Journal of the Korean Society of Remote Sensing, Vol.15, No.2, 1999, pp.119~130

Feasibility of Using Norad Orbital Elements for Pass Programming and Catalog Generation for High Resolution Satellite Images

Dong-Seok Shin*, Sung-Hee Kwak*, Young-Ran Lee*, and Tag-Gon Kim**

Remote Sensing Research Division, SaTReC, KAIST*, Dept. of Electrical and Electronic Engineering, KAIST**

고해상도 위성영상 촬영계획 수립 및 카탈로그 생성을 위한 NORAD 궤도 데이터의 이용 가능성 연구

신동석* · 곽성희* · 이영란* · 김탁곤**

한국과학기술원 인공위성연구센타 원격탐사연구실*, 한국과학기술원 전기 및 전자공학과**

Abstract : At present, many ground stations all over the world are using NORAD orbit element data in order to track and communicate with Earth orbiting satellites. The North American Aerospace Defense Command (NORAD) observes thousands of Earth orbiting objects on daily basis and provides their orbital information via internet. The orbital data provided by NORAD, which is also called two line element (TLE) sets, allows ground stations to predict the time-varying positions of satellites accurately enough to communicate with the satellites. In order to complete the mission of a high resolution remote sensing satellite which requires very high positional determination and control accuracy, however, a mission control and tracking ground station is dedicated for the observation and positional determination of the satellite rather than using NORAD orbital sets. In the case of KITSAT-3, NORAD orbital elements are currently used for image acquisitoin planning and for the processing of acquired images due to the absence of a dedicated KITSAT-3 tracking ground system. In this paper, we tested and analyzed the accuracy of NORAD orbital elements and the appropriate prediction model to determine how accurately a satellite acquisites an image of the location of interest and how accurately a ground processing system can generate the catalog of the images.

Key Words : orbit determination, pass programming, image catalog, NORAD TLE, SGP model

요 약 : 현재 전 세계적으로 많은 위성관제 및 위성영상데이터 수신처리 지상국에서 저궤도 위성의 추적 및 위성과의 통신을 위하여 NORAD 궤도데이터를 사용하고 있다. 공신력있는 북미우주방위사령부(NORAD)에서는 거의 매일 주기로 수천개의 지구 주회 물체를 관측하여 그 궤도데이터를 인터넷을 통해 전 세계로 공개하고 있으며 이 데이터를 사용한 위성 궤도 예측은 지상국에서 위

Received 15 March 1999 ; Accepted 5 May 1999.

성과 통신하기에 충분한 추적정확도를 제공한다. 하지만 고해상도 지구관측 위성의 임무수행을 위해서는 위성의 위치결정 정확도의 중요성 때문에 평균 궤도정보인 NORAD 데이터를 사용하는 대신 자체 위성 관측 및 추적 시스템을 운영한다. 우리별 3호의 지상국인 경우 자체 위성 추적 시스템이 없는 관계로 위성과의 통신 뿐 아니라 영상촬영 및 처리를 위한 궤도정보를 NORAD 데이터에 의존하고 있다. 본 논문에서는 이러한 NORAD 데이터를 이용하여 위성의 위치를 예측 또는 결정함으로써 고해상도 지구관측 위성이 원하는 지역을 얼마나 정확히 촬영할 수 있는지, 그리고 생성되는 영상 카탈로그의 위치는 실제 촬영된 위치와 얼마나 달라질 수 있는지를 실험, 분석한다.

1. Introduction

The accurate determination and control of the position of a high resolution Earth observation satellite is critical for its successful mission operation especially for the application of the image to high precision topographic and land use mapping. Almost all high resolution remote sensing satellite programs such as SPOT, Landsat and KOMPSAT-1 programs include tracking stations which are dedicated to determine the position of its own satellite accurately on regular basis. The accurately determined positional information is used for several purposes such as mission planning, pass programming, image catalog generation, image pre-processing and even end-use applications, of which all should be performed in order to satisfy the mission of the whole program.

There are several instruments for measuring the position of the satellites from ground stations such as an optical camera, a laser tranceiver, a radar system and a radio receiver and each system has its own advantages and drawbacks (RRL, 1992). At present, a large number of tracking stations for low Earth orbiting remote sensing satellites are using radio tracking systems which measure the position of a satellite by using radio inteferometry, Doppler effects or a radio ranging technique. Although the accuracy of this system depends on the accuracy and stability of signal carrier frequency and timing control systems both on board the satellite and the tracking station, several hundred meters' positional accuracy can be achieved with all weather conditions and without heavy system costs. The current trend shows that remote sensing satellites carry GPS (Global Positioning System) receiver on board, determine their own positions and transmit the positional information down to ground stations. Since the GPS system can determine the position of the satellite with the accuracy of a hundred meter's order constantly during the orbit, it can provide more accurate and robust positional information than the tracking station which estimates the satellite positions out-of-sight the tracking station by interpolating or extrapolating the measured orbital data. Earth observation satellite programs cannot however eliminate the necessity of the tracking facility on ground in case of on-board GPS system failure.

