RELATIVE ORBIT DETERMINATION OF GEOSYNCHRONOUS SATELLITES USING THE COWPOKE EQUATIONS

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Optical satellite tracking often reveals multiple satellites in a single telescope field of view. The Cluster Orbits With Perturbations Of Keplerian Elements (COWPOKE) equations are used to estimate the relative motion of geosynchronous satellites and determine if the satellites can be later identified based solely on relative position. This paper provides the development of the COWPOKE equations for modeling the relative motion of geosynchronous satellites and analysis demonstrating the feasibility of using these techniques for object correlation. Real data relative orbit determination results are provided using the optical tracking assets of the Air Force Maui Optical and Supercomputing (AMOS) site.

INTRODUCTION

Clusters of spacecraft in geosynchronous orbit (GEO) are becoming more common. Orbital slot allocations in GEO are rapidly being filled, and it is increasingly difficult to acquire slots for new satellites. Consequently, many organizations opt to collocate their spacecraft in the same slot. Eutelsat had as many as five satellites collocated in a formation at 13° E by 2001.[1] In addition, unintentional close approaches have occurred and could become more frequent as the GEO belt becomes more crowded. In 1997, Telstar 401, a satellite in GEO, experienced a major failure, and control of the spacecraft was lost.[2] It is drifting in GEO and has had encounters with other satellites as close as 4 km.[3] Since that time, other GEO spacecraft have also begun drifting uncontrollably. Close approaches and satellite formations create a challenge for space surveillance. Identification of the satellites in these clusters can be difficult, and cross-tagging (misidentification) occurs.[4] Resolvable imaging can be used to identify spacecraft in low Earth orbit but is not currently possible for GEO altitudes. Non-imaging approaches include comparing the brightness and characterizing the color of light reflected from the spacecraft for identification purposes.[5] However, identifying spacecraft solely from their dynamics would eliminate the need for special filters or other sensors. A better understanding of the relative motion of the spacecraft could reduce cross-tagging and improve close approach predictions. Improved determination of minimum approach distances could eliminate unnecessary collision avoidance maneuvers and minimize propellant usage.

Cluster orbits can be modeled using the Cluster Orbits With Perturbations Of Keplerian Elements (COWPOKE) equations of motion.[6] The COWPOKE equations predict spacecraft separations in the spherical radial, along-track, and cross-track coordinate frame based on the Keplerian elements of the reference satellite, the element differences for the second satellite, and elapsed time. These inputs for COWPOKE can be obtained with relative metric data from optical sensors or space surveillance products.

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Charge-coupled device (CCD) images of clusters of spacecraft should provide very accurate measurements of spacecraft separation since in-frame error sources theoretically cancel out. The United States Air Force currently operates several optical systems capable of imaging clusters at the Maui Space Surveillance Complex, such as Raven, Phoenix, and the Ground-Based Electro-Optical Deep Space Surveillance System (GEODSS). Raven uses small, commercially available telescopes to acquire CCD images of space objects for tracking.[7] Astrometry is used to match stars in the CCD image to the star catalog. Thus, the pointing accuracy of the images can approach the accuracy of the star catalog used. Phoenix is a Baker-Nunn telescope refurbished to take wide-angle CCD images.[8] As many as 21 satellites have been detected in one Phoenix image. After the Deep Stare upgrade, GEODSS could be used to acquire relative metrics as well.

This paper is an extension of previous work exploring the application of COWPOKE towards geosynchronous cluster orbit prediction.[9] First, a perturbation study is conducted to determine the force modeling required at GEO. Improvements are made to the COWPOKE equations that allow for better representation of GEO motion. A method is construed to estimate the Keplerian element differences using optical measurements of relative right ascension and declination. Finally, results are discussed for which COWPOKE was used to predict the relative motion of a cluster of satellites in GEO.

USING COWPOKE AT GEO

A study was conducted to identify perturbing forces that significantly affect the relative motion of a cluster of geosynchronous satellites. The effects of central body gravity, third body gravity, and solar radiation pressure were investigated using the Draper Semianalytic Satellite Theory (DSST). The Draper research and development version of the Goddard Trajectory Determination System (DGTDS) was used to propagate the orbits with DSST.[10] The motion of two spacecraft was propagated to generate a "truth" relative motion using an 8x8 JGM-2 geopotential field, luni-solar third-body point-mass using JPL ephemerides, and solar radiation pressure (SRP) based on a spherical satellite and cylindrical Earth-shadow model. Next, the relative motion of the two spacecraft was generated while neglecting one of the sources of perturbations, such as third-body gravity. The radial, along-track, and cross-track separations obtained from the "truth" relative motion were compared to those generated with the incomplete force model to find the approximate error that would result from neglecting that perturbation source in the COWPOKE formulation. These test runs were conducted two times; the first set of runs included long period effects propagated over 30 days, and the second set investigated short periodic effects propagated over 5 days. Table 1 shows the reference elements and the differential elements used in the propagation.

Table 1
INITIAL CONDITIONS FOR DSST RUNS REFERENCED TO THE MEAN EQUATOR AND EQUINOX OF THE B1950.0 COORDINATE SYSTEM.

