REMOTE SENSING GEOMETRIC CORRECTIONS

Satellite remote-sensing data have become an essential tool in many applications, mainly environmental monitoring. Although remote-sensing techniques have been applied in many different fields, operational use is still far from being achieved. New applications and increased possibilities are expected for the coming years due to the availability of a new series of advanced sensors with improved capabilities.

Apart from the need for a better understanding of the remotely sensed signals, most of the problems in using remote-sensing data have been due to inadequate data processing. Data-processing aspects become essential for actually obtaining useful information from remote-sensing data and for deriving usable products. Within these data-processing aspects, geometric corrections play an essential role. Multitemporal analyses are required for monitoring of changes and evolution, while multisensor data are typically needed to solve a particular problem. Integration of the different data, acquired under different viewing geometries and with different geometric characteristics (resolution, pixel shape, sensor spatial response function, interpixel overlaps, etc.), requires careful processing to avoid misleading results.

The article is structured as follows: after introduction of the topic and the driving concept of spatial resolution, a method to account for the geometric distortions introduced by orbital motion, scanning, and panoramic view in remote sensing data is presented. Although the relevant details depend very much on each particular sensor or even on each particular acquisition mode of each sensor, a general parametric approach is presented which can be potentially applied to any sensor, both airborne and spaceborne cases, with minimal changes of inputs parameters. Due to the many sensors and systems available for a given application, a general, consistent method to process the data is preferable, instead of specific approaches for each new particular sensor. After a description of the approach step by step, some approximations traditionally used are briefly presented (polynomial distortion models, linear cross-correlation), and then the need of some external cartographic reference is discussed, addressing the problems arising from the use of many different cartographic projections and the difficulties in the mathematical modeling of the earth as a simple geometrical figure. The problems introduced by topographic structure are then discussed. Then, when the geometric transformation model image-map is defined, the resampling of the image to a different pixel size/shape is discussed, pointing out difficulties with classical approaches and new algorithms based on image restoration. Other external factors which must be also taken into account, like calibration and removal of technical anomalies (noises) are then considered as additional problems. Finally, the generation of mosaics representing a large geographical area by compositing several or many individual images and the multitemporal compositing for monitoring changes are discussed, with a final comment about the challenges posed by the large amount of data to be processed with current or near-future sensors in the context of operational use of the data in practical applications.

To clarify some of the aspects, most of the examples given correspond to the case of NOAA (National Oceanographic and Atmospheric Administration) AVHRR (Advanced Very High Resolution Radiometer) data, one of the most widely used remote sensing data and one good example on how geometric distortions affect remote sensing images and how methods can be applied to correct for such distortions. By using general parametric approaches, similar methods have been applied for a wide range of sensors, like, for instance, from very high resolution hyperspectral airborne data (1) to low resolution data from meteorological satellites (2).

SPATIAL RESOLUTION

A critical aspect to be considered previously to any processing of remote-sensing data is spatial resolution. Current available systems can produce images with resolutions ranging from a few centimeters (for very-high-resolution airborne sensors) to about tens of kilometers (for low-resolution satellite passive microwave sensors). Obviously, the techniques, approaches, and limitations are quite different for each resolution range. However, to solve a particular problem it is often necessary to merge data from different sensors and with different resolutions, and then problems appear in handling the varying resolutions. An additional problem is given by the fact that high spatial resolution instruments generally have low temporal resolution, while medium spatial resolution sensors have greater temporal resolution, since the limiting factor is the whole amount of data to be transmitted or stored on board.

The concept of spatial resolution is well defined, especially in optoelectronics systems. The use of this concept in remote sensing is, however, not always clear and many times confusing. For one of the sensors described in more detail, the multispectral scanner (MSS) on board Landsat, the *resolution* has been defined in terms of geometric instantaneous field of view (IFOV), with values ranging from 73.4 m to 81 m, depending on the analysis criteria. The IFOV response function is another criteria, giving values between 66 m and 135 m for the derived corresponding resolution. Other criteria are based on the concept of *effective resolution,* giving a range between 87 m and 125 m. Other criteria, taking into account atmospheric spatial blurring and feature discrimination, assign other types of resolution ranging from 220 m to 500 m, depending on the final application. Another aspect different from spatial resolution is *pixel spacing* in the image. Correspondence between resolution and pixel spacing is sometimes unclear, unless a complete spatial characterization of the sensor is available for actual flight configuration. Actually, the spatial resolution of a sensor is a combination of the optical point spread function, sampling, and downstream electronics.

