

Algorithm Description for LEO Precision Orbit Determination with Bernese v5.0 at CDAAC

Overview

The COSMIC Data Analysis and Archival Center (CDAAC) at UCAR has processed radio occultation data from the GPS/MET, CHAMP, and SAC-C missions in post-processing and a near real time mode of operation for CHAMP. The GPS data processing at the CDAAC is performed with the Bernese v5.0 software package. The COSMIC mission requirement for LEO velocity uncertainty is 0.1 mm/s 3D rms. The recent upgrade of the Bernese software from version 4.3 to version 5.0 has improved the CDAAC CHAMP orbit quality from ~0.5 mm/sec 3D rms to approximately the 0.1 mm/sec level in post-processing, respectively. Bernese v5.0 is consistent with IERS 2000 conventions. In this document, the algorithms used for post-processed and near real-time precise orbit determination (POD) of LEO satellites at the CDAAC are described.

Data Inputs and Outputs

The data inputs and outputs for the CDAAC precision orbit determination system are listed below:

Inputs:

- IGS Final GPS orbits and Earth Orientation parameters
- IGU Ultra Rapid GPS orbits and Earth Orientation parameters (6 hr updates currently used for near real time mode of operation)
- IGS Weekly station solutions in SINEX format IGS Ground based 30-sec GPS measurements
- LEO satellite 10-sec GPS L1 and L2 pseudorange and carrier phase measurements
- LEO satellite attitude quaternion data if available
- IGS Sinex configuration file containing station, receiver, antenna, and antenna height information
- Bernese GPS satellite status file (SAT_YYYY.CRX)

Outputs:

- Zenith Troposphere Delay (ZTD) Estimates for ground stations
- Station position estimates for non-IGS Weekly stations
- High-Rate 30-sec GPS satellite clock estimates
- LEO satellite Earth-Centered-Earth-Fixed (ECEF) positions/velocities of center of mass of satellite in SP3 format
- LEO satellite inertial (J2000) positions/velocities of center of mass of satellite in Bernese STD format
- GPS satellite inertial (J2000) positions/velocities of center of mass of satellite in Bernese STD format

Post-Processing LEO POD

The CDAAC post-processing LEO POD strategy is performed on one-month batches of tracking data from the GPS ground network and from the LEO missions of interest. The LEO POD algorithm uses a reduced-dynamic approach with zero-difference ionosphere-free carrier phase observations. The zero-difference approach allows for a convenient separation of the ground-based and space-based processing, but does require the estimation of high-rate (synchronous with LEO epochs) GPS satellite clock offsets. Thus, the ground-based processing is responsible for estimating: the non-IGS (not provided in the IGS weekly solutions) station coordinates as monthly averages, all station zenith tropospheric delays, and all high-rate GPS satellite clocks for each day throughout the month. Once the ground-based processing is completed, the space-based LEO POD processing is executed with the zero-difference reduced-dynamic strategy for each day of the month. The IGS final GPS orbits and Earth orientation parameters (EOPs) as well as available weekly solution station estimates are held fixed in all processing. Details of the ground and space-based processing algorithms are discussed below.

Ground-based GPS Processing

The primary data inputs to the ground-based GPS data processing are 30-sec IGS ground station data, IGS final orbits and EOPs, and weekly IGS station coordinate estimates. The ground network used by CDAAC consists of all available IGS low latency sites and some additional higher-latency sites that provide good global distribution for high-rate GPS clock estimation. The ground-based processing is executed by invoking the following CDAAC perl scripts: mkBernFiles5.pl, gpsOrb5.pl, fidTrop5.pl, estCoord.pl, mkBernFiles5.pl, estTrop.pl, and comClk5.pl. Functional descriptions of these perl scripts and the relevant Bernese programs are described below.

mkBernFiles5.pl: Bernese file configuration

This script is executed to setup configuration of required Bernese files (SAT_YYYY.CRX, GPS satellite problem file; MISSION.STA, station information file; MISSION.CRD, station coordinate file). The first call of this script provides a MISSION.CRD file with reasonably accurate a priori coordinates. The second call of this script provides a MISSION.CRD file with precise coordinates that include the IGS weekly estimates when available and CDAAC station estimates (from estCoord.pl) not provided by the IGS.

gpsOrb5.pl: Fitting of IGS Final Orbits to Bernese Orbit Model

The first step of the GPS processing is to fit the Bernese orbit model to the IGS final orbit positions. Also included in this step is a fitting of the IGS final clock offsets to polynomial functions. The following Bernese programs are used in this processing step.

