P1.27

5th GOES Users' Conference: GOES-R Advanced Baseline Imager Image Navigation and Registration

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ABSTRACT

Highly accurate image navigation and registration (INR) of data collected using remote sensors is key to satisfying mission requirements for satellite observation systems. Locating image data in a specifically defined scene has become a challenge of providing sub-pixel level knowledge of the location of the raw collected samples when computed in the designated scene. The precision INR solution presented in this study is one in which the instrument is used to collect measurements as a means of estimating the instrument line of sight attitude and thermal line of sight perturbations. The approach is applied to the GOES-R Advanced Baseline Imager (ABI) mission which collects star measurements (visible and IR) and using a Kalman filter with an order of magnitude fewer states than baseline GOES, estimates line of sight attitude and thermal drift. The algorithm computes corrections to the line of sight to compensate for thermal changes as the sample data are navigated and co-registered to the specified scene. Instrument line of sight and thermal deformation effects modeling are presented and simulation results show the attitude determination accuracy for the instrument line of sight as well as the location accuracy of samples navigated to the mission-defined scene.

1 – INTRODUCTION

1.1 NEXT GENERATION INSTRUMENT

The GOES-R Advance Baseline Imager (ABI) represents a new generation of imaging capability for the weather community: significantly more channels than previous GOES Imager instruments, sample rates are much and resolution is also greatly increased. Spatial resolution and image location accuracy requirements are more stringent than for previous GOES Imagers.

1.2 CHANGES IN PERFORMANCE REQUIREMENTS FROM GOES-N

Key Performance Parameter Comparison

Requirement	GOES Imager	GOES ABI
Number of Spectral Bands	5	16
Data Rate	2.6 MBPS	66.6 MBPS
Spatial Resolution Wavelengths > 3 microns	4 km	2 km
Time for Full Disc Scan	26 minutes	15 or 5 minutes
Spatial Resolution Wavelengths < 3 microns	1 km	0.5 – 1.0 km
Absolute Image Navigation and Registration	26 μrad (EW) 20 μrad (NS) Excluding Diurnal Repeatable Distortion	21 μrad (EW) 21 μrad (NS)
Cross Channel Image	50 μrad (Visible to IR)	6.3 μrad (0.5, 1.0 to 2 km)
Co-registration	28 μrad (IR to IR)	5.6 μrad (0.5, 1.0 to1 km)

Image navigation and registration (INR) on the GOES program preceding GOES-R employs image motion compensation (IMC) on board the spacecraft/imager to assure the image line of sight is accurately pointed to desired locations on the earth scene. ABI INR relies on a ground-based real time image navigation process to achieve increased knowledge accuracy using precise encoder readings and star image data. During the Earth scene collection, the instrument uses attitude information provided by the spacecraft to compensate for the spacecraft's attitude motion; however the precise image navigation and registration is achieved through ground processing to determine where the image data were actually collected relative to the fixed grid scene.

2 – BACKGROUND

2.1 OBSERVATIONS FROM GEOSYNCHRONOUS ALTITUDE

When collecting image samples from geosynchronous altitude small pointing errors at the instrument location can result in very large changes in what scene is being collected at the earth surface. The navigation requirement for 21 μrad results in about a 0.75 km offset in the image location on the earth surface at nadir as illustrate in Figure 1. For this reason, it is more practical to determine where the instrument line of sight was actually pointing during imaging than to attempt to point the instrument to extreme accuracies. This is possible because the scenes are slightly oversized and swaths overlap sufficiently to account for line of sight pointing uncertainty and thermally induced diurnal line of sight variation – no part of the scene will be missed.