Keplerian Elements	Reference Elements	Element Differences
a	42,164 km	0
e	0.01	0.01
i	3°	1°
Ω	0°	1°
ω	0°	1°
M_0	0°	1°

Cases that neglected all non-spherical gravity forces were conducted at differing initial mean anomalies. Those omitting higher order geopotential terms, but including J_2, were conducted with varying longitudes of the node to survey the longitudinal dependencies of the tesseral harmonics. Tests examining luni-solar effects ran at varying days of the year while those for SRP effects used different days of the year as well as at various differential area-to-mass ratios for the spacecraft. Errors were calculated by dividing the difference in radial, along-track, or cross-track separation by the maximum separations. Fig. 1 shows the worst case errors produced by neglecting each of the perturbing forces after 30 days.

The SRP results in Fig. 1 arise from a case in which the area-to-mass ratio of one satellite is ten times that of the other. As the separation between the spacecraft decreases to zero, the effect of neglecting gravitational effects also decreases to zero; however, SRP effects do not decrease to zero if the area-to-mass ratios differ. Because of this, SRP effects should be taken into account if high accuracy is warranted over long periods or if the satellites are within several kilometers.

The effects of SRP on an orbit were formulated using Keplerian elements and the element differences, assuming that the latter quantities are small. However, because Keplerian elements are singular for $i = 0$ and $e = 0$, orbits in GEO can have large differences in Ω, ω, and M_0 and still remain within a few kilometers of each other. Simulations found that this formulation of SRP did not prove to be useful for GEO and therefore was not used in later tests. However, for most cases, two-body motion results in acceptably low error.
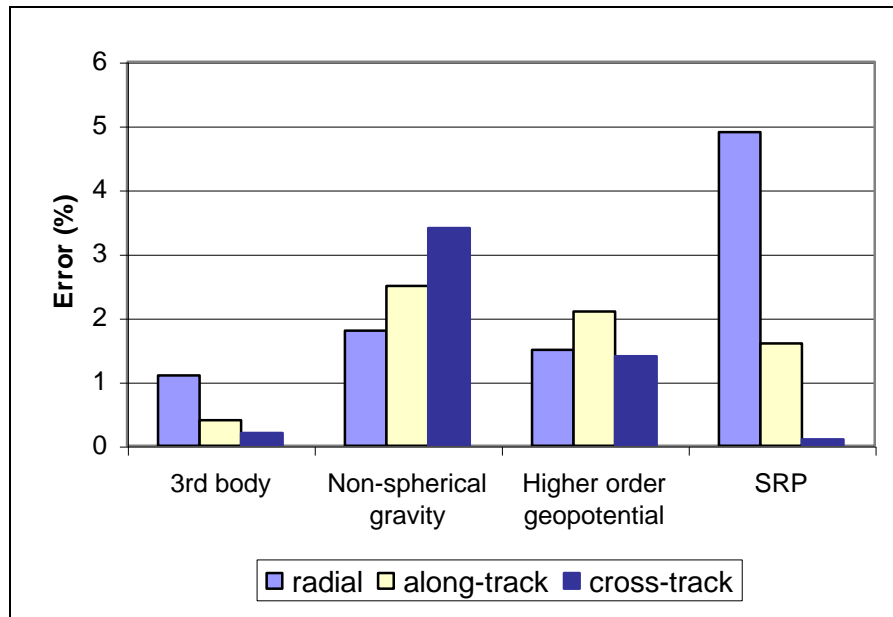
Figure 1 Maximum error encountered in the separation of two satellites at GEO due to the neglect of a perturbing force after a 30-day orbit propagation.

Another source of orbit perturbation is stationkeeping and momentum control maneuvers. Since maneuvers were not modeled in COWPOKE, they present an additional source of error if occurring during the observation period.

IMPROVED COWPOKE EQUATIONS

Although COWPOKE has been shown to be an effective predictor of the relative motion of a cluster of satellites, there are some sources of error. For GEO, the right ascension of the ascending node, argument of perigee, and mean anomaly element differences may not be small which violates the assumptions of the original COWPOKE derivation. In particular, the approximation of the true anomaly difference was linear in terms of the mean anomaly difference; this causes error, particularly in the along-track direction, when the mean anomaly difference is significant. The cross-track term component of COWPOKE also showed error with large right ascension differences.

Replacing the linear approximation of the true anomaly difference with an exact difference of the two true anomaly terms substantially reduced the along-track error. For the near-circular GEO case, the true anomaly of each satellite as a function of time is approximated by a first order expansion in terms of eccentricity and mean anomaly which was shown to be effective in Ref. 6. The cross-track component was

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improved by an investigation into the spherical geometry involved. Corrections were made to both amplitude and phasing of the cross-track component which are accurate for large values of right ascension of the ascending node, argument of perigee, and mean anomaly differences. The improved COWPOKE equations are

$$\delta r = \frac{(a+\delta a)\left(1-(e+\delta e)^2\right)}{1+(e+\delta e)\cos(M+2e\sin(M)+\delta v)} - \frac{a\left(1-e^2\right)}{1+e\cos(v)}$$

$$\frac{\delta xt}{r} = -2\sin\left(\frac{\delta\Omega}{2}\right)\sin(i)\cos\left(\omega+\frac{\delta\omega}{2}+M+2e\sin(M)+\frac{\delta v}{2}\right)$$
$$+\delta i\sin(\omega+\delta\omega+M+2e\sin(M)+\delta v) \qquad (1)$$

$$\frac{\delta at}{r} = (\delta\omega+\delta v)\cos(\delta i)+\delta\Omega\cos(i)$$

where

$$\delta M = \delta M_0 + \left(\sqrt{\frac{\mu}{(a+\delta a)^3}} - \sqrt{\frac{\mu}{a^3}}\right)t \qquad (2)$$

$$\delta v = \delta M + 2(e+\delta e)\sin(M+\delta M) - 2e\sin(M)$$

δr is the separation in the radial direction, δxt is the cross-track separation, and δat is the along-track separation. δv is the difference in true anomaly. a, e, i, Ω, ω, and M are the orbital elements of the reference satellite, and δa, δe, δi, $\delta\Omega$, $\delta\omega$, and δM are the differences in the elements of the two satellites. μ is the gravitational parameter, and t is the time elapsed since the epoch of M.