- PRETAB: This program is used to rotate the ECEF SP3 ephemerides to the inertial mean equator and equinox of 2000 (J2000) system. It is also configured to perform a fit to the GPS SP3 clock values with a quadratic polynomial every 12 hours.
- ORBGEN: This program performs a least squares fit to J2000 coordinates in the PRETAB output file. The orbit model state used consists of 6 osculating elements and 9 additional radiation pressure acceleration terms (bias and 1 cycle-per-orbit-revolution in 3

orthogonal directions defined by the s/c-to-sun and solar panel axis vectors). The typical level of fit is at the 1 cm rms level.

fidTrop5.pl: Generation of Normal Equation files

The station coordinate and ZTD estimates are solved for using an efficient stacking of double-difference normal equation systems (NEQs). This script generates a normal equation file for 1 hour of ground tracking data. It is run in parallel for every hour throughout the month. The GPS satellite orbits and EOPs are held fixed throughout the processing. A processing flow diagram for this script is given in Figure 1. Functional descriptions of the Bernese programs shown in Figure 1 are described below. Note: when a Bernese program is followed by an underscore and text string, the text string identifies the Bernese panel option (OPT) directory where the program input file resides (e.g. the program input panel for GPSEST_C1, GPSEST.INP, resides in the C1 OPT directory).

- BXOBV3: The BXOBV3 program converts a binary binex formatted measurements to the Bernese binary observation file format. All raw measurements are passed through to the Bernese file irrespective of signal-to-noise ratio or presence of cycle slip flags.
- CODSP: This program computes the receiver clock offsets for all the receivers in the ground network. The clock offsets are computed with accuracy of < 1 microsecond and are written into the Bernese phase observation files. A minimum elevation angle of 10 degrees is used.
- SNGDIF: This program forms single difference observables that are subsequently formed into double difference observables in program GPSEST. The strategy used to form baselines is called 'SHORTEST' as described in Hugentobler (2001). The SHORTEST strategy was chosen instead of strategy OBS-MAX in an effort to minimize baseline length and to create the same set of baselines from hour to hour.
- MAURP: This program performs cycle slip detection and correction for all single-difference observation files that were included into the optimal baseline set by program SNGDIF. Linear combinations of L1 and L2 measurements are used to determine clean cycle-slip free sections of data. If a data section cannot be defined as clean, an attempt is made to correct it for cycle slips according to the algorithm described in Hugentobler (2001). If the cycle slip cannot be corrected, then new L1 and L2 ambiguities are defined in the observation files.
- GPSEST_C1: This first initiation of GPSEST is run to produce an ambiguity-free L3 solution. This solution is run in a network mode (correlation strategy is CORRECT) with elevation dependent weighting ($1/\cos(z)$) of observations. The primary purpose of this run is to check the quality of the data and save residual files that will be checked and marked (in the Bernese obs. file) by the programs RESRMS and SATMRK. A 30-sec sampling rate is used so all residuals can be tested. The weighted rms of the residuals of the solution is typically near the 1.0 mm level.
- RESRMS: This program checks the residuals written to file for outliers. The L3 outlier detection level is set to 5 mm. The output EDT file describes the data pieces that are requested to be edited.
- SATMRK: This program reads the requested edit EDT file and marks the observations as bad in the Bernese observation files.

