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Orbit Determination for the QuikSCAT Spacecraft

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An operational orbit determination system for QuikSCAT has been developed to meet the requirement for 100-m (3σ) positioning knowledge. This is nominally accomplished by processing global positioning system (GPS) position solutions in a dynamic filter. The operational orbit determination system produced 24-h overlapping arc position errors between 15 and 25 m (root-sum-square) and 3-h arc overlaps between 5 and 6 m (root-sum-square) for seven-day and one-day arcs, respectively. We also investigated the use of short segments of GPS pseudorange and carrier phase data and obtained results that differ by less than 10 m from the nominal orbit solutions. A third investigation considered the feasibility of a backup orbit determination system using antenna azimuth and elevation angles from three ground tracking stations. The methods and results of processing these three data types are presented.

Introduction

THE QuikSCAT spacecraft was launched from Vandenburg Air Force Base on 19 June 1999. It carries the SeaWinds scatterometer for measuring wind speed and direction near the ocean surface.[1] The key operational orbit and spacecraft characteristics are listed in Table 1. The satellite carries a Viceroy™ global positioning system (GPS) receiver that generates point position and velocity solutions onboard.[2] These navigation solutions are nominally recorded at 60-s intervals and telemetered to the ground.

The QuikSCAT spacecraft was built by Ball Aerospace Systems Division and is being operated by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado. The program is managed by the Jet Propulsion Laboratory. Prior to launch, the Colorado Center for Astrodynamics Research developed an operational orbit determination (OD) system that uses the GPS navigation solutions computed onboard. Additionally, we investigated the performance of orbit determination systems based on 10-min bursts of pseudorange data and tracking station antenna angles data. The purpose of this paper is to present the methods and results of processing these three data types: 1) GPS navigation solutions, 2) GPS pseudorange burst data, and 3) ground-based azimuth and elevation data.

Method

The QuikSCAT orbit determination system consists of an advanced user interface built around the MicroCosm® orbit determination software system.[3,4] The interface is designed to handle all tasks required to routinely generate daily satellite ephemerides at 60-s intervals. The ephemerides are computed in the inertial true-of-date coordinate system, compatible with ground system operations software at LASP. The observations consist of once-per-second point positions (navigation or NAV solutions) computed by the onboard GPS receiver. Because the velocity solutions are not computed to better than 1 m/s, orbit arcs are fit only to the navigation position solutions. No attitude telemetry data were used in the solutions. A mean cross-sectional area (Table 1) of the spacecraft was provided by LASP.

MicroCosm is used to estimate the epoch state and drag coefficient (Cd) based upon seven days of data and to subsequently produce position estimates at 60-s intervals over the seven-day period. MicroCosm uses a high-fidelity dynamic model incorporating the following[4]: 1) JGM-3 gravity model complete to degree and order 70, 2) Jacchia-71 atmospheric density model, 3) tabular data consisting of solar flux, geomagnetic data, and Earth-orientation parameters (updated on a weekly basis), and 4) planetary ephemerides to account for third-body perturbations.

Shortly after launch, satellite operators and analysts at LASP determined that the point solutions have a consistent timing offset of exactly 1 s. The QuikSCAT operational OD system was adjusted to account for this timing offset in a data preprocessing routine that converts the NAV solutions to the proper format for use by the MicroCosm tracking data formatter program.

To assess orbit accuracy, six seven-day arcs were selected in the period immediately following the QuikSCAT orbit raising campaign. The seven-day length was selected in order to ensure a good estimate of the orbit and an accurate orbit prediction. Each arc overlaps the adjacent arcs by 24 h.

Orbit Determination Using Onboard GPS Navigation Solutions

Table 2 shows the rms of fit to the NAV positions and the estimated drag coefficient for each of the 6 arcs computed.

Orbit determination consistency was assessed by overlap comparisons of successive arcs. Orbit comparisons (differences) were computed at 60-s intervals for the 6 arcs listed in Table 2. Table 3 shows the mean and rms of differences in the radial, alongtrack, and crosstrack directions. Also included in Table 3 is the rss of the rms of difference in each direction; this is representative of the total error in position.

Based on overlap comparisons for the six arcs shown, the orbit accuracy (total position) for the QuikSCAT spacecraft is estimated to be 25 m (1σ) or better. This accuracy meets the 100-m (3σ) mission requirement. However, the estimates of the drag coefficient are not consistent from one arc to the next. These variations could be caused by errors in the gravity and atmospheric density models or by the absence of attitude data in the drag model for QuikSCAT. The alongtrack differences seen in the overlap comparisons dominate, further suggesting inconsistent modeling of forces acting in

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the alongtrack direction or systematic timing errors that manifest themselves in the alongtrack direction.

