capturing process. Data is usually required to be available either at timed intervals or at non-regular intervals specified at the time of capture. Another requirement is very short TTFF, since in many use cases the capturing device is turned on for periods of only a few seconds. Timed intervals are usually used for data logging or tracking applications. Non-regular intervals specified by the user or platform at the time of data capture are usually applicable for geotagging applications (capture is triggered when a digital image is saved) or for tracking and data logging applications (capture is triggered by a movement or light sensor).

THE OFF-BOARD GNSS APPROACH

An improved approach is proposed for the applications highlighted above. This approach is based on an off-board SNAP positioning concept. The basic concept in off-board SNAP positioning is conducting a short (as brief as a few tens of milliseconds) data capture on the required platform, saving the captured data to a file (SNAP file) and processing the data at a later time on a network connected device. The processing device may be the capturing device, or another device such as a personal computer. This method reduces the TTFF, since the navigation message data is obtained through a network resource during off-board processing. SNAP data is only saved upon user or platform trigger, therefore a minimal amount of data is acquired and receiver power consumption is kept at the absolute minimum.

GNSS SNAP PROCESSING

The efficient SNAP processing method is a hybrid of coherent and non-coherent 2D processing. Processing of GNSS SNAPs is performed on-board or off-board a mobile device. Efficient processing yields faster results and consumes less power on the processing device. Therefore, the method has advantages for both on-board and off-board scenarios. Additionally, the 2D processing method offers good noise/jamming immunity. These factors are advantageous for urban scenarios and co-existence with other transmitting radios on the same platform.

Please note that the specific sample rates, frequencies and bandwidths discussed in this section are applicable for the GPS L1 C/A signal. The general method, however, applies in a straightforward manner to all CDMA GNSS signals, and with slight modifications also to the GLONASS L1 FDMA signal.

Processing comprises of 7 steps, for hybrid coherent and non-coherent processing. The processing algorithm flow is shown in Fig. 1.

Step 1: SNAP Data Collection

Digital IF data is received by the digital baseband, which converts the received signal to baseband, conducting decimation and filtering. The sample rate of baseband data in the SNAP is 1024 kHz represented with 1 or 2-bit complex (I/Q) samples.

Step 2: SNAP 2D Matrix Representation

SNAP data is arranged in a 2D matrix, where each column contains 1024 complex samples. Each column represents an epoch of 1 msec of the received GPS signal. The number of columns depends on the length of the SNAP which may vary from a minimum of a few msec to several seconds long. The number of columns is therefore equal to the length of the SNAP in msec, and is hereafter defined as N_{SNAP}.

The following processing steps are performed on groups of N_{Col} columns. Each group of N_{Col} columns is coherently processed using the described 2D coherent processing (Steps 3-5). Following coherent processing, the groups are further integrated non-coherently (Step 6). Since coherent processing is not necessarily bit-synchronized, some processing loss will occur. In order to minimize processing loss, the value of N_{Col} should be smaller than the length of the processed GNSS transmission data bits: $N_{Col} < N_{DataBit}$

Step 3: Doppler Processing

Doppler processing is conducted on each row in the matrix, in groups of N_{Col} columns. Remember that each row represents a sampled signal at 1 kHz rate. This signal is not affected by the CDMA PRN (Gold) code, since it was sampled at the same period as the PRN code.

The signal in row r_k is represented as follows:

$$A \cdot Gold(r) \cdot \exp\{j \cdot [\omega(rT + n \cdot 1mSec) + \phi_r]\}$$

Where n is the column index in the range $[1..N_{Col}]$.

For simplicity, let us assume that ω, the Doppler frequency, falls exactly on a frequency grid of 1/N kHz:

$$\frac{\omega}{2\pi} = k \cdot 1kHz + \frac{C}{N} \cdot 1kHz$$
$$C \in [1..N_{Col}]$$

Performing a discrete Fourier transform (DFT) of the time-domain samples row elements (N elements) will transform the row into the frequency domain. In the frequency domain, the signal will be concentrated in column C only.

