

PBO Level 2 Product Generation

1. Introduction

The generation of the GPS level 2 products is carried out in two stages. In stage 1, the analysis centers (ACs) at Central Washington University (CWU) and Berkeley Seismological Laboratory (BSL) process GPS phase and pseudorange data to generate estimates of the coordinates of the stations averaged over the 24-hour duration of the data in the daily processing. The models used in this processing are given for each of the ACs in Tables 1 and 2. In these analyses, the GPS satellites orbits are fixed either to the orbits generated by the Jet Propulsion Laboratory (JPL) (CWU analysis) or the International GPS service (BSL). The CWU analysis also uses the JPL clock products. In stage 2 of the analysis, performed by the Analysis Center Coordinator (ACC), the results from the ACs are aligned to the PBO realization of the Stable North America Reference Frame (SNARF). In this frame, motions of sites on stable North America are due solely to glacial isostatic adjustment (GIA). The AC results are also combined and the combined analysis (denoted pbo) aligned to this same frame. The standard PBO position and velocity results are the combined, frame-realized product. The product AC and ID are pbo and either final_frame or rapid_frame depending on the age of the data. (Final products are not available until 6 to 13 days after data collection; rapid results are available with 1-day latency). Products are made available in SINEX format and a plain text files.

2. Analysis Characteristics

The station coordinates estimated by the ACs are not referred to any particular reference frame: They can be rotated and translated (to some extent) to align them with a reference frame chosen for PBO products. The station coordinates in the BSL products are loosely constrained and the loose SINEX files have large standard deviations for the coordinates (approximately 0.5 meters). The covariance matrix for the BSL has rotational uncertainty and because of the relative small aperture of the network relatively large translational uncertainty (~50 mm). The CWU loose sinex files are determined by point positioning in which clocks and satellite orbits are assumed perfectly known, however the reference frame for the orbits is not well determined. The standard deviation of the coordinates in the CWU "loose" sinex files are very small and reflect the uncertainty in a well defined reference frame. In the analysis of the CWU sinex files, a 1-meter translation and 0.3-meter rotational uncertainty covariance matrix is added to the CWU sinex file to covariance to allow the coordinates to rotate and translate into different reference frames.

The basic models used by both PBO ACs are consistent with IGS analysis standards with one major exception. BSL is using the adopted IGS values for the positions of the phase center of the transmission antenna on the satellite relative to the center of mass of the satellite. CWU is using the values adopted by JPL that differ from the IGS ones by 63 cm in the Z-component (radial) for Block IIR GPS satellites. This difference in the models introduces scale differences between the BSL and CWU solutions of about 2.5 parts-per-billion that needs to be accounted for when the BSL and CWU results combined. In the PBO product generation, scale is explicitly

included in the estimated parameters, with different scale estimates for the BSL and CWU analyses.

In PBO analyses, rotations, translations and scales are estimated and the final values of these parameters set to best align the PBO daily and long-term results with the PBO realization of the SNARF reference frame. For PBO daily analyses, SNARF is realized by aligning with the positions of 130 stations in North America (127), Eastern Russia (1) and central Pacific (2). The distant stations serve to maintain the orientation of the daily reference frame realizations. The list of sites used in the daily realization is given in Table 3. Their locations are shown in Figure 1. The position and velocities of these sites are taken from `pbo.final_frame.vel`.

The PBO reference frame itself is determined from a Kalman filter combination of all final sinex files from BSL and CWU for the period between Jan 1, 2004 (GPS week 1251, day 4) and August 27, 2005 (GPS week 1337 day 6) in which the position and velocities of all sites were estimated. The velocity and positions of the 13 IGB00 reference sites listed in Table 4 were used to align the frame with the SNARF reference frame. These locations are also shown in Figure 1.

In all the frame alignments, only rotations, translations and scale are estimated and therefore the internal geometry and evolution of the station positions is retained in the transformations. The current reference frame definitions will be retained until the next large re-analysis that is expected early 2006 when the IGS adopted new absolute antenna phase center models for both ground and space antennas.