The U.S. Department of Defense deactivated selective availability (S/A) on the GPS signals on 1 May 2000. An orbit determination study was conducted using data collected after this date to determine the effects of S/A on the QuikSCAT orbit accuracy. Five orbit arcs were computed after S/A was removed from the GPS signals. As before, each arc was seven days long, and 24-hour overlaps were used to assess performance. The results are shown in Tables 4 and 5.

These results show that the rms of fit is better than the results obtained using data with S/A (Tables 2 and 4), but total position solution error (rss) for overlapping arcs is about the same magnitude. The fit is improved because the observation errors are reduced. The orbit error is not significantly affected because the dynamic modeling used in the seven-day batch processing was able to eliminate the effect of the relatively high-frequency measurement errors.

An analysis was conducted using one-day arcs for the period 15–18 July 1999. This data set is also used for the burst data analysis in the next section. The results of the NAV orbit fits are shown in Tables 6 and 7. The fact that the one-day arcs are more consistent than the seven-days arcs is attributed to deficiencies in the dynamical model, mostly gravity and drag, that is, these errors have less impact on the shorter arcs. Although the one-day arcs are more consistent than the seven-day arcs, they are not thought to be more accurate.

The one-day arcs were also compared with the seven-day arc spanning the same time periods (15–22 July 1999). The results of the overlap differences are shown in Table 8. As before, the significant differences appeared in the alongtrack direction. This can be attributed mainly to uncertainties and variations in atmospheric density. The seven-day arc incorporated one drag coefficient to span the entire seven-days, effectively filtering through any daily (or shorter period) atmospheric variations. Each one-day arc estimated a new, independent drag coefficient once per day. The rss of position for the overlaps shown in Table 8 are on the order of 10 m, whereas the overlaps for the seven-day arcs are on the order of 20 m. The overlaps of Table 8 are smaller because the data used for the one-day arcs were subsets of the seven-day arc data. The rss differences in Table 8 further support the claim that the mission orbit requirement (100 m, 3σ) is being achieved by the operational orbit determination system.

Orbit Determination Using GPS Pseudorange Burst Data

During nominal operation, the GPS receiver onboard QuikSCAT does not send raw pseudorange and carrier phase data to the ground. The standard downloaded GPS data consist of onboard computed NAV solutions. However, the receiver and satellite communication subsystems can be configured to send short sets of raw GPS pseudorange and carrier phase data, along with other telemetry information. These short sets consist of approximately 10 min of contiguous data gathered three to four times per day. These data sets are referred to as "burst data."

Processing burst data with MicroCosm begins by fitting an orbit to the NAV positions in order to generate a reference orbit. This fit is used to provide the initial conditions for the solution based on the GPS burst data and is also used as a basis for comparison for the generated orbits. The MicroCosm results presented here are based on processing only the pseudorange data.

To process the pseudorange data, it is necessary to know the positions of the GPS satellites. A fit by MicroCosm to the precise ephemerides provided by the International GPS Service was used for this purpose. This fit was then used to provide MicroCosm with the precise positions of the GPS satellites during processing of the QuikSCAT burst data. Early processing runs suggested that single-day arcs might be too short for processing the burst data. The value of Cd and the overall orbit accuracy varied extensively between single-day arcs. For the solution results presented next, a three-day arc was used. This longer arc gives a much more reasonable estimate for Cd and compares well to a solution based on smoothing the NAV positions. Four solution estimates were produced using different combinations of the available data and estimated parameters (see Table 9). All solutions estimated satellite position, velocity, and Cd. Solutions involving one-way pseudorange data also required the estimation of receiver clock biases. Single-difference pseudorange data involves two one-way pseudorange observations for two different GPS satellites taken at the same epoch. These two observations are differenced, yielding an observation data type that is free of GPS receiver clock biases.[5]

The results shown in Table 10 are the differences of positions between the various solutions shown in Table 9 and the reference trajectory based on smoothing the NAV solutions. Note that the estimates of drag coefficients shown in Table 11, although small, are very consistent.

The results show that it is possible to process the pseudorange burst data and generate a consistent orbit solution. The results further indicate that the pseudorange burst data can also be used to augment the onboard navigation solutions. At the time of this investigation, we did not have access to enough contiguous burst data to compute orbit overlap statistics. Future work will include multiple arcs of burst data, both pseudorange and carrier phase data, so that overlap comparisons can be performed.