The column value where the signal resides is, of course, the same for all 1024 rows. The signal in each row has the following value:

$$A \cdot Gold(r) \cdot e^{j\phi_r} = A \cdot Gold(r) \cdot e^{j\omega rT}$$
$$\phi_r = \omega rT = (\omega T)r$$
$$\frac{\omega}{2\pi} = Doppler\ \ frequency$$

A = Signal amplitude
r = Row number [1..1024]
T = Sampling rate

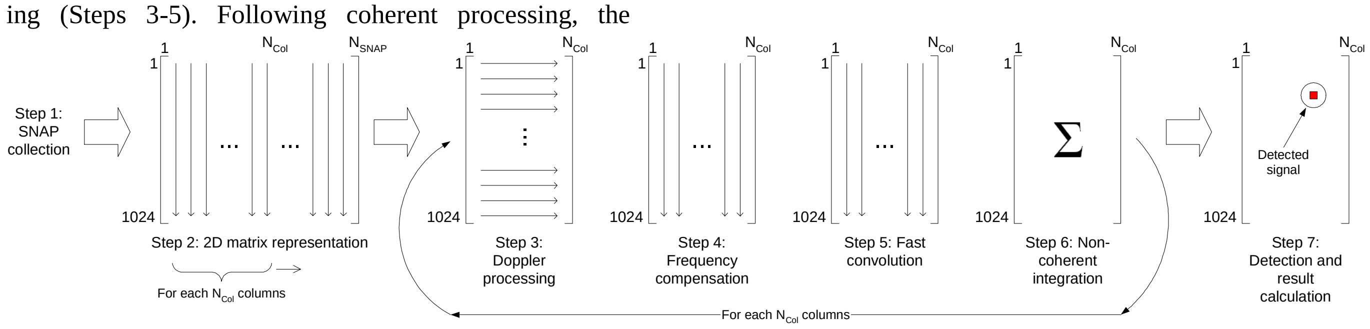

Fig. 1. SNAP Processing Algorithm

The phase element (ϕ_r) is a result of the fact that the first sample point for each row is time shifted, by T, relative to the preceding row (first sample of row 1 is taken at start SNAP time).

Step 4: Frequency Compensation

This step is required in order to remove the ϕ_r element per column. Each column in the 2D matrix now represents a different frequency, so frequency compensation is conducted for each column by the appropriate Doppler frequency corresponding to that column.

The frequency compensation term is as follows:

$$e^{-j2\pi rT\left(k\cdot 1kHz+\frac{C}{N_{Col}}\cdot 1kHz\right)}$$

C = Column number
r = Row number (1..1024)
k = integer of coarse frequency

The resulting column signal after compensation is:

$$A\cdot Gold(r)$$

r = 1..1024

At the end of this stage, one of the columns will contain a gold code modulated signal, down converted to zero frequency.

Step 5: Fast Convolution

For each column, a fast convolution is performed in 3 steps:

1. FFT of column element (1k complex FFT).
2. Multiplying by FFT* of required SV gold code (1k complex multiplications).
3. Performing IFFT on the result of (2) (1k complex FFT).

Step 6: Additional Non-Coherent Integration

Following processing of all N_{Col} columns in accordance with steps 3-5, non-coherent integration is performed on the results. The absolute values of resulting 2D coherently processed matrices in incoherently integrated by:

1. Calculating absolute values of all elements of the 2D matrix.
2. Summarizing the absolute values with results from the previous steps element-by-element.

Step 7: Detection and Result Calculation

The following steps are conducted on the matrix resulting from stage 6:

1. Setting a detection threshold.
2. Threshold crossing detection.
3. Exact delay and Doppler calculation by interpolating adjacent rows and columns.
4. Using above pseudo-ranges and pseudo-range rates to calculate the mobile location and velocity.

HYBRID ON/OFF-BOARD

There are applications that may benefit from a hybrid on/off-board approach. Such applications may, for example, require real-time feedback only at user-specified intervals. Additionally, in such applications, it may not be feasible to generate real-time output using an on-board solution due to operational conditions.

For example, a receiver that has been started in warm-start conditions will not be able to produce real-time output before it downloads satellite ephemeris data. This yields an average initial TTFF of at least 30 seconds in open-sky conditions or as long as a few minutes in dense urban areas.