3. AC SINEX file weighting

The BSL and CWU ACs use different models for the phase noise in the GPS processing and different decimation factors. These differences are accounted for multiplying the covariance matrices from the two center's SINEX by factors that make the chi-squared per degree of freedom fits to the PBO reference frame near unity (on a daily basis) for the two centers. The estimated factors derived by averaging results from the first 18 months of data analysis are 0.7 for BSL and 4.8 for CWU. When the results from the two centers are combined, these factors are doubled so that the standard deviations of the position estimates from the combined analysis are similar to those from the individual centers.

4. Product Time Tables

The PBO rapid analyses are performed with 1-day latency. The generation of these products takes place when the IGS rapid orbits become available. Generally, the analysis is completed near 0 hrs UT for the previous day of data (i.e., the products are ready 18 hrs EST). The final products are generated weekly when the IGS final orbit for the week becomes available. Usually, these orbits are ready by Friday each week for the GPS two weeks before. The latency of the products varies between 14 to 20 days depending on which day of the week the GPS data were collected.

In the event on an earthquake in the PBO area of sufficient size to displace stations by more than 1 mm, a "position-offset" product for the effected sites will be generated using the last full day of

data before the earthquake and first full day of data after the earthquake. There will be no position estimates for the effected sites on the day of the earthquake. The position-offset products will be generated from the rapid solution with a maximum 48-hour latency. Offsets will only be available for sites operating the day before and the day after the earthquake.

Table 1: Central Washington University Processing Strategy

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                          PLATE BOUNDARY OBSERVATORY
                          CWU Processing Specifications
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Analysis Center | Central Washington University Geodesy Lab
                | Dept. of Geological Sciences
                | Central Washington University
                | 400 University Way
                | Ellensburg, WA 98926
                | Phone:  ++ 1 509 963 2799
                | Fax:    ++ 1 509 963 1109
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Contact Person(s) | Tim Melbourne      e-mail: tim@geology.cwu.edu
                  |                   phone : ++ 1 509 963 2799
                  | Marcelo Santillan e-mail: marcelo@geology.cwu.edu
                  |                   phone : ++ 1 509 963 1108
                  | Craig Scrivner    e-mail: scrivner@geology.cwu.edu
                  |                   phone : ++ 1 509 963 1446
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Software Used     | Gipsy/Oasis R4 V2, developed at Jet Propulsion Laboratory
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Preparation Date  | September 30, 2005
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Modification Dates | None
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Effective Date for | September 30, 2005
Data Analysis
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                          MEASUREMENT MODELS
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Observable | RAPID: non-differenced estimates of ionosphere-free
            | combinations of L1 and L2 carrier phase (point-
            | positioning, see Zumberge, (1997)).
            |
            | FINAL: Double-differenced, ionosphere-free combination
            | L1, L2 carrier phases. Pseudorange are used only
            | to obtain receiver clock offsets and in ambiguity
            | resolution.
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Data weighting | Sigma on doubly difference LC phase: Site and elevation
            | dependent based on iterated analysis.
            | Cleaning at 30-second rate.
            | Sampling rate: 5 minutes
            | Elevation angle cutoff : 15 degrees
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Data Editing | Cycles slips detected and fixed.
            | Unresolved cycle slips estimated in solution.
            | Iterative editing using sequential slip deletion while
            | slips exceed RMS
-----
RHC phase rotation corr. | Phase polarization effects applied (Wu et al, 1993)
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Ground antenna phase center calibration | Elevation-dependent phase center corrections are
            | applied according to the model IGS_01 and info.003.
            | These corrections
            | are given relative to the Dorne Margolin T antenna.
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Troposphere	A priori zenith delay: nominal constant; 2-hour piece-wise linear function estimated, 1 NS and EW gradient per day. ----- Met data input: none -----
	Mapping functions: (Niell, 1996) -----
Ionosphere	Not modeled (ionosphere eliminated by forming the ionosphere-free linear combination of L1 and L2). -----
Plate motions	ITRF2000 velocities -----
Tidal displacements	Solid earth tidal displacement: constant Love number tides frequency dependent radial tide (K1) ----- Pole tide: Applied to Mean IERS pole position ----- Ocean loading: Applied (Scherneck Model) -----
Atmospheric loading	Not applied -----
Earth orientation	IERS Bulletin B plus diurnal and semidiurnal variations in x,y, and UT1 models (EOP) R. Ray [1995], IERS Tech. Note 21 [1996] -----
Satellite center of mass correction	Sat. Phase centers hardwired into GIPSY R4. Values can be found at # \ satellites. Values used are: Block I x,y,z: 0.2100, 0.0000, 0.8540 m ----- Block II/IIA x,y,z: 0.2790, 0.0000, 0.09679 m ----- Block IIR x,y,z: 0.0580, -0.0680, -0.06300 m -----
Satellite phase center calibrat	Not applied -----
Relativity corrections	Relativistic corrections applied -----
GPS attitude model	Yaw computed using model of Bar-Sever (1996), using nominal rates or estimates supplied by JPL -----