In the case of synthetic-aperture radar (SAR) data the concept of spatial resolution is also somehow confusing, since the resolution depends on the way the original raw data is processed. Typical available systems can provide a resolution of only few meters. However, this resolution cannot be used in regular applications due to the presence of noise (or undesired signals). Two approaches are followed: spatial averaging and multilooking, reducing the spatial resolution by increasing pixel spacing, and local filtering reducing the spatial resolution but keeping the same pixel spacing. In both cases, the local filtering or average is performed over a window determined from the local level of noise. If the statistical properties of the data are so that the local entropy can be determined, optimal resolutions can be established. Otherwise, the effective resolution can be critical for accomplishing the requirements of the selected applications. Spatial resolution considerations play a significant role in the case of SAR data processing, especially in those approaches based on statistical analysis.

GENERAL PARAMETRIC APPROACH FOR IMAGE GEOCODING

Many different approaches have been described in the literature for geometric registration or geocoding of remotely sensed data. Some of them are quite sensor-specific. Owing to the current available technologies for global positioning, a quite general approach can be adopted, valid even for satellites, aircraft, and most of the sensors, including optical and

SAR (2,3). First, the platform trajectory is determined; second, the attitude angles of the platforms are instantaneously calculated; third, the viewing geometry of each particular sensor is related to platform orientation and the instantaneous viewing direction is derived, parametrized as a function of universal time t. Each point over the surface can be observed only at a given time t (Fig. 1). After derivation of the time t, by solving a system of coupled nonlinear equations, the exact viewing geometry can be derived for each point over the surface (map) or, alternatively, for each pixel in the image.

Platform Trajectory Determination

The platform trajectory can be derived by different methods, and typically becomes known quite accurately for non-real-time data processing and less accurately for real-time applications.

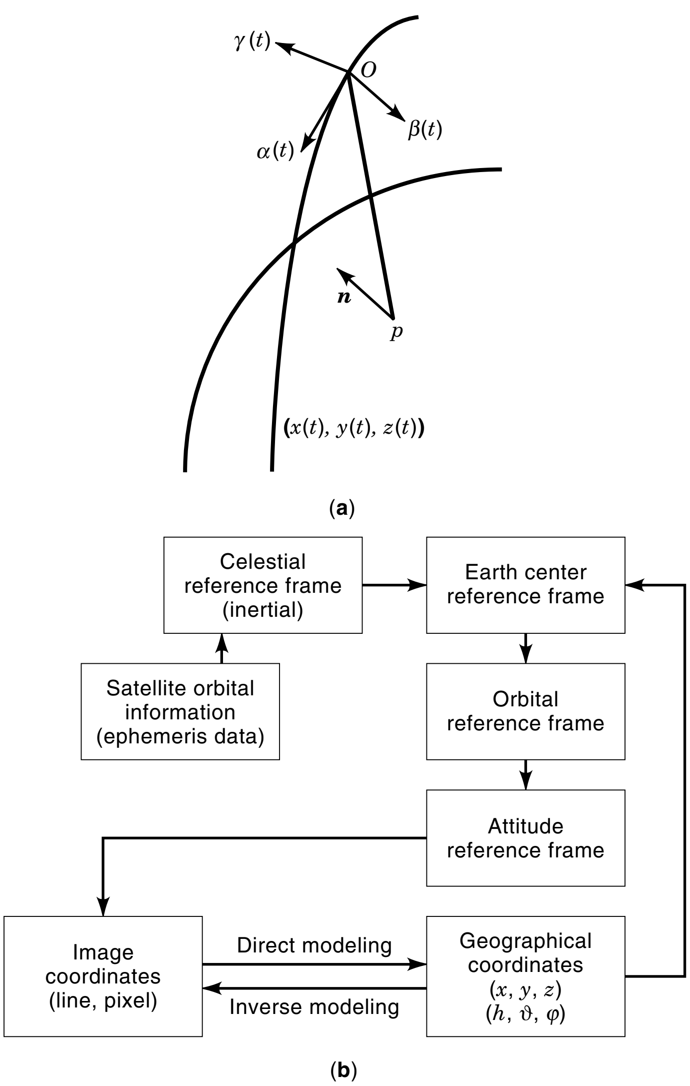

Figure 1. (a) Variables involved in the definition of local observation geometry: platform trajectory $O \equiv (x(t), y(t), z(t))$ and orientation $[\alpha(t), \beta(t), \gamma(t)]$ are functions of time t. Location P, with normal $\boldsymbol{n}$, can only be observed at some time t', which is determined by numerical solution of the system of parametric equations in t for the whole set of variables involved. (b) Steps in the geometrical processing of satellite remote sensing data.

