Real-time GPS and Glonass Integrity Monitoring and Reference Station Software

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Summary

At the Delft University of Technology (DUT) a software suite has been developed for Continuously Operating GPS/GLONASS Reference Stations. The most important features of this software suite are a real-time GPS receiver interface, real-time integrity monitoring and communication with a computing centre. The sample rate of the receiver and the transmission rate to the computing centre can be selected independently, and the data is sent in discrete batches of several minutes up to 24 hours, or continuously. The data is stored on the local computer disk with the receiver's sample rate. The real-time quality control and integrity monitoring is based on a single channel approach. It uses a Kalman filter based Detection, Identification and Adaptation (DIA) procedure.

Presently, the AOA Turbo Rogue, Javad Positioning System, Trimble 4000SSI(E) and Trimble 4700 receivers are supported. The software includes also an interface for meteorological sensors. The software has been used since 1997 for the Dutch Permanent GPS Network and since 1999 for DUT's IGEX GPS/GLONASS reference station.

1. GPS/Glonass reference station software

Already in 1993, during the definition phase of the Active GPS Reference System for The Netherlands (AGRS.NL), it was recognised that real-time applications of permanent GPS arrays would become increasingly important in the near future. Therefore, the reference station software for the AGRS.NL was developed with near real-time applications in mind.

Each reference station of the AGRS.NL is equipped with a geodetic quality dual-frequency GPS receiver, meteorological sensors, a PC with multiport serial controller, modems, telephone connections, uninterruptable power supply and remote power on/off switch. The software running at the reference station, developed by DUT, performs the following tasks:

- Control receiver (e.g., set observation interval, minimum elevation, data format) and collect GPS data.
- Real-time integrity monitoring (or data validation) of dual-frequency GPS code and carrier data.
- Control meteorological sensors (set interval) and collect temperature, pressure and relative humidity data.
- Log events (time the receiver started or stopped tracking a satellite, time a new navigation message was collected, time the integrity monitoring's was initialized, time an outlier or cycle slip was found).
- Temporarily store GPS data, quality control parameters and meteorological data on the reference station's local hard drive in a dedicated binary format. The data will be automatically removed after a user-defined period.
- Transmit data, again in binary format, to the central processing facility. Before transmission, data may be decimated to a user-defined interval. Data transmission can be done continuously or in batches. When a connection is established, the reference station and central facility negotiate about the first block of data to be transmitted. This will guarantee a complete data transfer. If no connection can be established or if data transmission is interrupted, the software will try to (re-)establish the connection.
- Generate alarms, e.g., when the receiver did not track any satellites for a certain interval.

Recently, the software was adapted to also incorporate the validation of Glonass observations. Currently interfaces are available for the TurboRogue family of receivers, Trimble SSE/Ssi, Trimble 4700 and JPS Legacy receivers. The JPS Legacy is a GPS/Glonass receiver. Data can also be processed off-line for these receivers. In addition, an interface was developed for the off-line processing of Rinex data.

For the central facility, software was developed to receive the reference station data, store it and make it available to users in Rinex format for further processing. The following tasks are performed:

- Collect GPS and meteorological data from all reference stations and store this data. If no data is received within a pre-set timeout period an alarm is generated (SMS or pager).

- Collect and store precise orbits and other data of interest from IGS,
- Process the data, i.e., compute a network solution to monitor the stability of the reference stations and compute atmospheric parameters, such as integrated water vapour.
- Distribute data to AGRS users through a WWW based service, (van der Marel, 1998).

Data distributed to users may consist of the actual reference station data or data generated for a virtual reference station close to a user's survey location. The virtual reference station's data is generated using the real data from the actual reference stations, (ibid.).

For the efficient transfer and storage of GPS and related data, the receiver independent compressed binary (CBI) format has been developed. The current version of the CBI format contains records for station, receiver and antenna data; dual-frequency GPS code and carrier observations; GPS navigation messages; meteorological data; events. The CBI format has been optimised with respect to size for efficient transfer and storage. To this end, the data is packed in a unique binary format. CBI files are typically about four times smaller than corresponding Rinex files. The efficiency of the format is illustrated by the fact that well-known compression tools, like PKZIP, results in a file size reduction of only 20%, and unzipped CBI files are smaller than zipped Rinex files. Unlike compressed Rinex, (Hatanaka, 1996), the CBI format is a "stand-alone" format. This means that the contents of a record do not depend on the availability of other records to reconstruct for example the original observations. All required information is contained in a single record. The downside if this is that, the CBI files are typically about two times larger than the usual Unix/Hatanaka compressed files.

