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Volume 11, Analysis of Selected Orbit Propagation Models for the SeaWiFS Mission

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ABSTRACT

An analysis of orbit propagation models was performed by the Mission Operations element of the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project, which has overall responsibility for the instrument scheduling. The orbit propagators selected for this analysis are widely available general perturbations models. The analysis includes both absolute accuracy determination and comparisons of different versions of the models. The results show that all of the models tested meet accuracy requirements for scheduling and data acquisition purposes. For internal Project use the SGP4 propagator, developed by the North American Air Defense (NORAD) Command, has been selected. This model includes atmospheric drag effects and, therefore, provides better accuracy. For High Resolution Picture Transmission (HRPT) ground stations, which have less stringent accuracy requirements, the publicly available Brouwer-Lyddane models are recommended. The SeaWiFS Project will make available portable source code for a version of this model developed by the Data Capture Facility (DCF).

1. INTRODUCTION

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project is a Code 970.2 activity at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC). The primary responsibility of the Mission Operations element is to provide command schedules to maximize performance. Producing these command schedules requires the propagation of orbit positions over periods of days to weeks. It is of central importance to the successful performance of Mission Operations to select and use an orbit propagation model that will be accurate over these time scales.

A secondary responsibility of the Mission Operations element is to provide pointing vectors and orbit models to worldwide ground stations to enable the acquisition of SeaWiFS data, which are directly broadcast in real time. These direct broadcast data are in High Resolution Picture Transmission (HRPT) format. The time scales for these activities are typically much less than for command planning (usually less than three days).

The purpose of this paper is to assess several widely available orbit propagation models for use by Mission Operations. Selection of orbit models for use by Mission Operations follows three steps: 1) collect requirements for performance, 2) assess availability of candidate models, and 3) analyze performance in relation to requirements. This analysis was a joint effort by the Mission Operations element and the SeaWiFS Data Capture Facility (DCF), which is responsible for supporting the HRPT ground stations and has also implemented some of the tested orbit prediction models.

2. BACKGROUND

SeaWiFS is designed to make routine, global observations of ocean color for a five-year mission lifetime. It is a follow-on sensor to the highly successful Coastal Zone Color Scanner (CZCS), which was carried on NIMBUS-7 in operation from 1978 to 1986. The SeaWiFS instrument will be contained on the SeaStar spacecraft, on which it is the sole occupant.

In a unique arrangement, the sensor, spacecraft, and launch vehicle (Pegasus) are being built and will be operated by Orbital Sciences Corporation (OSC) of Chantilly, Virginia. NASA's role will be to purchase the SeaWiFS data from OSC and provide command schedules to enable global coverage of the Earth and facilitate calibration of the sensor. Mission Operations serves as the component which determines these schedules and passes them to OSC for uploading.

SeaStar will be placed in a 705 km, sun-synchronous, near-local-noon descending node orbit. These and other orbit characteristics are summarized in Table 1.

Table 1. SeaStar spacecraft orbit parameters.

Orbit Parameter	*Value*
Altitude	705 km
Eccentricity	< 0.002
Orbital Repeat Time	16 days (233 orbits)
Period	98.9 minutes
Inclination	98.2°
Equator Crossing Time	Noon Local Time
Node Type	Descending
Successive Equatorial Crossing Longitude	−24.721°

2.1 Mission Operations

As stated earlier, the primary role of the Mission Operations element is to provide OSC with schedules of command sequences to maximize the coverage and scientific usefulness of SeaWiFS data and ensure data acquisition. All of these commands are scheduled according to viewing conditions or events which are a direct function of the spacecraft orbit position. The commands under the responsibility of Mission Operations include: sensor electronics on and off times, data down-link times at NASA's Wallops Flight Facility (WFF), tilt change times, gain changes, calibration times, and broadcast times for research HRPT stations.

2.2 Orbit Propagation Models

There are basically two classes of orbit propagation models: general perturbations models (GPMs) and special perturbations models (SPMs). GPMs are reformulations of the equations of motion so that an analytical solution may be found. Typically, they include only the perturbing forces of a low order Earth gravity field, although, some also may contain atmospheric drag. A common example is the Brouwer-Lyddane model. GPMs are fast and computationally inexpensive at the cost of a reduction in accuracy.

SPMs are characterized by the requirement of numerical integration of the equations of motion. Such methods are computationally expensive and output is much slower than for GPMs. The advantage is that they can take into account more perturbing forces, such as a high-order Earth gravity field, multiple body gravitational forces, atmospheric drag, solar radiation, tides, and others. Consequently, SPMs can be very accurate, but they can also be more unstable and are intimately sensitive to the initial conditions.

2.3 Orbital Elements

A spacecraft orbit can be parameterized in several ways. Three common representations are: mean element sets, osculating elements, and orbit state vectors. Both mean and osculating element sets include the six classical Keplerian elements (semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of perigee and mean anomaly), but in fact they have quite different interpretations. Mean element sets represent an average of the orbit and are specifically designed for use with GPMs. Commonly distributed orbital elements sets by the U.S. Space Command (formerly the North American Air Defense, or NORAD), Naval Space Surveillance (NAVSPASUR), and the National Oceanic and Atmospheric Administration (NOAA) are all mean elements. Mean element sets are not used directly to compute the spacecraft position, but are converted to osculating elements for this purpose.

Osculating elements are an instantaneous Keplerian representation of the orbit; the osculating elements vary significantly over the orbit for low Earth spacecraft and are not readily propagated. Orbit state vectors are defined as the Cartesian position and velocity vectors in the geocentric reference frame. Orbit state vectors are frequently used as the input to SPMs and are the standard output for all models. Orbit state vectors, or derived quantities such as latitude, longitude, and altitude, are the information required for scheduling.

The SeaWiFS Project has two potential sources of orbital parameters: distributed element sets such as those from NORAD or NAVSPASUR, or the Global Positioning System (GPS) data included in the spacecraft down link. While the GPS data is considered the primary source of orbit position information for navigation, at present there is no proven method for using this data in an orbit propagation model. Thus, distributed element sets are to be considered the first choice of orbit parameters.

2.4 Requirements Analysis

The most critical requirement for orbit propagation accuracy is to provide antenna pointing information for the down-link times at WFF. The Wallops antenna to be used for acquisition of SeaWiFS data is 9 m in diameter and autotracking with x-y tracking capability. The requirements for acquisition of data by this antenna are 3 seconds along track, and 0.5° in azimuth, for a two-day propagation. A lesser requirement is to provide predicted down-link times three weeks in advance for conflict analysis, for which the accuracy required is two minutes along track. The requirement for acquisition sets the limit for accuracy for the mission; none of the other commands have such a stringent accuracy requirement.

Regarding HRPT ground stations, the SeaStar satellite L-band down-link has been designed to resemble all of the transmission parameters of the TIROS satellites. This was done in order to minimize the impact on small satellite ground stations around the world. The SeaWiFS Project, in turn, has adopted the TIROS data quality requirements, with a maximim bit error rate (BER) of 10^{-6}. In order for this BER to be met, OSC has suggested the system gain to total system noise temperature (G/T), a measure of a ground station's quality performance, should be not less than 6.0.

The antenna tracking requirements are given next. The L-band tranmission parameters are given in Table 2.

Table 2. SeaStar L-band transmission parameters.

Parameter	*Value*
Frequency	1207.5 MHz ±34.05 KHz
Polarization	Right-Hand Circular
Bandwidth	1.2 MHz (−3 db)
Data Rate	665.4 Kbps

The pointing accuracies required for various recommended antenna dish sizes (including 1° of buffer) are shown in Table 3.

Table 3. Pointing accuracies for different dish sizes.

Dish Size [ft]	*Pointing Accuracy [°]*
8	3.31
6	4.75
5	5.88

The SeaWiFS Project does not recommend using an antenna dish size of less than 5 ft since the BER of 10^{-6} is not guaranteed unless the system noise temperature is extremely low.

These requirements are interpreted in terms of orbit prediction accuracies as follows.

1. The 3-second timing requirement, for a typical orbit velocity of 7.5 km s^{-1}, corresponds to 22.5 km along track.
2. The 0.5° azimuth error requirement at acquisition can also be evaluated in terms of along-track errors. At the planned SeaStar altitude, the station-to-satellite distance is approximately 2,500 km at a typical acquisition of 5° above the horizon. 0.5° of azimuth error corresponds to 21.8 km of error in the predicted satellite position perpendicular to the line of sight.
3. For the HRPT stations, the 8-foot dish has the most stringent requirement at 3.31°; assuming that small stations do not have autotracking antennas, this requirement would have to be met by the orbit propagator throughout the contact. The orbit propagation errors would have maximum effect when the satellite is directly overhead; at an altitude of 705 km, 3.31° corresponds to 40.7 km.

Thus, the WFF acquisition timing and azimuth requirements are most stringent and roughly equal in terms of orbit propagation accuracy.

2.5 Approach

The approach presented here is limited to assessing the feasibility of several widely available GPMs. The fast, computationally inexpensive analytical solutions of such models, in conjunction with mean element sets, are appealing if the requirements can be met.

3. METHODS

3.1 Selection of Models for Evaluation

The selection of orbit propagation models for evaluation was based on the following criteria:

a) Availability of source code; this was necessary to allow the model to be configured as either a standalone program or a subroutine, to enable it to be run on any of several platforms and also to allow the format of the output to be closely tailored to the needs of Mission Operations;

b) Use of known methods and models, with references to published derivations or specification; and

c) Compatibility with readily available orbital element sets.

For the last criterion, either NORAD two-line element sets or Navy elements from NAVSPASUR were considered as readily available for SeaWiFS. The so-called TBUS elements provided by NOAA for their satellites were not considered, because NOAA is not expected to provide this service for SeaWiFS.

Two orbit propagation models were selected for evaluation; each was available in two separate implementations. The first was a standard Brouwer-Lyddane model, an analytic propagator which does not include atmospheric drag. The two implementations of this were as follows: a set of routines previously developed by one of the authors (Hoisington) for the DCF, using the original published work of Brouwer (1959) and Lyddane (1963), and also specifications for the Goddard Trajectory Determination System (GTDS) (Cappellari et al. 1976); and the BRWLYD routine developed by NOAA (Kidwell 1991). The latter model is presumably already widely used in the NOAA and Advanced Very High Resolution Radiometer (AVHRR) user communities. Brouwer-Lyddane propagators use a mean element set as input; the derivation of this set from NORAD two-line elements is discussed below.

