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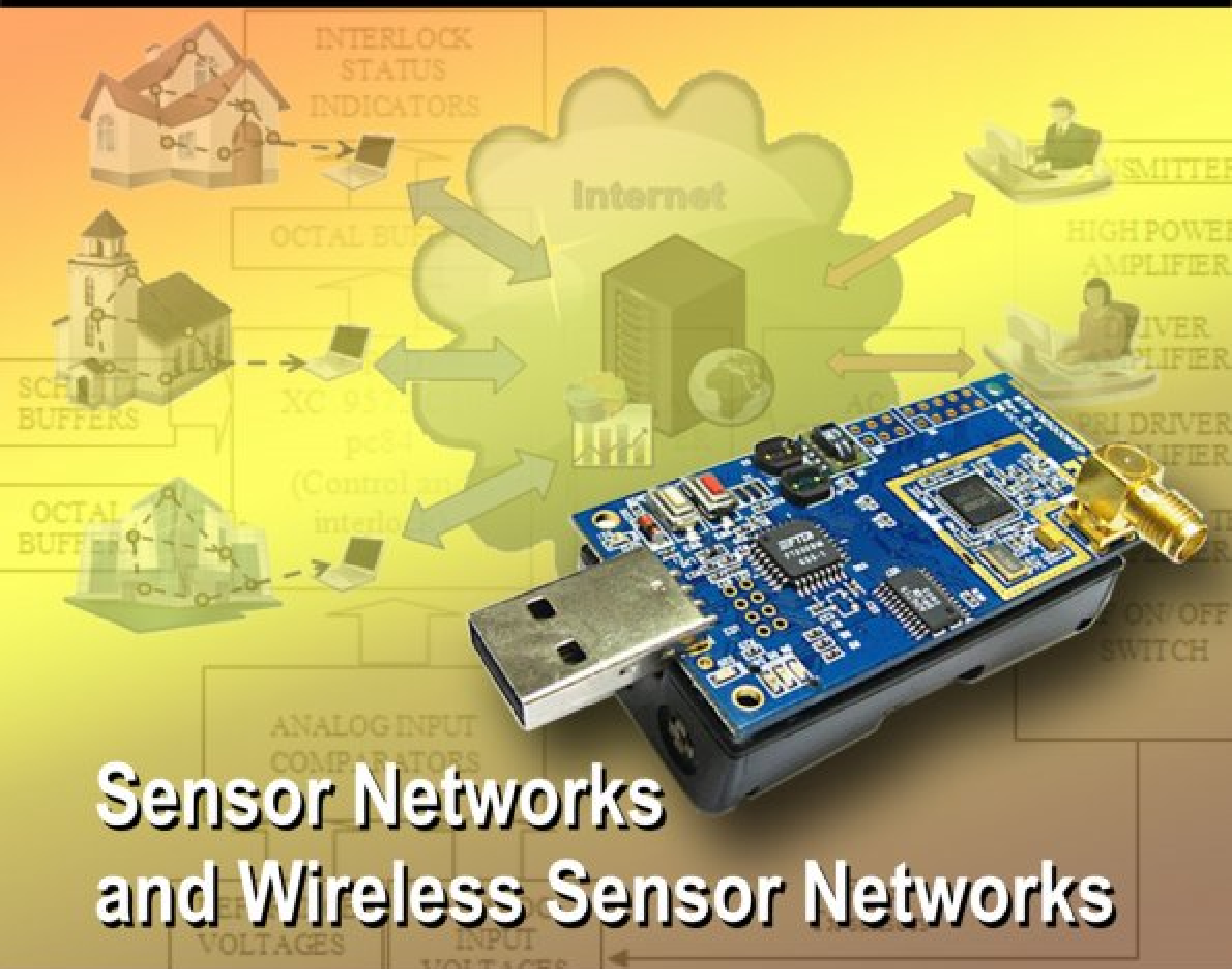