Another example is an application, such as a digital camera, in which the user would like to synchronize the system clock using a GNSS receiver, but would later prefer to switch to off-board positioning mode in order to save power. This may be achieved using a hybrid on/off-board approach.

A hybrid on/off-board GNSS receiver system is presented in Fig. 2. The hybrid receiver is capable of performing on-board or off-board operation in a firmware selectable manner. The firmware may be configured to automatically switch between off and on-board operation according to the operational conditions. Alternatively, the user may manually select the mode of operation when working with different applications.

An additional benefit of the hybrid system is that is it fully capable of running all GNSS processing algorithms on the mobile platform, even when working in off-board mode. Using this capability, the system is able to provide a predicted success indicator when operating in off-board mode. Success indication is important feedback for the user. It indicates the likelihood that the off-board processing will later be able to extract a position from the recorded GNSS SNAP data. Success prediction is performed using the satellite detection algorithm presented earlier in this section. It is conducted aboard the mobile device, and returns positive feedback to the user where the number of detected satellites satisfies a predefined threshold.

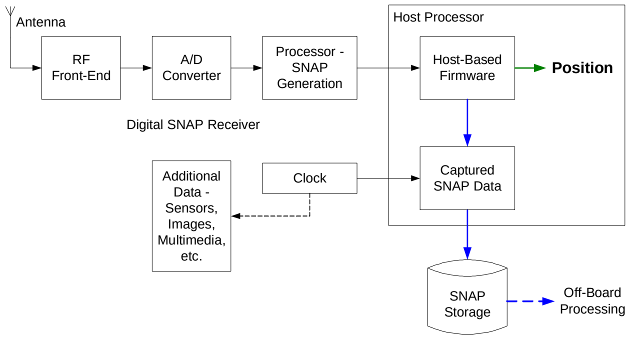

Fig. 2. Hybrid On/Off-Board GNSS Mobile Device

PROTOTYPE SYSTEM

A prototype system that uses the off-board positioning method has been developed and implemented. The main building blocks of the prototype system are shown in Fig. 3. The prototype system comprises a mobile unit that captures SNAP data and an off-board processing unit that runs on a PC.

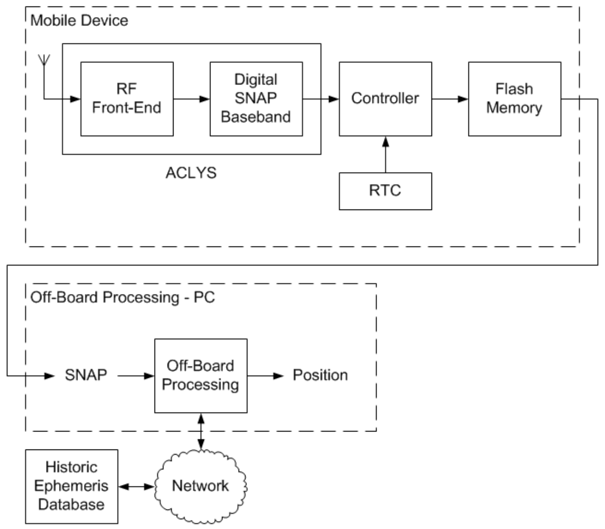

Fig. 3. Off-Board Positioning Prototype System

The mobile device is used to capture GPS SNAP data and store it to the flash memory. Data capture may be triggered either manually or automatically based on a timer mechanism. The prototype platform uses the CellGuide ACLYS GPS chip to generate SNAP data. ACLYS is a single die RF and baseband GPS solution that generates SNAP data when controlled from a host. The prototype system uses a Samsung S3C2443 controller. A firmware component running on the controller configures the ACLYS chip to capture SNAP data, and saves resulting SNAP data to the flash memory.

The off-board processing system is based on a PC that is connected to an historic ephemeris database using a network connection such as an internet connection. The off-board processing software processes SNAP files from the mobile capture device. For each processed file, the off-board software queries the historic ephemeris database and retrieves ephemeris data that was present at the time of capture. The SNAP is processed using the presented algorithm. The output of the off-board processing method is the position, velocity and time of capture of the mobile platform at the time of SNAP capture.