Table 1 QuikSCAT characteristics and mean orbital elements (April 2001)

Parameter	Type/value
Orbit type	Sun synchronous
Period	101 min
Altitude (perigee × apogee)	807 × 827 km
Inclination	98.63 deg
Eccentricity	0.0001187
Argument of perigee	62.426 deg
Spacecraft mass	820.48 kg
Cross-sectional area (average)	3.2 m^2

Table 2 Orbit determination results for seven-day arcs

Arc		rms of fit, m	Estimated Cd
1	15–22 July 1999	28.8	4.1
2	21–28 July 1999	29.1	3.1
3	27 July–3 August 1999	30.7	3.3
4	2–9 August 1999	29.1	3.0
5	8–15 August 1999	29.4	1.7
6	14–21 August 1999	28.8	1.8

Table 4 Post-S/A orbit determination results

Arc		rms of fit, m	Estimated Cd
1	3–10 May 2000	10.97	3.34
2	10–17 May 2000	12.3	3.42
3	17–24 May 2000	11.51	3.19
4	24–31 May 2000	12.31	2.53
5	31 May–7 June 2000	12.63	2.58

Table 3 Twenty-four-hour overlap comparisons for seven-day arcs, m

Overlapping arcs	Mean radial	Mean alongtrack	Mean crosstrack	rms radial	rms alongtrack	rms crosstrack	Total position (rss)
1 and 2	0.17	9.1	−0.04	6.73	17.5	3.57	19.1
2 and 3	0.22	18.9	0.04	6.05	24.1	2.80	25.0
3 and 4	−0.24	15.4	0.00	5.53	21.2	2.43	22.0
4 and 5	0.21	11.2	0.00	3.83	15.6	3.02	16.3
5 and 6	−0.35	3.51	−0.03	2.94	15.0	2.49	15.5

Orbit Determination Using Azimuth and Elevation Tracking Data

The final investigation was for a backup orbit determination method to process azimuth and elevation angles collected from ground-based tracking stations. Such a system could be used in the event of a failure of the onboard GPS receiver. There are three tracking stations used to command the QuikSCAT satellite and download telemetry. As QuikSCAT passes over each station, azimuth and elevation angle observations are collected from the station antennas. A QuikSCAT pass over a tracking station typically lasts about 10 min, during which observations are collected every 10 s. Approximately five observation sets are collected in a 24-h period from the three stations combined. The tracking station locations were considered fixed; they were not estimated in the OD process (see Table 12).

The data used in this analysis were collected during the month of August 2000. From these data a five-day subset (15–19 August) was selected and assumed to be representative of a typical five-day period. The observation uncertainties (1σ noise levels) of the azimuth and elevation angles are not known for the three tracking stations. By analyzing the prefit residuals of the five days of data (nearly 5000 azimuth and 5000 elevation observations), the approximate data noise levels were very conservatively estimated (1σ) to be 1 deg for both azimuth and elevation.

Figure 1 is a plot of the a priori azimuth residuals (3σ edited) from all three stations with time gaps removed. For brevity, only azimuth residuals are plotted. Tabular results of azimuth and elevation residuals indicate that the two data types have similar noise levels. The unedited residual mean was −0.32 deg, and the rms was 6.86 deg. After discarding data points having a residual greater than 3σ (or 3×6.86 deg), the residual mean was −0.44 deg, and the rms was 3.65 deg (Fig. 1). Even after removing the 3σ outliers, the raw data have a relatively high level of systematic error. Figures 2–4 show the unprocessed azimuth residuals for each of the three individual tracking stations. It appears that tracking station 29 (Alaska) provides observations best suited for the OD process. Stations 30 and 64 have large discontinuities and sharp changes in the measurements.

The azimuth and elevation angles data from the ground tracking stations are stored in binary files in the Universal Tracking Data Format.[6] The data file name contains the station number and date the observations were made. It was discovered that some files had names that did not correspond to the actual data within the file. A program was written in C++ to convert the binary angles data into the GEOS-C format, which is suitable as input to MicroCosm.[4] The program extracts the station, date and time, azimuth, and elevation of each observation, reformats the data, and produces three text files. Each file contains all of the observations in the proper format for each of the three tracking stations.

