Modeling Spaceborne and Airborne Sensors in Software

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ABSTRACT: Digital photogrammetric workstations use software to model sensors. A sensor model includes support data software, ground-to-image functions, and triangulation interface functions. Proper selection of adjustable parameters ensures that bundle adjustment will produce accurate results. Photogrammetric software must continually evolve to support new sensors.
KEYWORDS: Photogrammetry, softcopy workstations, sensor models, bundle adjustment, sensors.

DIGITAL PHOTOGRAMMETRIC SOFTWARE

Software for digital photogrammetric workstations inputs digital imagery from satellites, digital cameras, or scanned film and generates DTMs, orthophotos, vector data, image maps, perspective scenes, and other products.

Computation of ground locations from imagery requires sensor model software that converts coordinates from ground space to image space, or vice versa. The sensor model is used by nearly every photogrammetric application.

The design of sensor model software must address many considerations including:

- Execution speed
- Triangulation (bundle adjustment)
- Accuracy
- Data Sharing
- Maintainability.

A well-designed sensor model ensures that products generated from the imagery will be as accurate as possible.

When a new sensor is put into service, new sensor model software must be developed.

SENSOR MODELS

Here is a list of sensors supported by SOCET SET, a typical photogrammetric package, which is developed by GDE Systems and distributed by LH Systems:

- Frame camera
- SPOT
- JERS
- Landsat
- Panoramic camera
- Point Position Databases (US Government)
- Orthophotos (e.g. USGS Digital Orthophoto Quadrant)
- Digitized maps (Polar, Transverse Mercator, Stereographic, Lambert Conic, Polyconic, etc.)
- Reconnaissance sensors (US Government)
- Radarsat
- ERS-1, -2
- OMNI digital panoramic (airborne)
- IRS-1C, -1D
- SIR-C.

SENSORS ADDED RECENTLY

When a new sensor is deployed, software must be developed to enable photogrammetric applications to support the sensor. For example, the following sensors have been added recently to SOCET SET:

Radarsat

Radarsat is a synthetic aperture radar (SAR) satellite operated by the Canadian Space Agency. The resolution is 9 to 100 meters. SOCET SET supports the Path Image and Path Image Plus processing levels. SOCET SET supports the following beam modes: ScanSAR Narrow, Extended Low, Wide, Standard, and Extended. The sensor model used by SOCET SET for modeling Rardarsat is described below.

European Remote Sensing (ERS)

The ERS-1 and ERS-2 satellites are operated by the European Space Agency and contain a large number of sensors, including a SAR sensor with nominal 26 meter resolution. SOCET SET supports the Precision Image ERS SAR product.

OMNI Digital Panoramic Camera

OMNI is a digital panoramic, panchromatic camera flown in an airplane. The camera is manufactured by Image America Inc. (formerly Omni Solutions International Ltd). The sensor model used by SOCET SET includes compensations for atmospheric refraction, lens distortion, and forward motion of the aircraft.

Indian Remote Sensing (IRS)

IRS is a family of satellites operated by the Indian Space Research Organization (ISRO). The satellites have three electro-optical sensors on-board. SOCET SET supports the Panchromatic sensor (5.8 meter resolution) and the LISS multispectral sensor (23 meter resolution). SOCET SET supports the following IRS processing Levels: Raw, Browse, and Standard.

Panchromatic imagery is provided in 1, 2, or 3 overlapping sub-frames. Subframes are not co-registered and therefore cannot be easily merged into one image. SOCET SET includes a process to register the subframes by treating them as separate images and using tie points and bundle adjustment to register them.

The three bands of the color sensor (bands 2,3, and 4) are not co-registered, therefore a user cannot easily combine the bands into a single disk file. SOCET SET includes a process to register and merge the color bands: (1) measure tie points between the bands; (2) perform a bundle adjustment on the bands; (3) create orthophotos from each band; and (4) merge the orthophotos into a single color image.

SOCET SET does not process the infrared band of the multispectral sensor, nor the Wide Field Sensor (WiFS).

Spaceborne Imaging Radar (SIR-C)

SIR-C imagery is obtained from a SAR sensor built by NASA and flown in the Space Shuttle cargo bay. The resolution is nominally 30 meters.