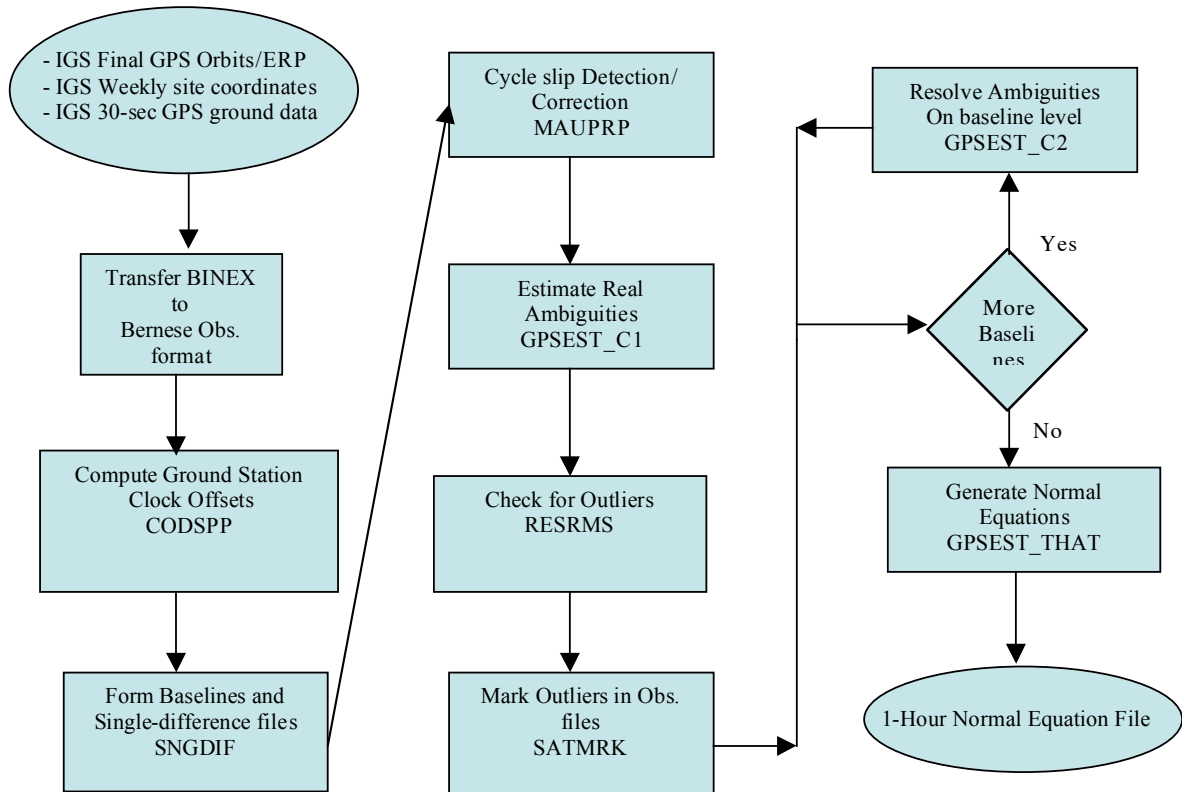


Figure 1: Generation of 1-hour double differenced Normal Equation files for ground-based processing with script fidTrop5.pl.

- GPSEST_C2: This initiation of GPSEST is used to resolve L1 and L2 ambiguities with the Quasi-Ionosphere-Free (QIF) strategy baseline by baseline as shown in the baseline loop in Figure 1. The ambiguities are resolved one baseline at a time to minimize cpu and memory usage. Troposphere estimates from the previous ambiguity-free L3 solution are introduced as known. No a priori ionosphere model is used to improve the ambiguity resolution with the QIF strategy. Resolved ambiguities are written to the single difference Bernese observation files.

- GPSEST_THAT: The final run of GPSEST is a full network ionosphere-free solution. All stations and ZTD parameters are estimated. Resolved ambiguities are held fixed in the process, and unresolved ambiguities (treated as real parameters) are pre-eliminated. The data are decimated to 120 second sampling rate and elevation dependent weighting of observations is used. The troposphere mapping function used is WET_NIELL. The normal equation matrices containing station coordinate and ZTD parameters are saved in NEQ files to be stacked (added) later.

estCoord.pl: Estimation of Non-IGS Station Coordinates

The non-IGS station coordinates are estimated as constant values over the duration of the month that is being processed. This is performed by stacking all of the 1-hr NEQ systems for the entire month. For computational efficiency, the ZTD parameters are pre-eliminated from each 1-hr NEQ system before stacking with the other 1-hr NEQ

systems. The geodetic datum of the estimated coordinates is realized by tightly constraining the IGS weekly coordinates to their monthly mean values.

- ADDNEQ2: The ADDNEQ2 program is used to pre-eliminate the ZTD parameters, stack the modified NEQ systems, and invert the NEQ systems to provide the non-IGS station coordinate estimates.

estTrop.pl: Estimation of ZTD parameters

This script is used to estimate hourly ZTD parameters for all stations in the network over the duration of the month that is being processed. This is performed by first pre-eliminating the station coordinates from the 1-hr NEQ systems for the entire month. After pre-elimination, the 1-hr NEQ systems are stacked together and then inverted to provide ZTD estimates for the entire month interval.