Table 1. NASA NORAD Two-Line Orbital Element Set Format, Detailing the Orbital Information Daily Available for All Orbiting Satellites. For Many of them, Additional, More Detailed Information Is Also Available from Other Specific Sources.

Line	Column	Description
1	01–01	Line number of element data
	03–07	Satellite number
	10–18	International designator (last two digits of launch year + launch number of the year + piece of launch)
	19–20	Last two digits of epoch year
	21–32	Julian day and fractional portion of the day
	34–43	First time derivative of the mean motion (or ballistic coefficient)
	45–52	Second time derivative of the mean motion
	54–61	Drag term, General Perturbation-4 (GP4) perturbation theory (or radiation pressure coefficient)
	63–63	Ephemeris type
	65–68	Element number
2	01–01	Line number of element data
	03–07	Satellite number
	09–16	Inclination (degrees)
	18–25	Right ascension of the ascending node (degrees)
	27–33	Eccentricity
	35–42	Argument of perigee (degrees)
	44–51	Mean anomaly (degrees)
	53–63	Mean motion (revolutions per day)
	64–68	Revolution number at epoch revolutions

Additional numbers are added at the end of each line as a check sum.
Example: ERS-2
1 23560U 95021A 97188.14082342 .00000503 00000-0 20289-3 0 4065
2 23560 98.5461 262.6711 0001003 102.2708 257.8609 14.32248108115670

Satellite Sensors: Orbital Mechanics. Most remote-sensing satellites are placed in quasi-polar orbits, because of the preferable observation repetivity, i.e., repeatable solar positions, and mainly due to helio-synchronicity capabilities (4–6). Two types of satellite orbits must be identified: some satellites are almost kept in a given, predefined orbit, by means of constant operations to compensate for deviations due to perturbations in the Earth's gravitational field; other satellites are allowed to drift as a consequence of gravitational and other (such as atmospheric drag) perturbations. In both cases, daily routine monitoring of satellite positions allow determination of instantaneous positions with relative accuracy (few kilometers) on global basis.

Several sources, mostly military, are available to navigate satellite data by means of actual ephemeris information. NORAD [currently U.S. Space Command (USSC)] two-line orbital element (TLE) sets (also called NASA Prediction Bulletins) for all orbiting satellites and some documentation and software are available via the World Wide Web and anonymous file transfer protocol from several sources, and they are updated almost daily. Each satellite is identified by a 22-character name (NORAD SATCAT name). A brief description of the format is included in Table 1 for reference. For more detailed information see Ref. 7. Other sources are also available. However, it is very important to point out that each ephemeris data [TLE, Television Infrared Observation Satellite

(TIROS) Bulletin United States (TBUS), etc.] are derived by means of a particular reduction of observations to some specific model (7–9). For each ephemeris type, the corresponding orbital extrapolation model has to be used in order to get consistent results according to the model used to derive the orbital elements. Ephemeris types are not exchangeable. The use of some orbital information with a wrong orbit extrapolation model is one of the major sources of problems in some current processing algorithms.

Due to the recent advances in the global positioning system (GPS), very significant progress in satellite data processing is becoming possible in terms of geometric aspects, mainly due to the improved capabilities in positioning observation platforms.