2. Integrity monitoring of GPS/Glonass observations

The integrity monitoring functions were developed based on the philosophy that they should be applicable irrespective of the application(s) for which the data may originally have been collected. They should therefore not require any external information, like satellite and receiver positions, velocities and clock behaviour or information on atmospheric effects. This can be accomplished by using the geometry-free observation model, (Euler & Goad, 1991; Jonkman, 1998), as a basis for the measurement and dynamic models. In this model, observations are not parameterised in terms of the unknown station coordinates. Instead, the observations remain parameterised in terms of the original, unknown (pseudo-) ranges, ionospheric delay and phase ambiguities. Data is processed on a single-channel basis. This means that data from each satellite is processed independently. There is consequently no minimum number of satellites required for the integrity monitoring to work. Although originally developed for GPS data, (de Jong, 1996), the approach has proven to work for Glonass data as well, (de Jong & Jonkman 1999).

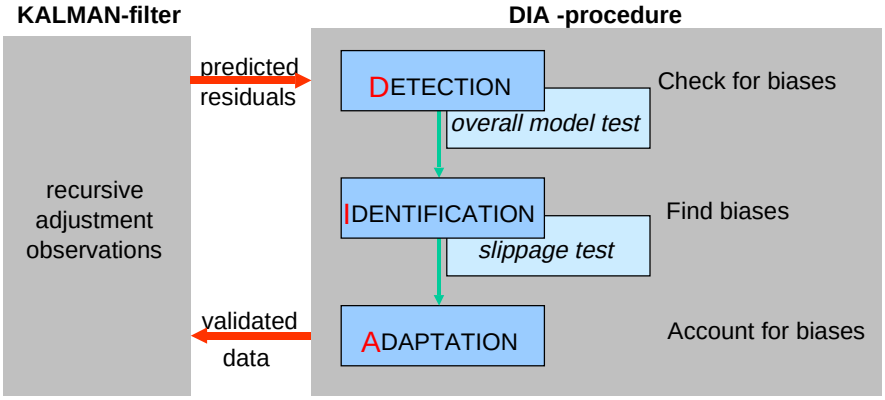

Figure 1: Kalman filter and DIA procedure.

The integrity monitoring (or validation) of code and carrier observations is based on the recursive Detection, Identification and Adaptation (DIA-) procedure, (Teunissen, 1990), running in parallel to a Kalman filter, (Kalman, 1960), see Figure 1. Up to five basic observables may be available from the GPS (and Glonass) satellites: two carrier observations (L1, L2) and three code observations (P1, P2, C/A). Using the geometry free model, each of the observations can be parameterised in terms of the unknown (pseudo-) range (distance and clock), ionospheric delay

and an offset (phase ambiguity or instrument bias). The distance and clock terms are eliminated, simply by subtracting one observation from the other ones. As a result, the only parameters that remain to be modelled in the Kalman filter are the biased (by carrier ambiguities and/or hardware delays) ionospheric effects and the offset between P1 and C/A code. Each of these parameters corresponds to one particular observation. Thus, if one or more observations are missing, the corresponding observations and parameters are simply omitted from the measurement model. For the ionospheric effect it is assumed that it can be modelled by a first order polynomial. The parameter describing the ionospheric rate of change is common to all observations in the measurement model. The corresponding dynamic or transition model for the ionospheric effect and its first order time derivative is assumed to consist of a zero-mean white noise process, characterised by its spectral density.

Although it is possible to include in the Kalman filter a dynamic model for the distance between receiver and satellite, this will only work well if the observation interval is small and if the receiver clock behaviour can be described by a low-order polynomial. Since both conditions are often not met, this is not done. In addition to the above-mentioned parameters, it is also possible to include a dynamic model to describe biases in the code observations, (Jin, 1996; de Jong, 1996). These biases are mainly due to multipath, see also (de Jong, 1999).

The recursive Detection, Identification and Adaptation (DIA-) procedure, running in parallel to the Kalman filter, aims to detect possible misspecifications in the observation model of the Kalman filter by means of statistical hypothesis testing. The procedure consists of the following steps

Detection: An overall model test is carried out to diagnose whether unspecified model errors have occurred. If the overall model test statistic exceeds a critical value, which is based on the distribution of the overall model test statistic under the null-hypothesis, the null-hypothesis is rejected.

Identification: If a model error is detected in the previous step, testing the original or nominal observation model against models extended with bias parameters (alternative hypothesis) identifies its potential source. The hypothesis corresponding to the largest test statistic is said to describe the most likely misspecification of the observation model. However, the test statistic also has to exceed a critical value, which is based on the distribution of this statistic under the null hypothesis. If this is not the case, and the overall model test has been rejected, a misspecification other than the ones described by the alternative hypotheses is likely.

Adaptation: After the identification of the most likely source for the model error, the observation model is adapted to eliminate the biases in the filters' state vector.

The test statistics associated with the DIA-procedure are based on the filter's predicted residuals or innovations sequence, and its corresponding covariance matrix. Under the null-hypothesis, the expectation of the predicted residual is zero. The size of the model error that can be detected in the Identification step with a probability γ, the so-called power of the test, is referred to as the Minimal Detectable Bias (MDB).