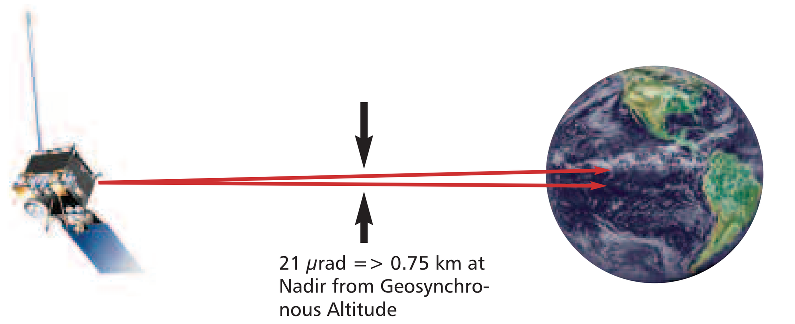


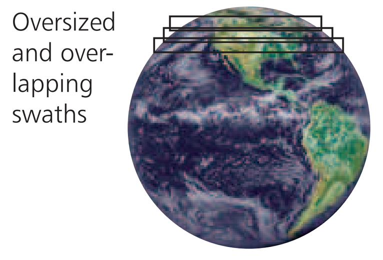
Figure 1.
Small angles cover large distances at geosynchronous altitude.

2.2 GEOMETRY AND MAGNITUDE OF POINTING AND STEERING

Image collection performance for the ABI is governed by the attitude knowledge provide by the spacecraft, the control accuracy of the pointing servo control for the instrument and the diurnal line of sight variation. The spacecraft provides the following information:

- Attitude Quaternion: ~ 75 μrad uncertainty (sampled at 1 Hz)
- Attitude rate measurements: < 20 μrad drift over 15 minutes (sampled at 100 Hz)
- Spacecraft Position: 35 m in-track, 35 m cross-track and 70 m radial over 15 minutes (sampled at 1 Hz)
- Spacecraft Velocity: < 6 cm/sec uncertainty per axis (sampled at 1 Hz)

The contribution of satellite data uncertainty to pointing results in less than 100 μrad uncertainty. Approximately an additional 100 μrad are allocated to diurnal line of sight variation, scanner control, jitter and collection start time (East-West only). With a margin factor of 10% the scenes are oversized by about 220 μrad East-West and 130 μrad over sizing for North-South swath overlap as shown in Figure 2. Image scene data samples are navigated on the ground to the required LOS knowledge accuracy through a combination of star images collected by the instrument and instrument scan encoder readouts. These are used in conjunction with attitude rate data and position/velocity estimates provide by the spacecraft.



Oversized and over-lapping swaths

Figure 2. Image swaths are oversized and overlap to collect entire scene.

2.3 PERFORMANCE METRICS IN TERMS OF EAST AND NORTH IN FIXED GRID FRAME

GOES-R Performance and Operational Requirements Document (PORD) states the following performance requirements for the INR process.

REQUIREMENT	EW (3_)	NS (3_)
Navigation	±21 μrad	±21 μrad
Frame-to-Frame Registration 0.47, 0.64, 0.865, and1.61 micron channels. Frame-to-frame registration error is the difference in navigation error for any given pixel in two consecutive images within the same channel.	±17.6 μrad	±17.6 μrad
Frame-to-Frame Registration 1.378, 2.25, 3.9, 6.185, 6.95, 7.34, 8.5, 9.61, 10.35, 11.2, 12.3, and 13.3 micron channels	±21 μrad	±21 μrad
Within Frame Registration	± 21 μrad	±21 μrad
Swath-to-Swath Registration	± 5.6 μrad	± 5.6 μrad
Channel-to-Channel Registration 2-km to 2-km, 1-km, 0.5-km	± 6.3 μrad	± 6.3 μrad
Channel-to-Channel Registration 1-km to 1-km, 0.5-km	± 5.2 μrad	± 5.2 μrad

3 – ABI ARCHITECTURE

3.1 HOST SPACECRAFT INTERFACE

ABI is nadir oriented on the GOES-R spacecraft such that the principal axes of the instrument are co-aligned with the spacecraft's reference frame.

- Instrument misalignment and spacecraft motion must be accounted for.
- To allow ABI to point to the Earth scenes, the spacecraft provides reference data: Attitude Quaternion (J2K reference), Attitude Rate (inertial reference), Spacecraft position and velocity estimates (see figure 3).
- The same telemetry is subsequently downlinked for use by the INR ground process.