The first assessment of orbit determination accuracy was to compare solutions of the primary, GPS-based OD system with solutions computed by using the backup azimuth and elevation data system. For this analysis the GPS solution was considered to be the "truth." The truth orbits were computed using five days of GPS NAV data. By experimenting, it was found that at least five days of angle data are required to converge on an OD solution reasonably close to that of the truth (that is, convergence within several hundred meters). Shorter

Table 6 Orbit determination results for one-day arcs

Arc		rms of fit, m	Estimated Cd
1	15–16 July 1999	29.26	3.44
2	16–17 July 1999	28.51	4.74
3	17–18 July 1999	29.44	5.44

Table 5 Twenty-four-hour post-S/A overlap comparisons for seven-day arcs, m

Overlapping arcs	Mean radial	Mean alongtrack	Mean crosstrack	rms radial	rms alongtrack	rms crosstrack	Total position (rss)
1 and 2	0.55	14.93	−0.06	4.69	25.13	3.11	25.27
2 and 3	−0.32	17.70	0.01	5.53	22.99	3.13	23.85
3 and 4	0.36	19.79	−0.05	5.96	25.27	3.78	26.23
4 and 5	−0.16	27.62	0.03	6.72	30.86	2.21	31.66

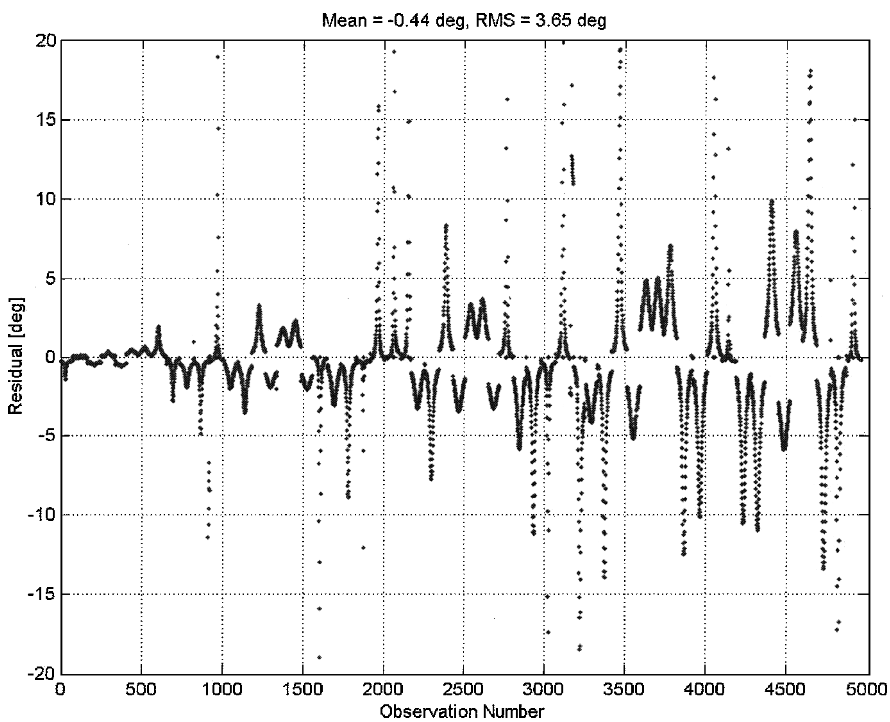

Fig. 1 The 3σ edited prefit azimuth residuals (all stations).

Table 7 Three-hour overlap comparisons for one-day arcs, m

Overlapping arcs	Mean radial	Mean alongtrack	Mean crosstrack	rms radial	rms alongtrack	rms crosstrack	Total position (rss)
1 and 2	0.03	−2.48	0.04	1.44	4.13	2.10	4.85
2 and 3	0.03	5.25	−0.15	1.48	5.91	1.37	6.25

Table 8 One-day arcs overlapped with seven-day arc, m

One-day arc	Mean radial	Mean alongtrack	Mean crosstrack	rms radial	rms alongtrack	rms crosstrack	Total position (rss)
1	−0.06	−1.12	−0.01	4.22	8.91	0.93	9.90
2	0.05	0.08	−0.05	2.31	4.58	2.56	5.73
3	0.02	4.77	0.01	0.80	5.09	0.68	5.20