The second model was the SGP4 low Earth orbit model developed by NORAD Project Spacetrack. This is a modified Brouwer propagator, which includes an atmospheric drag term, and is specifically designed to be compatible with NORAD element sets. This model was also implemented by Hoisington for the DCF from NORAD documentation (Hoots and Roehrich 1980). After the evaluation was started, an updated version of the SGP4 source code was obtained directly from Project Spacetrack and was used for additional testing.

As a side note, the SGP4 orbit model has restrictions placed on its use—it can only be used by U. S. government agencies and their contractors.

3.2 Orbital Elements Used for Evaluation

The evaluations were performed using NORAD two-line element sets for the following NOAA and Land Resource Satellite (LANDSAT) spacecrafts: NOAA-12, which is in a polar orbit at a higher altitude than planned for SeaStar (822 versus 705 km); and LANDSAT-4 and 5, which are in very similar orbits to that planned for SeaStar. Element sets were available at frequent intervals for all three satellites.

The LANDSAT satellites perform regular orbit adjustment maneuvers, making extended evaluations impossible, since no thrust model is available. NOAA-12 is completely free flying, but at its higher altitude it is expected to experience a lower atmospheric drag effect. Thus, the NOAA-12 elements were used for extended studies, while the LANDSAT elements were used for short-term (up to 10 days) analyses, as possible between orbit maneuvers, and also to validate the evaluation performed with the NOAA-12 elements. The actual element sets were obtained from a bulletin board maintained by GSFC Code 513, and spanned the dates of July 1 through November 16, 1992.

The use of the NORAD two-line element sets for the Brouwer-Lyddane models required a conversion since the NORAD elements are not explicitly mean element sets. Specifically, the mean motion provided with the NORAD elements sets must be converted to a semi-major axis. This conversion does not use the classical form, as described for Keplerian orbits in standard textbooks. The actual conversion was taken from the SGP4 source code and uses the mean motion, inclination, and eccentricity (a detailed description is provided in Appendix A). Mean element sets derived in this manner were found to be entirely satisfactory for use in the Brouwer-Lyddane model.

3.3 Constants Used in Models

All of the models utilize constants to specify the gravitational field terms and Earth radius. In order to compare the various models and implementations, it was necessary to choose a consistent set of constants. The constants selected were taken from the system accepted by the International Astrophysical Union (IAU) in 1976 and published in the 1984 Astronomical Almanac (see Table 4).

Table 4. Modeling constants for the Earth.

Constant	*Value*
Radius, R_e	6,378.137 km
Gravitational Constant, G_e	398,600.5 $\mathrm{km}^3\ \mathrm{s}^{-2}$
Gravity Field Terms:	
$J2$	0.0010863
$J3$	−0.0000254
$J4$	−0.0000161

The Brouwer-Lyddane models also include a $J5$ gravity field term, which was not specified in the IAU system of constants; both of the versions tested had this constant specified, but with different values. These constants were retained for the absolute accuracy analyses, but for comparison purposes they were set to zero.

3.4 Evaluation Methods

The evaluation was performed in two parts: 1) determination of the absolute propagation accuracy of each model, and 2) comparison of the propagations between the models. The former was used to determine whether the models would meet the accuracy requirements for SeaWiFS Mission Operations, while the latter was performed mainly to compare different implementations of the same model.

The final output of each model is in the form of Cartesian orbit state vectors (position and velocity) in the geocentric inertial reference frame. The two parts involved a somewhat different approach to selecting the orbit vectors used for the comparisons, but in each case the actual vector comparisons were identical.

Determining the absolute accuracy of a propagated orbit requires the availability of a *truth* model. All of the orbit information for the subject spacecraft was obtained from the same source: the NORAD two-line elements sets. NORAD elements are intended to support scheduling requirements, as described earlier, not high-accuracy applications (such as navigation). In fact they are believed to be degraded at the level of a few kilometers. This is still sufficient to determine whether the propagated orbit meets the SeaWiFS scheduling requirements, which are on the order of tens of kilometers.

The use of NORAD elements at epoch as a truth model would be ideally validated by comparison with an external source of orbit data. While SeaWiFS Mission Operations does not have access to independent data sources for the NOAA-12 and LANDSAT orbits used for this analysis, an evaluation of GPS data from the Extreme Ultraviolet Explorer (EUVE) satellite is currently being performed. The NORAD elements for EUVE are also available, but at longer intervals than for the NOAA-12 and LANDSAT elements. However, the GPS data, which spans the epoch time for a few of the NORAD element sets, demonstrates that the elements are accurate to within one kilometer at epoch.

It was therefore assumed that the orbit vector determined from each element set at its epoch time would be a reasonable truth model since no propagation was involved, just a conversion from mean elements to vectors. Thus, the approach in determining absolute propagation accuracy was as follows. For each element set, an orbit state truth vector was computed at the epoch time. Then each element set was used to propagate the orbit to the epoch time of every other element set. This generated a number of orbit vectors representing various propagation times, all of which were compared with the truth vectors.

The comparisons between models used a simpler approach. For a given element set, orbit vectors were generated at fixed intervals for a specified period using each model. In this type of evaluation, no particular set of vectors could be designated as truth, since all were generated by propagation; the point is to compare vectors from different models which have been propagated for the same time since epoch.

For both types of evaluations, the comparisons were performed as follows. The difference between two orbit position vectors was computed by subtracting each Cartesian component (for the absolute accuracy evaluation the truth vector was subtracted from the propagated vector; for the comparisons the order of subtraction is purely arbitrary). The difference vectors were then converted to along track, cross track and radial (i.e., in the direction of the position vector) components. Determination of these components was performed by first determining the unit vectors in the directions of the orbit velocity, orbit normal (computed as the vector cross product of the position and velocity vectors), and orbit position. Specifically, for position and velocity vectors $\vec{P}$ and $\vec{V}$, and an orbit position difference vector $\vec{D}$,

$$\vec{O} = \vec{P} \times \vec{V}, \tag{1}$$

$$D_{\mathrm{at}} = \vec{D} \cdot \frac{\vec{V}}{|V|}, \tag{2}$$

$$D_{\mathrm{ct}} = \vec{D} \cdot \frac{\vec{O}}{|O|}, \tag{3}$$

and

$$D_{\mathrm{rad}} = \vec{D} \cdot \frac{\vec{P}}{|P|}, \tag{4}$$

where D_{at} is the along-track position difference, D_{ct} is the cross-track position difference, and D_{rad} is the radial position difference.

4. RESULTS AND DISCUSSION

The orbit propagation accuracy requirements for SeaWiFS are stated for periods of 7 and 21 days. The results are shown for periods of 10 and 30 days, to demonstrate how well the requirements are met beyond the minimum times. Along-track propagation differences are expressed in both kilometers and seconds, since the primary accuracy requirements are stated in terms of timing errors.

4.1 Absolute Accuracy Results

This evaluation used 70 sets of NOAA-12 NORAD elements spanning the period July 1 through November 16, 1992. The plots of absolute along-track propagation errors versus days since epoch for NOAA-12 are shown in Figs. 1–8. The results produced by SGP4, DCF/SGP4, DCF/Brouwer, and NOAA/Brouwer are shown for propagations of 10 and 30 days.

The most significant factor in the absolute accuracy of the orbit propagations is the presence of a drag term in the SGP4 routines and the lack of such a term in the Brouwer-Lyddane routines. The drag model allows the mean along-track propagation error of the SGP4 routines to be near zero, even after 30 days, while the Brouwer propagations always show systematic (negative) errors, with what appears to be a second order time dependence.

All of the models met the stated timing accuracy requirements of 3 seconds after 2 days and 120 seconds after 21 days. In fact, the 3-second requirement for acquisition was not exceeded for more than 7 days in all cases. The largest errors observed after 7 days were approximately 10 km, or 1.5 seconds, for both of the SGP4 routines and 15 km, or 2 seconds, for DCF/Brouwer. After 21 days, the largest errors were less than 15 seconds for all models. The plots for the SGP4 models showed a dispersion around roughly zero mean (Figs. 1–4), while the Brouwer models clearly showed the consistent degradation in accuracy from the lack of a drag term (Figs. 5–8).

The azimuth requirement, equivalent to 21.8 km along track after 2 days, was also met by all of the models as shown by Figs. 1–8. The maximum errors after 7 days were approximately 10 km for the SGP4 models and 12 km for the Brouwer models.

The most stringent HRPT station requirement, which is 40.7 km along track for an 8-foot dish, was easily met by all models well beyond 7 days. The Brouwer propagation errors were less than 40 km. for approximately 12 days, while the SGP4 models meet this requirement for at least two weeks.

The other components of the propagation errors (cross track and radial) were consistently much smaller than the along-track errors, by as much as two orders of magnitude. Sample plots of the cross-track and radial errors for DCF/SGP4 over 30 days are shown in Figs. 9 and 10. The maximum cross-track errors at 7 and 21 days were less than 0.5 km and slightly more than 1 km, respectively, while the radial errors were less than 0.5 km and 1 km, respectively. Thus, the effects of orbit propagation on timing and antenna pointing can be assumed to be almost exclusively a result of the along-track errors.

However, even with the SGP4 models, there are substantial variations in the effectiveness of the drag model. This depends on the accuracy of the drag term included in the NORAD element sets. (This term is usually referred to as `BSTAR` in the documentation and code; no units are given.) Examination of the `BSTAR` term for the NOAA-12 element sets showed large variations around the average, ranging from near zero to approximately double the average value. The performance of the SGP4 propagation correlates very closely with these variations in the `BSTAR` term; the points on the SGP4 plots which show the largest negative trend correspond to a `BSTAR` of approximately zero, and show essentially the same behavior as the Brouwer model (see Figs. 2 and 4).

The cause of the large variations in `BSTAR`, which is determined by NORAD along with the other elements, is unknown. In practice, the extreme values of `BSTAR` can easily be found by a cursory examination of the elements and rejected; this was not done for this evaluation to avoid skewing the results in favor of the SGP4 model. Filtering of the elements sets in this manner would be expected to reduce the maximum SGP4 propagation errors to less than 1 second at 7 days and less than 10 seconds at 21 days, respectively.