The along-track term still exhibits error when the $\delta\Omega$ and δi terms are large. To avoid this as an error source in the relative orbit determination experiments, it was decided to use the along-track component from Vadali's unit sphere model for relative motion.[11] The Vadali unit sphere model is very similar in philosophy to COWPOKE; relative motion is modeled through Keplerian elements and element differences. Vadali's geometric model, however, is more rigorous than the simple COWPOKE approach. Here is the along-track component of Vadali's unit sphere model which was incorporated into COWPOKE for the remainder of this analysis:

$$\frac{\delta at}{r} = \cos^2(i/2)\cos^2((i+\delta i)/2)\sin(\delta\omega+\delta v+\delta\Omega)$$
$$+\sin^2(i/2)\sin^2((i+\delta i)/2)\sin(\delta\omega+\delta v-\delta\Omega)$$
$$-\sin^2(i/2)\cos^2((i+\delta i)/2)\sin(2(\omega+v)+\delta\omega+\delta v+\delta\Omega)$$
$$-\cos^2(i/2)\sin^2((i+\delta i)/2)\cos(2(\omega+v)+\delta\omega+\delta v-\delta\Omega) \qquad (3)$$
$$+\frac{1}{2}\sin(i)\sin(i+\delta i)\left[\sin(\delta\omega+\delta v)+\sin(2(\omega+v)+\delta\omega+\delta v)\right]$$

DETERMINATION OF ELEMENT DIFFERENCES

Predicting the relative motion of a cluster of satellites with COWPOKE requires a set of orbital elements for the reference satellite and the relative elements of the second satellite. A least-squares orbit determination method was used to find these element differences.[12]

COWPOKE expresses spacecraft separations in the spherical radial, along-track and cross-track reference frame, but the optical observations used in this effort are in the topocentric right ascension and declination frame. Therefore, the topocentric observations had to be converted to geocentric observations, which requires satellite range knowledge as well as the local sidereal time.[13] For this analysis, a constant range value was used and values of UT1-UTC, precession and nutation angles, and lunar terms were ignored; it is believed that these approximations do not have significant impact once the observations are differenced. The COWPOKE cross-track and along-track separations could then be equated with the geocentric right ascension and declination frame as follows:

$$\delta\alpha = \delta at \cos\theta - \delta xt \sin\theta$$
$$\delta d = \delta xt \cos\theta + \delta at \sin\theta$$

(4)

where

$$\theta = i\cos(\omega + \upsilon)$$

(5)

Let Y be the relative observation vector, and X the state vector containing the orbital element differences. Eqs. (4) & (5) represent a nonlinear mapping between the state vector and the observations. In order to invert the problem, we must linearize the equations about a reference trajectory, X^*.

$$Y = \begin{bmatrix} \delta\alpha \\ \delta d \end{bmatrix} = F(X) \approx F(X^*) + \frac{\partial F}{\partial X}\bigg|_{X^*} (X - X^*)$$

(6)

$$X = \begin{bmatrix} \delta a & \delta e & \delta i & \delta\Omega & \delta\omega & \delta M_0 \end{bmatrix}^T$$

(7)

The $\delta\alpha$ terms are the observed differences in right ascension, and the δd are the observed differences in declination. Eq. (6) can be rearranged and terms can be redefined as follows:

$$Y - F(X^*) \approx \frac{\partial F}{\partial X}\bigg|_{X^*} (X - X^*)$$
$$y = Hx$$

(8)

where y is the difference between the observed and calculated relative observations, H is the linearized observation-state relationship, and x is the estimated correction to the state matrix. If at least 3 relative observation pairs are included in the y vector, one can estimate the state deviation as shown below:

$$x = \left(H^T H\right)^{-1} H^T y$$

(9)

The estimate of the state can be updated in an iterative fashion, as shown below, until the solution converges.

$$X^*_{i+1} = X^*_i + x$$

(10)

Using this method, an estimate of the Keplerian element differences was obtained. This method requires that the Keplerian elements of the reference satellite are known. The NORAD two-line element set (TLE) of the reference satellite was used for the reference orbit in this study. With the element differences, the relative right ascension and declination of the two satellites can be predicted using COWPOKE.

SIMULATION STUDY

In order to test the feasibility of using COWPOKE to better predict relative motion, a simulation was performed using 2 collocated geosynchronous satellites. Truth orbits were propagated using the Cowell Special Perturbations (SP) propagator internal to DGTDS. The truth orbits spanned from Jan 1 – Feb 5, 2003. Table 2 contains the osculating orbital elements for the satellites referenced to the mean equator and mean equinox of the B1950.0 coordinate system.

Table 2
THE INITIAL ORBITAL ELEMENTS OF THE TWO SATELLITES USED IN THE IDENTIFICATION STUDY WITH EPOCH JANUARY 1, 2003, 0 HR.