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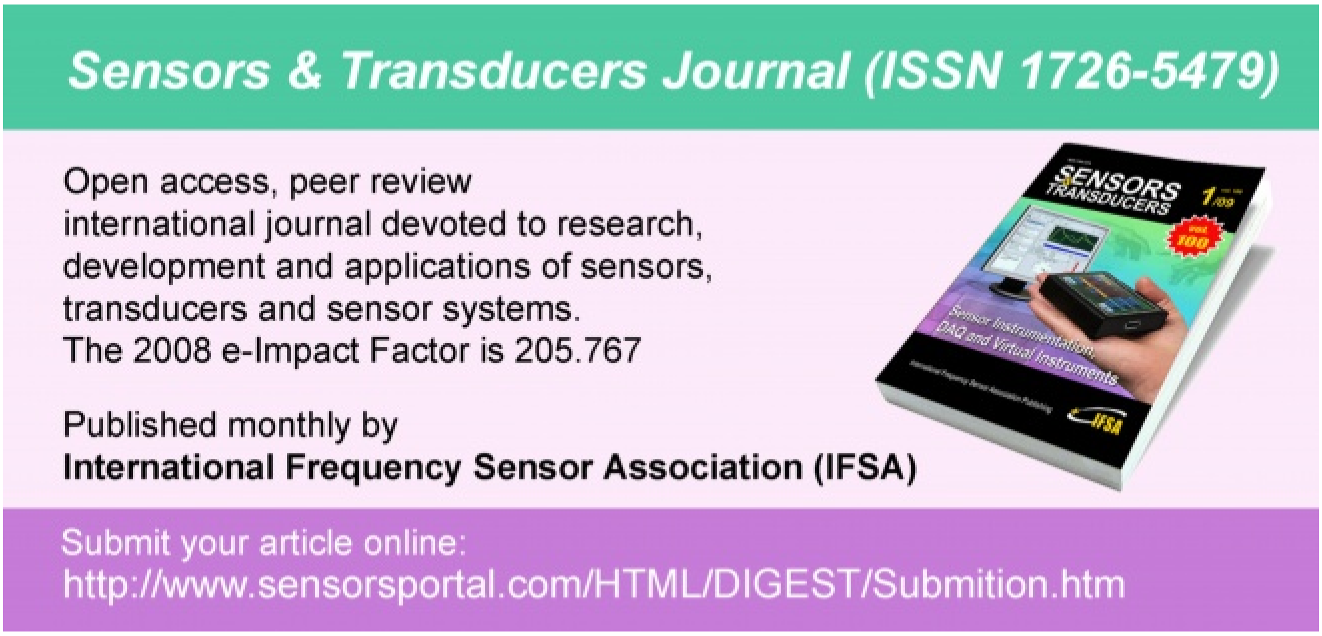

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Attitude Modeling Using Kalman Filter Approach for Improving the Geometric Accuracy of Cartosat-1 Data Products

[1]Nita H. SHAH, [2]B. ISLAM

[1]Department of Mathematics, Gujarat University Ahmedabad –380 009, Gujarat, India
[2]Space Applications Centre, ISRO, Ahmedabad - 380015, India
E-mail: nitahshah@gmail.com

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Abstract: This paper deals with the rigorous photogrammetric solution to model the uncertainty in the orientation parameters of Indian Remote Sensing Satellite IRS-P5 (Cartosat-1). Cartosat-1 is a three axis stabilized spacecraft launched into polar sun-synchronous circular orbit at an altitude of 618 km. The satellite has two panchromatic (PAN) cameras with nominal resolution of ~2.5 m. The camera looking ahead is called FORE mounted with +26 deg angle and the other looking near nadir is called AFT mounted with -5 deg, in along track direction. Data Product Generation Software (DPGS) system uses the rigorous photogrammetric Collinearity model in order to utilize the full system information, together with payload geometry & control points, for estimating the uncertainty in attitude parameters. The initial orbit, attitude knowledge is obtained from GPS bound orbit measurement, star tracker and gyros. The variations in satellite attitude with time are modelled using simple linear polynomial model. Also, based on this model, *Kalman filter* approach is studied and applied to improve the uncertainty in the orientation of spacecraft with high quality ground control points (GCPs). The sequential estimator (*Kalman filter*) is used in an iterative process which corrects the parameters at each time of observation rather than at epoch time. Results are presented for three stereo data sets. The accuracy of model depends on the accuracy of the control points. *Copyright © 2010 IFSA.*

Keywords: Collinearity model, *Kalman filter*, Geometric Modeling, Cartosat-1, Geometric accuracy.

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1. Introduction

Cartosat-1 is the first Indian remote sensing satellite to provide high resolution stereo imagery of earth surface, launched into polar sun-synchronous circular orbit at the altitude of 618 km. The satellite carries two identical panchromatic (PAN) cameras with nominal resolution of ~2.5 m and a swath of ~30 km with the spectral range covering 0.50-0.85 µm. Both the cameras are tilted with respect to the nadir direction in order to get two views in along the track, one at an angle of +26 deg and the other at -5 deg.