ORBIT MODELS CWU USES STANDARD JPL RAPID AND FINAL SATELLITE ORBITS -----	
Geopotential	EGM96 degree and order 9 ----- GM = 398600.4415 km**3/sec**2 ----- AE = 6378.1363 km -----
Third-body	Sun and Moon as point masses ----- Ephemeris: CfA PEP NBODY 740 ----- GMsun = 132712440000 km**3/sec**2 -----

	GMmoon = 4902.7989 km**3/sec**2
Solar radiation pressure	A priori: nominal block-dependent constant direct acceleration; corrections to direct, y-axis, and B-axis constant and once-per-rev terms estimated
	Earth shadow model: umbra and penumbra
	Earth's albedo: applied
	Satellite attitude model not applied
Tidal forces	Solid earth tides: frequency independent Love number K2= 0.300
	Ocean tides: None
Relativity	Applied (IERS 1996, Chapter 11, Eqn.1)
Numerical Integration	Adams-Moulton fixed-step, 11-pt predictor-corrector with Nordsieck variable-step starting procedure (see Ash, 1972 and references therein)
	Integration step-size: 75 s; tabular interval: 900 s
	Arc length: 24 hours

ESTIMATED PARAMETERS (A PRIORI VALUES & SIGMAS)	
Adjustment	Square-root information filter with smoothing of terminal estimate backwards through time over all data
Station coordinates	16 networks of ~20 stations per network, dynamically updated daily as PBO expands. 2 common sites between networks. Weak constraints applied to site coordinates.
Satellite clocks bias	Standard JPL Satellite clocks error estimates are used
Receiver clock bias	Time estimated from pseudoranges.
Orbital parameters	Initial Position and Velocity (IC) plus 9 radiation-pressure terms: constant and sin/cos once-per-rev terms for a direct, y-axis, and b-axis acceleration. ICs estimated each day. Radiation parameters treated as random walk with process noise based on independent daily estimates. ICs fixed to IGS Final orbit values.
Troposphere	Piece-wise linear function in zenith delay estimated once per 2-hr for each station constrained by random walk process to 5e-8 km/sqrt(sec); one N-S and one E-W gradient parameter per day for each station
Ionospheric correction	Not estimated (first-order effect eliminated by linear combination of L1 and L2 phase)
Ambiguity	Resolution attempted for all baselines but resolving Melbourne-Webena Widelanets for L2-L1 using pseudo-

	ranges with differential code biases applied, and then L1 from geodetic solution using ionospheric free observable.
Earth Orient. Parameters (EOP)	Pole X/Y and their rates, and UT1 rate estimated once per day.
GPS attitude model	Not estimated

REFERENCE FRAMES	
Inertial	Geocentric; mean equator and equinox of 2000 Jan 1 at 12:00 (J2000.0)
Terrestrial	ITRF2000, No constrained sites coordinates.
Interconnection	Precession: IAU 1976
	Nutation: IAU 1980

REFERENCES:

- Ash, M. E., Determination of Earth satellite orbits, Tech. Note 1972-5, Lincoln Laboratory, MIT, 19 April 1972.
- Bar-Sever, Y. E., A new module for GPS yaw attitude, in Proc. IGS Workshop: Special Topics and New Directions, edit. G. Gendt and G. Dick, pp. 128-140, GeoForschungsZentrum, Potsdam, 1996.
- Dong, D., and Y. Bock, Global Positioning System network analysis with phase ambiguity resolution applied to crustal deformation studies in California, Journal of Geophysical Research, 94, 3949-3966, 1989.
- Dong, D., T. A. Herring, and R. W. King, Estimating Regional Deformation from a Combination of Space and Terrestrial Geodetic Data, J. Geodesy, 72, 200-214, 1998.
- Niell, A. E., Global mapping functions for the atmospheric delay, J. Geophys. Res., 101, 3227-3246, 1996.
- Ray, R.D., ftp://maia.usno.navy.mil/conventions/chapter8/ray.f (IERS Standards), 1995
- Schaffrin, B., and Y. Bock, A unified scheme for processing GPS phase observations, Bulletin Geodesique, 62, 142-160, 1988.
- Springer, T. A., G. Beutler, and M. Rothacher, A new solar radiation pressure model for the GPS satellites, IGS Analysis Center Workshop, Darmstadt, 9-11 February 1998.
- Wu, J. T., S. C. Wu, G. A. Hajj, W. I. Bertiger, S. M. Lichten, Effects of antenna orientation on GPS carrier phase. Manuscripta Geodaetica 18, 1993, 91-98, 1993.
- Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, and F.H. Webb, Precise point positioning for the efficient and robust analysis of GPS data from large networks, Journal of Geophysical Research, B, Solid Earth and Planets, 102 (3), 5005-5017, 1997.

Table 2: Berkeley Seismological Laboratory processing strategy

PLATE BOUNDARY OBSERVATORY BSL Processing Strategy Summary	
Analysis Center	Berkeley Seismological Laboratory (BSL) 215 McCone Hall University of California Berkeley, CA 94720-4760 Phone: ++ 1 510 642 3977 Fax: ++ 1 510 643 5811
Contact Person(s)	Mark Murray e-mail: mhmurray@seismo.berkeley.edu phone : ++ 1 510 642 2601 Douglas Neuhauser e-mail: doug@seismo.berkeley.edu phone : ++ 1 510 642 0931 Barbara Romanowicz e-mail: barbara@seismo.berkeley.edu phone : ++ 1 510 643 5690
Software Used	GAMIT v. 10.2, GLOBK v. 10.2, developed at MIT/SIO
Preparation Date	September 23, 2005
Modification Dates	New
Effective Date for Data Analysis	September 23, 2005

MEASUREMENT MODELS	
Observable	Doubly differenced, ionosphere-free combination of L1 and L2 carrier phases. Pseudorange are used only to obtain receiver clock offsets and in ambiguity resolution.
Data weighting	Sigma on doubly difference LC phase: Site and elevation dependent based on iterated analysis. Cleaning at 30-second rate. Sampling rate: 2 minutes Elevation angle cutoff : 10 degrees
Data Editing	Cycles slips detected and fixed. Unresolved cycle slips estimated in solution. Postfit editing using 4 times RMS deletion.
RHC phase rotation corr.	Phase polarization effects applied (Wu et al, 1993)
Ground antenna phase center calibrations	Elevation-dependent phase center corrections are applied according to the model IGS_01. The corrections are given relative to the Dorne Margolin T antenna.
Troposphere	A priori zenith delay: nominal constant; 2-hour piecewise linear function estimated, 1 NS and EW gradient per day. Met data input: none Mapping functions: (Niell, 1996)

Ionosphere	Not modeled (ionosphere eliminated by forming the ionosphere-free linear combination of L1 and L2).
Plate motions	ITRF2000 velocities
Tidal displacements	Solid earth tidal displacement: constant Love number tides frequency dependent radial tide (K1) Pole tide: Applied to Mean IERS pole position Ocean loading: Applied (Scherneck Model)
Atmospheric loading	Not applied
Earth orientation	IERS Bulletin A plus diurnal and semidiurnal variations in x,y, and UT1 models (EOP) R. Ray [1995], IERS Tech. Note 21 [1996]
Satellite center of mass correction	Block I x,y,z: 0.2100, 0.0000, 0.8540 m Block II/IIA x,y,z: 0.2790, 0.0000, 1.0230 m Block IIR x,y,z: 0.0000, 0.0000, 0.0000 m
Satellite phase center calibrat	Not applied
Relativity corrections	Relativistic corrections applied
GPS attitude model	Yaw computed using model of Bar-Sever (1996), using nominal rates or estimates supplied by JPL