	Satellite1	Satellite2
Semimajor Axis (km)	42164	42164
Eccentricity	0.000512	0.000812
Inclination (deg)	0.05	0.05
Right Ascension of the Ascending Node (deg)	20	340
Argument of Perigee (deg)	33	67
Mean Anomaly (deg)	0	6

The next step in the process was to develop TLE representations of the truth orbits. This step was necessary since TLEs are used in the observation correlation process. To do this, an orbit using the GP4/DP4 propagator internal to DGTDS was fit to the position and velocity vectors produced by the Cowell truth trajectory. The position and velocity data spanned 1 Jan to 1 Feb and were spaced at every hour. The resulting fits were accurate to around the 2 km level RMS. Fig. 2 plots the DP4 trajectories relative to the truth orbit of Sat 1 over February 1-5, a 5-day prediction interval.

One can clearly see in Fig. 2 that the TLE trajectory for Sat 2 comes closer to the Truth location for Sat 1 than the Truth location for Sat 2 during a significant portion of the orbit. Similarly, the TLE trajectory for Sat 1 comes close to the Truth location for Sat 2 during a portion of the orbit. Both of these situations could lead to a cross-tag in the observation correlation process (i.e., observations of Sat 2 could be incorrectly attributed to Sat 1 and vice versa).
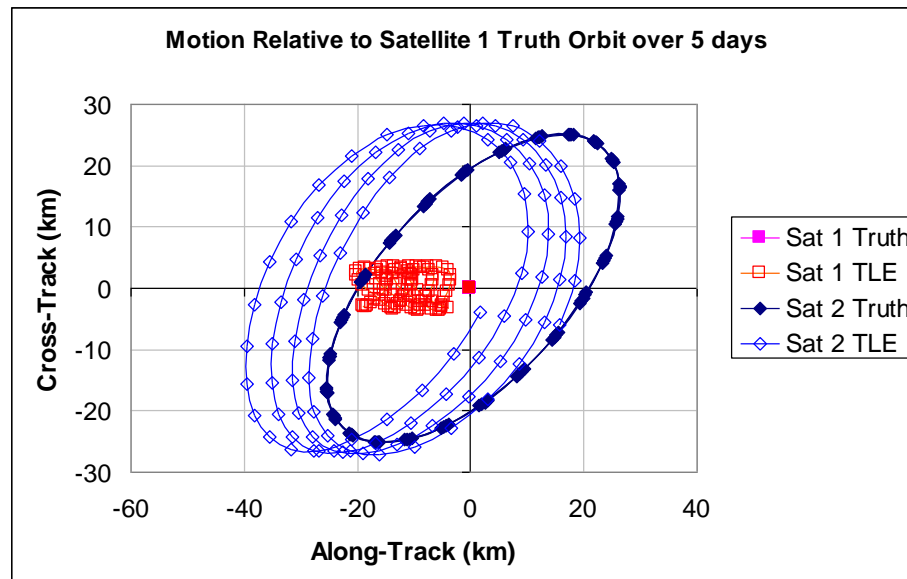
Figure 2 TLE orbit predictions of the motion of Satellite 2 relative to Satellite 1 truth orbit compared to the truth relative motion.

The mean orbital elements from the TLE fits (epoch 1 Feb) were differenced and used to initialize the COWPOKE equations along with the TLE elements for Sat 1. One can see in Fig. 3 that even using the flawed initial conditions produced by the TLE fits, the relative motion is very representative of the Truth relative motion. This signifies that the relative position is a powerful piece of information that can be used to help correlate optical observations at the sensor.
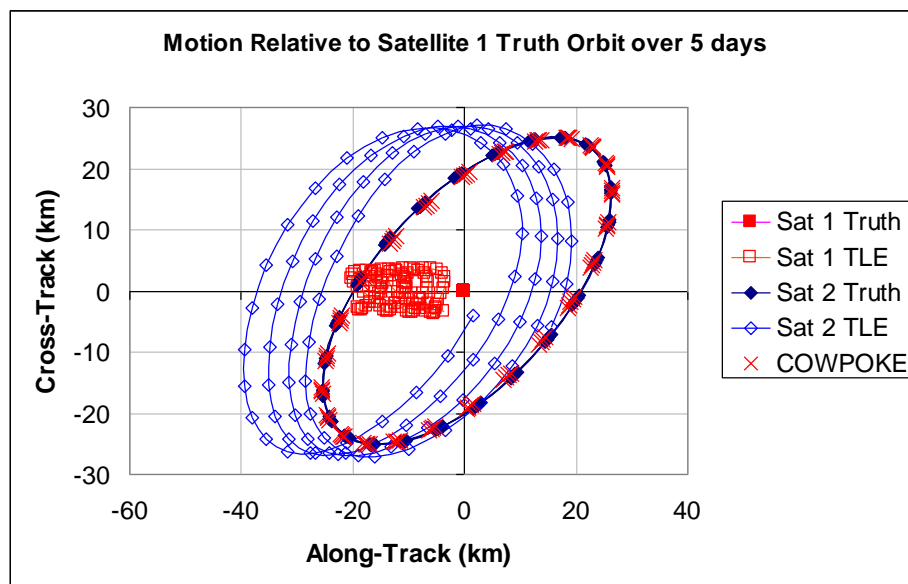

Figure 3   COWPOKE relative motion predictions with TLE and truth orbits.