The camera which is mounted in spacecraft looking ahead is called FORE camera and the other one looking near nadir is AFT camera. Both the cameras are mounted on a thermally isolated and stable payload platform. The PAN cameras are significant for photogrammetry and cartography due to its fine resolution and stereo acquisition capability. The push-broom scanning technique is used in Cartosat-1 for acquiring images like in the other IRS satellites. For satellite imagery, each line is imaged in a different instant of time, unlike in aerial imaging. Therefore, exterior orientation parameters for each line are different, and these are functions of time. In this paper we present the *Kalman filter* approach to improve the accuracy of the Cartosat-1 imaging model using a few ground control points (GCPs).

The basic system level accuracy for Cartosat-1 data is nearly 200 m which varies from scene to scene to some extent depending on the uncertainties in the attitudes.

The satellite imagery suffers from distortions due to changing spacecraft orientation during imaging. These distortions can be removed if the attitude and the position of the spacecraft can be estimated to sufficient precision. Generally, polynomials are fitted to the sampled attitude time series with same order. But some times this fitted attitude is not sufficient to achieve required accuracies (Caron and Simon, 1975). Therefore, the determination of each attitude component should be made more precise and accurate using a priori information along with GCPs and appropriate modeling.

The estimation of the spacecraft orientation parameters using *Kalman filter* is discussed here in this paper. It is a discrete time sequential optimal estimator in mean square sense, which uses the GCPs as observation (Caron and Simon, 1975). This approach has been first time tested with Cartosat-1 datasets, as this along-track stereo sensors having different imaging geometry compared to other high resolution IRS satellites. Also the source of GCP's achieved from GPS navigation system which was not available in earlier IRS missions (Singh *et. al.* 2002) data product generation.

2. Kalman Filter Principle

Kalman filter principle is a sequential optimal estimator, generally corrects the state vector at the time of each observations rather than at epoch time (Wertz, 1975). After the state is updated using one or more observations, it is propagated or extrapolated (by mathematical model) to the time of next set of observations to provide an initial estimate for the next update. The filter's confidence in its estimate of the state is allowed to degrade from one update to another using model of noise in the state vector. This causes the influence of earlier data on the current state to fade with time so that the filter does not lose sensitivity to current observations (Brown and Hwang, 1997).

The optimal *Kalman gain* is found out by using the minimum mean square criterion and it minimizes the trace of the error covariance matrix. We wish to minimize the trace of the error covariance matrix because it is the sum of the mean square errors in the estimate of all the elements of the state vector. We can use the argument here that the individual mean square errors are also minimized when the total is minimized, provided that we have enough degrees of freedom in the variation of *Kalman gain*, which we do in this case. We next differentiate the trace of error covariance matrix w.r.t. *Kalman gain* and equate it to zero for solving the optimal gain. The one gain that minimizes the mean square estimation error is called *Kalman gain.*

The formulations for Kalman filter is given below:

Let y = y(1) be an initial measurement. *Kalman* says the new optimal estimate is

$$P_{k+1} = P_k - P_k H^T [H P_k H^T + V]^{-1} H P_k \quad (2.1)$$

$$K_k = P_{k+1} H^T V^{-1} \quad (2.2)$$

$$x_k = x_{k-1} + K_k (y - Hx_{k-1}), \quad (2.3)$$

where P_{k+1} is the updated error covariance matrix, K_k is the *Kalman filter* gain, M is the partial derivative matrix w.r.t. biases components and x_{k-1} is taken as correction factors(initial approximations) and V is the noise covariance matrix.

The simplified equation of error covariance matrix is given below:

$$P_k = (I - K_k H_k) P_{k-1} \quad (2.4)$$

The *Kalman filter* consists of repeated use of Eq. [2.1] through [2.4] for each iteration.

The Eq. [2.4] is a bad simplification of Eq. [2.1]. It is true that if K is given by Eq. [2.2], then Eq. [2.1] simplifies to Eq. [2.4]. However, even the smallest error in computing Eq. [2.1] (due to round off) can lead to large errors when using Eq. [2.4]. The original Eq. [2.1] is numerically stable and yields correct answers even when K is inaccurate. Eq. [2.4] is numerically unstable and can lead to catastrophic errors. The adopted approach and mathematical formulations are given in the next section.

3. Mathematical Formulations

One of the prime tasks of the spacecraft control system onboard in remote sensing mission is that keeping the camera axis continuously directed towards the centre of the earth, we term this condition as the ideal imaging condition. The spacecraft attitude (roll, pitch and yaw) is defined as the deviation in orientation from the ideal imaging condition. For Cartosat-1, the imaging geometry for FORE and AFT is modeled by considering the mounting angles (+26deg and -5deg in along track directions) in separate rotation matrix and the actual instantaneous body attitude(from star measurements) as additional orientation matrix in order to bring the camera axis for ideal imaging condition.

