

On the Use of the Object Oriented Paradigm for Multisensor Geocoding

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ABSTRACT

The ability to conduct quantitative analysis with multitemporal and multisensor datasets is critical to the future success of remote sensing based resource management and global change monitoring systems. Such analysis needs the data to be co-registered to a common geometric frame of reference requiring the removal of complex geometric image distortions inherent in the raw data. This task, referred to as geocoding, can best be accomplished by using all available *a priori* knowledge to model the physics of the image acquisition. Given the diverse nature of this knowledge and the need for flexibility to accommodate the multitude of imaging technologies, the object oriented paradigm provides an ideal framework for developing multisensor geocoding software. To demonstrate the utility of this approach, an object-oriented geocoding toolbox was engineered and successfully used to geometrically register an extensive multisensor data set.

Key Words: Geometric Image Correction, Orthorectification, Sensor Modelling, Object Oriented System.

1 INTRODUCTION

The quantitative use of remotely sensed imagery is key to the success of resource management and global change monitoring systems. Such problem domains require the direct comparison and analysis of large multisensor and multitemporal datasets. Before such inter-comparisons can be performed, the raw image data must be radiometrically and geometrically corrected to lie in the same radiometric and spatial domains.

The goal of the geocoding process is to precisely register the raw imagery to the earth's surface. This is a pre-requisite to any serious quantitative analysis as the results are only meaningful if they can be attributed to a specific region on the earth's surface. Only then is it possible to compare or fuse the data and make meaningful observations.

Geocoding is accomplished in a two-stage process. In the first stage, a mapping is constructed relating pixels in the raw image to geographic coordinates on the surface of the earth. This implies the removal of complex geometric distortions introduced during image acquisition by the sensor, the platform, the viewing geometry and the local topography. The second stage uses this mapping to resample the imagery aligning it with a standard grid in the desired map projection. In what follows, the geocoding procedure is discussed in more detail.

2 GEOCODING METHODS

Given the fundamental importance of geocoding for remote sensing, the question arises how geocoding is best achieved. There are two major geocoding methods: image warping and image acquisition modelling. The main difference between these methods is their use of *a priori* and *a posteriori* knowledge. Before describing the two methods, consider first the available knowledge.

There is a wealth of *a priori* knowledge which describes the image acquisition conditions:

- the sensor characteristics are known (eg. a linear array

scanner or a SAR sensor).

- the sensor platform is known to be dynamically constrained both for its translational and rotational degrees of freedom;
- there are often navigational data such as gyro readings of platform attitude or orbital elements;
- the platform movement during the imaging time can often be assumed to feature constant (or at least well understood) altitude, speed and heading;
- the relative importance of the platform movement for the imaging process is known. For instance, the distortions introduced by platform pitch typically cannot be distinguished from along-track movements of the platform;
- the approximate shape of the earth is known to conform to a chosen datum;
- the region's topography may be known from available or derived Digital Elevation Models (DEMs).

There are two types of *a posteriori* knowledge:

- absolute information tying a feature in the image to a known location on the earth. This information takes the form of either ground control points (GCP) marked by the user, or registration control points (RCP) obtained via correlation with a base image;
- relative information (without absolute earth location) tying two or more raw image features together, so-called tie-points (TIP);

The first geocoding method, image warping, uses only the *a posteriori* information to model the geometric distortions in the raw image[2]. Here, GCPs, RCPs, and tie points are fit to functions (typically low order polynomials, or a triangular irregular network (TIN)) to model the warping from the raw image coordinates to map coordinates.

The second method, image acquisition modelling, uses both the *a priori* and *a posteriori* information[1]. The *a priori*

knowledge is used to construct a physical model of the image acquisition process. The *a posteriori* knowledge is only used to fine-tune the model parameters. This model is then used to resample the raw image.