- ADDNEQ2: The ADDNEQ2 program is used to replace the a priori station coordinate values with the monthly average station coordinates, then pre-eliminate the station coordinate values, and finally invert the NEQ systems to provide the hourly ZTD estimates. Relative (hour to hour) constraints are not applied in this procedure.

comClk5.pl: Estimation of High-Rate GPS Satellite Clock Offsets

This script is used to estimate high-rate (30-sec) GPS satellite clock offsets for one day. A mission dependent parameter file (comClk5.parms1) is used to specify processing changes that are required for different missions. The data inputs include: 30-sec ground network data, precise ground station coordinates, IGS orbits and EOPs in Bernese format, and hourly ZTD parameters for all stations in the network. The output is a Bernese format GPS satellite clock file that includes the 30-sec GPS clock estimates. A ground station elevation cutoff of 10 degrees is used.

- BXOBV3: The BXOBV3 program converts binary binex formatted measurements to Bernese binary observation file format. All raw measurements are passed through to the Bernese file irrespective of signal-to-noise ratio or presence of cycle slip flags.

- CLKEST: The CLKEST program is used to generate ground station and GPS satellite clock corrections as described in [Bock et al, 2000]. In that algorithm, the ground network pseudorange and carrier phase observation equations for a given receiver i and satellite j and epoch l are modeled as

$$p_{il}^j = \rho_{il}^j - c \cdot \Delta t_l^j + c \cdot \Delta t_{il} + \Delta \rho_{il,ion}^j + \Delta \rho_{il,trop}^j + \varepsilon_p \quad \text{and}$$

$$\phi_{il}^j = \rho_{il}^j - c \cdot \Delta t_l^j + c \cdot \Delta t_{il} + \Delta \rho_{il,ion}^j + \Delta \rho_{il,trop}^j + \lambda \cdot N_i^j + \varepsilon_\phi$$

where p_{il}^j and ϕ_{il}^j are the pseudorange and carrier phase observations, ρ_{il}^j are the geometric ranges, $c \cdot \Delta t_l^j$ is the clock offset for satellite j , $c \cdot \Delta t_{il}$ is the receiver i clock offset, $\Delta \rho_{il,ion}^j$ are the ionospheric delays, $\Delta \rho_{il,trop}^j$ are the tropospheric delays, $\lambda \cdot N_i^j$ are the initial carrier phase ambiguities, and ε are noise terms. If ionosphere-free

pseudorange observations are considered, and previously solved for GPS orbits, station coordinates, and ZTDs are used to subtract known terms, then the modified pseudoranges, LC_{il}^j , are only dependent on the clock terms as shown below

$$LC_{il}^j = -c \cdot \Delta t_i^j + c \cdot \Delta t_{il} + \varepsilon_p$$

If a ground receiver clock offset is held fixed as a reference, then epoch by epoch solutions of the satellite and receiver clocks can be estimated. Moreover, if we consider time differences of ionosphere-free phase observations to eliminate the ambiguity terms, then a similar approach can be used to estimate precise clock differences from epoch to epoch. These epoch by epoch GPS satellite clock offsets and clock offset differences can be combined into a symmetric tri-diagonal NEQ system to solve for combined clocks. An alternate approach that is used in CDAAC processing is to discard the pseudorange observations and use only the precise phase-derived clock offset differences. The reference clock is then transformed from the ground reference to a linear fit to the sum of all available IGS final GPS clock offsets. This procedure provides very precise satellite-to-satellite clock offsets with low multipath and noise characteristics due to multi station visibility. The reference clock is accurate enough in absolute time to compute LEO clock offsets and thus GPS satellite positions with sufficient accuracy in future zero-difference LEO POD processing.