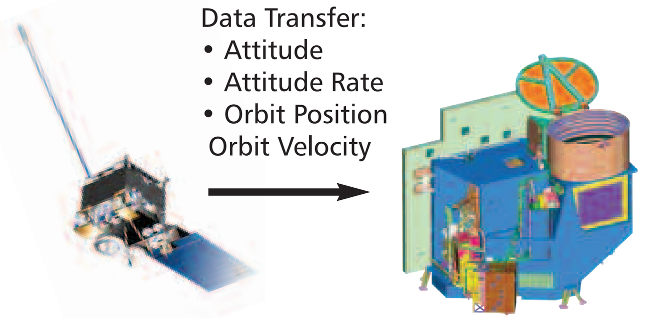


Figure 3.
Data interface between Spacecraft and ABI supports INR Process

3.2 ABI PERTURBATIONS

- Orbit and attitude errors

The GOES-R General Interface Requirements Document (GIRD) states the spacecraft attitude and orbit position are to be controlled to given tolerances. Inclination and station longitude are maintained to within ±0.5° of ideal. Spacecraft attitude errors and rates are also bounded.

Line of Sight Perturbations

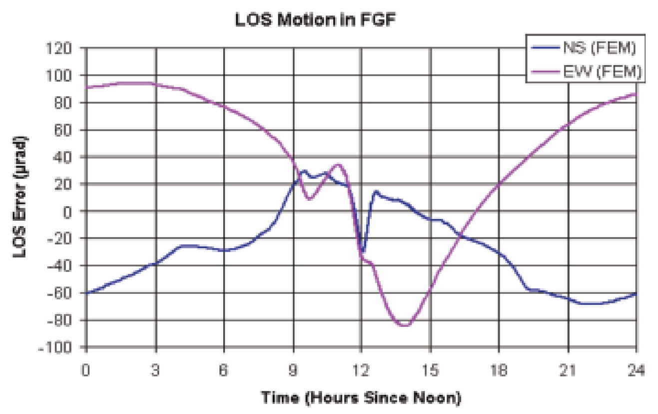


Figure 4.
Line of sight motion predicted Optical/ Thermal/Structural Finite Element Analysis.

In addition to Orbit and Attitude errors, perturbations to the instrument line of sight result from Spacecraft to Instrument mounting frame perturbation and thermally induced line of sight variations as illustrated in Figure 4.

3.3 STAR IMAGING DETERMINES ATTITUDE AND LINE OF SIGHT VARIATIONS

It can be seen that the attitude perturbations with a combination of spacecraft attitude, instrument mounting and thermal line of sight diurnal variations can be on the order of 700 μrad. Using measured star images obtained by the instrument, the instrument attitude and line of sight errors can be estimated by comparison to the star location as recorded in the star catalog.

4 – SYSTEM DESIGN

4.1 SPACECRAFT DATA AND INSTRUMENT DATA PROCESSED TO DETERMINE LINE OF SIGHT

INR is a system process that combines inputs from spacecraft and instrument measurements to estimate the instrument attitude and line of sight motion (Figure 5). For ABI INR, the states estimated to describe instrument attitude and line of sight are determined in the instrument frame. Precise star image data are used to formulate a measurement in the instrument line of sight frame which is compared to an estimated value for the star measurement using the system state estimate just prior to the measurement update. Star measurements acquired to obtain East, North and rotational line of sight motion estimates. A Kalman filter formulation is used to update state estimates for the time of measurement collection as driven by the difference between estimated line of sight to stars and measured line of sight to stars.

