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GEODETIC POINT POSITIONING WITH GPS CARRIER BEAT PHASE DATA FROM THE CASA UNO EXPERIMENT

Stephen Malys and Major Peter A. Jensen

Defense Mapping Agency, USA

Abstract. The Global Positioning System (GPS) carrier beat phase data collected by the TI4100 GPS receiver has been successfully utilized by the US Defense Mapping Agency in an algorithm which is designed to estimate individual absolute geodetic point positions from data collected over a few hours. The algorithm uses differenced data from one station and two to four GPS satellites at a series of epochs separated by 30 second intervals. The 'precise' GPS ephemerides and satellite clock states, held fixed in the estimation process, are those estimated by the Naval Surface Warfare Center (NSWC). Broadcast ephemerides and clock states are also utilized for comparative purposes.

An outline of the data corrections applied , the mathematical model and the estimation algorithm are presented. Point positioning results and statistics are presented for a globally-distributed set of stations which contributed to the CASA UNO experiment. Statistical assessment of 114 GPS point positions at 11 CASA UNO stations indicates that the overall standard deviation of a point position component, estimated from a few hours of data, is 73 centimeters. Solution of the long line geodetic inverse problem using repeated point positions such as these can potentially offer a new tool for those studying geodynamics on a global scale.

Introduction

The Defense Mapping Agency (DMA) has been developing a geodetic point positioning algorithm which is designed to estimate individual geodetic point positions from data collected with a TI4100 geodetic GPS receiver. Descriptions of the pseudorange and carrier beat phase data which this receiver collects can be found in Goad [1985].

The DMA point positioning algorithm has been introduced in Malys and Ortiz [1989]. The preprocessing and position estimation software which mechanize this algorithm are known respectively as STARPREP and GASP. GASP is an acronym for Geodetic Absolute Sequential Positioning program.

As a participant in the CASA UNO experiment, DMA acquired a subset of the available CASA UNO TI4100 tracking data. The authors selected a subset which would aid in evaluating and enhancing the developing algorithm. In particular, a set of globally-distributed CASA UNO stations which contributed data over the longest series of days was selected. One of the primary goals of the DMA study reported here was to evaluate the agency's ability to estimate globally distributed, geodetic-quality point positions from the current (Block I) GPS constellation. Statistical analysis of positioning results over the series of independent data sets is used to evaluate the precision of any individual position estimate. A limited assessment of accuracy is also possible for some stations.

Since the introduction of this positioning algorithm in Malys and Ortiz [ibid.], a number of important enhancements have been made which contributed to significant improvements in the precision of position estimates. These improvements will be described in the sections which follow.

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Data Preprocessing

Before the TI4100 carrier beat phase data is used to estimate point positions, the 'raw' data is corrected for the effects of the ionosphere, troposphere, general relativity, Earth rotation and satellite antenna offsets. The satellite clocks are also corrected to GPS-time and data epochs of receipt are changed to epochs of transmission. With one exception, the formulation for the computation of these data corrections can be found in Malys and Ortiz [op cit.]. The ionospheric correction to the carrier beat phase data has been revised to account for the initial integer cycle ambiguities on the L_1 and L_2 channels for each satellite being tracked. After the receiver's frequency offsets are accounted for, the initial number of integer cycles is subtracted from all subsequent data values until a discontinuity in the ionospheric correction is detected. When a discontinuity is detected, it is attributed to a loss of lock (cycle slip) on one of the trackers and a new 'initial' integer is stored and subtracted from subsequent data values. Moreover, when a discontinuity is detected, the receiver frequency offset correction is applied such that the first data epoch after the discontinuity is used as a reference epoch until another discontinuity is detected. Since the GASP algorithm is tolerant of occasional losses of lock and data gaps, there is no attempt made at repairing cycle slips.

In addition to applying the above corrections, the preprocessor interpolates and stores the satellite ephemerides and clock states for the data span of interest. Either broadcast or precise ephemerides and clocks can be utilized. The broadcast satellite clock corrections are used only if the broadcast ephemerides are adopted.