GPS (10) was developed by the U.S. Department of Defense as an all-weather, satellite-based system for military use, but now it is also available for civilian use, including scientific and commercial applications. The current GPS space segment includes 24 satellites, each one traveling in a 12-h, circular orbit at 20,200 km above Earth. The satellites are positioned so that about six are observable nearly all the time from any point on the earth. There is also a GPS control segment of ground-based stations that perform satellite monitoring and command functions. The GPS satellites transmit ranging codes on two radio-frequency carriers at L-band frequencies, allowing the locations of the receivers (the user segment) to be determined with an accuracy of about 16 m in a stand-alone, real-time mode. By using corrections sent from another GPS receiver at a known location, accuracy in relative position of 1 m can be obtained. Subcentimeter accuracies can be achieved through the simultaneous analysis of the dual-band carrier-phase data received from all GPS satellites by a global network of GPS receivers by means of postprocessing. The use of GPS techniques in the processing of remote-sensing data is not only limited to satellite positioning, but they are also used for identification of surface points used for reference to increase the accuracy in automatic registration.

In more recent satellites, such as the European Earth Remote Sensing Satellites (ERS 1/2), a product called *precise orbit* is provided by ESA in specific format (after refinement of models plus observations with laser tracking data) with radial nominal accuracy below 1 m. Other systems, like SPOT and Topex/Poseidon, use a combined system of satellite laser ranging and a dual-Doppler tracking system (DORIS) that allows determination of satellite's position to within a few centimeters from the earth's center. With the new GPS systems, accuracies in satellite positioning within 2.5 cm have been demonstrated. Hopefully, when all these techniques become fully operational in all new platforms, geometric data processing of data acquired by such platforms will be much more easy and accurate.

Airborne Sensors. The same positioning capabilities are true not only for satellite systems but also for the case of airborne sensors. In the case of airborne sensors, geometric distortions are critical due to changes in aircraft flight patterns, especially for low-altitude flights. Moreover, there is no possible simplified orbital modeling here, but the trajectory must be kept in the form of (x, y, z) coordinates and local trajectory reconstructed by means of polynomials in time t.

Platform Orientation and Sensor Geometry

Once the platform trajectory is determined, a reference basis on each point of the trajectory must be defined. For instance, one axis can be chosen in the direction of the instantaneous velocity vector, and another axis can be normal to the plane defined by the velocity vector and the local geocentric or geodetic (see Ref. 11) direction, with the third axis completing the orthogonal reference. In this reference frame, each sensor on board the platform has specific viewing direction vectors, which are sensor-dependent, but are firmly linked to the platform orientation. A convenient way of optimizing computations is to reduce formulation to a given vector $\boldsymbol{u}$ that defines the local viewing direction. This vector changes with time. If selected properly, we can guarantee that variations in $\boldsymbol{u}$ can be described as small-angle rotations, the so-called attitude variations.

If we rotate the vector $\boldsymbol{u}$ an angle σ around the direction given by a vector $\boldsymbol{w}$, the components of $\boldsymbol{u}$ change according to

$$\boldsymbol{u}' = R(\boldsymbol{w}, \sigma)\boldsymbol{u} = (\boldsymbol{w} \cdot \boldsymbol{u})\boldsymbol{w} + \cos\sigma(\boldsymbol{w} \times \boldsymbol{u}) \times \boldsymbol{w} + \sin\sigma(\boldsymbol{w} \times \boldsymbol{u}) \tag{1}$$

with $\boldsymbol{u}'$ the transformed vector. The transformation R($\boldsymbol{w}$, σ) can also be expressed as a three-axis rotation of angles σ_1 (pitch), σ_2 (roll), and σ_3 (yaw), around the three unitary vectors that define the instantaneous local orbital reference frame, as in the classical modeling of attitude angle effects

$$R(\boldsymbol{w}, \sigma) = R(\boldsymbol{e}_3, \sigma_3)R(\boldsymbol{e}_2, \sigma_2)R(\boldsymbol{e}_1, \sigma_1) \tag{2}$$

As attitude angles are always very small, the order of rotations is not quite important. Moreover, Eq. (1) can be reduced, at the first order, to

$$\boldsymbol{u}' = \boldsymbol{u} + \sigma(\boldsymbol{w} \times \boldsymbol{u}) \tag{3}$$

Parameterization of $\boldsymbol{w}$ and σ as a function of three (because $\boldsymbol{w}$ is unitary) functions of time t allows a very adequate description of platform attitude variations (3,12), and references therein.

Determination of Instantaneous Surface Observation Geometry

Since all intervening variables are parametrized as functions of time t, the resulting approach implies the necessity for solving a system of nonlinear equations in parametric form (13), the universal time (UT) being used as iterative parameter.