A small satellite program such as the KITSAT-3 program does not have its own ground tracking facility. KITSAT-3, an experimental satellite, however, carries a high resolution (13.5m at 720km) imaging camera which requires accurate orbital information for the imaging mission operation. Although KITSAT-3 carries an experimental GPS receiver on-board, its operation and accuracy has not been proven yet. The

KITSAT-3 mission control and the processing of KITSAT-3 images therefore require external orbit information. In order to do that, NORAD TLE (two line element) sets are used on regular basis.

NORAD TLE sets can be easily accessed via internet, and are used by many ground stations for tracking and cumminicating with satellites (details in Section 4). Although the positional accuracy generated by the corresponding orbital model has been proven to be good enough for TT&C (Tracking, Telemetry and Command) communications, its accuracy has never been analyzed for the mission operation of high resolution remote sensing satellites. In this paper, therefore, the positional accuracy of a satellite determined by NORAD TLE sets and an optimum orbit propagation model is tested and analyzed for the mission operation of a high resolution Earth observation program, especially for pass programming and image catalog generation. This research was initiated by KITSAT-3 mission operation program. However, the results will be applicable for various other purposes which concern the accuracy of NORAD orbital elements.

2. Pass Programming and Image Catalog Generation

Pass programming refers to the scheduling of a satellite where, how and when to acquire images. During the pass programming procedure a mission controller determines several controllable parameters such as the followings:

- Sensor parameters : camera gains, spectral channels
- Viewing parameters : mirror or body tilt angle
- Time parameters : image acquisition commence and termination time.

Once these parameters are determined the satellite is programmed by a telecommand ground station operator and finally the satellite acquires Earth images as programmed. Accurate pass programming can be done just a few days before the pass at the earliest because the viewing and the time parameters depend on the orbit prediction accuracy. In other words, if the viewing and the time parameters were determined by inaccurate orbit prediction outputs, the satellite will result in taking images of wrong place at wrong time. In the case of the SPOT satellite, the pass programming is allowed only within 72 hours before the pass (SPOTIMAGE, 1997).

Orbit prediction error is defined as a difference between the predicted position and the actual position at the time of interest. This positional error can be divided into three components in the orbit coordinate system: along-track error, across-track error and radial error. As the terms are defined, the along-track (across-track, radial) error is defined as the positional error in the direction of the along-track (across-track, radial) as shown in Figure 1.

The radial error is not critical for the pass programming because it only changes the field of view, *i.e.* the swath of image. Several tens of kilometers' radial error results in several hundreds of meters in image swath with the altitude