Sensor Models Planned for Future

The next version of SOCET SET, scheduled for 1999, is planned to have models for Space Imaging (IKONOS), SPOT 4, SPIN 2 (Russian KVR-1000), and Earthwatch QuickBird.

WHAT IS A SENSOR MODEL?

A sensor model in SOCET SET consists of three software modules:

- Support data input/output
- Ground-to-Image function (or, alternatively, image-to-ground function)
- Triangulation interface functions.

Support Data Input / Output

Support data includes information such as sensor location, velocity, orientation angles, focal length, time of acquisition, and camera calibration data. Support data is often supplied in a header file attached to the raw imagery. SOCET SET stores the support data for an image in an ASCII disk file called a support file. It does not store the data in the same file as the imagery.

The support data input/output software reads and writes this support file and also reads the "raw" sensor support data from CD, tape, or disk and reformats it to a support file. This action is called *importing* the raw imagery.

Unfortunately, there is no standard format available for storing support data in disk files. This make it hard to share support data between systems. GeoTIFF or DOQ can be used for orthophotos; and GeoTIFF may soon be expanded to support frame imagery, but there are no interchange formats for satellite support data.

The Committee on Earth Observation Satellites (CEOS) has a standard distribution format for imagery, but it is not well suited for disk file storage of support data. The Landsat Technical Working Group (LTWG) also has a distribution format but, like CEOS, it is suited for distributing imagery, not storing support data.

Ground-to-Image and Image-to-Ground functions

The primary purpose of a sensor model is to convert ground space locations to image space locations, or vice versa. These transformations are used in nearly every photogrammetric process, such as orthophoto generation or DTM extraction.

These transformations are implemented in software as two functions: ground-to-image and image-to-ground. The ground-to-image function inputs a ground point (latitude, longitude, elevation) and outputs an image point (line, sample). The image-to-ground function inputs an image point and ground elevation, and outputs ground latitude and longitude.

The sensor model must include an explicit implementation of either a ground-to-image function or an image-to-ground function. If the ground-to-image function is provided, then the image-to-ground function is computed numerically using an iterative algorithm. Conversely, if the image-to-ground is provided, then the ground-to-image is computed iteratively. If speed of execution is a concern, both functions can be written explicitly.

The choice of image-to-ground or ground-to-image is usually easy to make because one of the two algorithms is faster and simpler than the other. For SAR imagery, the image-to-ground function is simpler. For frame imagery, the ground-to-image function (embodying the co-linearity equations) is simpler.

Triangulation Interface Functions

The triangulation functions must be implemented if there is a requirement to triangulate the sensor's imagery in a bundle adjustment. Triangulation interface functions are optional. If they are not provided, the model can still be used successfully in all other SOCET SET applications, including DTM generation, orthophoto, perspective scenes, image map, etc.

Triangulation interface functions are relatively simple and include:

- Identify which parameters of the sensor model are adjustable (i.e. are to be estimated as unknowns)
- Provide names of adjustable parameters (for user interface)
- Give default accuracies (i.e. weights for each adjustable parameter)
- Provide perturbation values used to compute partial derivatives numerically.

EXAMPLE OF A SENSOR MODEL: SAR

SOCET SET uses a single sensor model for all SAR sensors, including Radarsat, ERS, and SIR-C.

Parameters Defining a Single SAR Image

The parameters that define a single SAR image are stored in the support file and include:

- Sensor location (usually a path consisting of several discrete points)
- Times associated with each location point
- Sensor velocity vectors (associated with each location point)
- Sensor "squint" angle (angle of radar pulse relative to flight path vector)
- Image size
- Function to map line/sample coordinates to range/time values (linear function).

SAR Image-to-Ground Algorithm

The SAR image-to-ground function is implemented explicitly because the ground-to-image function is slower and more complex.

The inputs to the image-to-ground function are

- Line and sample coordinates
- Ground Z elevation (height above ellipsoid)
- Image parameters (see above).

The outputs from the image-to-ground function are

- Ground X and Y (latitude and longitude).