Once the observation time is obtained by solving the corresponding equations, the satellite position, platform orientation, and sensor angles can be immediately determined, which allows direct derivation of the exact pixel number in the image. Also, observation time directly determines the line number of the image (shifts of the whole image data are sometimes necessary due to satellite internal clock drifts). Moreover, observation time allows derivation of instantaneous solar position, which makes possible exact pixel-by-pixel illumination corrections, which is critical in the case of optical data, especially for mosaicking and multitemporal composites.

In the case of SAR data the general parameterization is similar, but due to the way the synthetic image is generated other concepts appear in the parameterization of SAR image geometric corrections (slant-range, Doppler frequency). Due to the way in which the image is generated, motion compensation schemes applied in the processing of raw data is preferable to *a posteriori* geometric corrections of the already resulting (flat) image in slant range, especially if topography plays a significant role.

The approach just described is called *inverse mapping* because the observation geometry (line, column) is derived for each ground point. An alternative is to use the so-called *direct mapping* in which each image point is mapped into the surface cartographic projection. The first approach can result in oversampling, while the second approach can result in gaps. This second approach is typically more efficient and useful if no topographic information is available. However, for adequate resampling procedures the inverse mapping becomes more appropriate.

POLYNOMIAL APPROXIMATIONS

Under some circumstances (small, almost linear distortions), the general image transformation functions

$$x' = f(x, y), \qquad y' = g(x, y) \tag{4}$$

can be approximated as simple polynomials

$$\begin{aligned} x' &\approx a_0 + a_1x + a_2y + a_3x^2 + a_4y^2 + a_5xy + \cdots \\ y' &\approx b_0 + b_1x + b_2y + b_3x^2 + b_4y^2 + b_5xy + \cdots \end{aligned} \tag{5}$$

Note that this is nothing more than an approximation, useful only if few terms have to be retained for a given accuracy requirement, and cannot be considered as a general geometric correction procedure, even if a high-degree polynomial is used. Typical distortions cannot be described by polynomials, and numerical problems arise for high-degree polynomials (a ninth-degree polynomial is almost the limit for double-precision numerical calculations).

AUTOMATIC REGISTRATION TECHNIQUES

When increasing the amount of data does not allow detailed processing of each single image, automatic registration techniques are developed. The most widely used approach is based on linear cross-correlation, i.e., applicability only for almost-linear distortions. The essential idea is to define the transformation between two images in the form

$$I(x, y) \to I(x + \Delta x, y + \Delta y) \leftrightarrow I'(x', y') \tag{6}$$

The linear parameters Δx and Δy are determined by iteratively maximizing the correlation between $I(x, y)$ and $I'(x', y')$. The procedure is accelerated by reducing the range of Δx, Δy by working in a small window. The method becomes applicable only for small (linear) distortions, and it is typically used as a second step in the refinement of automatic procedures based on stand-alone geometrical models by using ephemeris or attitude data as a single input without any reference point, by cross-registration to a reference image, or for images with very small geometric distortions (close-nadir viewing cameras with optical or electronic compensation of attitude deviation effects).

More general transformations such as

$$I(x, y) \to I(\lambda(x + \Delta x), \mu(y + \Delta y)) \tag{7}$$

are possible, but extremely time-consuming and impractical unless λ and μ can be considered as constant across the whole image.

THE NEED OF GROUND CONTROL POINTS FOR ACCURATE REGISTRATION

Unfortunately, completely automated techniques still cannot provide accurate registration. Although the platform trajectory can be known very accurately, orientation angles and attitude changes cannot be known, at least by now, with the necessary accuracy, so that to achieve a subpixel registration among different images, some reference points [ground control points (GCP)] have to be identified and used in a refinement procedure. Satellite clock drifts and assumptions in the orbital model are additional sources of errors that need to be compensated.

The refinement procedures allow slight changes in orientation directions of the platform or sensor, redefined by means of GCP, and/or the platform trajectory, to compensate for the observed errors when "nominal" values are used first. In other cases, the refinement procedure is actually a second geometric correction procedure (based on polynomial transformation) after the image has been precorrected by a nominal full geometrical model.

But the identification of GCPs in the image and maps is not easy. The use of GPS for identification of GCP has increased the accuracy of using GCP techniques tremendously. Automatic correlation techniques can only be applied over boundaries (coastal, lakes, rivers), but the identification of GCPs in the image allows the use of single-point features in a very precise way.