REAL DATA RESULTS

Observations from Raven were used to test COWPOKE's effectiveness. Raven images were taken of the DirecTV 4S and AMC 4 spacecraft collocated at 101° West longitude during the nights of July 23-24 and July 29-August 1, 2003. One of these images is shown in Fig. 4.

Raven images were used to compute the separation of the two satellites. Sat 1, the reference satellite, was chosen to be AMC-4, and DirecTV 4S was designated Sat 2. The reference orbit for Sat 1 was generated using the TLE from July 20, 2003. Other TLEs might be available at an epoch closer to the 24th, but for R&D Raven operations, the catalog is only updated every few days. The observed separation in right ascension and declination on the night of the 23rd were used to estimate the Keplerian element differences. The observations from the 23rd didn't span a long enough period to accurately solve for the difference in semimajor axis, so an *a priori* estimate of 0 m was added for δa, with a standard deviation of 1000 km. With the resulting estimate of the element differences, COWPOKE was used to predict the relative position of the two satellites at the time of each observation taken on the night of the 24th. The COWPOKE predictions are compared to the positions predicted by the TLEs at the time of each observation in Fig. 5. The COWPOKE prediction of the location of Sat 2 was off by an average of 155 microradians, while the TLE predictions differed from the observations by an average of 576 microradians.
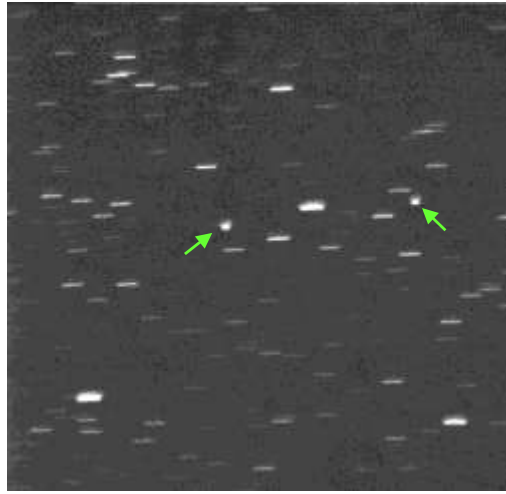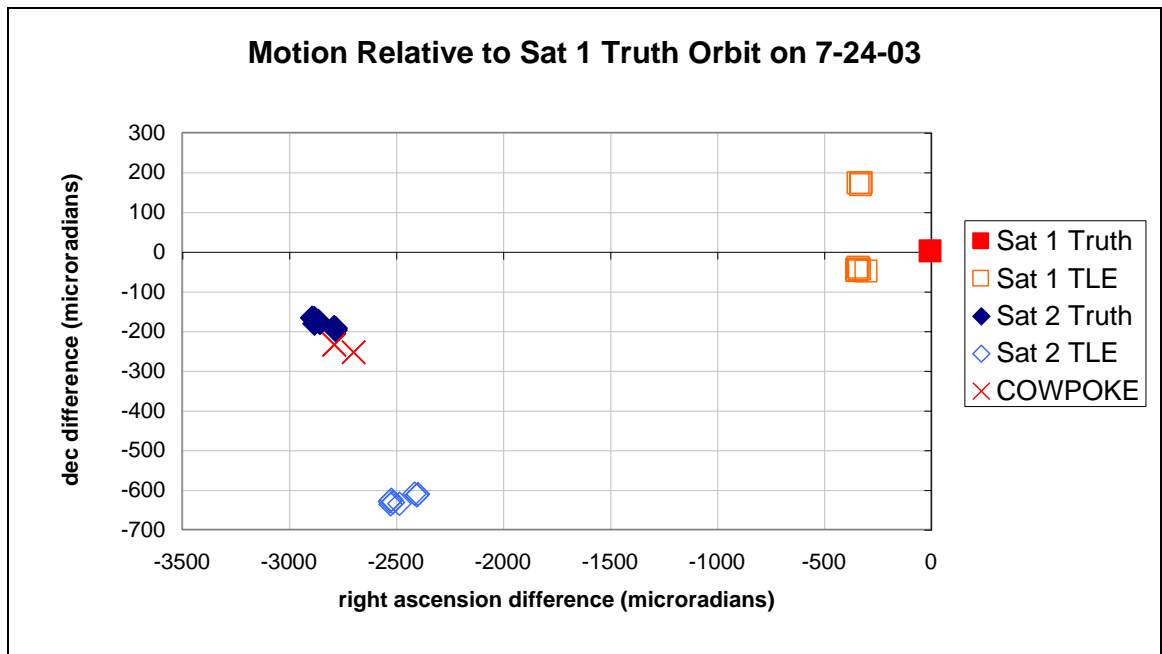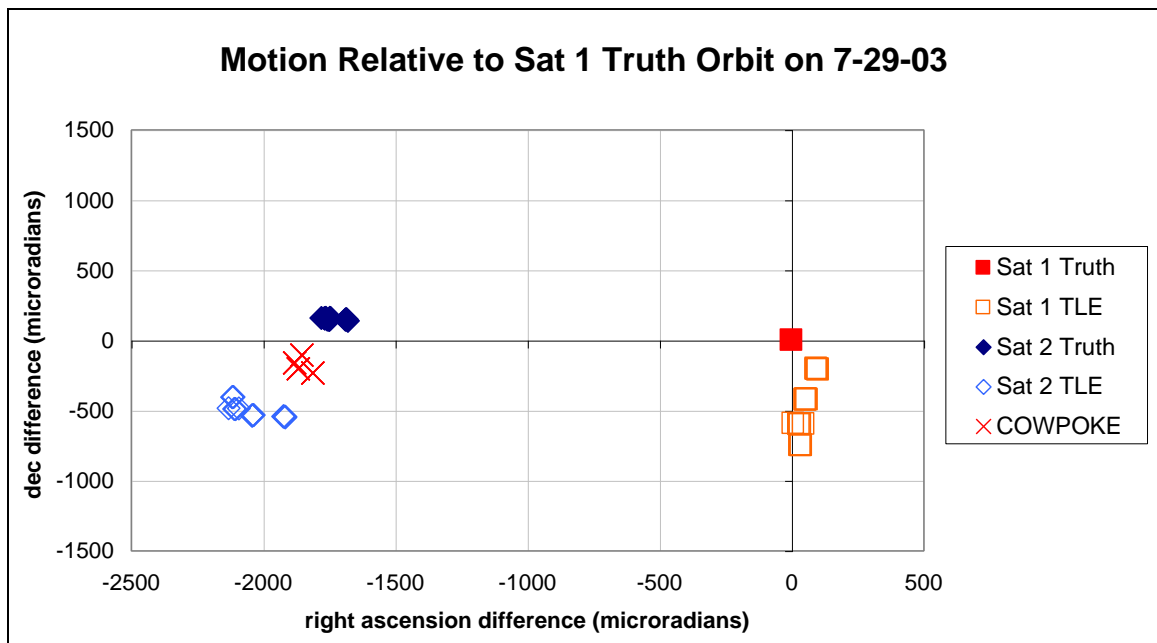
Figure 4 Raven image of AMC-4 and DirecTV 4S