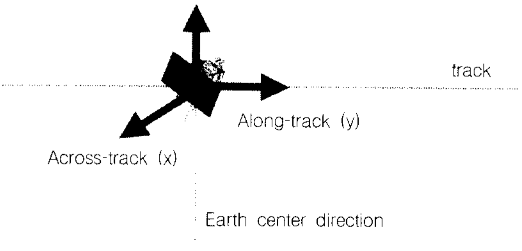
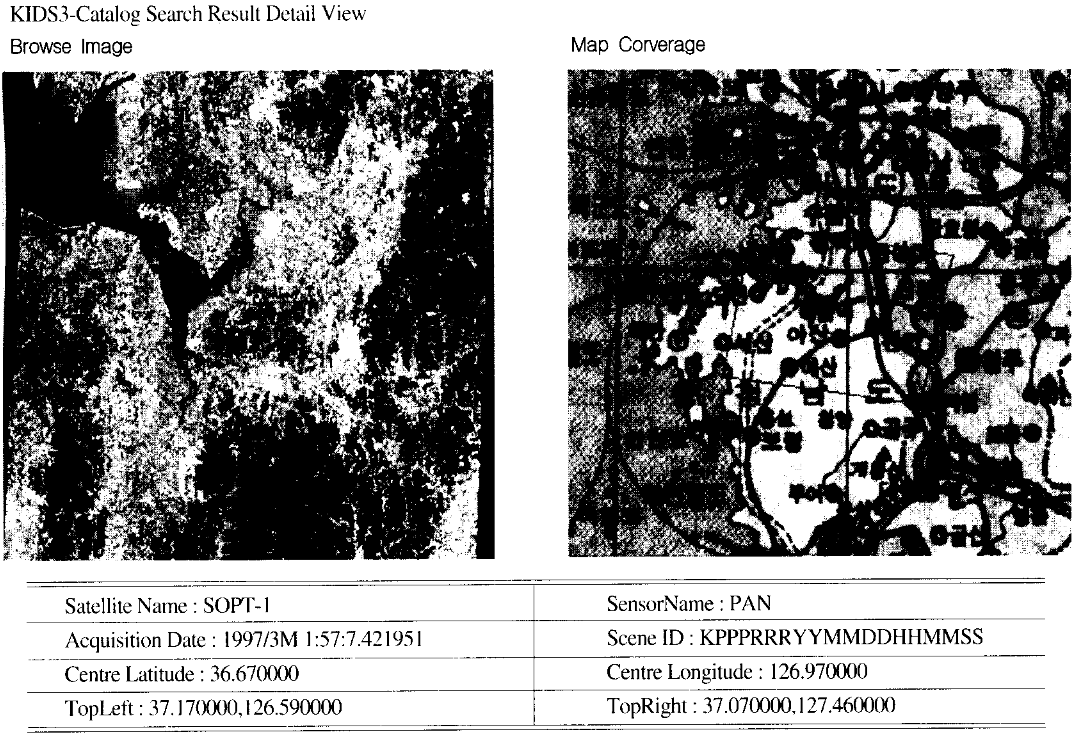


Fig. 1. Definition of orbit coordinate system.

of 800km. The along-track error is important for determining the time parameters ("when" to take images). Since a linear pushbroom sensor acquires images along the track and assuming we have some time margin, for example 10 seconds, the along-track error can easily be tolerated and ignored for the pass programming (10 seconds gives approximately 70km along-track errors for the normal velocity of low Earth orbiting satellite of 7km/sec). Therefore, we regard the across-track error to be the only one which affects the pass programming accuracy.

For simplicity, the across-track positional error can be considered to result in the same amount of side-by-side image shift. An across-track error larger than the image swath, therefore, results in a complete miss of the programmed targets. A rule of thumb in high resolution remote sensing satellite programs requires a minimum of 90% swath overlap between the programmed and the actual images. Since the swath of a KITSAT-3 MEIS (Multispectral Earth Imaging System) image is approximately 50km, across-track positional errors less than 5km should be guaranteed for KITSAT-3 orbit prediction.

Image catalog is the one which end users browse in order to find the images with location, quality and time of their interests. The geographic information of a scene in the catalog can be obtained from several fields such as scene center's lat/long, scene corners' lat/long, simplified map overlay as well as visually-identifiable browse image data (Lee *et al.*, 1998). Figure 2 shows an example of the catalog result page of a scene in which geographic information such as scene center's and corners' lat/long, scene boundary



KIDS3-Catalog Search Result Detail View

Satellite Name : SOPT-1	SensorName : PAN
Acquisition Date : 1997/3M 1:57:7.421951	Scene ID : KPPPRRRYYMMDDHHMMSS
Centre Latitude : 36.670000	Centre Longitude : 126.970000
TopLeft : 37.170000,126.590000	TopRight : 37.070000,127.460000

Fig. 2. An example of a scene catalog search result page view.

display over a map as well as a browse image.

The along-track error as well as the across-track error should be considered for the catalog generation because each item corresponds to a scene not to the whole pass data. Users certainly don't want to receive processed scene data which are different from the map display shown in the catalog. Unless the browse image in the catalog includes some easily recognizable features such as coastlines, it is difficult to determine whether the browse image contains the target that a user is interested in. Therefore, a large deviation of scene boundary locations in the catalog from that of an actual image causes troubles to the processing and distribution of image data. There is no general requirement imposed on the accuracy of the geographic information in the image catalog. The authors dare to say that 10% of errors both in along- and across-track directions may be accepted by end users and image processing and distribution operators.

The experimental results in Section 5 will show the positional accuracy of a satellite, be analyzed whether they meet the requirements for the accuracy of the pass programming and the catalog generation described in this section. In practice, the accuracy of the pass programming and image catalog depends not only on the orbital accuracy but also the accuracy of the attitude control and determination of a satellite. In this paper, however, we are concered only to the orbital accuracy.