Still the major problem in using GCPs is the lack of operationality, since the method requires necessarily the intervention of an operator, which not only slows the whole procedure but can also introduce subjective bias due to the different skills of each operator. Unfortunately, accurate registration still requires GCPs. The spectacular advance in platform positioning techniques in the past few years now makes it possible to reduce the number of GCPs to an absolute minimum. The determination of the instantaneous attitude angle will also soon be possible, by means of differential GPS techniques with different receivers located at the edges of the platform, but is still insufficient for accurate positioning, especially for very-high-resolution data. However, the major problems that make the use of GCPs necessary are the deficiencies in the cartographic modeling of the earth, and the lack of elevation information, in many cases, for each GCP.

CARTOGRAPHIC PROJECTIONS

When images have to be transformed from the original acquisition geometry (typically not useful for most applications) to some cartographic reference, a specific map projection has to be chosen. Local maps available for each area define the type of cartographic projection, which are different in each country. It is often difficult to identify the best projection to be used for a given particular problem.

To avoid such problems, in many cases data are simply projected to a latitude–longitude grid, where the latitude-longitude relative factor is compensated to make the resulting pixel (in kilometers over the surface) almost square. This is only possible for some reference latitude, which is chosen as the latitude of the central point in the reference area. One advantage of this projection, apart from the simplicity, is that most applications require computation of derived quantities that are given as functions of latitude and longitude, so that computations are easy if a latitude–longitude grid is used.

For cartographic applications, however, local references are needed. Fortunately, computational tools are available that allow transfer of data from any cartographic projection to any other by means of mathematical transformations. The problem is then the resampling of the data. Each time the geometry of the data is changed resampling is needed, with the unavoidable loss of some information and introduction of interpolation artefacts. Single-step procedures from the original acquisition geometry to the final cartographic product, by using a single resampling of the data, are always preferable.

THE PROBLEM OF TOPOGRAPHIC DISTORTIONS

Two effects have to be taken into account. On the one hand, given a sensor altitude over a reference surface (typically the earth ellipsoid) the effect of varying altitude of the target over the same reference surface is to introduce horizontal displacement ΔX [see Fig. 2(a)] with additional geometric distortion, plus a change in the sensor–target distance, relevant for ra-