In this approach we are assuming that the orbital parameters are sufficiently accurate and the attitude components is time varying but not sufficiently accurate. Therefore, these coefficients are to be derived with sufficiently accurate as they affect more in imaging geometry of satellite.

The imaging satellite sensor geometry is generally modeled by using photogrammetric *Collinearity condition* (Mikhail *et. al.* 2001). The condition states that, at any instant of imaging, the image point, corresponding ground point and the perspective centre, will all lie in a straight line.

In the approach discussed here, first the polynomial model in time is fitted for each attitude component and the obtained coefficients are used as the input to the *Kalman filter*. These coefficients are modified at each step (Ground Control Point) using an optimal *Kalman filter*.

Thus the Collinearity equation relating image space to object space is given by

$$\begin{bmatrix} x_f \\ -y \\ -z \end{bmatrix} = \lambda M \begin{bmatrix} X - x' \\ Y - y' \\ Z - z' \end{bmatrix}, \tag{3.1}$$

where, (x_f, -y, -z) is the image(focal) plane coordinates(x_f is taken as focal length), λ is the scale factor, (X,Y,Z) are ground coordinates w.r.t WGS 84 datum and (x′,y′,z′) is coordinate of the perspective centre of the camera related to the object reference systems and M is the orientation matrix.

The relation between the image and the object co-ordinate systems is expressed through (3x3) orthogonal matrix designed by M. The nine elements of M are functions of the orientation parameters. The rotation matrix M can be written as:

$$M = R_L\, R_A\, R_O\ ,$$

where, R_L is the rotation matrix, which gives transformation between Master reference cube to Payload cube and Payload cube to optical axis.

R_A = Ry Rr Rp, is the attitude matrix, where Ry, Rr and Rp represents rotation matrices w.r.t yaw, roll, pitch respectively. It describes the orientation of body co-ordinate system with respect to orbital co-ordinate system.

R_O is the orientation matrix which is a function of orbital parameters. It relates geocentric and orbital co-ordinate systems.

3.1. Calculation of the Scale Factor

The Collinearity equation as given in [3.1] can be changed to

$$\begin{aligned} X &= x' + \lambda' p \\ Y &= y' + \lambda' q\ , \\ Z &= z' + \lambda' r \end{aligned} \tag{3.2}$$

where

$$\begin{bmatrix} p \\ q \\ r \end{bmatrix} = M^T \begin{bmatrix} x_f \\ -y \\ -z \end{bmatrix}$$

and

$$\lambda' = \frac{1}{\lambda}$$

where λ is the scale factor.

The look vector will intersect the earth's surface (WGS 84), whose ground coordinate must satisfy the ellipsoidal equation

$$\frac{X^2 + Y^2}{a^2} + \frac{Z^2}{b^2} = 1 \tag{3.3}$$

where a and b are the semi major and semi minor axis of the ellipsoid (WGS 84).

Putting the values of X,Y,Z in the Eq. [3.3], we get the quadratic equation in λ'. Solving this we can calculate the scale factor.

The Eq. [3.2] can be written as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} + \lambda' M^T \begin{bmatrix} x_f \\ -y \\ -z \end{bmatrix}$$

Taking

$$O_a = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \; O_m = \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} + \lambda' M^T \begin{bmatrix} x_f \\ -y \\ -z \end{bmatrix}$$

where, O_a is the actual ground coordinate and O_m is the estimated coordinate of the corresponding ground control point from the image point using known orbit and attitude parameters. The above non-linear equation is linearized using the Taylor's series. In this expansion, the initial approximation values are taken from the available ancillary information over the period of interest. Here the iterative process is assumed to be Gaussian stochastic process. Therefore, it can be taken as

$$o_a(t) = o_m(t) + v(t), \tag{3.4}$$

where, v is the additive white Gaussian observation noise, we assume that equal uncertainties are associated with each components of O_a.

The coefficients obtained by fitting least square polynomial are used as the initial approximation of the attitude components. Let the state vector be x_k. Then x_k is $3(n+1)\times 1$ matrix of coefficients forms the state vector for the filter which will update corresponding to each iteration.

The attitude model assumed in this case is a linear error model, which can be expressed as

$$\alpha = \text{Original roll} + \alpha_0 + \alpha_1 time$$
$$\beta = \text{Original pitch} + \beta_0 + \beta_1 time$$
$$\gamma = \text{Original yaw} + \gamma_0 + \gamma_1 time$$

The *Kalman filter* as originally proposed deals with linear model only. In order to use *Kalman filter* approach to a non-linear discrete model, the equations must be extended by Taylor linearization.