3. Orbit Prediction and Perturbations

Two bodies which are gravitationally bound describe elliptical orbits with one focus at their center of mass. This famous rule was proved experimentally by Kepler and mathematically by Newton. The artificial satellite orbiting around Earth describes an elliptical orbit with one focus at the Earth' s center of mass due to its negligible mass compared with that of Earth. In general, 6 Kepler elements fully describe an orbit in 3D inertial space :

- Orbit size and shape: semi-major axis (a), eccentricity (e)
- Orbit plane orientation: inclination (i), right ascension of ascending node (Ω), argument of perigee (ω)
- Specific location of satellite at epoch: mean anomaly (M) (or time of perigee)

The classical orbit prediction procedure is as follows (Wertz, 1978).

- Time passage is calculated from the epoch time and the time of interest.
- Orbit period is calculated from the semi-major axis.
- Mean anomaly is calculated from the above two.
- Eccentric anomaly (E) are calculated numerically from the mean anomaly.
- 2D Cartesian coordinates in the orbit plane are calculated from the eccentric anomaly.
- 3D Cartesian coordinates in the inertial space are calculated from the orbit plane coordinates by using 3D rotational matrix composed of the orbit plane orientation parameters.

In practice, an orbit around Earth cannot be described accurately from this simple Keplerian motion due to various perturbation forces of which major contributions are non-spherical Earth's gravitational effect, lunisolar attraction, air drag and solar radiation pressure. The effects of these perturbing forces depend upon instant location of the satellite, time of year, and even the size/mass/attitude of the satellite. Scientists have therefore dedicated themselves to determine gravitational potential distribution of Earth, time-location varying atmospheric conditions and solar activitity as accurately as possible. These perturbation forces give both periodic and secular (progressive in time) effects to the satellite's orbit. Although only major secular effects can be considered for a long-term orbit planning, a short-term accurate orbit prediction must take the periodic effects into account. Supposed that these perturbing effects are accurately determined, the selection of an optimum orbit prediction model depends simply on the accuracy and computation time.

Cowell's method (Chobotov, 1996), which is widely used for accurate orbit prediction, can provide a high fidelity integrator. This is a time-based numerical integrator which solves the second order differential equation for the forces upon a satellite at a specific time instance.

$$\ddot{\vec{\gamma}} + \frac{\mu_E \vec{\gamma}}{\gamma_3} = \vec{\alpha} \qquad (1)$$

The above equation shows the classical Newton's law (left side) as well as all perturbing forces at the specific time and location of the satellite (right side). Cowell's method therefore divides the time difference between the time of interest and the epoch time into a very small time step and obtains new positional vectors progressively by applying time-varying perturbing forces. This method is very useful for predicting highly accurate positions of a satellite up to a few passes (equivalent to a few hours of time for low Earth orbits) due to its computational time. In addition, the integration time stepsize should be maximized as much as possible without causing too much integration errors. In order to achieve fast integration without losing accuracy, an embedded Runge-Kutta's method (Allen *et al.*) which uses adaptive stepsize and is suitable for systems with rapidly changing states is widely used.

4. NORAD TLE and SGP Models

1) NORAD Two Line Element Sets

The Space Control Center (SCC), which is located in Cheyenne Mountain, US and run by US Space Command for the North American Aerospace Defence Command (NORAD), has a mission to protect the North American continent and US against threats from space. To accomplish its mission, the SCC relies on the Space Surveillance Network (SSN) which is a network of sensors located at two dozen sites worldwide (see Figure 3) and operated by US Army Navy and Air Force personnel.

SSN uses three primary types of sensors to monitor Earth's artificial satellites: conventional radars, phased-array radars and an optical system. This network of dedicated sensors performs up to 80,000 satellite observations each day and sends the information back to SCC. SCC then maintains a catalog of the observed objects which are larger

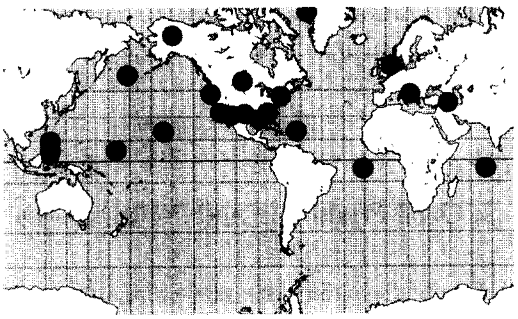


Fig. 3. Space Surveillance Network Location

than 10cm. At present, more than 8,000 objects are being tracked and catalogued. Among them, less than 7% are operational satellites and the remainings are either rocket bodies and space debris floating around Earth (Kelso, 1997).