Space-based LEO POD Processing

The new version of Bernese (v5.0) includes enhanced LEO POD capability using GPS data. It has been applied using zero-difference and double-difference (with and without ambiguity resolution) observations with dynamic, kinematic, and reduced-dynamic filtering strategies to determine CHAMP orbits at less than the 10 cm (0.1 mm/sec velocity) 3D rms level [Svehla and Rothacher, 2002]. Each processing strategy has certain advantages and disadvantages with regard to orbit errors and computational performance and simplicity. The zero-difference approach requires estimation of zero-difference ambiguities and epoch-wise clocks for the LEO and the availability of high-rate (synchronous with LEO epochs) GPS satellite clock offsets. Fortunately, the pre-elimination of LEO clocks and ambiguities from the NEQ system allows for efficient zero-difference processing. LEO-to-ground double difference processing has the highest orbit accuracy potential due to the possibility of resolving ambiguities, but this approach is complicated and computationally expensive due to the large number of observations and ambiguities. With regard to filtering strategies, dynamic methods are better suited for precise velocity estimation than kinematic approaches, because they reduce epoch to epoch noise and aren't as susceptible to data outages. Kinematic positioning is not sensitive to dynamic mismodeling, but the reduced-dynamic procedure allows for the estimation of pseudo-stochastic velocity pulses at user-defined epochs and is analogous to frequent estimation of non-conservative force parameters such as drag and solar radiation pressure [Svehla and Rothacher, 2002]. Due to the above reasons, CDAAC currently uses ionospheric-free observations in a zero-difference reduced-dynamic filtering approach for LEO POD.

leoOrb5.pl: Perform LEO POD

The perl script leoOrb5.pl is used to perform LEO POD zero-difference processing. A mission dependent parameter file (leoOrb5.parms1) is used to specify processing changes that are required for different missions. For post-processing, the LEO POD is performed over 24 hour arcs for each day. If for a given day there exists less than 24 hours of data, the data arc is chosen to be a multiple of 9 minutes. This is required for the Bernese software to operate properly. A diagram illustrating the data inputs and outputs and processing flow is shown in Figure 2. This processing can be divided into three main tasks: 1) computation of an a priori orbit 2) data pre-processing and cleaning and 3) orbit improvement or estimation. An a priori orbit is obtained by fitting the specified dynamic force model to pseudorange kinematic precise point position estimates. The a priori orbit used for the orbit improvement procedure uses one 24-hour arc. However, for the data cleaning procedure, the a priori orbit may be broken into four 6-hour arcs (depending on mission) to improve the orbit accuracy. The dynamic model state used in this processing consists of:

- 6 osculating elements
- 9 radiation pressure acceleration terms (bias and 1 cycle-per-orbit-revolution in radial, transverse, and normal directions)
- pseudo-stochastic velocity pulses in radial, transverse, and normal directions every 12 minutes

Additional perturbing accelerations modeled in the equations of motion include: the EIGEN1S Earth gravity model is used out to degree/order 140 [Reigber et al., 2002], third body tidal accelerations due to the sun and moon, indirect tidal accelerations due to solid Earth and ocean tides, and general relativistic effects. Additional effects modeled in the measurement model processing include: GPS and LEO phase center offsets, LEO attitude, and special and general relativistic effects.

Functional descriptions of the Bernese programs shown in Figure 2 are described below.

- BXOBV3: The program converts binary binex formatted measurements to Bernese binary observation file format. All raw measurements are passed through to the Bernese file irrespective of signal-to-noise ratio or presence of cycle slip flags.
- CODSPV_THAT: This initiation of program CODSPV computes kinematic precise point positions and epoch clocks of the LEO satellite with ionosphere-free pseudorange observations. The data inputs include the 30-sec LEO pseudorange measurements, LEO attitude quaternion data if available, GPS orbits and EOPs, and the previously computed high-rate 30-sec GPS clock offsets. A mission dependent minimum elevation angle is used (0 degrees for CHAMP). An output file is generated with the estimated kinematic point positions.
- KINPRE_THAT: The KINPRE program takes as input the kinematic point positions from the previous step and reformats them into the SP3 format.
- ORBGEN_PREORB: This program performs a least squares fit to the LEO kinematic point positions in SP3 format. The resulting Bernese standard orbit file is used for LEO clock estimation and cycle slip detection and correction. The dynamic orbit model state

used is specified above, without the pseudo-stochastic velocity pulses. For the CHAMP and SAC-C missions, 4 6-hour arcs are used to improve the orbit modeling.

- CODSP: This program computes the receiver clock offsets for the LEO receiver. Inputs include the high-rate 30-sec GPS clocks, GPS STD orbit file, LEO STD orbit file, LEO attitude file, and EOPs. The clock offsets are estimated with ionosphere-free pseudorange observations and written into the Bernese phase observation files. A minimum elevation angle of 0 degrees is used for CHAMP.

- MAUPRP: This program performs cycle slip detection and correction for the zero-difference LEO ionosphere-free observations. The inputs are LEO L1 and L2 measurements, 30-sec GPS clocks, GPS STD orbit file, LEO STD orbit file, LEO attitude file, and EOPs. If a data section cannot be defined as clean, an attempt is made to correct it for cycle slips according to the algorithm described in Hugentobler (2001). If the cycle slip cannot be corrected, then new L3 ambiguities are defined in the observation files.