The precise ephemerides (state vectors at 15 minute intervals) and clock state estimates (at 1 hour intervals) were estimated by NSWC for DMA. They are generated on a weekly basis from smoothed pseudorange data collected at ten globally distributed tracking sites. Five of these sites are operated by the US Air Force, and five by DMA in cooperation with agencies of other nations. The GPS orbit/clock determination algorithm (OMNIS), developed at NSWC through the sponsorship of DMA, has been described by Swift [1985, 1987]. Note that the routine production of these weekly precise ephemerides and clock states transitioned to the DMAHTC facility in August 1989. An assessment of the weekly precise GPS ephemerides and clock states has been presented by Gouldman et al. [1989]. The fixed, ten station tracking network has been analyzed by Malys [1988] and Swift [1989]. The STARPREP preprocessor uses an eight-point Lagrange interpolation method to obtain precise satellite position vectors and satellite clock offsets at the observation epochs (transmission epochs). All GPS-related algorithms in use at DMA and NSWC utilize the consistent set of geodetic models and constants defined by the World Geodetic System 1984 (WGS 84) [DMA,1987].

While the use of precise (post-fit) ephemerides and satellite clock estimates is preferred for geodetic applications, the authors purposely retained the ability to utilize the broadcast (predicted) information for possible adaptation of this positioning algorithm to use in the field, where post-fit ephemerides and clock states are not available. Moreover, the use of broadcast information facilitates a wide range of analyses regarding satellite performance and quality of the broadcast data.

Modeling and Estimation

The corrected carrier beat phase data is known to contain biases, integer cycle ambiguities and other undesirable characteristics which are dependent on factors such as initial acquisition epoch, cycle slips and receiver frequency standard fluctuations. Moreover, common errors may be inadvertently introduced through the application of less than perfect data corrections such as those associated with the atmosphere, and less than perfect estimates of the satellite ephemerides and clock states. In an attempt to remove these undesirable contributions, the GASP algorithm is designed around a differencing scheme which cancels common errors in the corrected data and adopted satellite ephemerides and clock states.

The first step in forming an observable is to difference two consecutive carrier beat phase observations (converted to kilometers) of the same satellite. For all data sets analyzed for this study, the interval between consecutive observations is 30 seconds. This between-epoch difference (a biased delta-range) is then differenced with a corresponding between-epoch difference from another satellite. One 'GASP observable' is formed from data collected at one station from two satellites at two consecutive epochs. Since the TI4100 receiver tracks up to four satellites simultaneously, a given pair of data epochs can yield up to three 'GASP observables'. A graphic representation of this differencing scheme is given in Malys and Ortiz [op cit.]. For each pair of data epochs utilized, one satellite is used as the reference from which the others are differenced. An important algorithmic improvement, implemented since the writing of Malys and Ortiz [op cit.], involves the selection of the reference satellite. Previously, the choice of this reference satellite did not change through a data span unless it (the lowest Pseudo Random Noise (PRN) number allowed through the preprocessor), became unavailable. For all the point positions estimated in this study, the choice of the reference satellite is sequential, such that for every new pair of epochs processed, the next higher available PRN number is used as the reference in the differencing scheme. The choice cycles back to the lowest available PRN number after the list of tracked satellites has been exhausted.

Before adopting this sequential reference satellite selection process, the authors tested the concept that the satellite with the most stable clock should be used as the reference throughout the data span. Comparison of statistics from repeated estimates however, indicated that the sequential approach offered many more benefits. One can rationalize these benefits in terms of reduced correlation among the observables. The implementation of this sequential reference satellite selection process improved day to day repeatability, the RMS of residuals (for most fits), and the variance-covariance and correlation matrices of the estimated parameters by up to 30%. In particular, the GASP-estimated longitudinal component reaped almost all of the benefits.

After forming an array of GASP observables, a least squares estimation technique is applied such that the vector of estimated parameters contains an 'alteration' to the a priori Earth-centered, Earth-fixed Cartesian station antenna position components. No other parameters are estimated. After three iterations of the non-linear model, the estimated parameters, their scaled variance-covariance matrix and the RMS of residuals are passed to a sequential estimation algorithm. This sequential technique (a Kalman filter) utilizes the RMS of residuals from the least squares fit as the variance of a GASP observable. In the sequential estimation technique, a parameter update is performed as each observable is processed. This allows plots to be generated which show the position component estimates as a function of the data set span. The level of convergence in the plots is one indication of the precision of the estimate. Analysis of residual plots and of a posteriori variance-covariance matrices are also helpful in evaluating an individual result. This two-fold estimation procedure provides a number of benefits which include realistic, automated weighting of the observables and enhanced quality control.