The *Extended Kalman filter* ((Brown and Hwang, 1997) equations (using Eq. 2.1-2.3) can be written:

$$P_{k+1} = P_k - P_k H^T [H P_k H^T + V]^{-1} H P_k$$

$$K_k = P_{k+1} H^T V^{-1}$$

$$x_k = x_{k-1} + K_k \left(Z_k - \overline{Z_k}\right) \quad (3.5)$$

where,
P_k is the error covariance matrix, depending on the uncertainty in attitude component;
K_k is the *Kalman gain* matrix, it is an optimal gain calculated by assuming the minimum mean square criteria of the error-covariance matrix;
V is the noise covariance matrix, which is a function of observation noise;
z_k is the actual ground coordinate matrix;
x_k is the updated of polynomial coefficients;
k is the suffix representing the number of GCP's;
$\overline{z}_k = o_m + H x_{k-1}$ is said to be the measurement residual. It simply says that we correct the a *priori estimate* by adding the measurement residual appropriately weighted by the *Kalman gain* K_k.

$$H = \left[\frac{\partial o_a}{\partial \alpha_0} \frac{\partial o_a}{\partial \alpha_1} \frac{\partial o_a}{\partial \beta_0} \frac{\partial o_a}{\partial \beta_1} \frac{\partial o_a}{\partial \gamma_0} \frac{\partial o_a}{\partial \gamma_1} \right]$$

is the partial derivative matrix is obtained for M w.r.t $(\alpha_0, \alpha_1, \beta_0, \beta_1, \gamma_0, \gamma_1)$ where we get the pre-multiplier Skew_Symmetric matrices for roll, pitch and yaw components (Lucas, 1963).

Here in the above Eq. [3.5] partially $(z_k - \overline{z}_k)$ shows the clear effect of Taylor's series but in some reference (Singh *et.al.* 2002*)* could not shows that effect, as we are using all the time varying and non–linear components. Also in reference (Singh *et.al.* 2002*)* they have not used any constant matrices (Skew_Symmetric) for the attitude components which indirectly help in adjustment of partial derivative matrix during iteration process.

4. Test Methodology

The inputs required for testing the approach are
(1) The attitude time series vector.
(2) Ephemeris time series vector in ECI (Earth Centered Inertial) frame of reference.
(3) Ground coordinates of the GCP in ECI.
(4) Image coordinates of the corresponding GCP identified on in RAD (radiometrically corrected) image.

As the shape of an orbit at any instant of time can be approximated to an ellipse in an inertial co-ordinate system. This is not true in an earth fixed geocentric co-ordinate system. This is due to the earth's movement both around the polar axis as well as the movement of polar axis with time. Therefore, it is necessary to consider an additional geocentric co-ordinate system that is inertial and at the same time has the same origin as the earth fixed geocentric co-ordinate system.

For the Cartosat-1 high-resolution satellite with FORE and AFT cameras separated by imaging time difference of approximately 52 s, three scenes are selected for both cameras in stereo mode. A few GCPs are identified in this stereo data. Since the GCPs coordinates are known in ECEF (Earth Centered Earth Fixed) frame of reference, they are first converted to ECI frame using the sidereal angle. Their imaging times were determined by using the relation

GCP imaging time = scene start time + (scan line x integration time).

The Following is the *Kalman filter* loop:

Initial error covariance matrix P_0 is given as the input and this matrix is created based on the biases of components. The partial derivative matrix of the function O_a w.r.t the elements of polynomial coefficients are obtained as in Eq. [3.5]. The following flow of *Kalman filter* (Fig. 1) equations are used here

Create the initial covariance matrix P_0 at time (t=0),

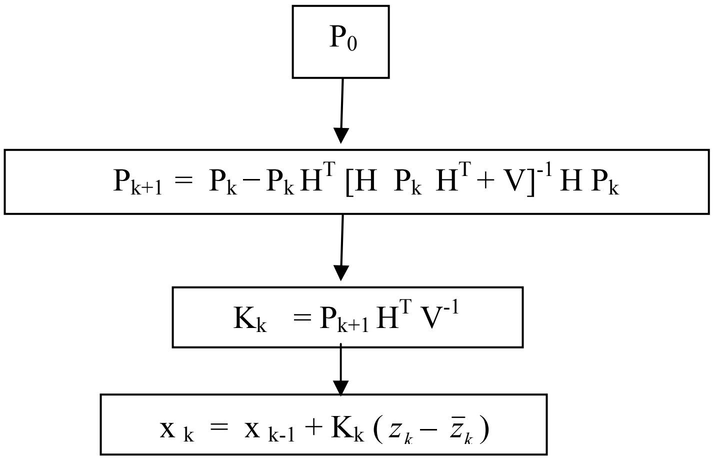

Fig. 1. Flow diagram of Kalman filter.