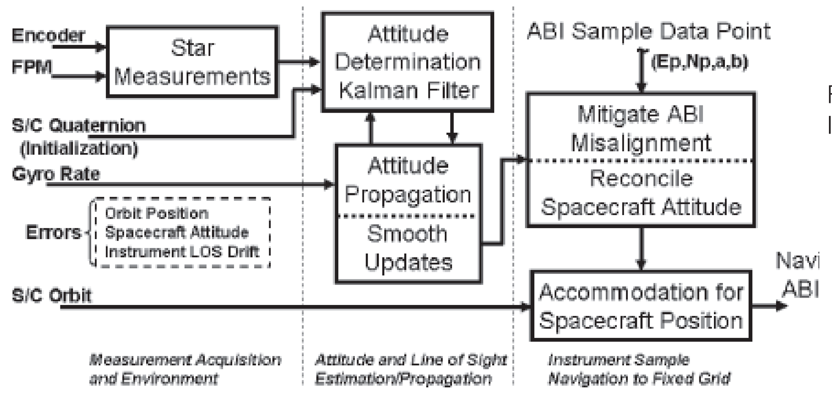


Figure 5.
INR System Process

Star images in one of the IR bands are also collected for the purpose of estimating drift between the Visible channels focal plane module (FPM) and the IR channels' FPM which are physically separate devices. The visible to IR coregistration uses a series of IR star measurements that are compared to estimates based on the visible line of sight states to generate an estimated correction for the drift between the visible and IR FPMs.

4.2 ATTITUDE ESTIMATE INITIALIZATION

Since the ABI instrument is nominally aligned with the spacecraft coordinate axes and the spacecraft attitude error is held to within ±360 μrad, the INR attitude estimate can either be initialized with the spacecraft quaternion data or simply be set to zero.
Star measurements are used to determine the instrument attitude within one to two sets of measurements. Line of sight motion offsets are characterized as more star measurements are collected. The filter performance is converged within an hour of initialization.

4.3 PROPAGATED ATTITUDE AND LINE OF SIGHT

Bulk motion of the ABI instrument line of sight is driven by the spacecraft attitude motion and motion induced at the instrument mounting interface. Between star updates, spacecraft gyro measurements are used to propagate the angular motion effect of the spacecraft on the instrument line of sight. In addition, the instrument line of sight variation states are driven by a set of rate bias estimates (including gyro bias) derived at the star measurement epoch. Propagated attitude states for the line of sight are used to navigate detector samples to the fixed grid.

4.4 NAVIGATING DETECTOR SAMPLES TO THE FIXED GRID

Detector samples collected during the imaging process are collected with respect to the line of sight of the instrument. The attitude and line of sight estimation and propagation process allows the information associated with the detector samples to be transformed to the Fixed Grid for re-sampling and image display.

Using the detector measurement data, a line of sight vector can be computed for the detector. This vector is therefore expressed in the line of sight frame of the instrument and is transformed to the fixed grid frame using the INR process attitude estimate.

The detector line of sight is then projected from the actual orbit location to the ideal location for the Fixed Grid using the orbit position estimate data provided in the spacecraft telemetry. The detector estimated line of sight vector projected in the Fixed Grid is finally expressed in terms of East and North coordinates. Figure 6 illustrates that the commanded collection for the swath may be different from the actual collected scene data. INR locates the samples in the fixed grid from the position in the scene from which they were actually collected.

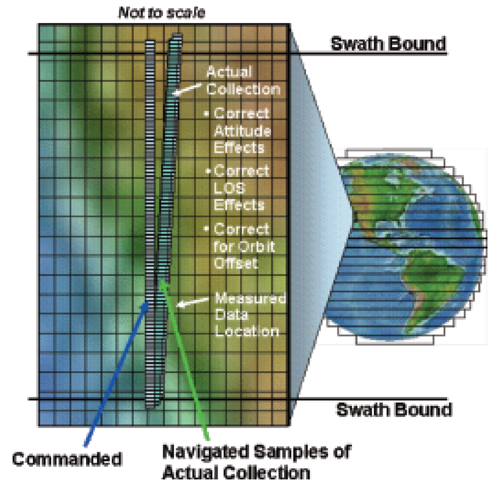


Figure 6. INR computes the actual location of samples as collected in the scene.