- ORBGEN: This program performs a least squares fit to the LEO kinematic point positions. The output consists of a STD orbit file and a radiation pressure file (RPR). The RPR file contains the variational equations (containing the partial derivatives of the equations of motion with respect to the dynamic state parameters) and is used next by GPSEST. Independent of mission, this execution of ORBGEN uses only 1 arc for the 24-hour period, which is a requirement of reduced-dynamic tracking in GPSEST.

- GPSEST: This initiation of GPSEST performs the LEO orbit improvement procedure with respect to the a priori orbit. Inputs include cycle slip corrected LEO L3 carrier phase measurements, 30-sec GPS clocks, GPS STD orbit file, a priori LEO STD and RPR orbit files, LEO attitude file, and EOPs. Estimated parameters include corrections to the 6 osculating elements and 9 radiation pressure acceleration terms, and the pseudo-stochastic velocity pulses every 12 minutes. The a priori sigmas for the stochastic velocity pulses are $2E-5$, $1E-5$, and $1E-5$ m/s in the radial, transverse, and normal directions, respectively. The ionosphere-free L3 ambiguities pre-eliminated from the NEQ system before inversion, and the LEO clocks are pre-eliminated epoch by epoch. The output element (ELE) file contains the dynamic state including the estimated stochastic velocity pulses.

- ORBGEN_THAT: This execution of ORBGEN is used to generate an updated standard STD orbit file with the estimated initial condition and stochastic velocity pulse information in the ELE file.

- STDPRE: This program creates a precise LEO SP3 orbit file from the updated STD orbit file. The output SP3 orbit file contains the LEO ECEF position and velocity at a 1 minute interval.

At the end of the leoOrb5.pl process, the number of observations successfully processed by GPSEST is checked. If the number of observations processed is less than 1000, the script ends in failure. If the number of observations processed is > 1000 , the GPSEST solution statistics are written to the 'mission_leoOrb5' database, the STD and SP3 files are copied to the /pub directory structure, and the script ends in success. In the post-processed mode of operation, the GPSEST solution statistics should be checked for reasonableness. For CHAMP, typical ranges for GPSEST solution statistics for successful processing are: number of observations (10,000 – 17,000), weighted rms (0.0025 – 0.0035 m). External orbit overlap comparisons with JPL Quick orbits should also be