Thus at these times, interpolated attitude are calculated. For the whole length of the stereo data, attitude time series sampled data (available at every 125 ms) are fitted with first order polynomial, which was observed to be sufficient.

Initial polynomial coefficients for attitude components are taken as
$(\alpha_0, \alpha_1, \beta_0, \beta_1, \gamma_0, \gamma_1)$. They are initialized with zero values.
where,
α_0, α_1 are the roll coefficients;
β_0, β_1 are the pitch coefficients;
γ_0, γ_1 are the yaw coefficients.

It was assumed that each component in state vector is uncorrelated. Uncertainty value in bias components initially taken as 0.002, 0.000001 degrees for time varying polynomial coefficients of the attitude components, to determine the initial error covariance matrix P_0. As it is uncorrelated, it will be different for three attitude components. Matrix P_0 was taken to be diagonal matrix based upon the above assumption. It is also assumed that equal uncertainties are there in each components of O_a (Eq. 3.4) and that they are uncorrelated. Thus the noise covariance matrix (V) is also diagonal matrix based on the measurements of GCP accuracy.

These values are input to the Kalman filter equations and at the nth GCP, we get the modified polynomial coefficients. Using these coefficients the attitude values are regenerated to get the updated attitude values. These values are internally used in ground to image transformation to obtain the refined image coordinates (Eq. 3.1).

5. Results and Discussions

Collinearity model along with the *Kalman filter* approach for attitude modeling has been used and tested using different datasets of Cartosat-1 having the scene size (30x30) km^2 with a few control points. Using the updated attitude components, the image points are computed corresponding to each control points and also at check points.

The Tables for three data sets (FORE and AFT) of Cartosat-1 show the details of Standard Deviation (Std. Deviation) and Root Mean Square Error (RMSE) while modeling the ground to image mapping and comparing with original and computed image points for both pre and post application of *Kalman filter*.

FORE camera results: The result shows that, at check points, the location error in terms of RMSE has been brought down drastically upto 6.05 (pixel) in scanline direction, and 7.36 (pixel) in pixel direction during post *Kalman filter* shown in Table 3.

AFT camera results: The result shows that, at the check points the location error in terms of RMSE has been brought down drastically upto 7.81 (pixel) in scanline direction and 4.33 (pixel) in pixel direction at post *Kalman filter* shown in Table 3.

The distribution of GCPs for different cases are presented in Fig. (2-4) and the Root Mean Square Error (RMSE) are presented in Fig. (5-7). The plots show the pre and post application of *Kalman filtering* for three data sets of Cartosat-1 for both the cameras FORE and AFT.

From Tables (2&3) as well as from the above observations, one can see that the results are consistent for both FORE and AFT cameras. Requirements for the utility of the model is minimum 5/6 well distributed GCP's of accuracy better than 1 pixel. The image positions of GCPs are manually identified and the identification accuracy is approximately ± 2 pixel. The corresponding ground position as geodetic coordinates is obtained from GPS survey. Experiments show that with minimum number (5/6) well distributed GCPs, the attitude biases are compensated with good convergency even if the GCP used for modelling is in one of the corner of the scene when the check points are uniformly distributed then the results are found satisfactory. Thus the method is not sensitive to the location of the GCP used on the modeling. The height range of the CASE-1, CASE-2 and CASE-3 are given as:

6. Conclusions

A *Kalman filter* approach and corresponding Software was developed for attitude modeling for improving the geometric accuracy of Cartosat-1 data. The model has been tested with three data sets acquired over different terrain types mentioned in Table 1. From the result one can see that the model is able to improve the biases in attitude components using *Kalman filter* approach for both FORE and AFT cameras, which can directly improve the location accuracy of Cartosat-1 imagery. In both FORE and AFT camera, the results are found out less than 10 pixels at post *Kalman filter*. Also, after fine tuning of biases in attitude components, the initial approximation corresponding to each components have been fixed up separately for both the cameras FORE and AFT, which indirectly helps to make the priori error-covariance matrix. Here we observed the divergency as well as oscillations (Fig. 5-7) of *Kalman filter* during the iteration process at some observations. This may be due to *linearized Kalman filtering,* as it does not depend on the measurement data of nonlinear dynamics (Brown and Hwang, 1997). Therefore, further investigation is required to test the algorithm with more data sets for fine-tuning of uncertainty values along with the *Extended Kalman filtering,* because this method continually updates the state estimates resulting from the measurement data. The conventional approach for Cartosat-1 (Srinivasan *et.al.* 2006) also results in around 10 pixel error. Hence this approach is comparable with the conventional approach results for the precision product generation. However, the investigation is going on about the methodology for generating the initial error-covariance matrix, based on the correlated attitude components. As it is a generalized model, it can be used for other future remote sensing missions with appropriate modifications of *Kalman filter* algorithm.