Figure 5 COWPOKE's prediction of the position of Satellite 2 on July 24th compared to the TLE predictions

The observations from July 23 and 24 were used to estimate the element differences and predict the relative motion for July 29, when the next telescope images were taken. DP4 predictions and the COWPOKE reference orbit were obtained using TLEs for Sat 1 and Sat 2 from the 26th and 27th respectively. The results for the 29th are shown in Fig. 6. The COWPOKE predictions differed from the truth by an average of 390 microradians, while the TLE predictions were off by 721 microradians.
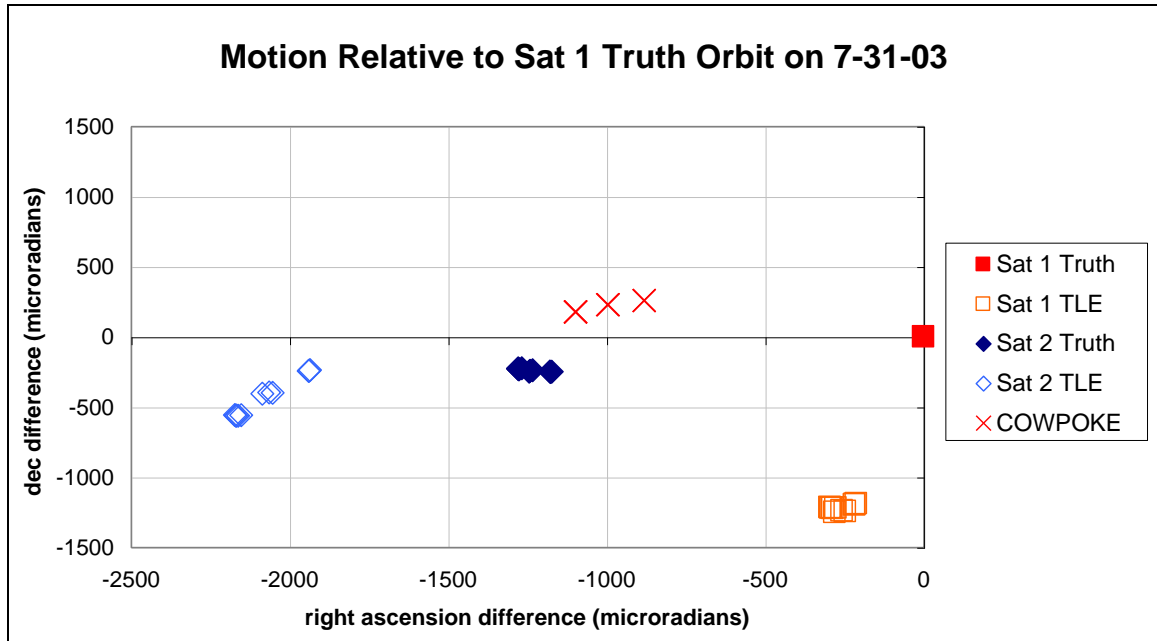
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Figure 6 COWPOKE's prediction of the position of DirecTV 4S on July 29 compared to the TLE predictions