The latter of the two geocoding methods is superior for a number of reasons. Firstly, image modelling requires significantly fewer, and even no GCPs or RCPs[3]. This is important, as the marking of GCPs is a manual operation, and thus expensive in time and labour. Similarly, even though RCPs are marked automatically, it can be computationally expensive to correlate two images on a fine grid and the correlation may fail in whole regions of the image. Secondly, image acquisition modelling is typically more accurate as simple polynomials cannot model the complex geometric distortions introduced during image acquisition. Thirdly, modelling is extensible over large areas but warping is not. Finally, image acquisition modelling is robust with respect to GCP or RCP errors. Because the imaging model is constrained by the physics, outlying RCPs or GCPs which would otherwise reduce the geocoding accuracy can be readily identified and discarded.

3 OBJECT ORIENTED GEOCODING

Considering the long and diverse list of available *a priori* knowledge the question arises how this knowledge is best organized to accommodate a multisensor geocoding facility. The requirements for the system demand the software be flexible so that it can handle a large variety of different sensors, platforms and refinement methods. Further, it should be easy to expand making it convenient to add new sensors and platforms. Finally, the system should be easy to understand and to use.

Given these requirements, the object oriented paradigm provides an intuitively pleasing framework in which the *a priori* geocoding knowledge can be structured. The key characteristics of the paradigm are *polymorphism*, *encapsulation*, and *inheritance*.

Polymorphism allows the system behavior to be formulated with respect to invariant generic objects. Many functions of geocorrection are generic to all types of imagery: earth models, DEMs, map projections, parameter estimators, sensor models. Polymorphism allows a large variety of specific sensors and platforms to be accommodated without code duplication or conditional clauses. For instance, an abstract object called `ImagingModel` can be created which describes the sensor and platform characteristics. This object can have a function (or *method*) called `raw_to_ECR` which converts raw line-pixel coordinates into the corresponding Earth Centered Rotating (ECR) coordinates. Other software can then use the `raw_to_ECR` method irrespective of whether the image was acquired using an optical linear array sensor or a SAR, or whether the sensor was installed on a satellite, or an aircraft.

Inheritance allows new sensors and platforms to be added to the system simply by modifying more generic sensor and platform models. For instance, both the AVIRIS sensor and the SPOT Panchromatic sensor share many of the same properties which can be abstracted into a generic `OpticalSensor` object and *inherited* by each sensor model. Only the specific differences between the two sensors (AVIRIS employs

a scanning mirror sensor while SPOT employs a linear array sensor) need to be implemented at the lower level. No code duplication is required; only the additional functionality beyond that of the `OpticalSensor` must be provided. A graphical illustration of this idea is given in Fig. 1.

Encapsulation allows the complexity of the various models to be hidden within objects. For example, the transformation from orbital elements to a position timestate (a vector of positions as a function of time) requires a complex orbit propagation model. By encapsulating this within an `orbit` object, all the complexity of this model is hidden from the user. Further, the orbit propagator can be updated or replaced at a later date with no apparent effect on the operation of the system. This makes the system behavior easier to understand and the system easier to use.

Finally, the object oriented features of polymorphism, inheritance and encapsulation make it simple to experiment with new sensors and modelling techniques. It also allows the software to be easily configured so as to suit special constraints on the *a priori* knowledge. This is particularly important when both airborne and spaceborne sensors are used. The geocoding procedure for these two classes is quite different

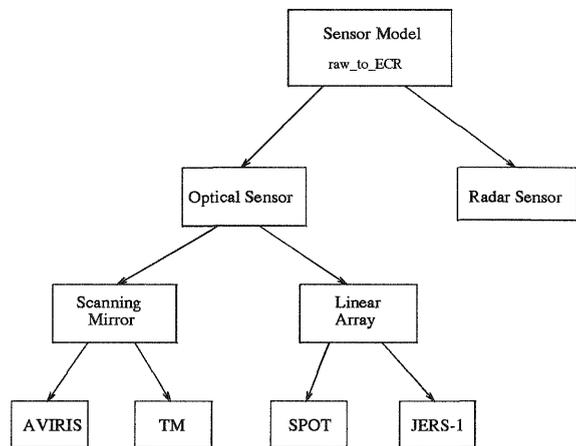


Figure 1: This object oriented sensor model inheritance hierarchy shows how a sensor model can be decomposed into models of decreasing abstraction.

because the limits of the applicability of *a priori* knowledge is different in both cases.