The observation data of each satellite which is typically elevation, azimuth, range and range rate values observed at a fixed time and a fixed location (tracking station) is converted to NORAD Two Line Element (TLE) format (Kelso, 1998). The NORAD TLE contains mean (not osculating) orbirtal elements (http://celestrak.com/) which are classical Kepler elements (epoch, inclination, right ascension of ascending node, argument of perigee, mean motion and mean anomaly) (Wertz, 1978) and some drag perturbation terms (first and second derivatives of mean motion and solar pressure drag term). The predicted data generated from the previous TLE and the newly observed data are used to update the TLE using so called a differential correction technique. In order to obtain a basic idea of the differential correction technique, let us say we have an element (x) and an observation (y). Those variables are related with each other via a transfer function (orbit propagation model), $y = f(x)$. Let the actual observation be y_a and the predicted observation be $y_p = f(x_p)$.

$$\frac{x_a - x_p}{y_a - f(x_p)} = \frac{dx}{dy} \qquad (2)$$

Solving for the actual value of the element to be determined, x_a, yields

$$x_a = x_p + (ya - f(x_p) \cdot \frac{dx}{df(x)} \mid_{x-x_p}) \qquad (3)$$

This is a basic iteration until the difference in the predicted and actual elements becomes small enough. For the orbit model f in this case a Simplified Perturbation Model 4 (SGP4) is used (see the next sub-section). In practice, a new TLE set is issued only when the position predicted by the current element set differs from the one predicted by the new element set by more than 5km with a 90% confidence interval. The most recent TLE as well as historical archives for the unclassified satellite are redistributed by NASA and can be accessed via internet.

2) Simplified General Perturbation (SGP) Models

There are tens of orbit determination models which propagate orbit elements at the epoch time to the time of interest by their own methods. Each model trades off the accuracy of an extremely complex description against the reduced computational burden of a simpler description. However, one must be very careful to use a orbit prediction model which is compatible with the way in which the elements were generated. Since NORAD TLE sets are generated by using SGP4 model as described in the previous section, the same model should be used for predicting orbit by using NORAD TLE sets in order to retain maximum prediction accuracy.

The NORAD element sets are mean values obtained by removing periodic variations in a particular way using SGP4. In order to obtain optimum predictions, these periodic variations must be reconstructed by SGP4 in exactly the same way they were removed. The first model adopted by NORAD, SGP, was developed by Hilton and Kuhlman (1966) and is used for near-Earth satellites. This model uses a simplification of the work of Kozai (1959) for its gravitational model and it takes the drag effect on mean motion as linear in time. The second model, SGP4, was developed by Lane and Cranford (1969). This model was obtained by simplification of the more extensive analytical theory which uses the solution of Brouwer (1959) for its gravitational model and a power density function for its atmospheric model. There are other models approved by NORAD such as SDP4 for deep-space satellites, SGP8/SDP8 for future upgrade.

One of the most important characteristics of the SGP-related models is that they predict orbits in analytic manners. In other words, if we know the time of interest we can directly calculate the state of the satellite's orbit at that time without the need to time-step integration as described in Section 3. Since NORAD predicts and observes thousands of objects on daily basis this analytic prediction technique has been essential in order to reduce the computational intense. The SGP models, however, handle not only the secular effects of atmospheric drag and gravitation but also long and short periodics so that quite accurate osculating elements can be derived from NORAD TLE by using SGP models. Full mathematical derivation of each SGP model is well documented in the reference (Hoots, 1980).

5. Experiments and Analysis

1) Dataset and Assessment Procedure

In order to assess the accuracy of the SGP model using NORAD TLE sets, "true" orbit data should be obtained for comparison. Although there is no true orbit data available in theory, we can use orbit data which was measured and determined highly accurately. In this sense, we used the orbit data of a geodetic satellite, TOPEX/Poseidon, as true orbit data. The TOPEX/Poseidon satellite was launched on 10 August 1992 with the objective of observing and understanding the ocean circulation. As a joint project between NASA, the U.S. space agency, and CNES, the French space agency, it carries two radar altimeters and precise orbit determination systems, including the DORIS system. Since TOPEX/Poseidon was launched together with KITSAT-1, its orbital characteristics are same as those of KITSAT-1 (1300km altitude, near-circular and 66o inclination). It therefore experiences space environment different from the environment for typical sun-synchronous low Earth orbit satellites (800km altitude and ~98° inclination). Although some differences such as air-drag and lunisolar attraction exist between the two orbits, they are considered as negligible for the accuracy assessment of SGP models because SGP models apply the corresponding perturbation effect calculations according to the both kinds of orbits (Hoots, 1980). The most important thing is that the TOPEX/Poseidon orbital data is currently approved as the most accurately measured data compared to the true orbit. From this reason, most of the accuracy assessment works of newly developed orbit prediction algorithms are carried out using TOPEX/Poseidon orbital data.