As mentioned previously, the NOAA-12 orbit is higher than the altitude planned for SeaStar (approximately 822 versus 705 km). The atmospheric drag at the higher altitude would be expected to be lower, and therefore the propagation errors for NOAA-12 may not be considered truly representative for SeaStar. The LANDSAT-4 and 5 orbits are much closer in altitude to SeaStar; however, due to the regular performance of orbit maintenance maneuvers, it is not possible to perform 30-day evaluations using LANDSAT elements. An evaluation was performed using

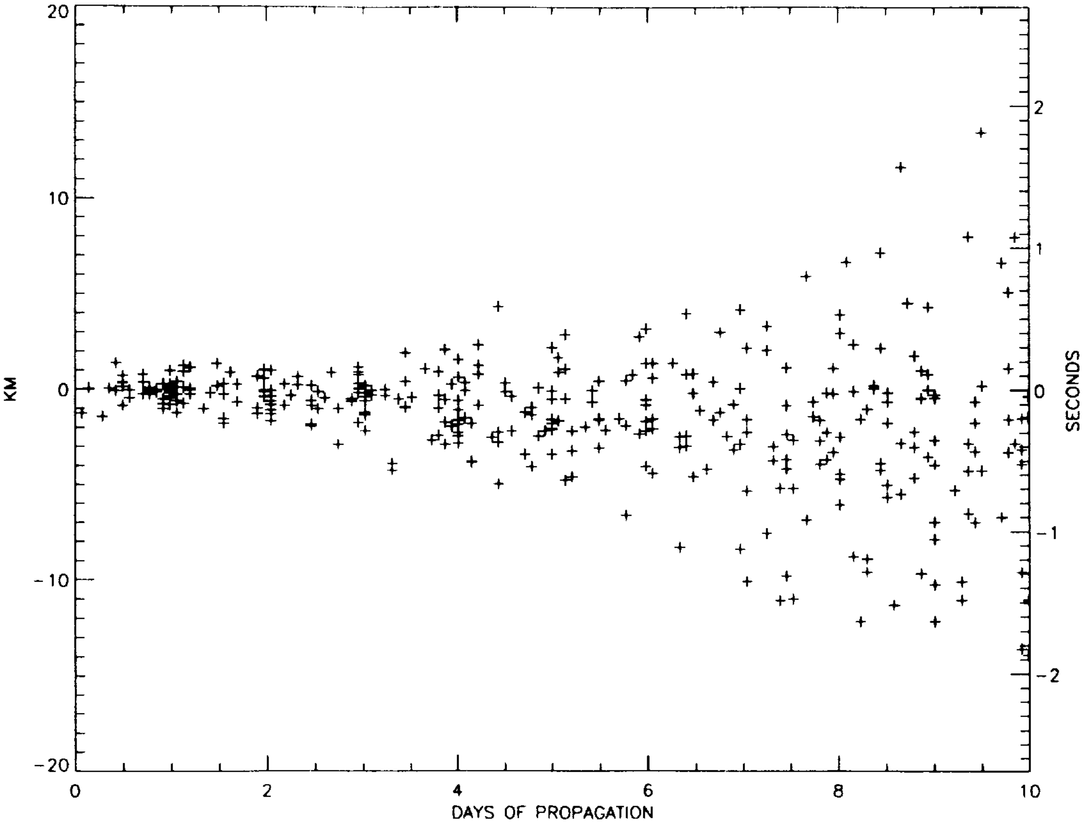

Fig. 1. SGP4 along-track propagation errors for NOAA-12: 0–10 days.

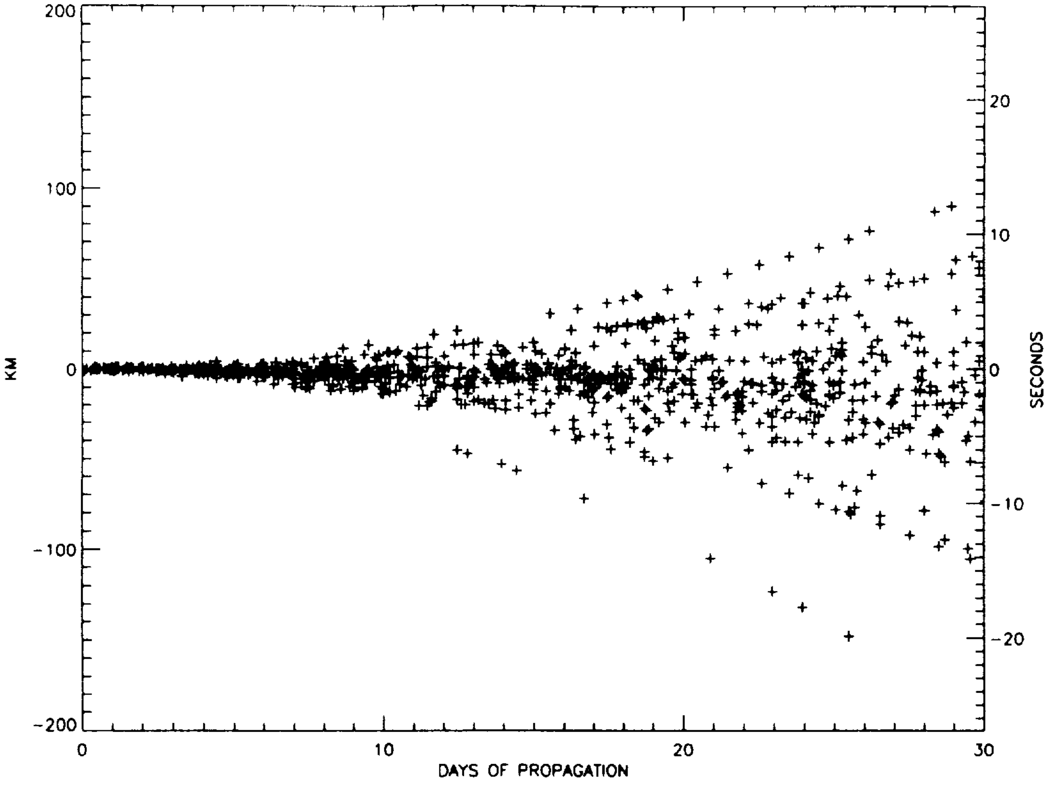

Fig. 2. SGP4 along-track propagation errors for NOAA-12: 0–30 days.

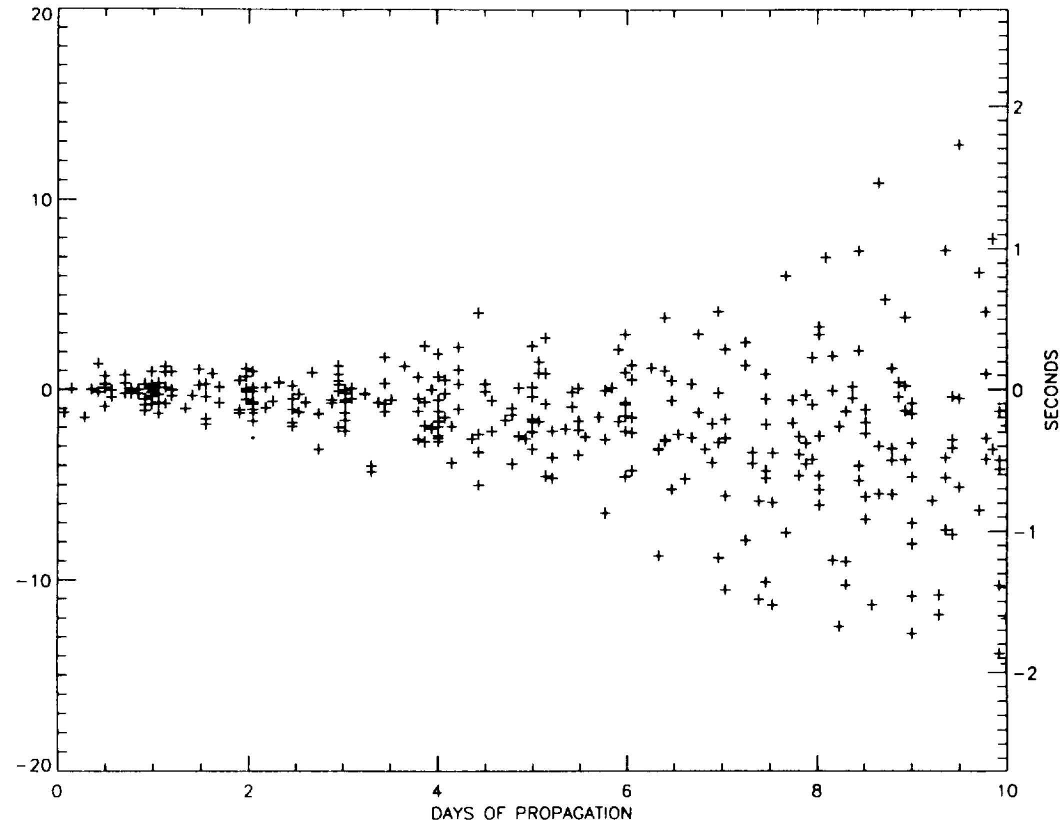

Fig. 3. DCF/SGP4 along-track propagation errors for NOAA-12: 0–10 days.