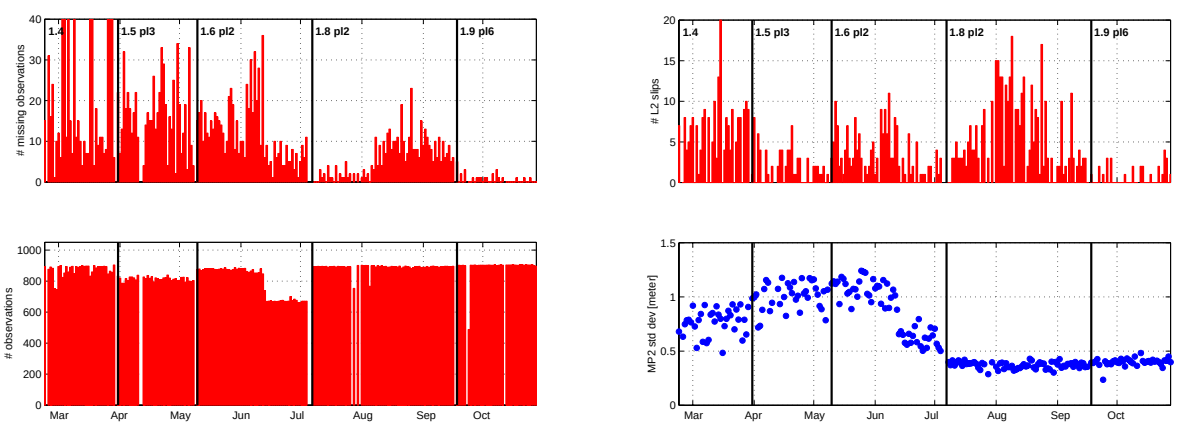

Figure 2: Statistics for PRN 06 for the IGEX station in Delft, from May 1999 until October 1999: missing observations (top left), number of observations (bottom left), number of L2 slips (top right) and mean noise on the L2 code (bottom right). Receiver firmware versions and upgrades are indicated in the figures.

3. Post-processing of Integrity Monitoring results

Post-processing of the output of the integrity monitoring software may yield valuable information on the performance of a GPS/Glonass reference station. In figure 2 the number of observations, missing observations, number of detected slips and the mean noise on the L2 code for PRN 6 is given, for an eight month period in 1999, for the IGEX station in Delft. The effect of various firmware upgrades and versions is clearly visible. In figure 3 the precision of the code observations is evaluated. Again the effect of different firmware versions is visible.

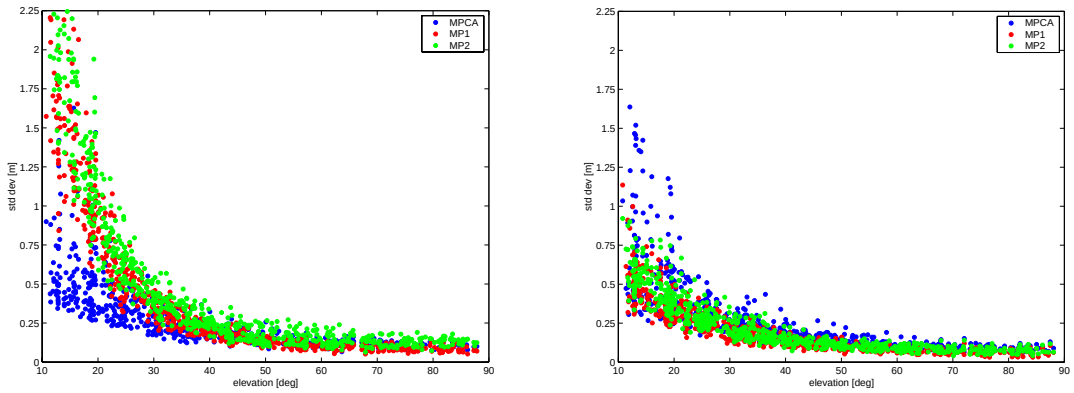

Figure 3: Precision of the code observations as function of elevation, for the IGEX station in Delft, using data from May 20 1999 with firmware version 1.6 (left) and September 27 1999 with firmware version 1.9 (right).

The integrity monitoring software is also an objective means to evaluate the susceptibility of a site's environment to multipath. It may therefore serve as a useful tool when selecting a point to become a reference station.

4. Conclusions

A description was given of the integrity monitoring functions, developed for the reference stations of the Dutch permanent GPS array AGRS.NL. The integrity monitoring is based on the recursive Kalman filter and the DIA (Detection, Identification and Adaptation) procedure, which is also recursive and parallels the Kalman filter. As a result, the developed procedures are well suited for real-time implementation. Moreover, the integrity monitoring functions do not require any external information and are therefore independent of the application for which the data may have been collected.

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