The SAR image-to-ground algorithm is:

1. Compute time and range from line/sample (use linear transform)
2. Compute instantaneous sensor position and velocity from time (use lagrange interpolation)
3. Compute ground XY by intersecting (a) sensor's doppler cone, (b) ellipsoid surface at con-

stant height, and the (c) range sphere. These three surfaces are represented by the equations:

$$\frac{\bar{V}}{|\bar{V}|} \bullet \frac{(\bar{G}-\bar{S})}{|\bar{G}-\bar{S}|} = \sin(squint)$$

$$\frac{GX^2 + GY^2}{(RadiusA + height)^2} + \frac{GZ^2}{(RadiusB + height)^2} = 1$$

$$|\bar{G}-\bar{S}| = range$$

4. Where S is the sensor position, V is the sensor velocity, G is the ground point to be solved, RadiusA and B are the major and minor radii of the earth ellipsoid, and height is height of the ground point above the ellipsoid. G, S, and V are measured in Earth Centered Fixed (ECF) coordinates.
5. The equations from step 3 yield two possible solutions and the final step is to select the solution that is consistent with the approximate region the sensor is looking at.

SAR Ground-to-Image Function

The ground-to-image function for SAR imagery is computed with a iterative Newton algorithm that relies on numerically computed partial derivatives.

SENSOR MODEL DESIGN ISSUES

Ground Space Coordinate System

Ground locations are used for storing some sensor parameters (such as location) and for input and output to the image-to-ground and ground-to-image functions.

The designer of a sensor model must select a coordinate system for location parameters. Choices include:

- Latitude/longitude
- UTM
- Earth-Centered Fixed (ECF)
- Earth-Centered Inertial (ECI)
- Local space rectangular cartesian (LSR)
- Map projection grids (e.g. state plane).

The ground-to-image and image-to-ground functions in SOCET SET permit any coordinate system to be used for the input/output to the image-to-ground and ground-to-image functions.

Image Space Coordinate System

When inputting or outputting image locations (line/sample) a convention needs to be established for the coordinates. The convention used by SOCET SET is that the (0,0) coordinate is the *center* of the upper left pixel. Line and sample coordinates are transferred as floating point numbers to support fractional pixel locations.

Polynomial Sensor Models

Polynomial sensor models are an alternative to physical sensor models. Polynomial models are often used in the remote sensing community and have several benefits over physical models:

- Good for data interchange
- Often execute faster than physical models
- Simpler to design and implement
- Requires little detailed information about the sensor itself.

Polynomial sensor models have some drawbacks compared to physical models:

- Cannot model high-frequency aspects of sensor
- Do not work as well in bundle adjustment algorithms
- Cannot recover physical parameters from polynomial coefficients.

To mitigate the lack of high-frequency components of polynomial models, the polynomials can be supplemented with correction tables.

Triangulation (bundle adjustment) can operate on polynomials by adjusting the coefficients but the results will not be as accurate as the results from a physical model because the polynomial coefficients do not correspond to actual variables in the real-world sensor (such as location, focal length, etc). Physical parameters are usually orthogonal, whereas polynomial parameters are not.

Fast Sensor Models

After triangulating a physical sensor model, a polynomial can be fitted to the physical model. The polynomial often yields faster execution times for computation-intensive processes such as graphical overlays, automatic terrain extraction, and orthophoto generation.

Orientation Angles

If the sensor model parameters include an orientation (pointing angles), the designer must establish a convention for measuring the angles. Several conventions exist for storing orientation angles, including omega, phi, kappa (ground-to-sensor); omega, phi, kappa (sensor-to-ground); heading, pitch, roll; and quaternions.

When the sensor parameters include orientation angles the designer must decide whether all angles are measured relative to a single reference coordinate system, or relative to individual per-image reference systems. For example, in the case of a block of Frame imagery, most triangulation packages prefer the orientation angles of all images to be measured relative to a single, shared LSR coordinate system.

Parameters Shared By Multiple Images

When doing a block adjustment, certain parameters may be constrained between two or more images. SOCET SET supports this requirement.

For example, consider a block of frame imagery acquired with airborne GPS. Adjustments to camera locations should be done per GPS strip (or partial strip, when there is a loss of GPS lock), not per image.