EXPERIMENTAL RESULTS

The performance of the prototype system has been evaluated under several operational scenarios. For each of the tested scenarios, we conducted numerous experiments using the off-board system and analyzed the accuracy of positioning. Results were evaluated with reference to a Javad TR-G3 receiver.

It is important to note that position data results were obtained independently for each of the SNAPs that were processed. No additional filtering or processing was applied between consecutive SNAPs. The resulting positioning accuracy therefore reflects the system performance for spontaneous, irregular SNAPs. There are applications in which this system would be used for positioning at regular intervals, such as in tracking and data logging applications. For these applications, additional processing such as Kalman filtering may be applied to improve the positioning result.

The first scenario used for evaluation is an open-sky condition. The experiment was conducted in an open parking lot near Rehovot, Israel. The goal of this scenario is to analyze actual system performance in an unobstructed environment. This reflects the system performance for outdoor areas and is useful for a variety of outdoor tracking applications. Results for the open-sky scenario are presented in Fig. 4.

The second scenario used for evaluation is an urban condition. The experiment was conducted in an urban area containing 3-4 story buildings in Rehovot, Israel. The goal of this scenario was to evaluate system performance in a more challenging environment that represents a common urban use case. Results for the urban scenario are presented in Fig. 5.

A summary of the experimental results is presented in Table 1.

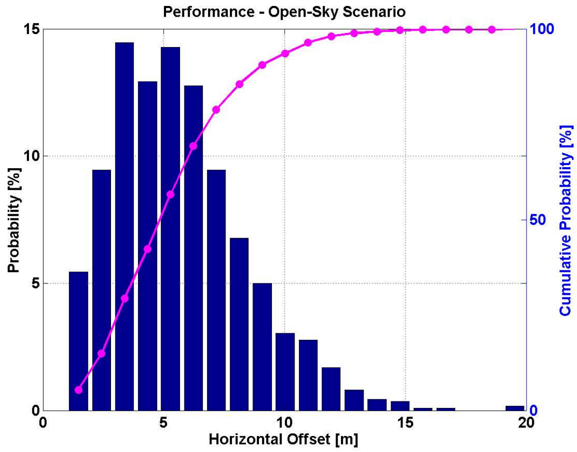

Fig. 4. Experimental Results for Open-Sky Scenario

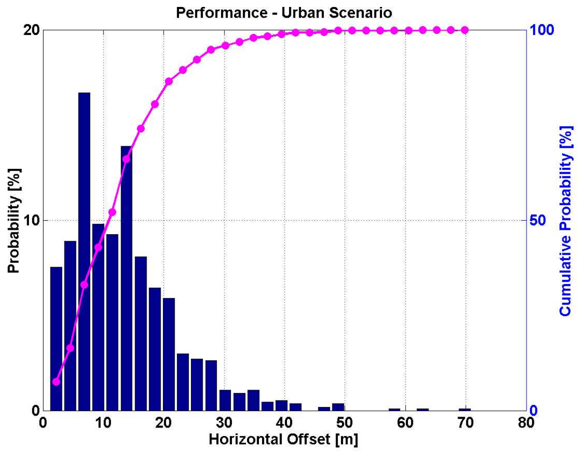

Fig. 5. Experimental Results for Urban Scenario

Table 1. Experimental Results Summary

Scenario	2-D Accuracy (CEP95) [m]	Success Rate [%]
Open-sky	11	100
Urban	30	100

CONCLUSION

An efficient GNSS SNAP processing algorithm for off-board GNSS positioning has been presented and analyzed. A prototype system has been built and experimental results are presented.

The off-board processing approach has numerous advantages for systems that do not require real-time positioning data. The main advantages of the off-board approach are the shorter acquisition time and lower power requirements when compared to conventional approaches.

A hybrid on/off-board approach has also been discussed and demonstrated. The hybrid approach enables additional advantages such as user or system selectable real-time feedback. The hybrid approach also enables further processing and improved on-board results using off-board processing of SNAP data.

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