The observations from July 23, 24, and 29 were then used to estimate improved element differences. Those element differences were used to predict the relative position of Sat 2 on the 30th, and the results are plotted in Fig. 7. COWPOKE had an average error of 300 microradians, and the TLE for Sat 2 averaged 894 microradians. Fig. 8 shows the results of similar predictions for July 31 using the observations from all previous nights. To be clear, the TLE prediction span at this point is several days while the COWPOKE prediction is only one day.
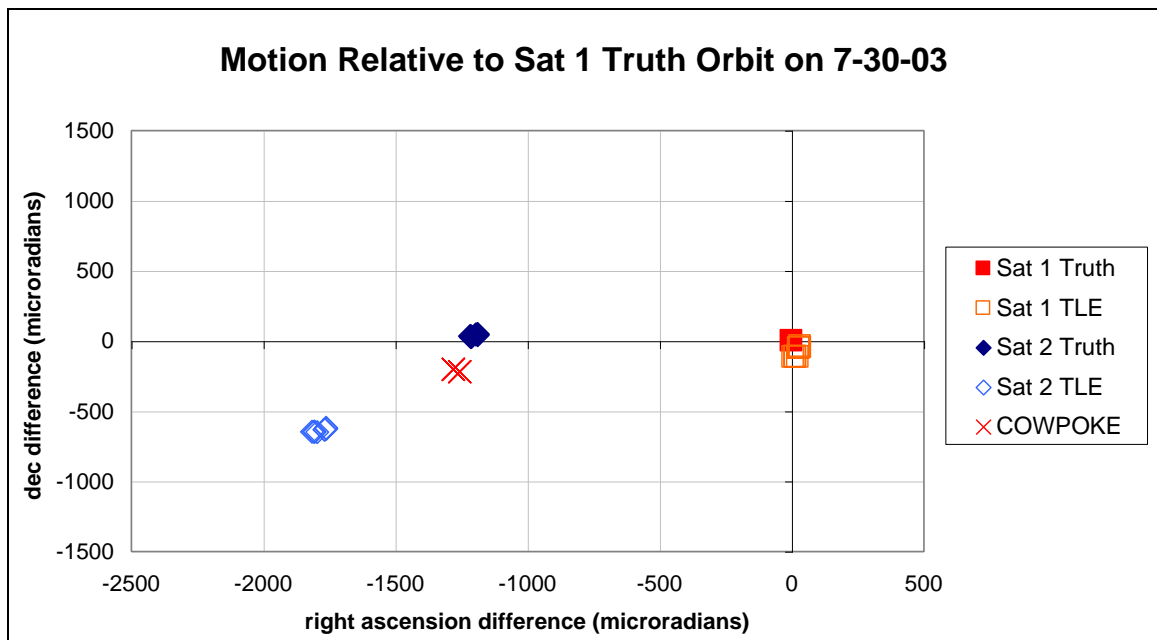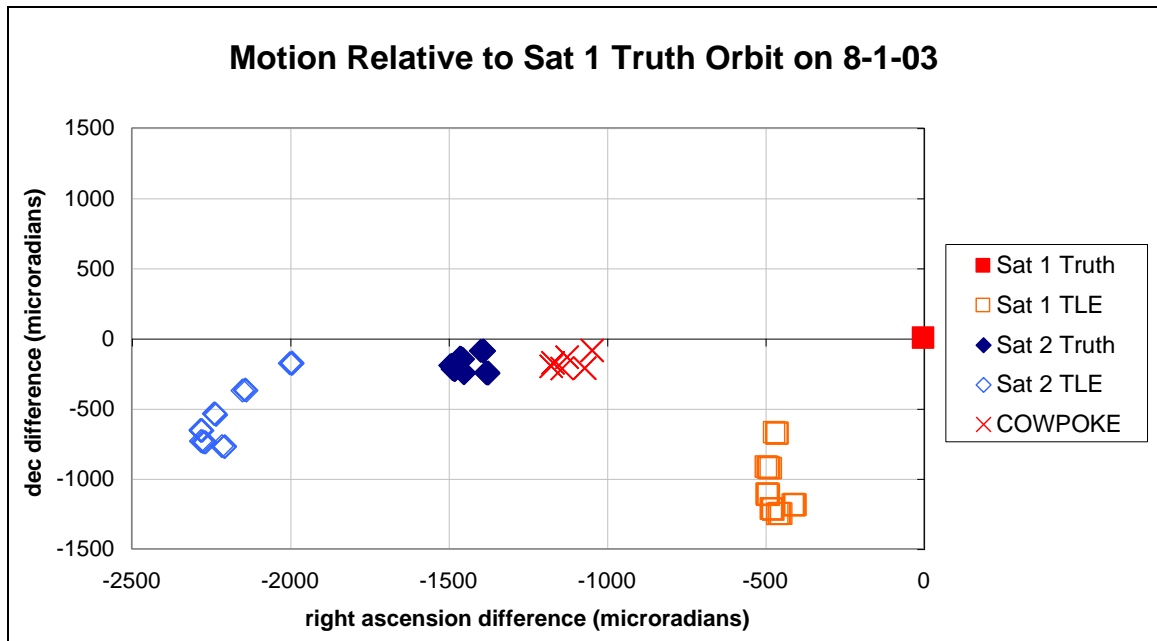

Figure 7 COWPOKE's prediction of the position of DirecTV 4S on July 30 compared to the TLE predictions

In Fig. 8, one can see that the true position of Sat 1 has shifted away from the TLE prediction since the night before. Also, the COWPOKE prediction no longer matches the observation for Sat 2, especially in declination. There is strong evidence that Sat 1 performed a stationkeeping maneuver between the 30th and the 31st. Even with the possible maneuver, COWPOKE still provided a better estimate of the relative motion than the TLE. COWPOKE had an average error of 450 microradians, and TLE for Sat 2 averaged 869 microradians.