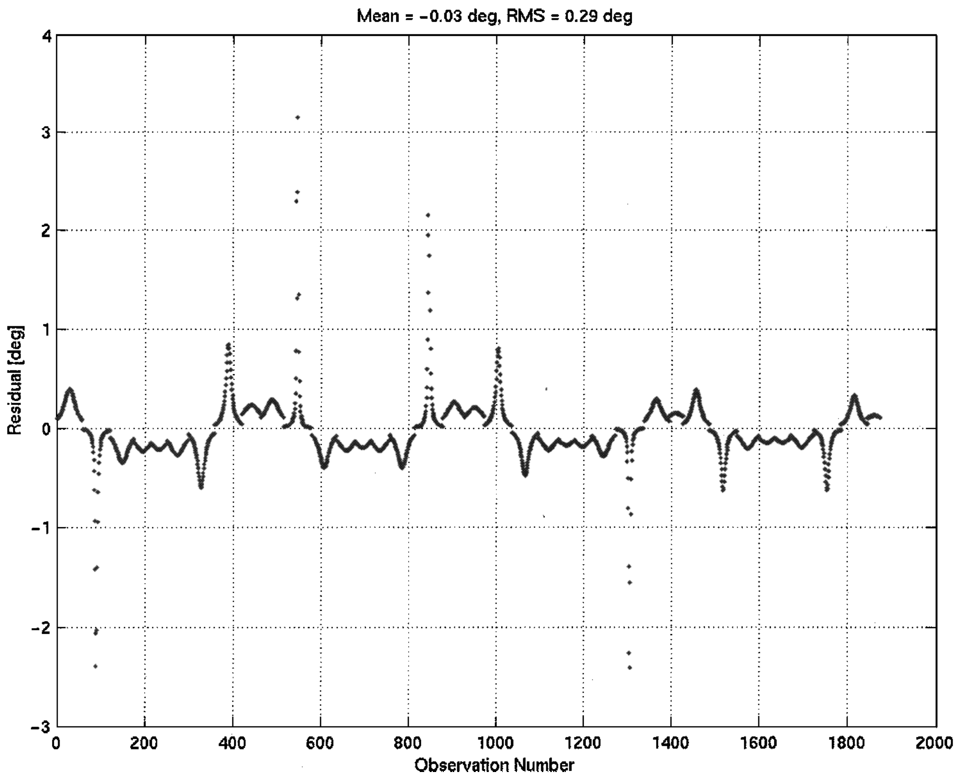

Fig. 2 Station 29 (Alaska) prefit azimuth residuals.

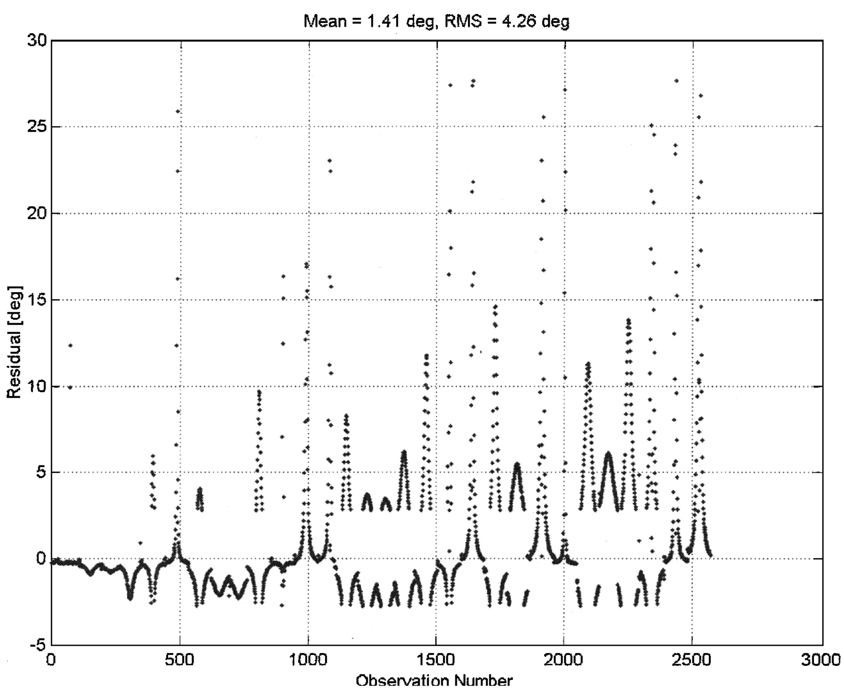

Fig. 3 Station 30 (Norway) prefit azimuth residuals.

Table 9 Data and parameter combinations for burst data solution types

Solution type	Observation data type	Additional estimated parameters
1	One-way pseudorange	Receiver clock bias and drift
2	Single-difference pseudorange	No clock estimation
3	NAV data combined with one-way pseudorange	Receiver clock bias and drift
4	NAV data combined with single-difference pseudorange	No clock estimation

spans of data generally resulted in an unstable convergence or divergence. The angles-only orbits were computed using angles data gathered over the same five days used for the primary OD system. The a priori state for the first arc of the angles-only system was computed using Gauss's method for angle-only orbit determination.[7,8] Subsequent a priori states were taken from the ephemerides generated before by the angles-only system.