4 GEOCODING TOOLBOX

To demonstrate the feasibility of the object oriented approach, an object oriented geocoding toolbox named GEOREG has been prototyped. It is written in C++ and is capable of geocoding and optionally orthorectifying imagery from multiple sources.

GEOREG's image acquisition model is developed in a two stage process. First, the physics of the image acquisition is captured with an imaging model composed of a platform model, a sensor model and an earth model which incorporates a geodetic datum and a DEM if available. Any *a priori* information including estimated or measured position and attitude data is used in generating this model. The second stage allows a refinement of this model by using *a posteriori* knowledge, i.e. the available GCPs and TIPs. These control points are used to solve a nonlinear optimization problem, the solution of which is a physical model of the actual imag-

ing process.

Typically, the model parameters which are refined during model optimization are the coefficients of polynomials which correct for systematic errors in the nominal trajectory of the imaging platform. Alternatively, one can optimize over Fourier series parameters. Adding other parameterizations would require adding new classes to GEOREG. However, by virtue of the object oriented design, this requires only a few lines of code. For instance, if a platform was known *a priori* to change its pitch over time in a saw-tooth fashion, but the amplitude, frequency, phase and ratio between ascending and descending segments of the saw-tooth were unknown, then a class could be added to GEOREG which used the *a priori* information on the shape of the pitch movement and allowed the unknown parameters like amplitude etc. to be estimated using GCPs and TIPs. To add this capability to GEOREG would require less than 10 lines of C++ code.

Moreover, GEOREG is not restricted to refining platform parameters but can be configured to simultaneously optimize any model parameter including sensor parameters such as camera focal length. Furthermore, when tie points are used GEOREG allows for the simultaneous nonlinear optimization of several acquisition models (or bundles) belonging to different images.

After the acquisition model is constructed, a remapping process is initiated which resamples the raw image to a user selectable map projection using a user selectable resampling kernel. If a DEM of the region is available, the imagery may be orthorectified to remove any terrain-induced distortions in the raw imagery.

These examples clearly illustrate that an object oriented design is very well suited to providing the flexible structure necessary in a geocoding facility which has to accommodate very diverse *a priori* and *a posteriori* knowledge.

5 GCP AND TIP ACQUISITION

The model parameter optimization mechanism relies on the availability of accurate GCPs and TIPs. Currently, there are two mechanisms to generate *a posteriori* information: Manual marking and automatic correlation with a reference image. Manual marking of ground control points is accomplished by marking common features in both the raw image and an accurate map. Alternatively, the map can be replaced by an already geocoded reference image. On the other hand, tie points are marked in multiple raw images.

Usually, only a few GCPs (<14) can be economically hand marked. If more GCPs are required and an orthorectified reference image is available, automatic correlation is used. For this purpose, the raw image is resampled using only the nominal information or information derived from just a few manually marked GCPs. There are GEOREG utility programs which allow the user to define a grid of control points in the raw image or in the reference image and then correlate the nominally resampled image with the reference image generating GCPs near the grid points. For example, using this method, an orthorectified SPOT scene of the Drum Mountains region in Utah was successfully used as a base map to generate control points for an AVIRIS image of the same region.

6 AIRBORNE AND SATELLITE DATA GEOCODING

There is a marked difference between the geocoding of optical airborne imagery and satellite imagery. It is possible to accurately geocode satellite images using only a small number of GCPs (<10) [3]. In general, this is not true for airborne imagery which require a much larger number of GCPs to achieve subpixel accuracy. The reason is that aircraft are significantly less stable imaging platforms than satellites and therefore causing geometric distortions in the image with large spatial high frequency content. Thus, airborne data correction becomes a test case for the capabilities of any geocoding facility.

Airborne images acquired over featureless areas such as some deserts and snow fields are particularly hard to geocode because of the difficulty of obtaining a sufficient number of ground control points. Further, if the airborne image and the reference image are taken in widely different ranges of the electromagnetic spectrum, it is exceedingly difficult to achieve reliable correlation and generate sufficient numbers of GCPs.