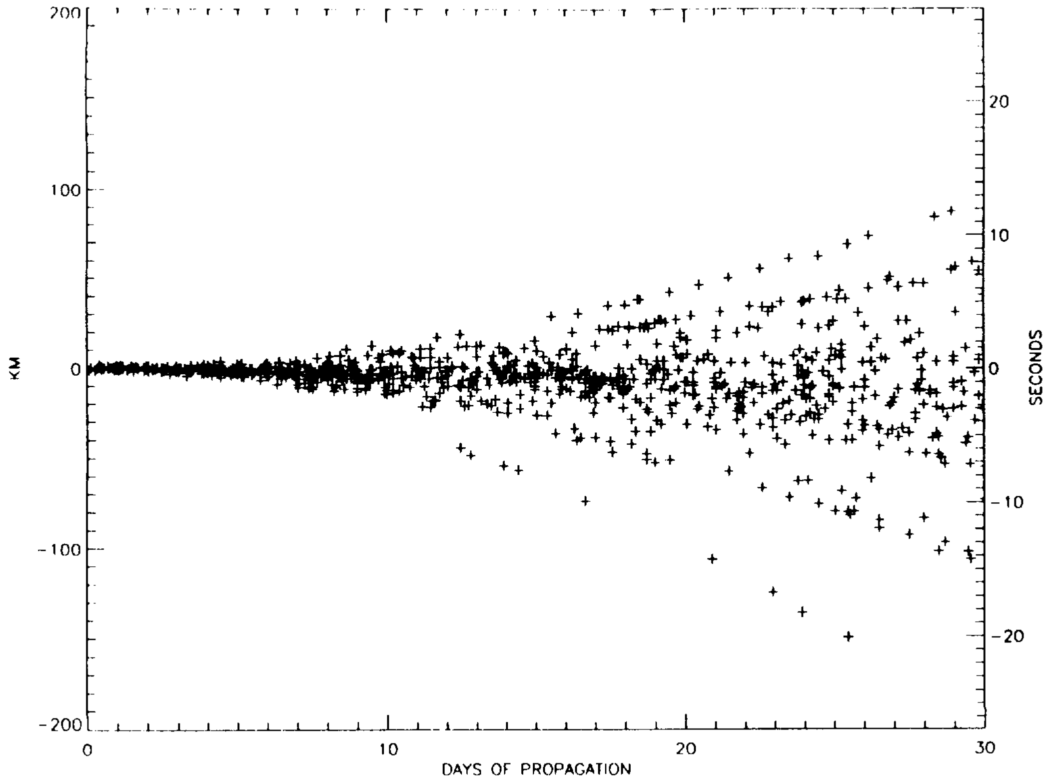

Fig. 4. DCF/SGP4 along-track propagation errors for NOAA-12: 0–30 days.

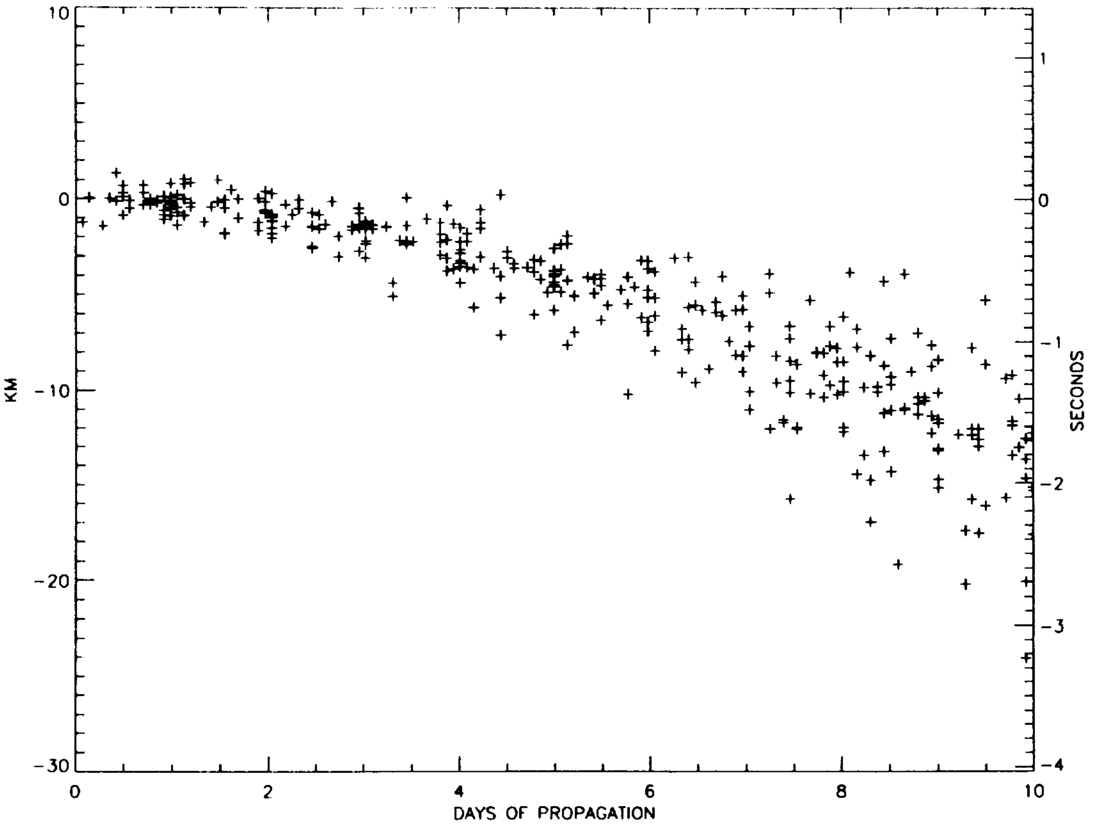

Fig. 5. DCF/Brouwer along-track propagation errors for NOAA-12: 0–10 days.

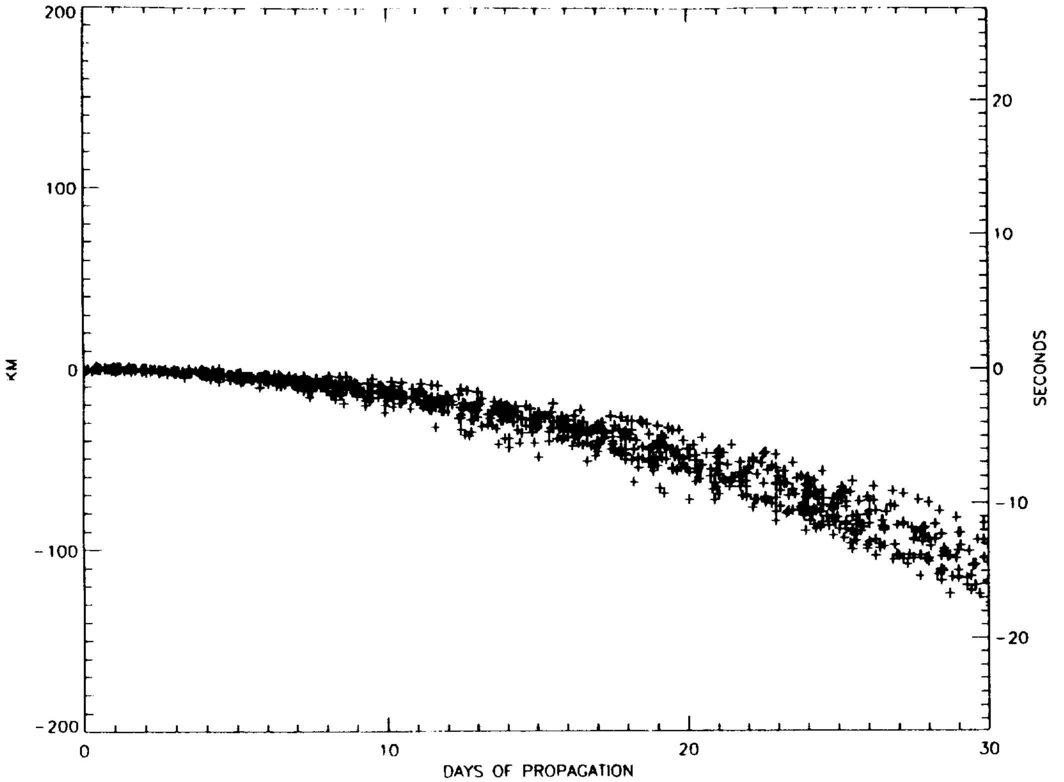

Fig. 6. DCF/Brouwer along-track propagation errors for NOAA-12: 0–30 days.

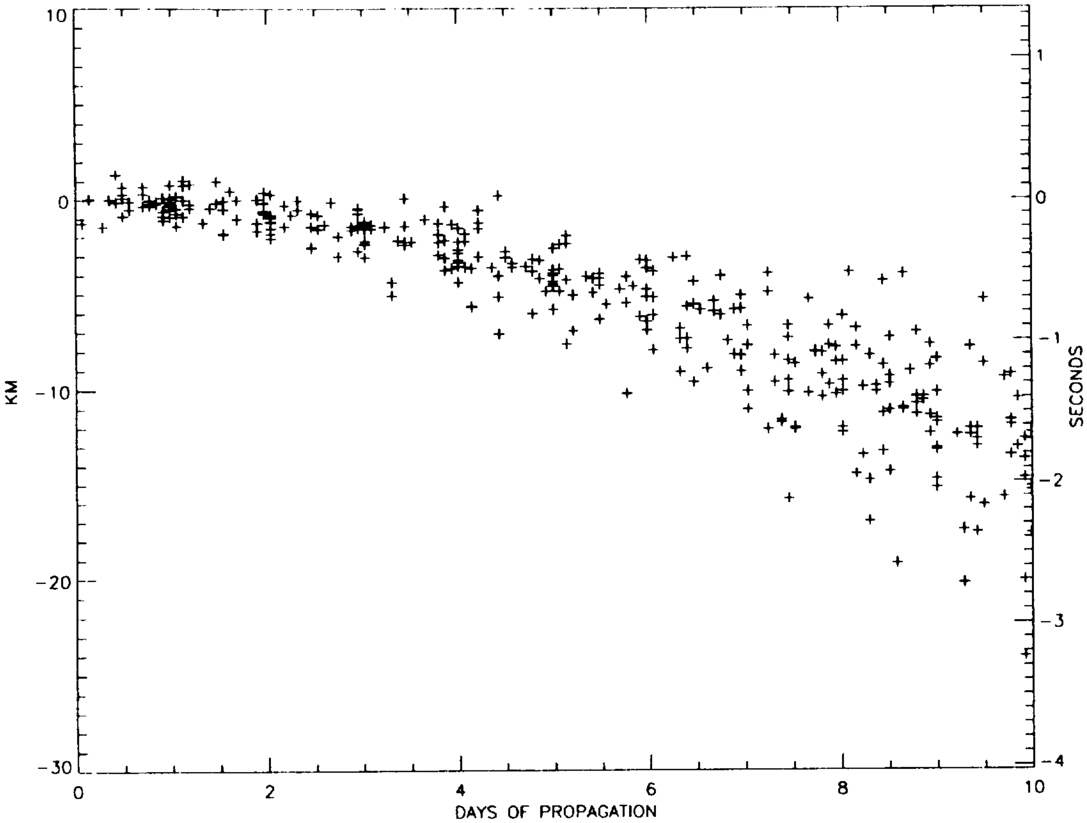

Fig. 7. NOAA/Brouwer along-track propagation errors for NOAA-12: 0–10 days.