Another example is satellite imagery: adjustments to sensor locations should be shared for images collected on the same orbital pass, because the orbit is smooth and therefore the position adjustment should be identical for all images acquired on the same pass.

TRIANGULATION

The SOCET SET triangulation application performs bundle adjustment.

Sensor Model Software Includes an Interface to Triangulation

The triangulation interface functions are not a required part of a sensor model. If the triangulation interface functions are not implemented the sensor model can still be used for all other SOCET SET applications, including DTM, orthophotos, and feature extraction.

Adjustable Parameters

Some sensor parameters should be adjusted by triangulation and some should not. Adjustable parameters are estimated as unknowns. The designer of the sensor model must make this decision for all parameters. For example, location and orientation angles may be adjustable (i.e. estimated), but focal length and time of acquisition may be fixed (i.e. not adjustable).

When the triangulation process is executed it uses default weights (i.e. accuracies) for each adjustable parameter. The operator can override the default weights, and also can select a subset of adjustable parameters to be fixed (i.e. not adjusted).

The designer of a sensor model faces a choice of adjusting the actual parameter itself (e.g. position X coordinate) or an offset (delta-X).

When a sensor's location is defined as a dynamic path (e.g. satellites) the set of position vectors is usually adjusted with a single XYZ offset. Velocity vectors are usually adjusted in same manner.

Triangulation adjustment to position should be measured in a coordinate system aligned to flight path (in-track, cross-track, radial) rather than aligned with a ground-based coordinate system Velocity should be adjusted in the same manner.

Mixing Sensor Types

The SOCET SET triangulation application permits different sensor types to be combined in a single adjustment, e.g. SPOT, frame, and Radarsat can be solved in a single adjustment.

This is feasible because the triangulation application contains no software that is specific to a single sensor type. Instead the least-squares algorithm is performed numerically, and the ground-to-image and partial derivative functions are computed by invoking the sensor model software, which is located outside the triangulation application.

PROCESS TO CREATE A SENSOR MODEL

The creation of a sensor model requires the following steps:

1. Gather information about the sensor, such as platform dynamics, optics, and distribution format.
2. Define the per-image parameters of the sensor
3. Define the ASCII file to hold support data
4. Create an import application
5. Create the ground-to-image or image-to-ground function
6. Create the triangulation interface functions
7. Put the ground-to-image (or image-to-ground) function into a specially defined shared library (also called a "dynamically linked library")
8. Execute SOCET SET. There is no need to re-compile or re-link SOCET SET: it will automatically access the sensor model software at run-time by calling functions in the shared library. All SOCET SET applications use the sensor model (DTM, triangulation, orthophoto, etc).

USER-DEVELOPED SENSOR MODELS

SOCET SET is equipped with a large number of physical and polynomial sensor models. These models are sufficient for most users, but a few users need to create their own sensor models. Users with such a need must have the following resources at their facility:

- Computer (PC-NT, Sun, SGI, or HP)
- SOCET SET license
- SOCET SET Developer's Kit
- Software libraries and header files
- C++ compiler.

The sensor models are stored in a shared (dynamically linked) library which is accessed at run-time by SOCET SET. Therefore, users do not have to re-link or re-compile SOCET SET.

Several Users Have Implemented Sensor Models

The following is a partial list of customers who have implemented sensor models that run with SOCET SET:

- NASA (USA)
- OM&M (Sweden)
- NIMA (USA)
- IGN (France)
- Swedish Space Corporation (SSC).

Lessons Learned

Some of the lessons we have learned from users' experiences of developing sensor models are:

- Users need photogrammetric expertise to define the ground-to-image (or image-to-ground) function
- Users need some software development skills (but "guru" level skills are not needed)
- Good test data set (with control data) is crucial for validation
- It is recommended that users attend the SOCET SET Developer's Kit training class because the process of developing a sensor model is sophisticated.

CONCLUSION

Extracting accurate ground locations from imagery in a digital photogrammetric workstation requires sensor model software. The sensor model must be carefully designed to ensure that triangulation is robust and accurate. The SOCET SET photogrammetric system includes a process whereby users can develop their own sensor models and use them in the SOCET SET applications, such as automatic terrain extraction, triangulation, and orthophoto generation.

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