For these types of geocoding problems it is paramount to use all available information and be able to configure the geocoding software to suit the particular problem at hand. An object oriented approach provides the flexibility and power necessary if subpixel accuracy is desired.

A key problem for this type of geocoding is the need to eliminate erroneous control points which are derived from false correlation matches. GEOREG can often eliminate this problem by rejecting GCPs which do not, by a certain margin, fit the best available image acquisition model. This can be achieved by ordering the GCPs time-sequentially and letting them drive an extended Kalman filter which for each instant in the imaging time produces a best estimate of the platform position and attitude given our estimates of the aircraft dynamics constraints, the measurement and state uncertainty covariance etc. If a GCP is inconsistent with this estimate, it is not allowed to change the state estimate. The sequence of Kalman filter state estimates then defines the desired platform trajectory. Even though this is not a global optimization over all GCPs, it nevertheless turns out to be a very efficient method for these hard geocoding problems.

As an example, consider the attitude time state for a GERAIS (Geophysical Environmental Research Corp. Airborne Imaging Scanner) image which is shown in Fig. 2. In this case, no systematic attitude information was available for the imagery. The attitude time state shown was generated using a previously orthorectified SPOT image as a base map, and GCPs which were automatically correlated, and input to the extended Kalman filter. The resulting derived attitude allowed the GERAIS image to be geocoded with <20 meters RMS error, versus the ca. 300 meters RMS error when no attitude was accounted for.

7 RESULTS

To assess the system, an extensive multisensor data set comprising of satellite and airborne sensor data over the Drum Mountains area of Utah was orthorectified and co-registered.

The data set consisted of both satellite imagery and airborne

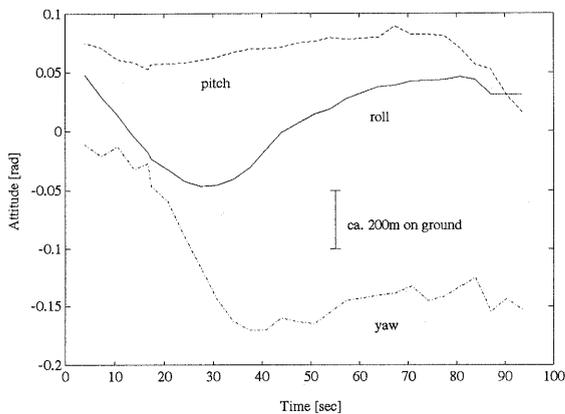


Figure 2: Attitude time state of GERAIS image, derived solely from automatically marked RCPs.

imaging spectrometer data. The satellite data included a SPOT Panchromatic stereo pair and a Landsat TM scene (7 bands). The airborne data contained two sequential AVIRIS scenes which were concatenated into a single larger scene (224 bands), two non-sequential GERAIS scenes (63 bands each), a TIMS scene (6 bands) and a GEOSCAN scene (24 bands).

In general, the sensor models for all these sensors were well known. However, there were differing amounts of information on the platforms associated with the images. This is summarized in Table 1. It is interesting to note that even when trajectory information was available for airborne platforms, it was, in general, quite noisy.

To begin, a DEM and an orthorectified SPOT image of the area were generated from the SPOT stereo pair using techniques outlined in [4]. Only a few manually marked GCPs were necessary for each stereo scene. Similarly, using only a few GCPs and the SPOT generated DEM, the Landsat TM image was orthorectified.

The orthorectified SPOT and TM images then served as reference images for the airborne images. The AVIRIS scene was the simplest to orthorectify because its U2 aircraft fly-

Dataset	Auxiliary Information
SPOT PLA	Orbital Elements
Landsat TM	-
AVIRIS	nominal position & attitude
TIMS	nom. position (no height) & attitude (roll corrected raw image)
GEOSCAN	nom. start & stop position
GERAIS	-

Table 1: Auxiliary information associated with imagery.

ing at 20 km height provided a stable platform. Moreover there was a wealth of measured aircraft position and attitude information available. Thus, only a relatively small number of RCPs were necessary to orthorectify the AVIRIS scene.