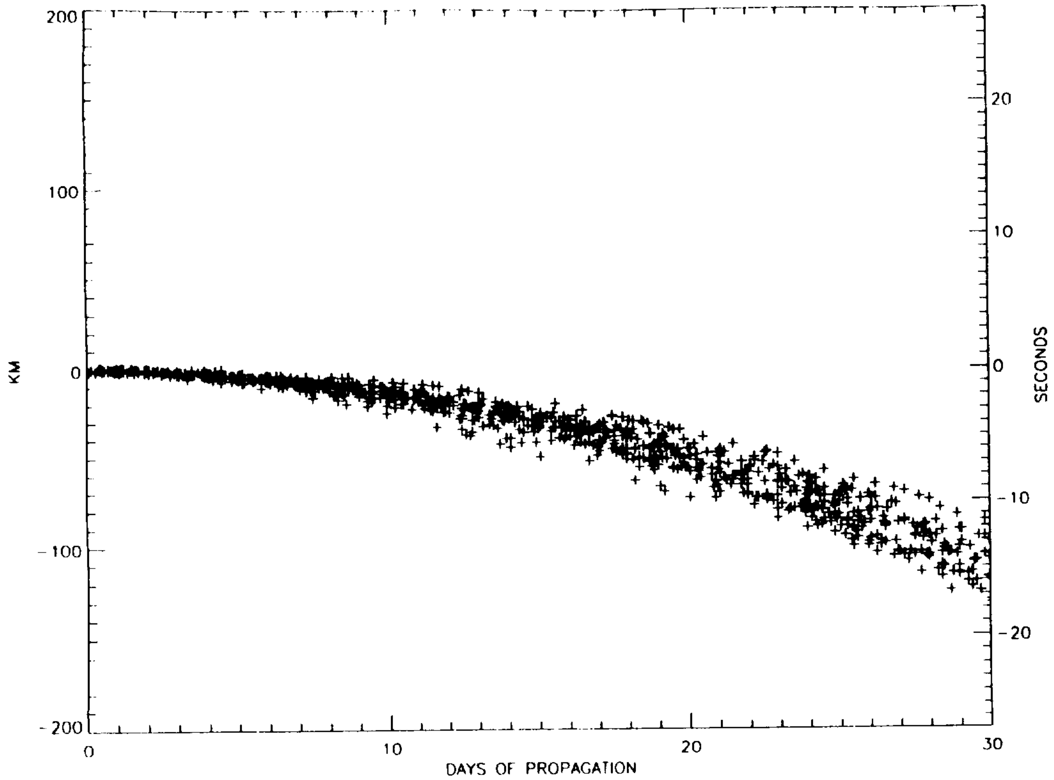

Fig. 8. NOAA/Brouwer along-track propagation errors for NOAA-12: 0-30 days.

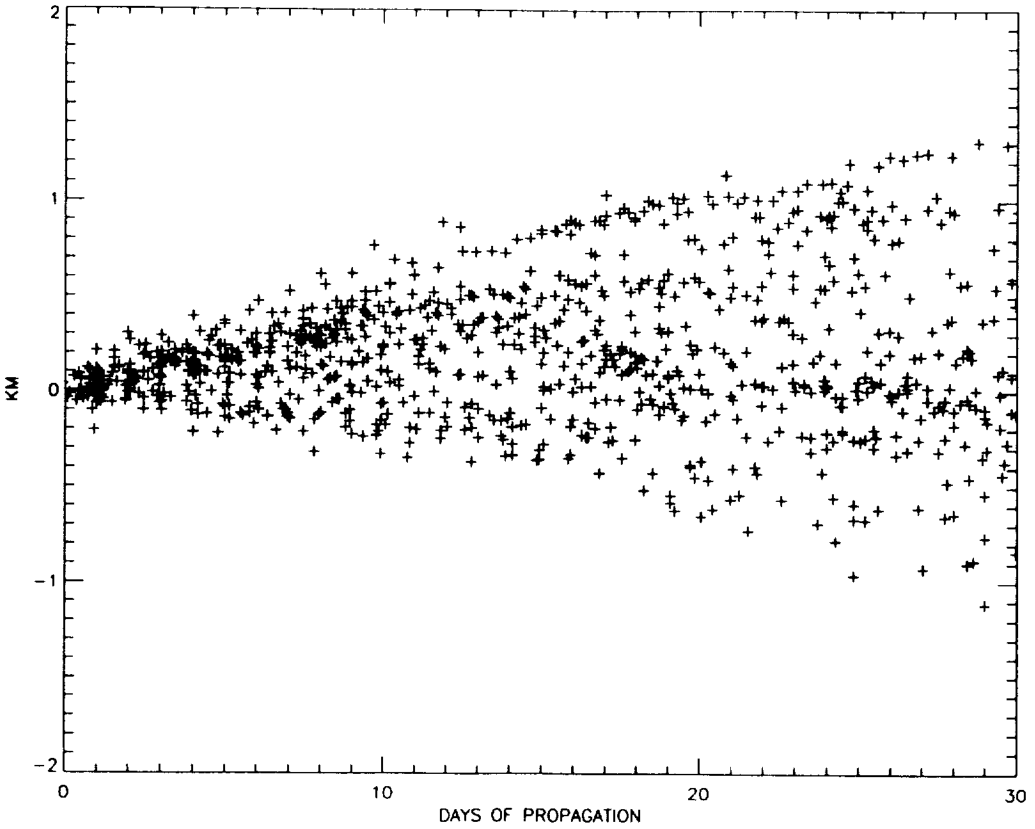

Fig. 9. DCF/SGP4 cross-track propagation errors for NOAA-12: 0–30 days.

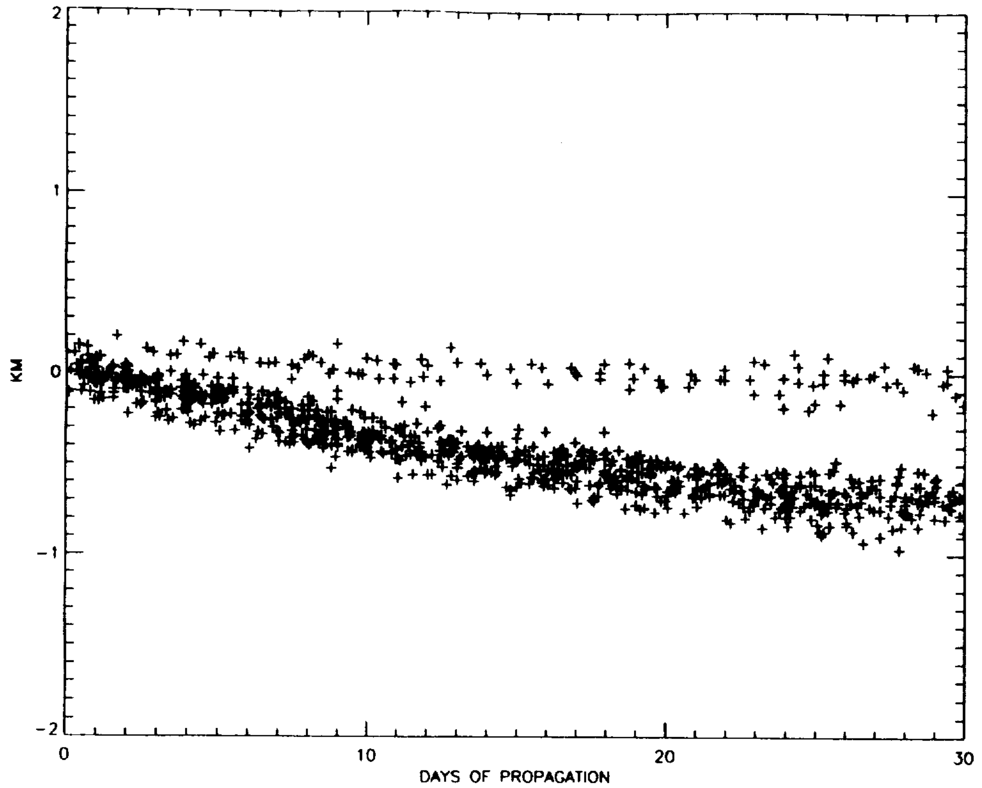

Fig. 10. DCF/SGP4 radial propagation errors for NOAA-12: 0–30 days.

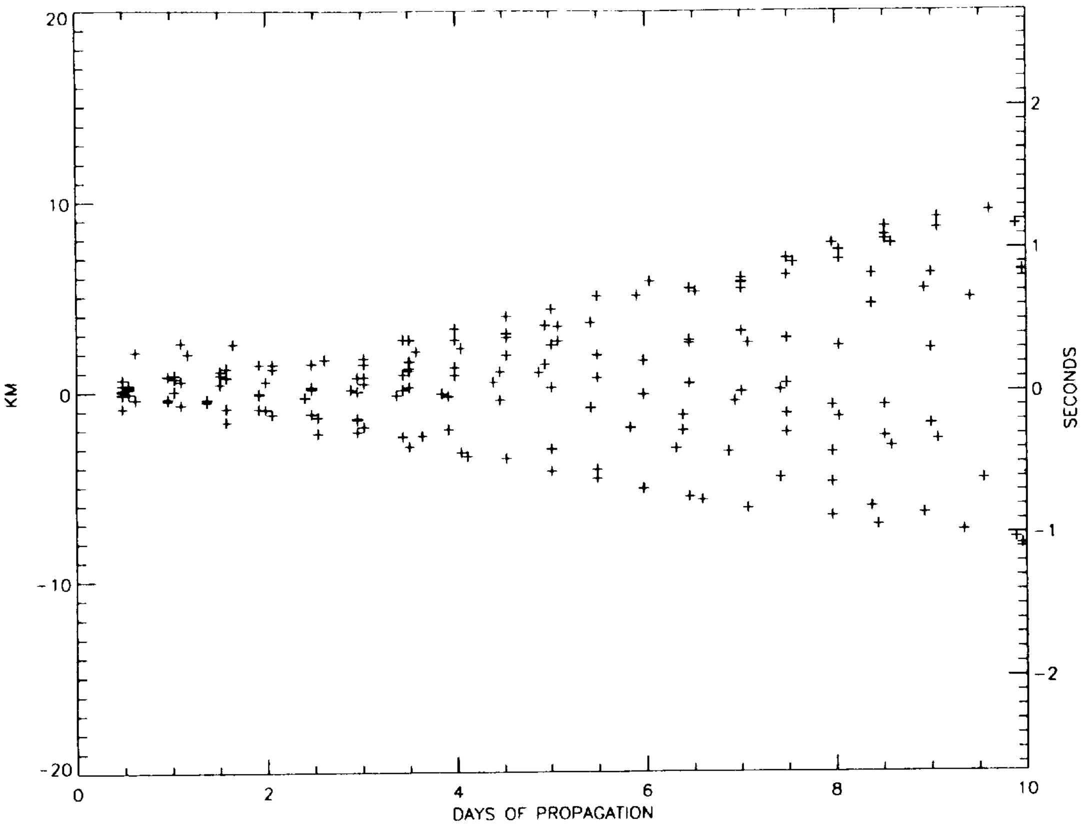

Fig. 11. SGP4 along-track propagation errors for LANDSAT-5: 0–10 days.