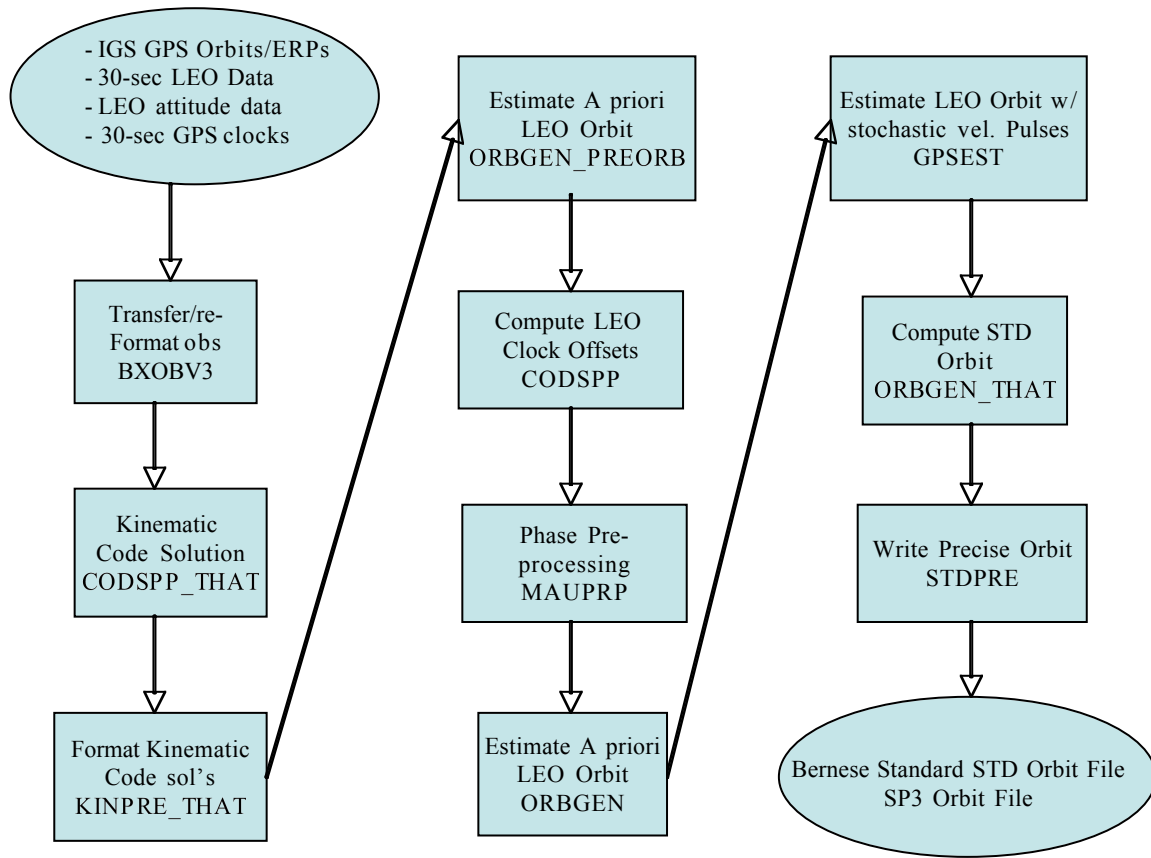


Figure 2: Processing Flow for LEO POD Processing executed by leoOrb5.pl

analyzed. For successful LEO POD, typical 3D rms external overlap results for position are ~14 cm.

Near Real-Time LEO POD

The near real-time LEO POD mode of operation is very similar to the post-processing approach in function, but it must process the ground data and LEO dump data as quickly as possible as they arrive at the CDAAC. In this mode, the ground-based processing is responsible for estimating all station zenith tropospheric delays and all high-rate GPS satellite clocks throughout the LEO dump interval. Ground network station coordinates are not estimated in the near real time mode. Station coordinates are provided from the previous month of post-processing. Predicted IGU (IGS Ultrarapid) orbits and EOPs with a 6-hr update rate are held fixed throughout the processing. Details of the ground and space-based processing algorithms that are different from post-processing mode of operation are discussed below. The largest difference for near real time processing is that the estimation of high-rate GPS clock offsets is performed in script leoOrb5rt.pl, and not in comClk5.pl as is done in post-processing. The high-rate GPS clocks are estimated throughout the entire LEO POD data arc.

Ground-based GPS Processing

The primary external data inputs to the ground-based GPS data processing are 30-sec IGS ground station data, and the IGS GPS orbits and EOPs. The ground-based processing is executed by invoking the following CDAAC perl scripts mkBernFiles5.pl, gpsOrb5.pl, fidTrop5.pl, and estTropRT.pl. Currently, the fidTrop5.pl script is executed when an adequate number of ground sites are available for the last 15 minutes of each UT hour.

estTropRT.pl: Estimation of ZTD parameters

This script is used to estimate hourly ZTD parameters for all stations in the network for the previous 12 hours. This is performed by first pre-eliminating the station coordinates from the 1-hr NEQ systems for the entire month. After pre-elimination, the 1-hr NEQ systems are stacked together and then inverted to provide ZTD estimates for the previous 12 hours.

Space-based LEO POD Processing

leoOrb5rt.pl: Perform LEO POD

The perl script leoOrb5rt.pl is used to perform LEO POD zero-difference processing in near real-time. A mission dependent parameter file (leoOrb5rt.parms1) is used to specify processing changes that are required for different missions. For near real time operation, the LEO POD is performed over arc lengths of at least 6 hours and not more than ~12 hours. The data arc length is chosen to be a multiple of 9 minutes for the Bernese software to operate properly. The estimation of high-rate GPS clock offsets is performed in this script throughout the entire LEO POD data arc.

- STDDIF: This program computes an internal orbit overlap comparison between the current and previous LEO STD dump files.

At the end of the leoOrb5rt.pl process, the rms difference of the internal overlap comparison with the previous dump is used to determine the success of the process. If the rms difference between two orbits is greater than 5 meters, the script ends in failure. If the rms difference is less than 5 meters or not defined (i.e. no previous dump), then the STD and SP3 files are copied to the /pub directory, and the script ends in success. For the current CHAMP near real-time processing, the internal orbit overlap comparisons are typically less than 10 cm.

References

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