The true orbit data were the ECI (Earth-centered Coordinate of Inertia) Cartesian coordinates determined every 1 minute interval from 1 June 1995 17:09:00 (UTC) to 11 June 1995 19:08:00 (approximately ten day's period which is called test period hereinafter). They are notated as (X_i, Y_i, Z_i) where $i = 0$ to 14159 (minutes).

The SGP4 model, which is the source model of the current NORAD TLE generation, was implemented in C^{++} and verificated to give less than 10m rounding errors compared with the original Fortran code (Hoots, 1980). The implemented model generated ECI positional vectors of TOPEX/Poseidon with 1 minute

Table 1. Epoch times of eight NORAD TLE sets used in the experiments.

22 May 1995 19:49:12.15	26 May 1995 21:15:31.62
31 May 1995 02:15:31.62	4 June 1995 09:30:20.43
8 June 1995 18:26:23.33	13 June 1995 08:59:43.44
17 June 1995 16:03:20.52	22 June 1995 04:44.14.80

interval during the test period. Eight NORAD TLE sets of TOPEX/Poseidon around the test period were obtained and their epoch times are listed in Table 1. The application of TLE sets with different epoch times shows the dependency of the SGP4 model accuracy on the time difference between the epoch and the time of interest, and hence, it would be possible to determine how recently obtained TLE sets should be applied to the SGP4 model in order to satisfy a given prediction and determination accuracy requirement. The SGP4-generated orbit data in ECI coordinates using each TLE sets are notated as (x_i, y_i, z_i).

The positional error (distance) between (X_i, Y_i, Z_i) and (x_i, y_i, z_i) can easily be calculated by the root of the squared sum of the difference of each vector component. In order to calculate the along-track and the across-track errors, however, ECI coordinates should be transformed to the orbit coordinates by 3D rotations and a displacement shift. Firstly, the vector of each orbit coordinate system axis shown in Figure 1 with respect to the ECI coordinate system can be obtained as follows,

$$\begin{aligned}(z_{1i}, z_{2i}, z_{3i}) &= \frac{(X_i, Y_i, Z_i)}{\|(X_i, Y_i, Z_i)\|},\\ (z_{1i}, z_{2i}, z_{3i}) &= (Vx_i, Vy_i, Vz_i) \times (z_{1i}, z_{2i}, z_{3i}) \qquad (4)\\ (y_{1i}, y_{2i}, y_{3i}) &= (z_{1i}, z_{2i}, z_{3i}) \times (x_{1i}, x_{2i}, x_{3i})\end{aligned}$$

where (Vx_i, Vy_i, Vz_i) is the ECI velocity vector of the true orbit at the *i*th interval. The (x_i, y_i, z_i) is then transformed to the true orbit coordinate system by the rotation using the direct cosine matrix obtained in Equation (4) and the shift by the radius vector of the satellite.

$$\begin{bmatrix} ALe \\ ACe \\ RDe \end{bmatrix} = \begin{bmatrix} x_{1i} & x_{2i} & x_{3i} \\ y_{1i} & y_{2i} & y_{3i} \\ z_{1i} & z_{2i} & z_{3i} \end{bmatrix} \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ \sqrt{\mathrm{X}^2_i + \mathrm{Y}^2_i + x^2_i} \end{bmatrix} \qquad (5)$$

The along-track errors (A*Le*) and the across-track errors (AC*e*) are calculated for each NORAD TLE sets, plotted and analyzed in the following sub-section.

2) Across-track Error Analysis

Figure 4. shows the trend of the across-track errors generated by SGP4 model using 4 TLE sets. The test period (from June 1 to the June 11) should be beared in mind. The figure shows that the across track errors are less than 2km even by using a TLE set which is 20 days before the pass (TLE epoch of May 22 and the time of interest at the end of the test period, June 11). The pass programming with less than 2km across-track errors can therefore be performed on weekly based using the SGP4 model with weekly-updated TLE sets. This operational plan can also be applied for the catalog generation if only across-track errors are concerned. Figure 4 also shows clearly that the errors are reduced as the TLE epoch time gets closer to the time of interest.