To ensure the best possible comparison between orbits, the dynamic model of the angles-only system was matched as closely as possible to the primary GPS OD system dynamic model. The gravity model, atmospheric model, third-body planetary ephemerides,

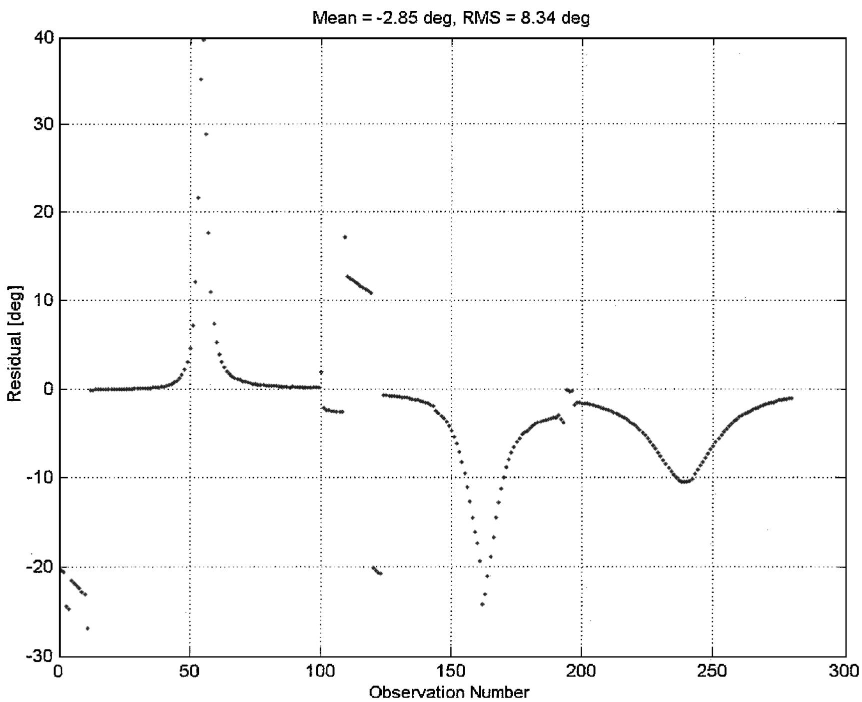

Fig. 4 Station 64 (Virginia) prefit azimuth residuals.

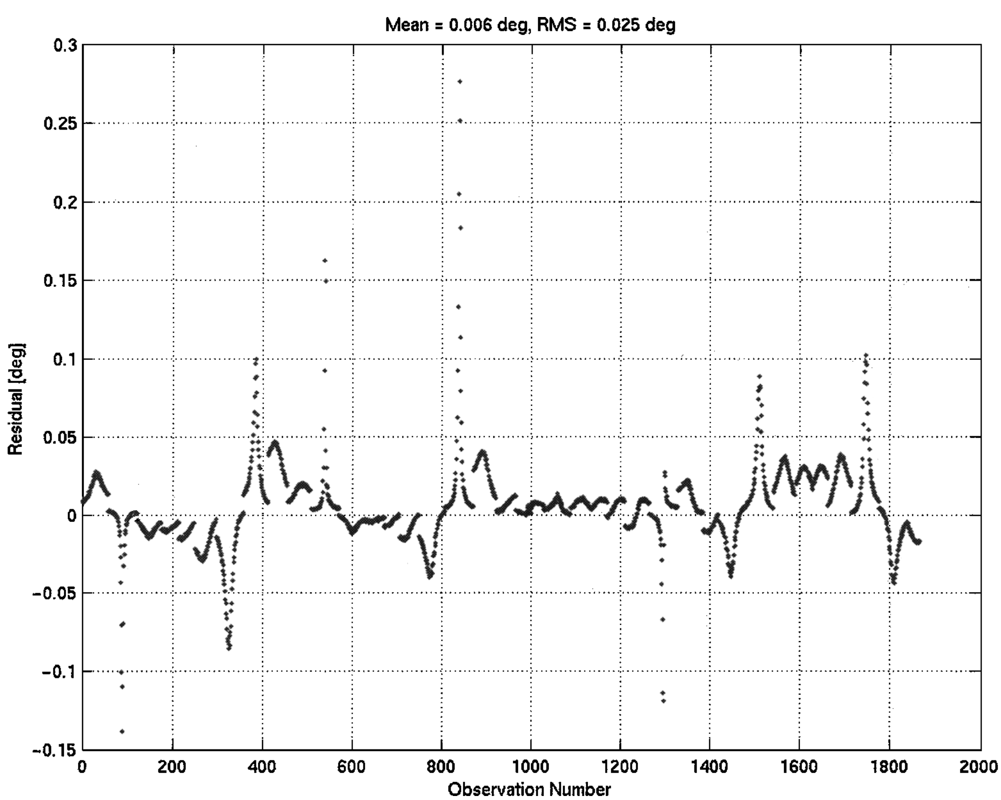

Fig. 5 Station 29 (Alaska) postfit azimuth residuals.