Other recent algorithmic improvements include the replacement of the sequential estimation module and redefining the level of process noise associated with the vector of estimated parameters. For the results reported in this study, a process noise of 1 cm^2 was assigned to each estimated position component.

Point Positioning Results

While the CASA UNO experiment focused on the Central and South American region, an extended (world-wide) fiducial network of tracking stations was necessary for improved orbit determination and orbit 'relaxation' by relative positioning algorithms. The globally distributed set of stations which contributed to the experiment provided an opportunity to evaluate the STARPREP and GASP software packages over a variety of geometries and tracking span scenarios. The stations which contributed data over a long series of days were especially valuable since a set of quasi-independent position estimates can be generated for such stations. The authors chose to label these estimates 'quasi- independent' because the daily tracking geometries are usually very similar at any given station. Table 1 contains a list of the CASA UNO stations which the authors selected for point positioning. The number of daily data sets used for each station is shown in the table. Note that there is no need for simultaneous observation from any two stations since each point position is estimated individually.

TABLE 1. Mean GASP-Estimated WGS 84 Point Positions

Station	Data Sets	Latitude			Longitude			Ellipsoid Height (m)
Albrook	16	8°	59'	16.311"	280°	26'	30.145"	71.69
Baltra	6	-0	27	38.410	269	44	27.910	61.70
Bucaraman.	9	7	7	0.863	286	49	5.613	1181.51
Cali	7	3	30	16.107	283	38	36.067	995.24
Cocos	15	5	32	51.311	272	57	17.206	143.48
Limon	12	9	57	52.530	276	58	23.833	13.55
Blackbirch	17	-41	44	42.813	173	48	20.104	1362.39
Canberra	18	-35	23	51.422	148	58	42.862	664.80
Kokee	8	22	7	34.518	200	20	6.315	1167.32
Onsala	3	57	23	43.071	11	55	31.891	47.71*
Wettzell	3	49	8	40.760	12	52	43.161	664.62*

*Ellipsoid height of antenna L_1 phase center, others are for monument.

Experience with the GASP algorithm has demonstrated that in most cases, a degradation of positioning precision occurs when a satellite crystal oscillator is allowed to contribute data. In this study, only one satellite (PRN 8) operated on a quartz crystal oscillator. The authors chose to use this satellite only at Bucaramanga for three of the nine days shown in Table 1. In these three cases, the satellite with a quartz oscillator completed a four-satellite tracking scenario.

The mean WGS 84 geodetic coordinates estimated for the selected set of CASA UNO stations are presented in Table 1. While these means were obtained from varying numbers of data sets and tracking geometries, the standard deviations shown in Table 2 indicate that the separate position estimates are all of comparable precision. Note that the standard

TABLE 2. Statistics From Repeated Point Position Estimates

Station	Data Sets	Standard Deviation of Daily Positions* X	Y	Z	φ	λ	h
		all units are meters					
Albrook	16	.72	.73	.55	.57	.77	.67
Baltra	6	1.63	.64	.52	.52	1.64	.64
Bucaramanga	9	.68	1.13	.82	.75	.78	1.12
Cali	7	.98	.94	.82	.78	1.04	.91
Cocos	15	1.02	.93	.48	.46	1.03	.93
Limon	12	.83	.89	.55	.51	.87	.89
Blackbirch	17	.95	.83	.72	.38	.80	1.15
Canberra	18	.67	.74	.57	.30	.61	.92
Kokee	8	.32	.98	.49	.40	.93	.52
Onsala	3	.08	.07	.35	.24	.09	.27
Wettzell	3	.81	.93	.74	.68	1.06	.72

* The standard deviation of the mean components given in Table 1 can be obtained by dividing the values given here by the square root of the number of data sets used.