The small across-track errors are due to two reasons. Firstly, the orbital plane change (across-track direction error) is very resistant to the pertuabation effects compared with the in-orbit positional change (along-track direction error) according to the orbit mechanics (Wertz, 1978). Secondly, the along-track observation errors are normally much larger than across-track or radial observation errors because a satellite travels very

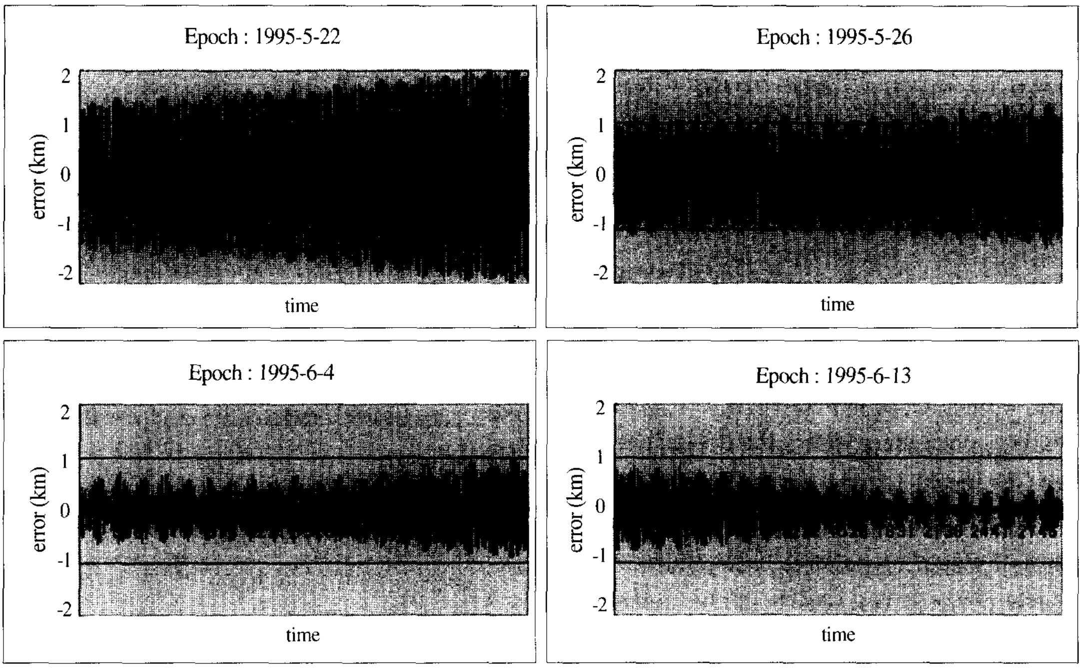


Fig. 4. Across-track error of the SGP4 model.

fast (~7km/sec). The significance of the along-track errors are shown in the next sub-section.

3) Along-track Error Analysis

The along-track errors are shown in Figure 5. Firstly, the upper two graphs show a constant bias of 8km in 5 days time difference between the epoch and the time of interest: e.g. the epoch of May 26 and the test time of June 1 (begining of the test period) as well as the epoch of May 31 and the test time of June 5 (middle of the test period). Even the TLE set with the epoch of May 31 shows a 4km bias in one day at the test time of June 1. The two graphs also show the linearly increasing along-track error at a rate of approximately 1km/day. The lower two graphs show completely different error pattern which are limited to 2km over the whole test period. This means that no bias exists and errors do not increase over time in at least 5 days.

Considering the results of the lower two graphs in Figure 5, we can conclude that weekly updated TLE sets can be used for catalog generation with the along-track errors less than 3km. We have to however pay more attention to the worse cases of the upper two graphs which show that even 3 day update of TLE sets can cause along-track errors larger than 5km.

5. Conclusions and Discussions

In this paper, the accuracy of NORAD TLE sets and their optimal propagator, SGP4 model was tested by using TOPEX/Poseidon orbit data as truth. The accuracy of the orbit prediction and determination was discussed with the requirements for pass programming and image catalog generation in high resolution remote sensing satellite programs. In conclusion,