LANDSAT-5 elements over 10 days to demonstrate the comparability with NOAA-12, and the results for SGP4, DCF/SGP4, and DCF/Brouwer are shown in Figs. 11–13. As these figures show, the 10-day performance for the SGP4 routines is very similar to that for NOAA-12, while the DCF/Brouwer errors are slightly larger (approximately 2.5 km after 7 days versus 2 km for NOAA-12). Given that the NOAA-12 results met the 21-day requirement by a substantial margin, it is expected the SeaWiFS propagations will meet this requirement as well.

4.2 Comparisons

Comparisons were performed of the different versions of each of the two models: between the SGP4 and DCF/SGP4 routines, and between the DCF and NOAA versions of the Brouwer-Lyddane model. Comparisons between SGP4 and Brouwer-Lyddane models were not performed, since the absolute accuracy evaluations clearly showed significant differences in the outputs of the two models, almost entirely due to the presence of the drag term in SGP4.

The comparison of the latest SGP4 routine with the DCF implemented version is of some interest. These routines have a common heritage, i.e., NORAD Project Spacetrack. An examination of the code shows the latest SGP4 implementation has been substantially updated from the version produced by DCF from the previous Project Spacetrack documentation. The question is whether the changes were in the logic or involved improvements to the model.

The comparison was performed using a typical set of NOAA-12 NORAD elements. Orbit vectors were produced at regular (30-minute) intervals for 30 days. The differences were computed as along-track and cross-track components. The results for the SGP4 models are shown in Figs. 14 and 15, which indicate that the propagation differences, while not completely negligible, are small compared to the overall propagation errors. The maximum along-track differences at 7 and 21 days are less than 0.2 second and 0.5 second, respectively, while the maximum cross-track differences are less than 0.1 km and 0.2 km, respectively. The maximum cross-track differences show very linear behavior in magnitude with apparently zero mean, while the along-track differences show some periodic effects with an overall linear trend and a positive mean. The along-track differences indicate that the mean of the absolute propagation accuracy distribution is closer to zero, possibly due to better drag modeling in the new SGP4. The cross-track differences appear to represent a small difference in the precession rate of the orbit plane.

The Brouwer model comparison (Figs. 16 and 17) show a very small linear trend in the along-track component (approximately 0.005 second after 21 days). The cross-

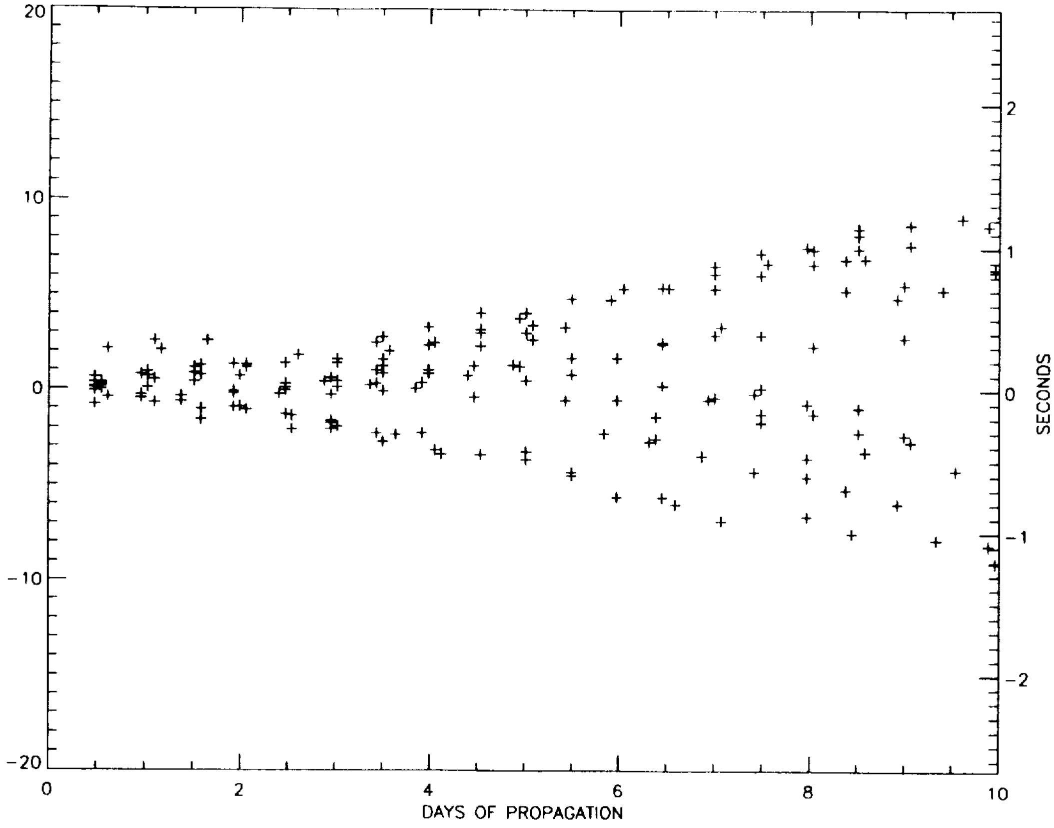

Fig. 12. DCF/SGP4 along-track propagation errors for LANDSAT-5: 0-10 days.

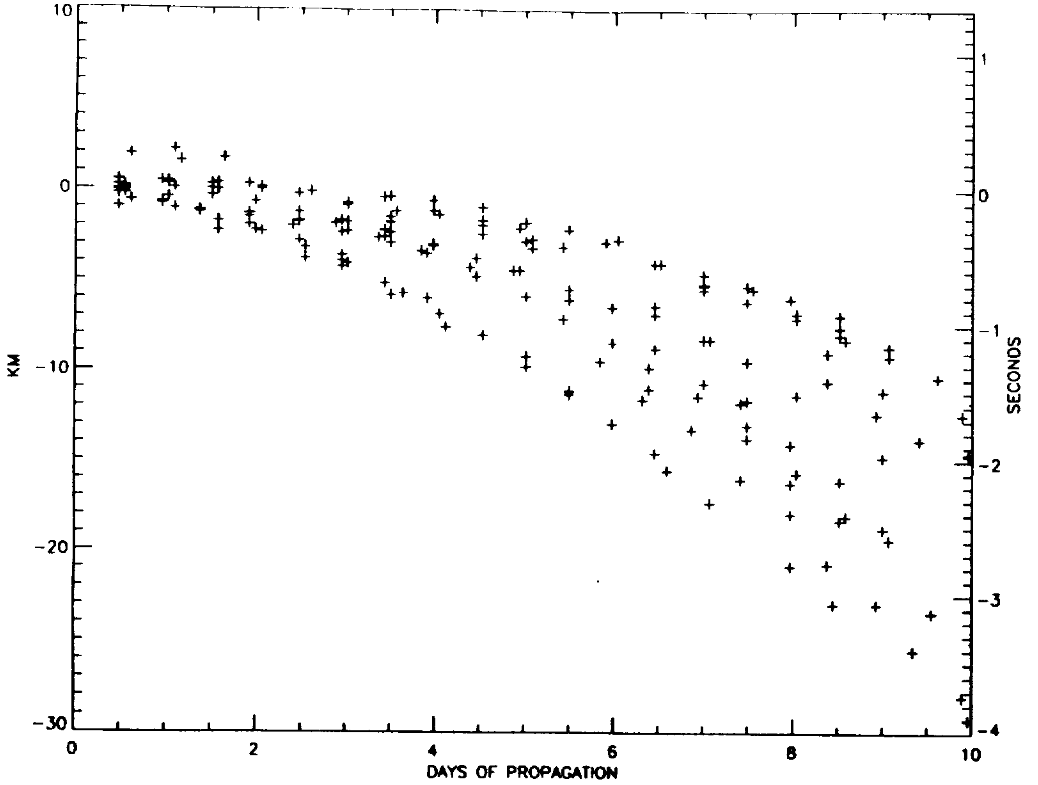

Fig. 13. DCF/Brouwer along-track propagation errors for LANDSAT-5: 0-10 days.