TABLE 3. Accuracy Assessment of GASP Point Positions

Station	Independent Positioning Source*	GASP Result - Independent Result all units are meters Δφ	Δλ	Δh
Albrook	TRANSIT	.13	-.24	-1.77
Canberra	VLBI/SLR	.52	.58	1.68
Kokee	VLBI/SLR	-.43	1.03	-.09
Onsala	VLBI/SLR	.31	.90	.47
Wettzell	VLBI/SLR	.56	1.48	1.05
Albrook	NSWC PT.POS.	.03	.03	-.32
Blackbirch	NSWC PT.POS.	.04	-.64	.03
Canberra	NSWC PT.POS.	-.09	-.78	-.07

* All comparisons were done on the WGS 84 ellipsoid.

deviations in Table 2 represent the dispersion of individual position component estimates, estimated from a single 4 to 6 hour data set. These standard deviations were obtained from the sample population of GASP positioning results. The GASP-generated standard deviations from any particular position estimate are in close agreement with the values shown in Table 2. There are no apparent deficiencies in any particular component. All results given in Tables 1 and 2 were generated using the WGS 84 precise satellite ephemerides and clock states. These ephemerides and satellite clock states are held fixed in the GASP algorithm. Common errors in the interpolated satellite position vectors and clock states difference away in the construction of the observables.

The mean value of the standard deviations listed in Table 2 (Cartesian or geodetic) is 73 centimeters. This mean value, obtained from 114 point positions at 11 CASA UNO stations, can be interpreted as an overall measure of positioning performance under a spectrum of field conditions and tracking geometries. The mean point positions, obtained by averaging the individual daily estimates for a given station are significantly more precise than any individual daily estimate. For example, the mean position components listed in Table 1 have an overall standard deviation of 25 cm.

Since the point positioning algorithm addressed here has potential field applications, the authors analyzed its performance in the case where the broadcast satellite ephemerides and clock state predictions were adopted in place of the precise estimates. The repeatability in this case is degraded by about a factor of two. This level of degradation indicates that the GASP-generated broadcast point positioning results can be geodetically useful for field applications. Note however, that the broadcast-derived mean ellipsoid height component, at the one station tested (Albrook), is 1.7 meters lower than the corresponding height component generated from the precise ephemerides and clock states. The source and systematic quantification of this possible bias remain to be explored.

In order to partially assess the accuracy of GASP absolute point positions, the GASP results at five CASA UNO stations were compared to positioning results generated from a collection of independent sources. Table 3 allows a comparison of the mean GASP-estimated positions with absolute positions obtained from three independent methods: TRANSIT Doppler point positioning, the VLBI/SLR-derived coordinates for CASA UNO stations presented by Schutz, et al.[1989], and NSWC GPS point positioning. The TRANSIT point position (for Albrook) was estimated by DMA from 64 NAVSAT passes, collected during the CASA UNO campaign (days 20-32). The VLBI/SLR-derived absolute station coordinates used for this evaluation were presented in Table 5 of Schutz, et al.[op cit.] and Table 2 of Abusali, et al.[1989]. The NSWC point positions were provided, as part of a comprehensive interagency test plan, by Hermann [personal communication ,1989]. Like the GASP mean positions, these NSWC positions are obtained by averaging the set of daily estimates derived from CASA UNO data sets. Hermann's GPS point positioning algorithm is a research-oriented, combination least-squares / sequential filter which uses undifferenced smoothed pseudoranges as observables. A description of this algorithm is given in Hermann [1988]. Note that the Hermann algorithm solves for the receiver's clock state while GASP differences the receiver clock away when the observables are formed.

The accuracy assessments given in Table 3 are limited in the sense that they each involve the mean GASP point position, obtained from the collection of data sets for each station listed. Any individual (daily) GASP position could deviate from the mean by an amount commensurate with the standard deviations shown in Table 2. Moreover, the biases shown in Table 3 do not necessarily represent a deficiency in the GASP point position estimates. Unquantified reference frame differences are suspected between the VLBI/SLR frame and the GPS realization of WGS 84. In addition, the TRANSIT and NSWC point positions used for this comparison may contain random or localized errors. Nevertheless, initial comparisons such as these confirm the geodetic utility of the GASP point positioning algorithm. Table 3 indicates that the mean difference, in absolute value, between a GASP position component and a VLBI/SLR component is 76 centimeters.