and integration controls were set identical to the GPS OD model. The elevation angle cutoff was set to 10 deg to attempt to remove atmospheric-induced errors encountered at low elevation angles. The a priori variances of the satellite position and velocity were conservatively set to 1.0×10^7 m^2 and 10.0 m^2/s^2.

Using only the data from station 29 (Alaska), four orbit arcs were generated with the angles-only OD system (see Table 13 for the dates of the arcs). These arcs were each generated using four separate five-day sets of data. The postprocessing azimuth residuals for the first arc are shown in Fig. 5. Approximately $\frac{1}{3}$ of the raw data were found to be outliers and were edited. As expected, it was found that better results (compared to the primary system) were obtained by only using tracking data from station 29. Although the OD system converged on a solution, it is apparent from Fig. 5 that the systematic errors are still present after processing. Table 13 contains the estimated values of Cd, which are consistent from arc to arc. The four arcs were compared to four arcs generated by the primary GPS OD system. Differences in the radial, alongtrack, and crosstrack directions were taken every 60 s over a five-day period. Statistical data on the differences of each arc comparison can be found in Table 14.

A second means of accuracy assessment was to compare overlapping arcs of solutions using only the angles data from separate sets of data. Three arc overlap comparisons were made. Each arc comparison was made by differencing the overlapping arcs every 60 s for a 24-h period. The results of these comparisons are shown in Table 15.

The results indicate that the QuikSCAT satellite orbit can be determined using only azimuth and elevation angles from one station, but the desired level of operational accuracy cannot be achieved. Failing to achieve the operational accuracy is primarily attributed to the quality (noise) and systematic errors in the tracking data. A simulation was conducted in order to determine the typical noise levels on azimuth and elevation data that would result in orbits with the desired accuracy. MicroCosm was used to generate simulated azimuth and elevation tracking data from a GPS-based QuikSCAT ephemeris. Increasing amounts of normally distributed noise (zero mean) were added to the simulated tracking data. The effects of the noise on the orbit accuracy were determined by comparing the orbit computed using the simulated data with the original orbit. The results are shown in Table 16 and Fig. 6.

The data in Table 16 indicate that the desired orbit accuracy may be achievable by using three tracking stations and a 1σ noise level no greater than approximately 0.05 deg. This conclusion is based only on a simulation and does not include effects of systematic errors.

Table 10 Burst data results differenced with nominal NAV solutions, m

Solution type	Radial	Alongtrack	Crosstrack	Total position (rss)
1	2.58	8.02	1.24	8.52
2	3.59	8.11	1.49	9.00
3	1.51	3.38	1.05	3.85
4	1.55	3.35	1.01	3.83

Table 11 Drag coefficient estimates from the burst data solutions

Solution	Cd
NAV fit	0.67
1	0.74
2	0.70
3	0.66
4	0.66

Table 12 Tracking station data

Station	ID #	Location	Geodetic latitude	East longitude	Elevation, m
AGS	29	Alaska	65.1167331°	212.5384511°	430.34
SGS	30	Norway	78.2303125°	15.3928411°	455.0
WAPS	64	Virginia	37.9249256°	284.5234775°	−20.10

Table 13 Drag coefficient estimation results for five-day arcs

Arc		Estimated Cd
1	14–19 Aug 2000	5.47
2	16–21 Aug 2000	5.50
3	18–23 Aug 2000	5.53
4	20–25 Aug 2000	5.48