Figure 8 COWPOKE's prediction of the position of DirecTV 4S on July 31 compared to the TLE predictions

Whatever the cause of the sudden shift, it was decided to start a new fit span. Only the observations from the night of the 31st were used to solve for the new element differences, and these were propagated forward with COWPOKE to the 1st of August. The COWPOKE and TLE predictions for that night are compared to the observations in Fig. 9. COWPOKE had an average error of 210 microradians, and the TLE for Sat 2 averaged 958 microradians. One of the advantages of COWPOKE is that the effects of maneuvers can be mitigated by using a one day fit span while TLEs typically use a longer fit span and will suffer the effects of maneuvers continuously.

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Figure 9 COWPOKE's prediction of the position of DirecTV 4S on August 1 compared to the TLE predictions

While the COWPOKE results are somewhat encouraging when compared to the TLE's, the overall performance is not as good as expected. Perturbation analysis indicate that the equations should be accurate with only a few percent error. The simulation results showed similar error levels. If the relative orbit estimation algorithms were functioning properly, one would expect to see results with errors at the few percent level. For the one day fit cases shown in Fig. 5 and 9, larger errors might be expected due to limited observability over a short data arc. For the five day prediction case shown in Fig. 6, one might also expect to see larger errors due to the prediction interval. Then there is the case, shown in Fig. 8, where the reference satellite appears to maneuver; this would also cause prediction error. However, one case remains, shown in Figure 7, where several days of data are used in the estimation process and the prediction interval is only one orbit; the COWPOKE prediction error is as large as all of the other cases and is around 10% of the separation distance. This is larger than expected and indicates that there may be an unknown error source in the algorithm or software tools. Regardless, efforts must be made to better understand the limitations of this approach.

CONCLUSIONS AND FUTURE WORK

This work has shown that the COWPOKE equations can be used to provide meaningful relative motion of geosynchronous satellite clusters. Perturbation analysis indicated that 2-body dynamics are adequate for medium accuracy applications. Improvements were made to the equations, however, to account for large right ascension of the ascending node, argument of perigee, and true anomaly element differences.

Estimating the Keplerian element differences and using the COWPOKE equations to predict the relative motion can supply valuable information in spacecraft identification. Using six nights of Raven images, it is shown that COWPOKE estimated the position of DirecTV 4S relative to AMC-4 much better than TLE predictions, even with unmodeled maneuvers. This indicates that COWPOKE holds the potential to be a valuable space surveillance tool.

Sizable error still remains in the relative orbit prediction results. These errors are larger than anticipated so care must be taken to detemine the major source of this error and remove it. If this can be accomplished, the relative orbit estimation approach will be far more valuable. Beyond those improvements, the effects of differential SRP should be formulated for circular, equatorial orbits to better predict the motion of GEO clusters.

ACKNOWLEDGMENTS

REFERENCES

1. Pattinson, L., V. Chechik, "Eutelsat Satellite Collocation," AIAA/AAS Astrodynamics Specialist Conference, Quebec City, Canada, August 2001, AAS 01-317.
2. Sabol, C., Burns, R., Wallace, S., "Analysis of the Telstar-401/GOES-10 Close Approach Using the Raven Telescope", AAS/AIAA Space Flight Mechanics Meeting, Monetery, CA, February 9-11, 1998, AAS 98-118.
3. Abbot, R., R. Clouser, E. Evans, J. Sharma, "Close Geostationary Satellite Encounter Analysis: 1997-2001," AAS/AIAA Space Flight Mechanics Meeting, San Antonio, TX, 27-30 January 2002, AAS 02-115.
4. Gist, R., D. Oltrogge, "Risk Management of Unintentionally Collocated Geosynchronous Spacecraft," AIAA/AAS Astrodynamics Specialist Conference, Quebec City, Canada, August 2001, AAS-01-321
5. Payne, T.E., Gregory, S.A., et al., "Space Object Identification of Geosynchronous Satellites," *Proceedings of the 1999 AMOS Technical Conference*, Maui, Hawaii, August-September 1999, pp. 195-203.
6. Sabol, C., C. McLaughlin, K. Luu, "Meet the Cluster Orbits With Perturbations Of Keplerian Elements (COWPOKE) Equations," AAS/AIAA Spaceflight Mechanics Conference, Ponce, Puerto Rico, February 9-13, 2003, AAS-03-138.
7. Sabol, C., Luu, K., Kervin, P., Nishimoto, D., Hamada, K., Sydney, P., "Recent Developments of the Raven Small Telescope Program," AAS/AIAA Space Flight Mechanics Meeting, San Antonio, Texas, January 2002, AAS 02-131.
8. Law, B., et al, "The Phoenix System: Development of a Wide-Field Optical Sensor," *Proceedings of the 2002 AMOS Technical Conference*, Wailea, HI, 16-20 September 2002.
9. Hill, K., et al, "Relative Orbit Trajectories of Geosynchronous Satellites using the COWPOKE Equations," *Proceedings of the 2003 AMOS Technical Conference*, Wailea, HI, 8-12 September 2003.
10. Sabol, C., S. Carter, and M. Bir, "Analysis of Preselected Orbit Generator Options for the Draper Semianalytic Satellite Theory," AIAA/AAS Astrodynamics Specialist Conference, Denver, Colorado, August 2000, AIAA-2000-4231.
11. Vadali, R., "An Analytical Solution for Relative Motion of Satellites," DCSSS Conference, Cranfield University, Cranfield, UK, July 2002.
12. Born, G., B. Tapley, B. Schutz, "Fundamentals of Orbit Determination, Class Notes for ASEN 5070." University of Colorado, Fall 2002.
13. Roy, A. E., *Orbital Motion*, J W Arrowsmith Ltd, Bristol, Great Britain, 1988.