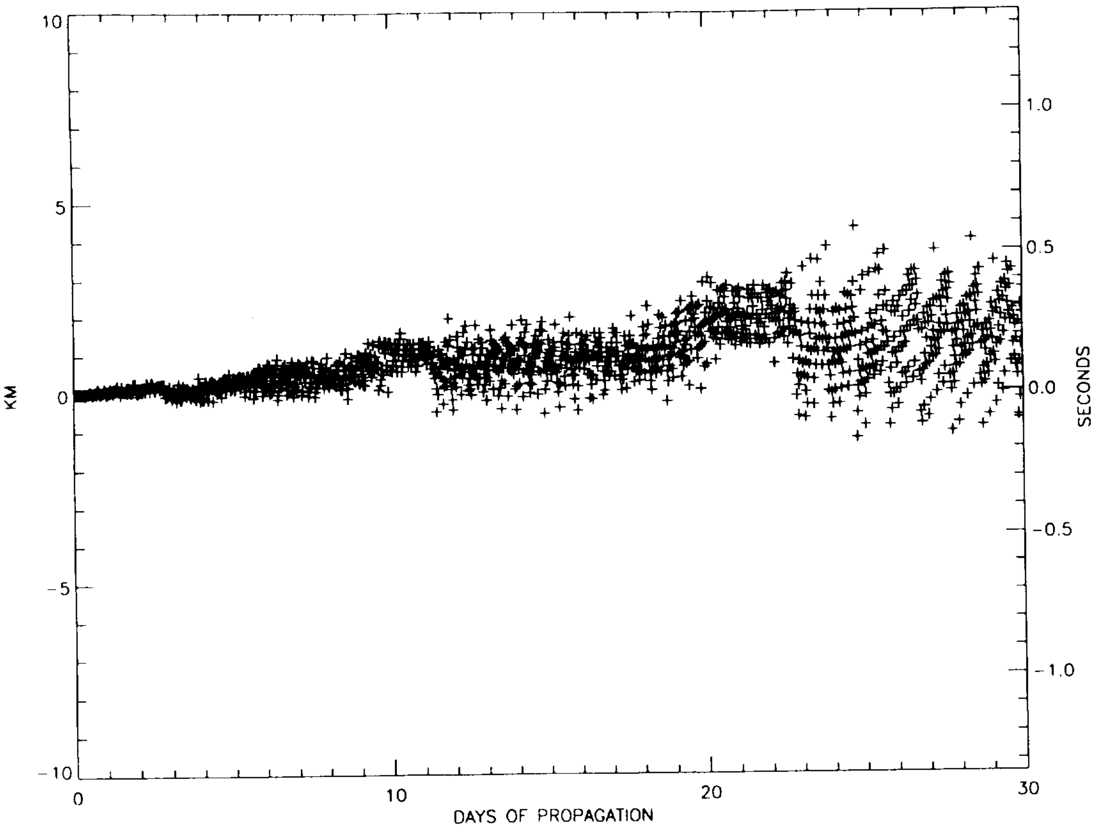

Fig. 14. Along-track propagation differences between SGP4 and DCF/SGP4.

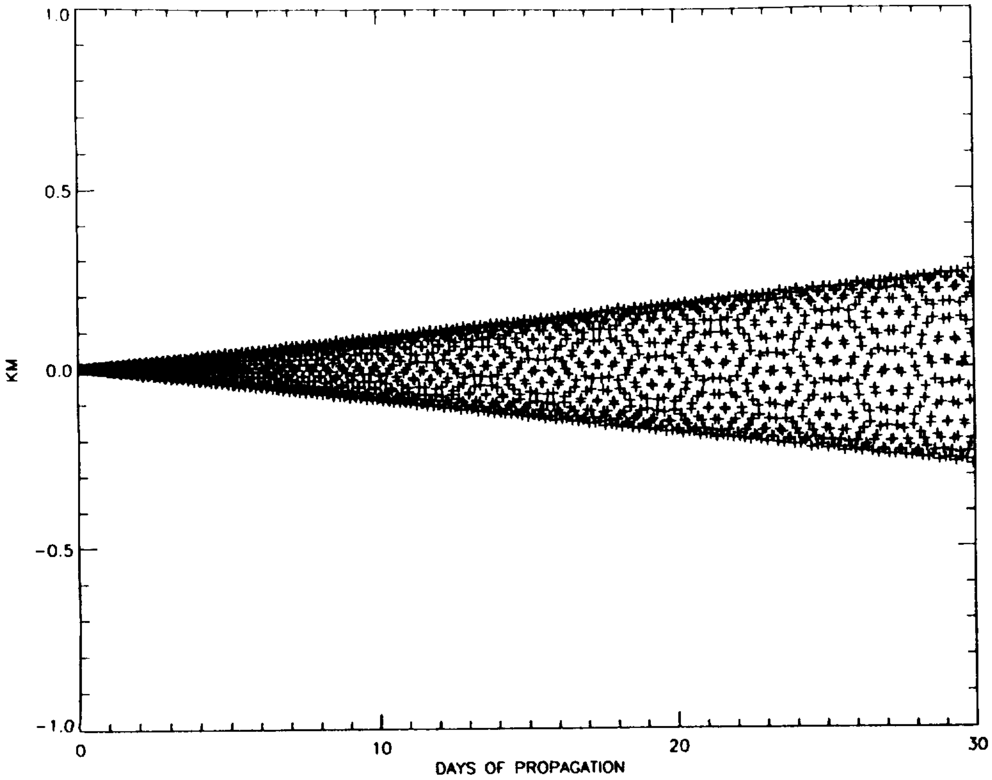

Fig. 15. Cross-track propagation differences between SGP4 and DCF/SGP4.

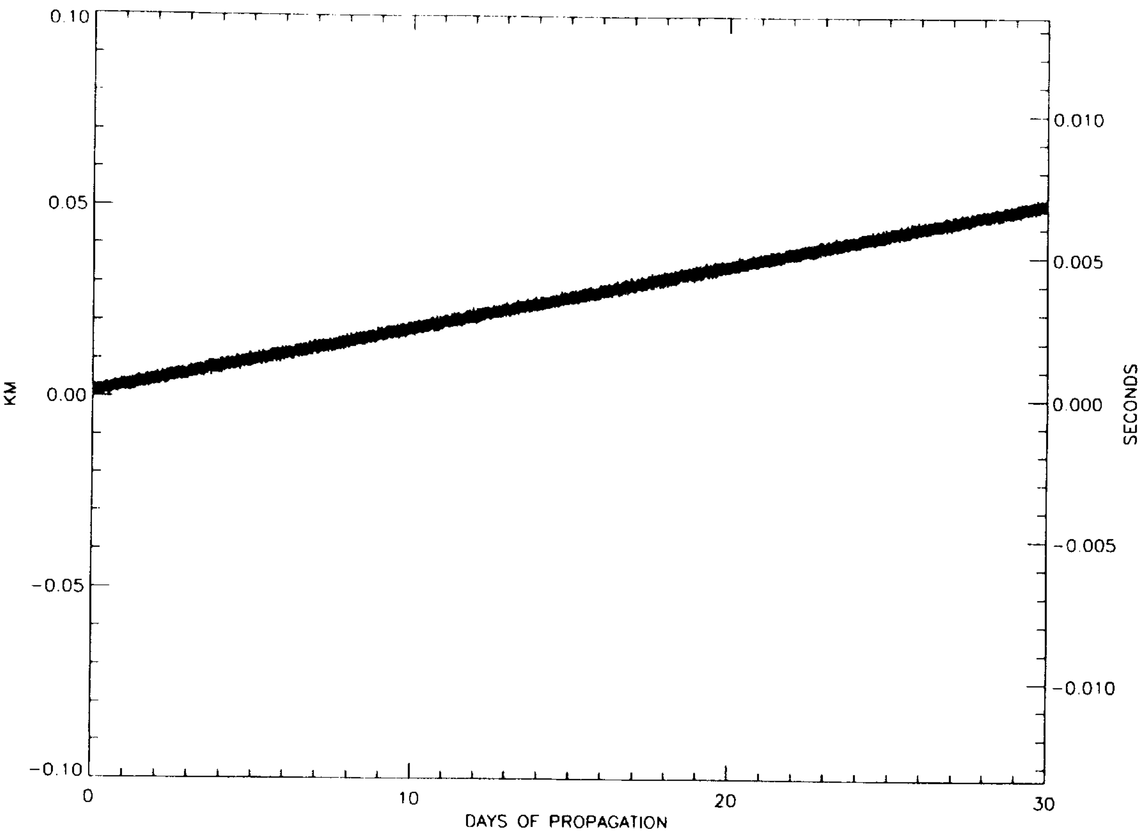

Fig. 16. Along-track propagation differences between DCF/Brouwer and NOAA/Brouwer.

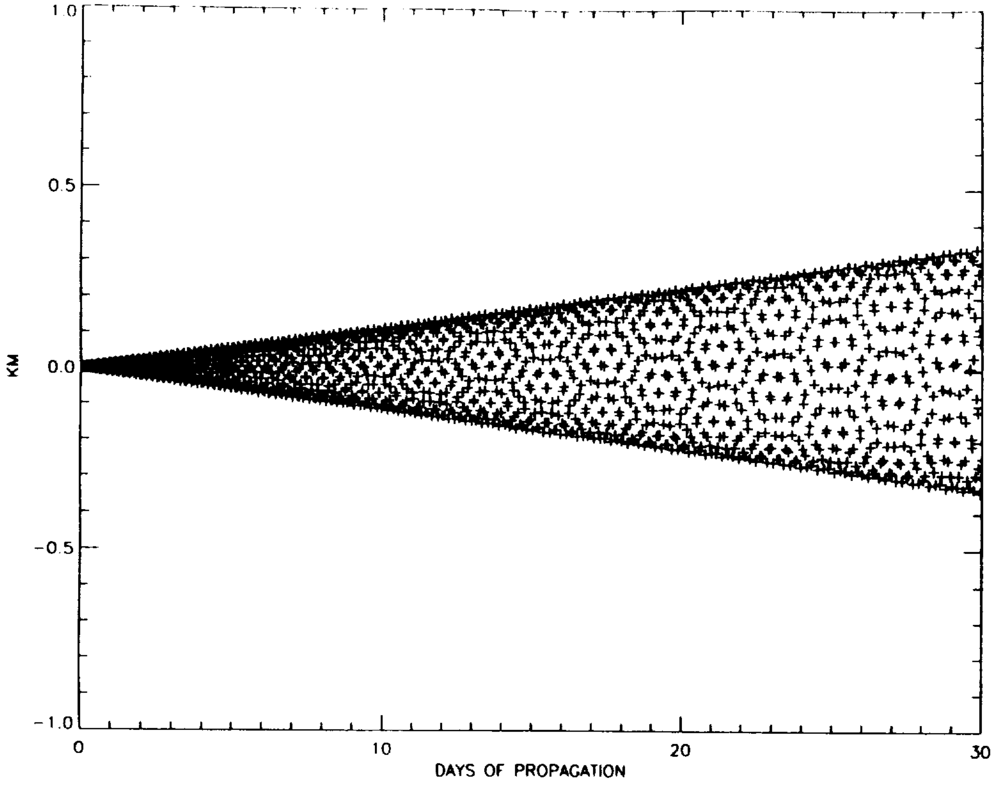

Fig. 17. Cross-track propagation differences between DCF/Brouwer and NOAA/Brouwer.

Table A1. The format of the NORAD element set.