The other images, on the other hand, had large high frequency components and severe correlation problems. The GEOSCAN platform was particularly unstable, whereas the TIMS imagery was particularly hard to correlate with either

TM or SPOT because of radiometric differences. With the exception of AVIRIS, all airborne sensors were orthorectified using an acquisition model generated by methods similar to the extended Kalman filter method mentioned before.

Using the methods and prototype system described in this paper, it was possible to co-register and orthorectify all the images with an RMS error smaller than one 20 m pixel size. Examples of the geocoded images from each of the sensors are shown in Figure 3.

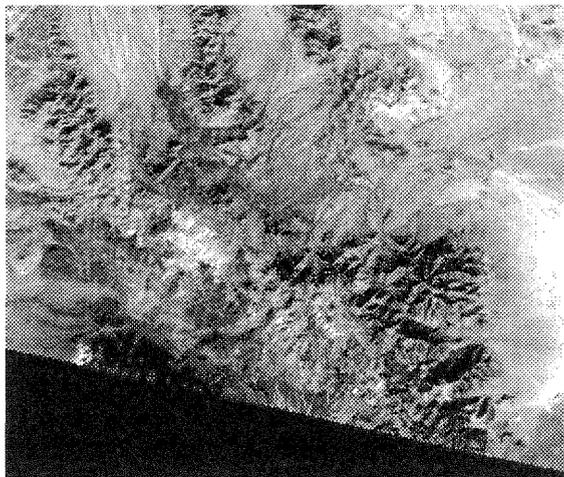
In conclusion, geocoding is an essential pre-requisite for quantitative analysis. Using all available *a priori* knowledge and organizing this knowledge in an object oriented design, we have shown that excellent geocoding results can be achieved even for very hard geocoding problems. An object oriented design can easily accommodate many diverse sensors and platforms. It also makes it easy to add new sensors, platforms or auxiliary knowledge about the image acquisition process. These properties make object oriented technologies an ideal candidate for the development of geocoding facilities.

ACKNOWLEDGEMENTS

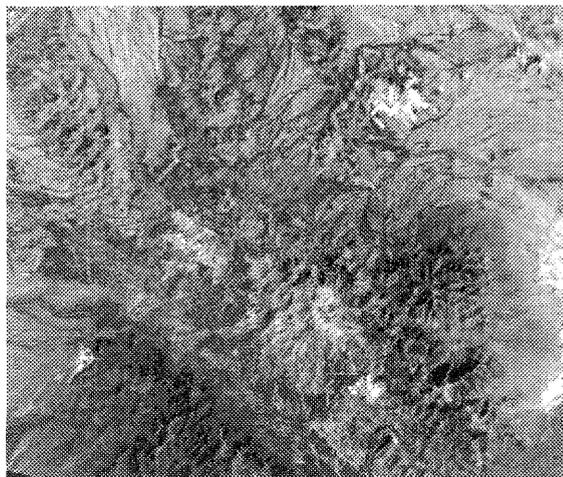
The authors would like to express their thanks to Bryan Bailey of the U.S. Geological Survey and the GEOSAT Committee for their help in supplying the image data over the Drum Mountains.