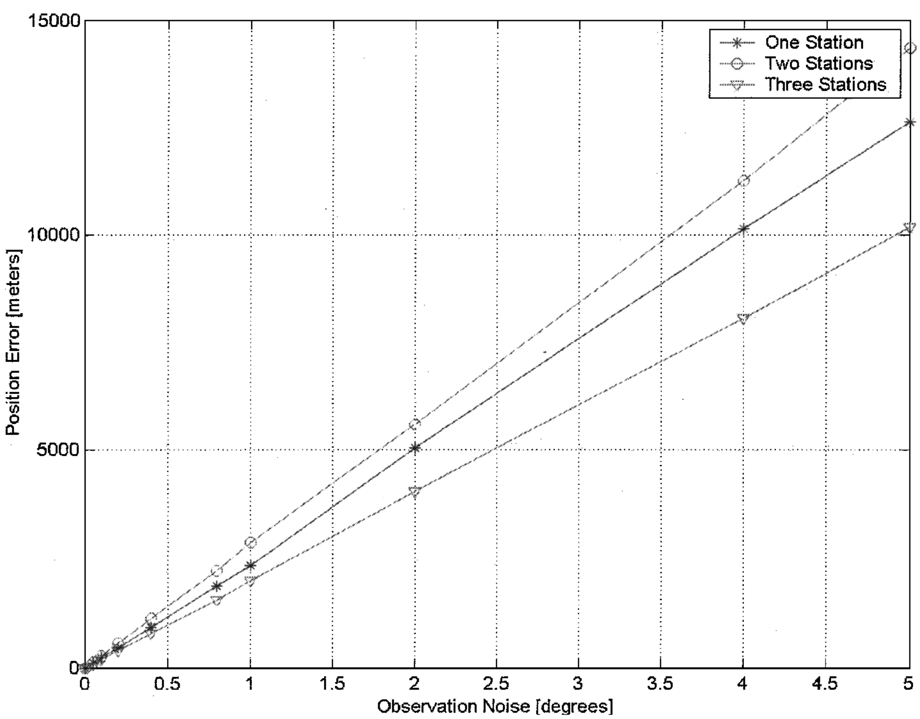

Fig. 6 Position error vs simulated observation noise.

Table 14 Angles-only arcs differenced with GPS NAV arcs, m

Arc	Mean radial	Mean alongtrack	Mean crosstrack	rms radial	rms alongtrack	rms crosstrack	Total position (rss)
1	−0.4	−243.5	−0.7	203.6	496.1	266.0	598.6
2	0.4	−477.7	1.6	250.3	693.3	284.4	790.0
3	−1.1	−411.7	−0.6	232.8	638.0	227.1	716.1
4	−0.9	105.5	1.0	159.4	354.5	185.5	430.7

Table 15 Twenty-four-hour overlap comparisons for five-day arcs, m

Overlapping arcs	Mean radial	Mean alongtrack	Mean crosstrack	rms radial	rms alongtrack	rms crosstrack	Total position (rss)
1 and 2	4.89	67.93	1.26	122.22	261.98	60.33	295.32
2 and 3	1.15	−204.89	0.60	24.06	211.96	26.95	215.02
3 and 4	−2.06	−587.00	−0.12	163.96	673.66	27.99	693.89

Table 16 Total (three-dimensional) position error, m

Observation noise, deg	Position error		
	1 Station	2 Stations	3 Stations
0.00	0	0	0
0.05	117	142	99
0.10	234	284	199
0.20	467	568	397
0.40	935	1,139	796
0.80	1,866	2,215	1,552
1.00	2,330	2,867	1,999
2.00	5,040	5,595	4,040
4.00	10,142	11,269	8,060
5.00	12,636	14,361	10,182

Conclusions

We have shown that the operational QuikSCAT orbit determination system, using on-orbit GPS NAV solutions as observations, produced 24-h overlapping arc position errors between 15 and 25 m (rss). This system fulfills the mission requirement of 100-m (3σ) position accuracy.

Comparison of the pseudorange burst data solutions to the GPS NAV solutions produced rms position errors between 4 and 9 m for three-day arcs. This, combined with the rms errors of the NAV solution, indicates that pseudorange burst data is also capable of achieving mission position accuracy requirements. The best approach for incorporating burst data is to use the MicroCosm batch filter with both NAV solutions and burst data as observations.

The investigation of using azimuth and elevation data as a backup OD system showed that this type of data could be used to track QuikSCAT in order to command the satellite and keep it operational. The test results show that the backup OD system computed solutions with a mean three-dimensional difference from the primary GPS NAV solutions between 100 and 480 m and a three-dimensional rms difference between 430 and 790 m over a five-day period. Twenty-four-hour overlaps of five-day arcs showed a mean three-dimensional difference between 68 and 587 m and a three-dimensional rms difference between 215 and 693 m. Therefore, 100-m (3σ) position accuracy does not appear to be achievable using this backup OD system. If data from all three tracking stations were comparable to those from station 29, the requirement could possibly be met. In the event of a GPS receiver failure, it would still be possible to operate the mission payload with the understanding that the position of the satellite will not be as well determined as it would be using the primary GPS OD system.

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