<table>
<tr><th colspan="4"><i>A generic NORAD two-line element:</i></th></tr>
<tr><td colspan="4"><i>Line 1:</i> sssssU␣ly␣ld␣␣A␣yyddd.ffffffff␣␣mmd1␣␣␣␣␣␣mmd2␣␣␣␣␣␣bstar␣␣␣0␣␣elno
<i>Line 2:</i> sssss␣␣ii.iiii␣lll.llll␣eeeeeee␣www.wwww␣mmm.mmmm␣nn.nnnnnnnn␣rrrrx</td></tr>
<tr><th colspan="2"><i>Line 1 Variables</i></th><th colspan="2"><i>Line 2 Variables</i></th></tr>
<tr><td>sssss</td><td>is the 5-digit spacecraft ID</td><td>ii.iiii</td><td>is the inclination (°)</td></tr>
<tr><td>ly</td><td>is the spacecraft launch year (not used)</td><td>lll.llll</td><td>is the right ascension of the ascending node (°)</td></tr>
<tr><td>ld</td><td>is the spacecraft launch day (not used)</td><td></td><td></td></tr>
<tr><td>yy</td><td>is the element epoch year (two digits)</td><td>eeeeeee</td><td>is the eccentricity (a decimal point is implied at the left)</td></tr>
<tr><td>ddd</td><td>is the element epoch day-of-year</td><td></td><td></td></tr>
<tr><td>ffffffff</td><td>is the element epoch time of day</td><td>www.wwww</td><td>is the argument of perigee (°)</td></tr>
<tr><td>mmd1</td><td>is a mean motion time derivative (not used)</td><td>mmm.mmmm</td><td>is the mean anomaly (°)</td></tr>
<tr><td>mmd2</td><td>is a mean motion time derivative (not used)</td><td>nn.nnnnnnnn</td><td>is the mean motion (revs/day)</td></tr>
<tr><td>bstar</td><td>is the drag term (mantissa and exponent)</td><td>rrrr</td><td>is the orbit number (not used)</td></tr>
<tr><td>elno</td><td>is the element set number (not used)</td><td>x</td><td>is not used</td></tr>
<tr><th colspan="4"><i>A typical NORAD two-line element set for NOAA-12:</i></th></tr>
<tr><td colspan="4">21263U␣91␣32␣␣A␣92183.30748338␣␣.00000257␣␣00000-0␣␣13333-3␣0␣␣3228
21263␣␣98.6941␣213.0068␣0013736␣146.1404␣214.0628␣14.22063660␣58773</td></tr>
</table>

Note: The bstar term represents a value of 0.00013333 (0.13333E−03) and the eccentricity is 0.0013736. All other values are formatted explicitly.

track component shows very similar behavior to the SGP4 comparison, with maximum differences of approximately 0.1 km and 0.25 km at 7 days and 21 days, respectively. This also seems to indicate a small difference in the orbit plane precession rate. Given the overall performance of these models, the differences are too small to demonstrate an advantage for either model.

5. RECOMMENDATIONS

The evaluations have shown that any of the four propagators evaluated, in conjunction with NORAD elements, are capable of meeting the stated accuracy requirements for SeaWiFS scheduling purposes. The SGP4 propagators provide superior results, especially if rudimentary quality assurance of the element sets is performed. The major disadvantage of the SGP4 model is the restriction to government agencies and contractors. The recommendations are, therefore, as follows:

1. The Mission Operations element should use the SGP4 model with NORAD elements to support scheduling. The performance of the new SGP4 routine and the DCF/SGP4 version are very nearly equivalent for this purpose, but the new SGP4 appears to model drag better.
2. The Brouwer-Lyddane model meets the needs of all non-government facilities which need SeaWiFS orbit propagations, using NORAD elements converted to mean elements as described in Appendix A. The requirements for this purpose are less stringent, as stated earlier. The SeaWiFS Project will provide the DCF Brouwer-Lyddane propagator to HRPT stations.

APPENDIX A

The NORAD two-line elements completely specify a spacecraft's orbit; unfortunately they cannot be used directly with the Brouwer-Lyddane orbit model. Specifically, the NORAD model uses the mean motion, whereas the Brouwer model requires the semi-major axis. These two parameters are redundant for classical Keplerian orbits but the conversion is more complex for non-spherical gravitational fields (i.e., low Earth orbits) and mean element sets.

The format of the NORAD element set is given in Table A1. The Brouwer models input the elements as a 6-element array, where the order of the elements is: semimajor axis (km), eccentricity, inclination, right ascension of the ascending node, argument of perigee, and mean anomaly. All but the semimajor axis can be copied directly from the NORAD element set.

The conversion of the mean motion to the semi-major axis is performed as follows. First, the mean motion is converted from revolutions per day (n) to radians per minute (**xno**):

$$\mathtt{xno} = n\frac{2\pi}{1{,}440} \qquad (A1)$$

The calculation of the semi-major axis uses the gravitational constant in units of fractional Earth radii ($R_e^{1.5}$) per minute, and also the $J2$ perturbation term. The Earth radius (R_e) and gravitational constant (G_e) were defined earlier (Table 4) in units of kilometers and seconds, and $J2$ (unitless) was also defined, as follows:

$$R_e = 6{,}378.137\ \mathrm{km} \qquad (A2)$$

$$G_e = 398{,}600.5\,\mathrm{km}^3\,\mathrm{s}^{-2} \qquad (A3)$$

$$J2 = 0.00108263. \qquad (A4)$$

The revised value of the gravitational constant used below (**xke**) is:

$$\mathtt{xke} = 60\sqrt{G_e R_e^{-3}} \qquad (A5)$$

$$= 0.0743668531 \qquad (A6)$$

where **xke** is in units of Earth radii$^{1.5}$ ($R_e^{1.5}$) per minute. The initial (classical) estimate of the semi-major axis (**a1**) is:

$$\mathtt{a1} = \left(\frac{\mathtt{xke}}{\mathtt{xno}}\right)^{2/3} \tag{A7}$$

where **a1** is in units of Earth radii.

The perturbation corrections to the semi-major axis use the inclination (i), the eccentricity (e), and $J2$ as follows:

$$\mathtt{temp} = 0.75\,J2\,\frac{3\cos^2(i) - 1}{(1 - e^2)^{1.5}} \tag{A8}$$

$$\mathtt{del1} = \frac{\mathtt{temp}}{\mathtt{a1}^2} \tag{A9}$$

$$\mathtt{a0} = \mathtt{a1}\left[1 - \mathtt{del1}\left[\frac{1}{3} + \mathtt{del1}\left[1 + \frac{134}{81}\mathtt{del1}\right]\right]\right] \tag{A10}$$

$$\mathtt{del0} = \frac{\mathtt{temp}}{\mathtt{a0}^2} \tag{A11}$$

$$\mathtt{a0dp} = \frac{\mathtt{a0}\,R_e}{(1 - \mathtt{del0})} \tag{A12}$$

where **a0dp** is the mean semi-major axis in kilometers. This value is entered into the first location of the Brouwer element array.

For the sample NOAA-12 element set listed in Table A1, $n = 14.22063660$ revolutions per day, $i = 98.6941°$ and $e = 0.0013736$. In this example, the equations above give a mean semi-major axis of 7,192.074 km.

GLOSSARY

AVHRR	Advanced Very High Resolution Radiometer
BER	Bit Error Rate
CZCS	Coastal Zone Color Scanner
DCF	Data Capture Facility
EUVE	Extreme Ultraviolet Explorer
GPM	General Perturbations Model
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
G/T	System Gain/Total System Noise Temperature
GTDS	Goddard Trajectory Determination System
HRPT	High Resolution Picture Transmission
IAU	International Astrophysical Union
LANDSAT	Land Resources Satellite
NASA	National Aeronautics and Space Administration
NAVSPASUR	Naval Space Surface Surveillance
NIMBUS	Not an acronym, but a series of NASA experimental weather satellites containing a wide variety of atmosphere, ice, and ocean sensors.
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defense (Command)
OSC	Orbital Sciences Corporation
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SPM	Special Perturbations Model
TBUS	Not an acronym, but a NOAA orbit prediction message.
TIROS	Television Infrared Observation Satellite
WFF	Wallops Flight Facility

SYMBOLS

a0	Intermediate perturbation correction variable.
a1	Orbital semi-major axis in units of Earth radii.
a0dp	The mean orbital semi-major axis in kilometers.
$\vec{D}$	Orbit position difference vector.
D_{at}	Along-track position difference.
D_{ct}	Cross-track position difference.
D_{rad}	Radial position difference.
del0, **del1**	Intermediate perturbation correction variables.
e	Orbital eccentricity.
G_e	Gravitational constant of the Earth (398,600.5 km^3 s^{-2}).
i	Orbital inclination.
$J2$	The $J2$ gravity field term (0.0010863).
$J3$	The $J3$ gravity field term (−0.0000254).
$J4$	The $J4$ gravity field term (−0.0000161).
$J5$	The $J5$ gravity field term.
n	Mean orbital motion in revolutions per day.
$\vec{O}$	Orbit normal vector ($\vec{P} \times \vec{V}$).
$\vec{P}$	Orbit position vector.
R_e	Mean radius of the Earth (6,378.137 km).
temp	Temporary perturbation correction variables.
$\vec{V}$	Orbit velocity vector.
xke	Revised gravitational constant in units of Earth radii.
xno	Mean orbital motion in radians per minute.

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13. ABSTRACT *(Maximum 200 words)*

An analysis of orbit propagation models was performed by the Mission Operations element of the Sea–viewing Wide Field–of–View Sensor (SeaWiFS) Project, which has overall responsibility for the instrument scheduling. The orbit propagators selected for this analysis are widely available general perturbations models. The analysis includes both absolute accuracy determination and comparisons of different versions of the models. The results show that all of the models tested meet accuracy requirements for scheduling and data acquisition purposes. For internal Project use the SGP4 propagator, developed by the North American Air Defense (NORAD) Command, has been selected. This model includes atmospheric drag effects and, therefore, provides better accuracy. For High Resolution Picture Transmission (HRPT) ground stations, which have less stringent accuracy requirements, the publicly available Brouwer–Lyddane models are recommended. The SeaWiFS Project will make available portable source code for a version of this model developed by the Data Capture Facility (DCF).

14. SUBJECT TERMS
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