ORBIT MODELS

Geopotential	EGM96 degree and order 9 GM = 398600.4415 km**3/sec**2 AE = 6378.1363 km
Third-body	Sun and Moon as point masses Ephemeris: CfA PEP NBODY 740 GMsun = 132712440000 km**3/sec**2 GMmoon = 4902.7989 km**3/sec**2
Solar radiation pressure	A priori: nominal block-dependent constant direct acceleration; corrections to direct, y-axis, and B-axis constant and once-per-rev terms estimated (Beutler et al., 1994; Springer et al. 1998) Earth shadow model: umbra and penumbra Earth's albedo: not applied Satellite attitude model not applied

Tidal forces	Solid earth tides: frequency independent Love number $K_2 = 0.300$ Ocean tides: None
Relativity	Applied (IERS 1996, Chapter 11, Eqn.1)
Numerical Integration	Adams-Moulton fixed-step, 11-pt predictor-corrector with Nordsieck variable-step starting procedure (see Ash, 1972 and references therein) Integration step-size: 75 s; tabular interval: 900 s Arc length: 24 hours

ESTIMATED PARAMETERS (A PRIORI VALUES & SIGMAS)	
Adjustment	Weighted least squares plus Kalman filter
Station coordinates	11 networks of ~38 stations per network. 2 common sites between networks. Weak constraints applied to site coordinates.
Satellite clocks bias	Initial values from linear fit to Broadcast ephemeris. Values estimated during data cleaning.
Receiver clock bias	Time estimated from pseudoranges.
Orbital parameters	Initial Position and Velocity (IC) plus 9 radiation-pressure terms: constant and sin/cos once-per-rev terms for a direct, y-axis, and b-axis acceleration. ICs estimated each day. Radiation parameters treated as random walk with process noise based on independent daily estimates. ICs fixed to IGS Final orbit values.
Troposphere	Piece-wise linear function in zenith delay estimated once per 2-hr for each station constrained by a random-walk process to $20\text{mm}/\sqrt{\text{hr}}$; one N-S and one E-W gradient parameter per day for each station, constrained to 10 mm at 10 deg elevation angle
Ionospheric correction	Not estimated (first-order effect eliminated by linear combination of L1 and L2 phase)
Ambiguity	Resolution attempted for all baselines but resolving Melbourne-Webena Widelines for L2-L1 using pseudoranges with differential code biases applied, and then L1 from geodetic solution using ionospheric free observable.
Earth Orient. Parameters (EOP)	Pole X/Y and their rates, and UT1 rate estimated once per day.
GPS attitude model	Not estimated

REFERENCE FRAMES	
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Inertial	Geocentric; mean equator and equinox of 2000 Jan 1 at 12:00 (J2000.0)
Terrestrial	ITRF2000, No constrained sites coordinates.
Interconnection	Precession: IAU 1976
	Nutation: IAU 1980

REFERENCES:

- Ash, M. E., Determination of Earth satellite orbits, Tech. Note 1972-5, Lincoln Laboratory, MIT, 19 April 1972.
- Bar-Sever, Y. E., A new module for GPS yaw attitude, in Proc. IGS Workshop: Special Topics and New Directions, edit. G. Gendt and G. Dick, pp. 128-140, GeoForschungsZentrum, Potsdam, 1996.
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- Schaffrin, B., and Y. Bock, A unified scheme for processing GPS phase observations, Bulletin Geodesique, 62, 142-160, 1988.
- Springer, T. A., G. Beutler, and M. Rothacher, A new solar radiation pressure model for the GPS satellites, IGS Analysis Center Workshop, Darmstadt, 9-11 February 1998.
- Wu, J. T., S. C. Wu, G. A. Hajj, W. I. Bertiger, S. M. Lichten, Effects of antenna orientation on GPS carrier phase. Manuscripta Geodaetica 18, 1993, 91-98, 1993.

Table 3: 4-character codes of the sites used in the PBO daily frame definition.