The Geodetic Inverse Problem

Once a pair of near-simultaneous (in the same GPS week) point positions have been estimated, the long-line geodetic inverse problem can be solved for geodesic distance (on the ellipsoid) and geodetic azimuth between the two stations. The vector between the two stations can also be obtained by differencing the Cartesian point position components.

Since these methods do not suffer degradation with increased inter-station distances, repeated solutions of the inverse problem can potentially offer new, all-weather tools to those studying global geodynamics. To demonstrate these tools, the authors used the daily GASP point positions described here to solve the geodetic inverse problem for two pairs of stations: Cocos to Limon (geodesic distance: 659 km) and Canberra to Albrook (geodesic distance: 14305 km). For the 'short' geodesic, the standard deviations in geodesic distance and geodetic azimuth, over 9 daily positions, were 38 cm (0.57 ppm) and 0.33 arc seconds, respectively. The very long baseline, over 15 daily positions, achieved standard deviations of 69 cm (0.05 ppm) in geodesic distance and 0.04 arc seconds in geodetic azimuth.

The standard deviations of the mean geodesic distances were 13 cm (0.19 ppm) for the 'short' geodesic and 18 cm (0.01 ppm) for the very long geodesic. The mean geodetic azimuths had standard deviations of 0.11 and 0.01 arc seconds, respectively. When the full GPS constellation is deployed, the global nature of mean geodesics such as these may open a range of possible geodynamic study which has, to this point, been restricted to those utilizing less-mobile satellite laser ranging techniques.

Summary and Conclusions

The CASA UNO experiment provided an opportunity to demonstrate the abilities of the DMA GPS point positioning algorithm. Statistical assessment of repeated position estimates indicates that geodetic-quality (sub-meter level) point positions have been obtained on a world-wide basis from GPS TI4100 data collected over a period of a few hours. The overall standard deviation of a point position component, estimated from a few hours of data, is 73 centimeters. When a series of repeated point positions are averaged, the mean components have an overall standard deviation of 25 centimeters. When these mean position components are compared to coordinates derived from the VLBI/SLR technique, a mean difference of 76 centimeters is seen. This precision and accuracy was achieved through the utilization of the DMA/NSWC precise WGS 84 satellite ephemerides and clock states. When the broadcast ephemerides and satellite clock states are used with a few hours of data, positioning results are degraded by about a factor of two.

Despite the abilities and achievements of GPS relative positioning algorithms, geodetic point positioning will continue to be necessary for activities such as mapping control and the estimation of transformation parameters between a World Geodetic System and a local or regional geodetic datum. Relative positioning has limited application in these areas since the 'fixed' end of the baseline, which must be well-known in advance, predominantly defines the reference frame of the floating end of the baseline. For remote areas, where 'fiducial' stations have not been established, geodetic point positioning will be required to fix one end of a new baseline. The logistical requirements of relative positioning surveys (multiple receivers observing simultaneously) also make the point positioning method attractive for many geodetic applications.

Solution of the geodetic inverse problem using repeated GPS point positions may soon offer a new tool to those studying geodynamics on a global scale. Unlike relative positioning algorithms, the quality of the inverse solution (baseline) does not degrade with geodesic length. A 14305 kilometer geodesic, (Canberra Australia to Albrook Panama), has been estimated from 15 repeated data sets with standard deviations of 18 centimeters (0.01 PPM) in distance and 0.01 arc seconds in orientation. As the authors expect to continue refining the DMA point positioning methodology, and as the growing GPS constellation creates more favorable tracking geometries, the STARPREP/GASP algorithm is likely to succeed beyond the levels of positioning precision and accuracy demonstrated here. In particular, a station's position with respect to the center of mass of the earth can now be measured (by GASP) at the level of several decimeters. Model refinement, optimized geometry and longer data sets are expected to continue reducing this dispersion. As an example of model refinement, the authors intend to introduce a stochastic zenith tropospheric delay parameter in the estimation process. In the mean time, GPS point positioning will serve as a more than adequate replacement for TRANSIT point positioning.

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S. Malys and Major P. Jensen, Defense Mapping Agency Systems Center / EG, Washington D.C. 20315-0030.

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