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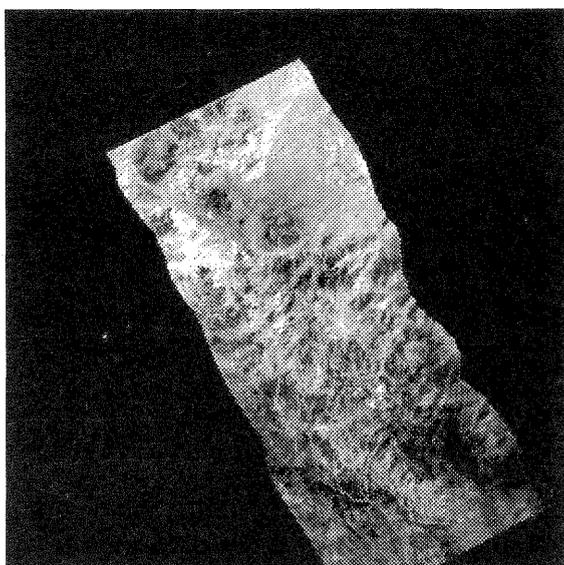
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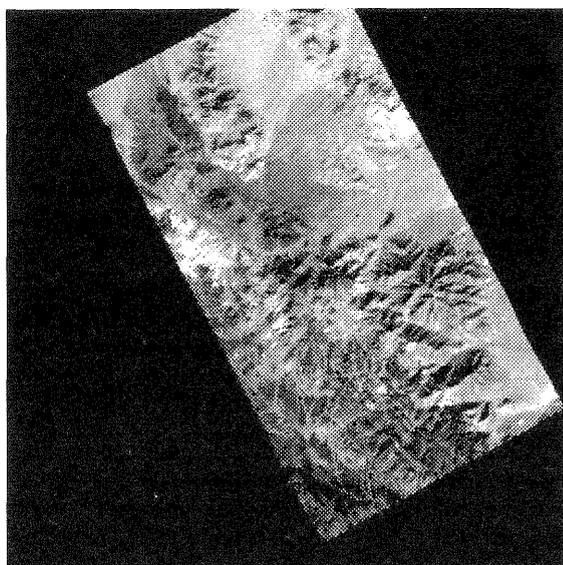
SPOT, panchromatic ©1989 CNES



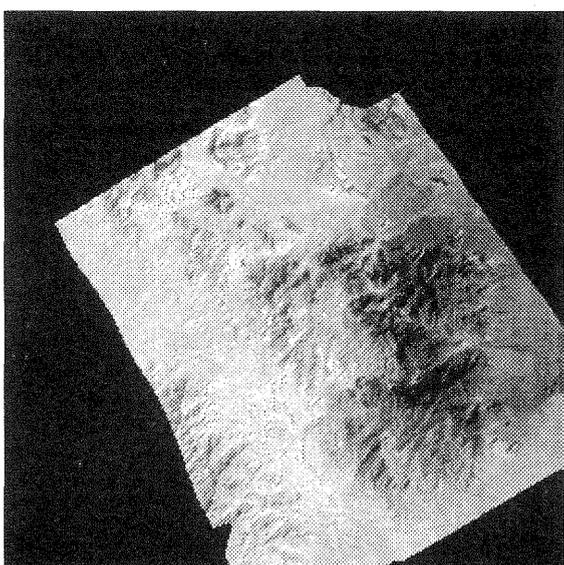
TM, band 2



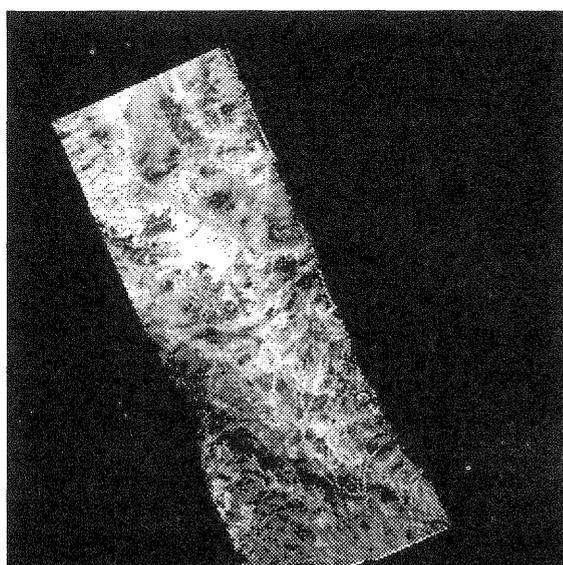
GEOSCAN, band 12



AVIRIS, band 100



TIMS, band 5



GERAIS, band 39

Figure 3
Drum Mountains, Utah, multisensor images orthorectified using GEOREG.