AGMT BAMO BBRY BEMT BEPK BILI BILL BKAP BKMS BLW2 BMHL BRMU BSRV
 BVPP CAST CAT1 CAT2 CCCC CDMT CEDA CHMS CIRX CNPP COPR CORV CRHS
 CRRS CRU1 CSCI CSST CTDM CTMS DRAO DUBO ECCO ECFE ECHO EDPD ELKO
 EWPP FERN FGST FLIN FMVT FOOT FRED GARL GLRS GMRC GNPS GOSH GTRG
 HCMN HEBE HNPS HVYS IID2 KELY KOD1 KTBW LAPC LDES LDSW LEWI LFRS
 LKCP LNMT LORS MAT2 MAUI MDO1 MIG1 MKEA MLFP MPWD MUSB NBPS NEWP
 NHRG NLIB NRC1 OPBL OPCL OPCP OPCX OPRD ORES ORMT P474 P562 P584
 PABH PBPP PHLB PPBF PVRS RAMT RDMT REDM RSTP RUBY SBCC SC00 SCIA
 SDHL SEAT SFDM SHIN SHLD SHOS SLMS SMEL SNI1 SOMT SPIC SPMS SRS1
 THCP THU3 TOIY TONO TUNG UPSA USGC VDCY VIMT VNCX WGPP WILL WOMT
 YELL

Table 4: 4-character codes of the IGb00 stations used to align the PBO reference frame the SNARF position and velocities.

ALGO BILI CHUR DRAO DUBO FLIN GODE GOLD KELY MDO1 MKEA NLIB NRC1
 PIE1 SCH2 STJO THU3 WES2 YELL

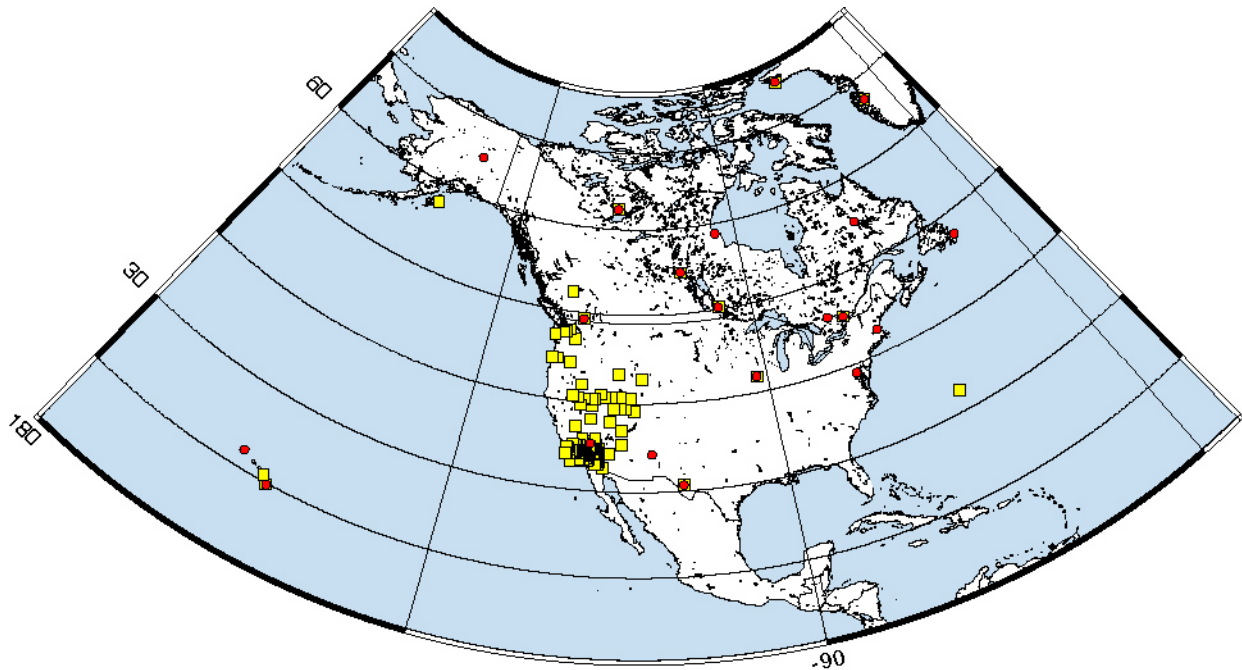


Figure 1: Locations of PBO Reference frame sites (yellow squares) and the IGb00 North America reference sites (red circles). Not shown on the plot is BILI (166.4 deg longitude, 68.1 deg latitude)