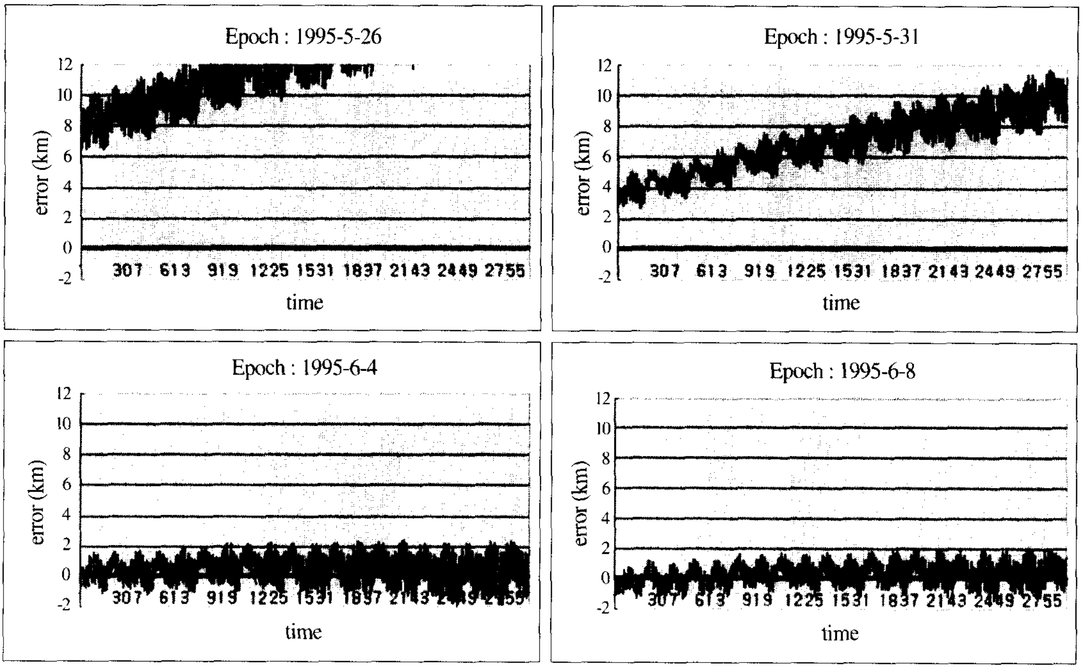


Fig. 5. Along-track error of SGP4 model

- weekly update of NORAD TLE sets are as accurate as 2km in ground track for pass programming on weekly basis and
- the SGP4 propagator using a TLE set with an epoch as close as 3 days to the image acquisition time can cause larger than 7km

In the case of KITSAT-3 of which the image size is 50km by 30km, 90% of overlap in pass programming can easily be achieved using weekly updated TLE sets. The along-track errors in image catalog can however be larger than 20% of the scene size.

There are more factors to be considered. Firstly, the attitude accuracy of a satellite is the other critical factor which determines the accuracy of the pass programming and the image catalog. The accuracy of the attitude control and determination system in a satellite depends on its own stability. Secondly, the different space environment in between sun-synchronous orbits and the TOPEX/Poseidon ordit should also be considered. Thirdly, more experiments using several truth data and test periods are recommended to be carried out in order to generalize the conclusions in this paper.

References

Allen, S.E., P.H. Austin and J.M. Stockie. Lab 4 ODE Lab - Runge-Kutta Methods, http://www.geog.ubc.ca/numeric

Brouwer, D., 1959. Solution of the Problem of Artificial Satellite Theory without Drag, Astronomical Journal, 64:378-397.

Chobotov, V.A, 1996. Orbital Mechanics, 2nd Ed., AIAA Education Series.

Hilton, C.G and J.R. Kuhlman, 1966. Mathematical Models for the Space Defense Center, Philco-Ford Publication No. U3871, 17-28.

Hoots, F.R, 1980. Spacetrack Report No. 3, NORAD.

Kelso, T.S, Sep 1997. Space Surveillance, Satellite Times.

Kelso, T.S, 1998. NORAD Two Line Element Set Format, http://celestrak.com/

Kozai, Y., 1959. The Motion of a Close Earth Satellite, Astronomical Journal, 64:367-377

Lane, M.H. and K.H. Cranford, 1969. An Improved Analytical Drag Theory for the Artificial Satellite Problem, AIAA Paper 69-925.

Lee, Y.R., D. Shin and T.G. Kim, 1998. KITSAT-3 Image Browse and Distribution System, J. Korean Association of Geographic Information Studies, 1(2):37-43.

RRL, 1992. Research and Development on the Satellite Tracking and Receiving Techniqu (I), Final Report (1st year).

SPOTIMAGE, 1997. SPOT to Direct Receiving Station Interface Document, S-IF-O/E-10-SI Ed.2-Rev.0

Wertz, J.R, 1978. Spacecraft Attitude Determinatio and Control, Kluwer Academic Publishers