5 – ABI INR PERFORMANCE EXPECTATIONS

5.1 INR PERFORMANCE CONSIDERATIONS

The ABI INR team has considered perturbation sources which impact performance estimated performance based on error allocations. Error source allocations are expected to be conservative and bound the upper level of performance. Simulation analysis is expected to reflect interactions between model contributors which more closely emulate instrument performance.

ABI's INR performance prediction considerations include the following effects:

- Diurnal thermal disturbances on structural and optical elements
- Orbit and attitude offsets from ideal location and perturbations off Nadir
- Effects of moving mechanisms and their associated disturbances
- Sensor noise and sampling uncertainty
- Star detection and estimation uncertainty

The performance investigation also accounts for various seasonal effects as a result of the position of the sun relative to the orbit plane because it is known that diurnal profiles change from equinox to summer and winter solstice geometries.

5.2 INR Error Expectations

The following table reflects a summary performance margins based on error budget allocations.

		E-W / N-S	
Spec (μrad)	Value	% Margin	% Margin
Navigation non-eclipse	21.0	41%	40%
Navigation eclipse	21.0	41%	40%
Frame-Frame 0.5 & 1 km	17.6	20%	22%
Frame-Frame 2 km	21.0	33%	34%
Within Frame	21.0	29%	29%
Swath-Swath	5.60	15%	28%
Chan-Chan 2 - 2,1,0.5 km	6.30	10%	10%
Chan-Chan 1 - 1,0.5 km	5.20	14%	22%

Figure 7.
Expected Performance Margins for Metrics

5.3 ABI INR PERFORMANCE EXPECTATIONS

ABI Image Navigation and Registration performance is computed by comparing the error between modeled hardware estimates of positions to points in the Fixed Grid versus expected true locations of the evaluation points.

Instrument attitude and line of sight estimates can be compared to the true expectations of the line of sight East/North offsets in the Fixed Grid.

Line of sight determination is performed in the INR simulation to show accuracy and the ability to estimate the type of diurnal variations shown in Figure 4. It is expected that the estimation accuracy based on residual errors from star measurement for the EW and NS line of sight components in the fixed grid would support the ability of ABI INR to meet requirements. Measurement residuals represent the difference between the estimated star location and the measurements acquired. Residual errors are expected to be nearly zero mean and the standard deviations reflect random measurement error such as the values shown here.

ABI INR Line Of Sight Estimation Expected Accuracy:

Residual Mean Error:	**0.0255 μrad (EW),**	**0.0215 μrad (NS)**
Residual Standard Deviation:	**2.04 μrad (EW),**	**2.6 μrad (NS)**

Figure 8
Line of Sight Expected Estimation

INR Metric Requirement	EW (3σ) / NS (3σ)	Margin
Navigation	±21 μrad	> 30%
Frame-to-Frame Registration (Visible)	±17.6 μrad	> 20%
Frame-to-Frame Registration (IR)	±21 μrad	> 30%
Within Frame Registration	±21 μrad	> 25%
Swath-to-Swath Registration	± 5.6 μrad	> 10%
Channel-to-Channel Registration (IR)	± 6.3 μrad	> 5%
Channel-to-Channel Registration (Visible)	± 5.2 μrad	> 10%

Figure 9.
ABI INR Metric Performance Expected Margin

6 – CONCLUSIONS

- ABI INR satisfies the much more stringent performance metrics which have been specified over the current GOES imager.
- Improved Mirror, Telescope and detector designs have reduced system noise inputs allowing improved consistent INR performance over the full range of operating conditions.
- Slowly varying thermally induced diurnal effects and gyro drift rates are accommodated with a Kalman Filter Estimator which is much simpler than the previous GOES attitude estimation process. The simplification has been achieved through a reduced complexity estimator based on instrument-centric system model
- INR Metrics expected to be met with margin. Navigation typically has on the order of 40% performance margin and most other performance metrics have greater than 10% margin with this CDR level design.

ABI INR performs well for the specified PORD performance metrics. Requirements are met for all hours of operation, sun angle conditions and all regions of the fixed grid.

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