Following tables (Table 2 and Table 3) show the results obtained using Kalman Filter approach for Cartosat-1 FORE and AFT Cameras.

Table 1. The height ranges for all the area of studies.

CASE-1	CASE-2	CASE-3
Highly hilly(m)	Moderate(m)	Hilly(m)
172 to 2653	192 to 258	400 to 574

Table 2. Pre Application of Kalman filter.

FORE

No. of GCP	RMS Error SCAN (in pixel)	RMS Error PIXEL (in pixel)	Std. Deviation SCAN (in pixel)	Std. Deviation PIXEL (in pixel)
		CASE-1		
8	5.73	14.59	5.06	2.95
4	5.15	16.56	3.35	1.56
		CASE-2		
50	29.05	11.13	1.26	2.14
6	28.21	12.41	1.25	2.58
		CASE-3		
35	30.09	5.46	2.65	2.16
6	29.58	7.7	5.34	3.86

AFT

No. of GCP	RMS Error SCAN (in pixel)	RMS Error PIXEL (in pixel)	Std. Deviation SCAN (in pixel)	Std. Deviation PIXEL (in pixel)
		CASE-1		
8	12.74	4.64	2.59	2.6
4	14.52	5.7	0.49	1.35
		CASE-2		
50	17.11	26.67	1.23	1.76
6	19.91	27.92	2.11	0.75
		CASE-3		
35	12.62	3.3	1.99	2.11
6	12.33	3.22	0.67	1.38

Table 3. Post Application of Kalman filter.

FORE

No. of GCP	RMS Error SCAN (in pixel)	RMS Error PIXEL (in pixel)	Std. Deviation SCAN (in pixel)	Std. Deviation PIXEL (in pixel)
		CASE-1		
8	5.97	5.53	5.27	2.94
4	5.5	6.49	3.48	1.56
		CASE-2		
50	1.43	3.67	1.21	2.21
6	1.32	6.56	0.92	1.59
		CASE-3		
35	2.57	2.8	2.57	2.26
6	6.05	7.36	5.31	4.22

AFT

No. of GCP	RMS Error SCAN (in pixel)	RMS Error PIXEL (in pixel)	Std. Deviation SCAN (in pixel)	Std. Deviation PIXEL (in pixel)
		CASE-1		
8	1.82	4.94	1.78	2.59
4	5.61	1.35	0.65	1.35
		CASE-2		
50	5.86	9.61	1.67	1.76
6	5.07	6.09	2.2	0.74
		CASE-3		
35	6.07	4.06	1.85	2.01
6	7.81	4.33	0.61	1.24

Note 1: Root Mean Square (RMS) error and Standard Deviation 'in pixel' can be converted to 'meter' by using ~2.5m (resolution of Cartosat-1).

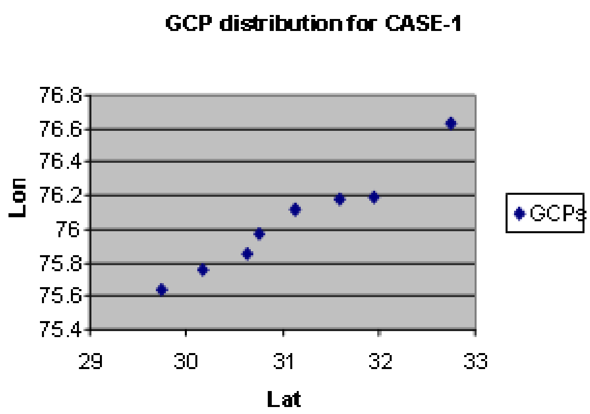

Fig. 2. GCP distribution of corresponding scene for CASE-1.

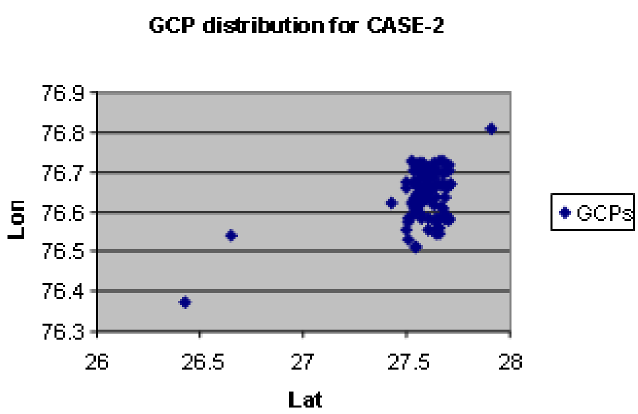

Fig. 3. GCP distribution of corresponding scene for CASE-2.

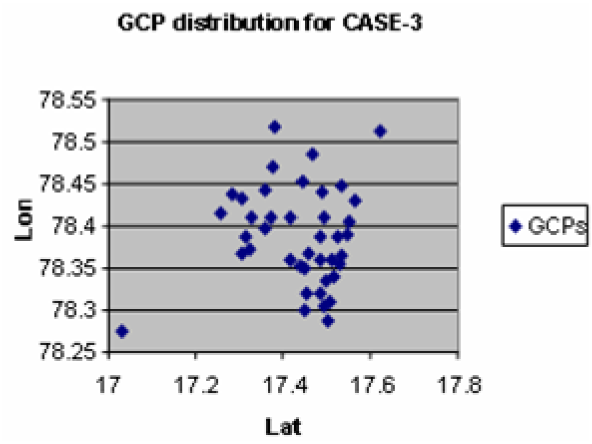

Fig. 4. GCP distribution of corresponding scene for CASE-3.

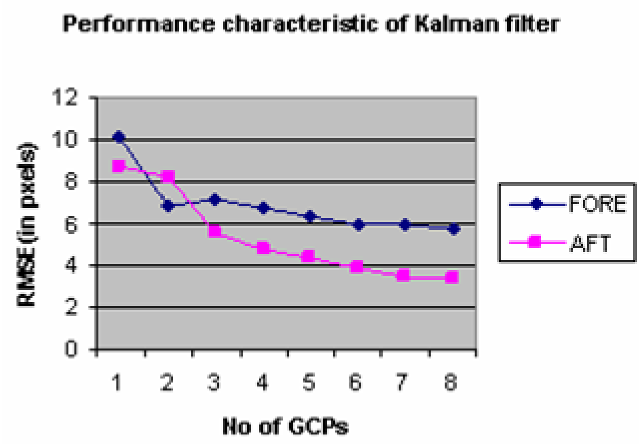

Fig. 5. Shows that the accuracy achievement with increase of no. of GCPs for CASE-1.

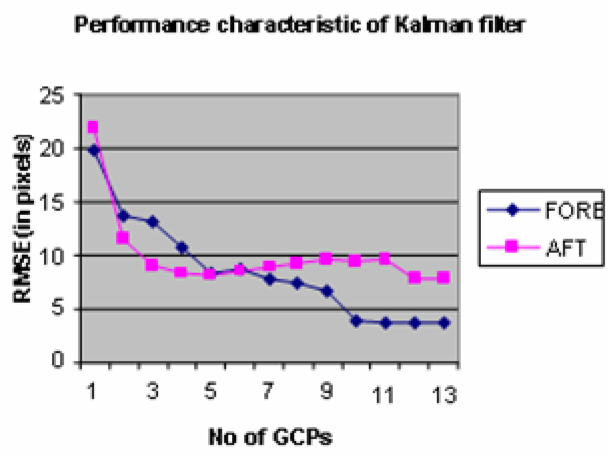

Fig. 6. Shows that the accuracy achievement with increase of no. of GCPs for CASE-2.

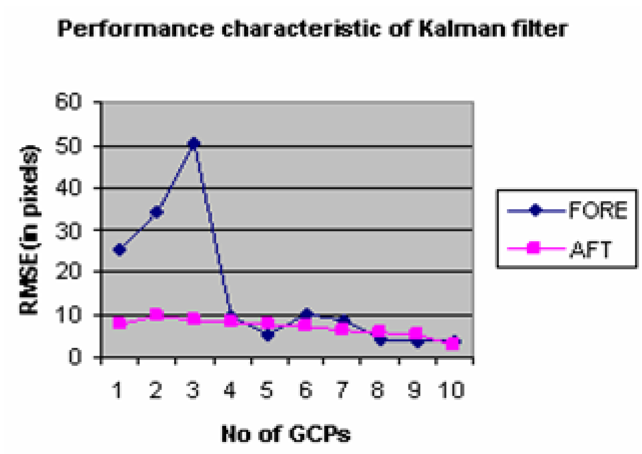

Fig. 7. Shows that the accuracy achievement with increase of no. of GCPs for CASE-3.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 8-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

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