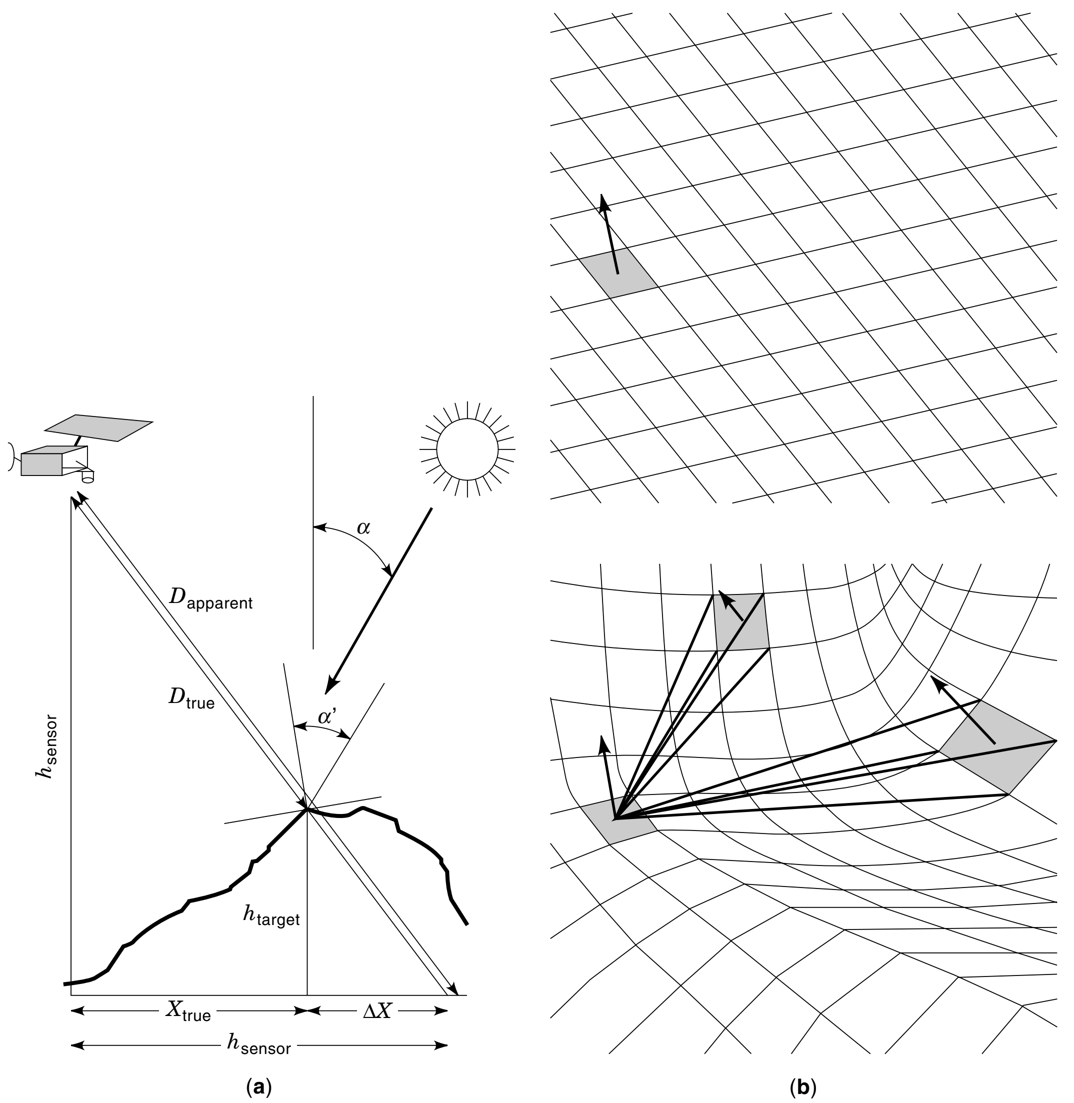

Figure 2. Effects introduced by topography in the geometric processing of remote sensing data. (a) Geometric distortions due to relief for off-nadir viewing geometry, including horizontal displacement ΔX of apparent positions, change in sensor–target distance D, and changes in the local illumination angle α' over the nominal illumination angle for a horizontal surface α. (b) Radiometric distortions due to changes in illumination angle and viewed area, as well as additional reflections due to adjacent slopes, for the case of topography (bottom) as compared to the case of flat surfaces (top).

diometric corrections and with relevant effects in radar data processing. On the other hand, the change from a flat to a rugged surface introduces alterations if the effective illumination angle and effective scattering area, plus additional reflections coming from adjacent slopes with alterations in the desired signal from the target [Fig. 2(b)]. The first effect is purely geometric and can be easily accounted for provided enough information about earth topographic structure (digital terrain model). The second one is much more difficult to correct, and only first-order effects are usually compensated in correction approaches.

The parametric geometric model fully describes the incorporation of topographic effects as direct, especially in the inverse mapping approach. Several techniques have been suggested to include (at least first-order) topographic corrections in polynomial models. The method is only applicable in areas with low topographic distortions, like close-nadir viewing or limited altitude changes across the area. For more general cases, a full 3-D geometrical model is required to account for geometric projections of objects over the perpendicular plane to the viewing direction.

The modeling of radiometric effects due to topography is, in a rigorous way, quite difficult: local slope and orientation, plus the local horizon line, at least, have to be determined for each point in the image. Each viewing/illumination condition determines a changing geometry in the resulting scene. Although most studies consider very simple approaches to describe radiation exchanges in rugged terrain, other approaches take full advantage of computer graphics technologies for a realistic description of intervening effects. Ways to speed up calculations while still keeping a realistic description of the major intervening effects have been developed (14), but a proper description of effects introduced by topography, suitable for correction/normalization of the data from such perturbations, remains an open issue.

RESAMPLING

Once the remotely sensing data can be located geographically or registered over a spatial database, resampling techniques become the next critical issue. The most simple method is called the nearest-neighbor technique, in which you simply assign to each new pixel the value of the closest one in the original image, without the need for recalculations. But many more advanced techniques have been developed (15–20).

Assign a value of 1.0 for the central processing unit (CPU) time for the nearest-neighbor algorithm, considered as the basic procedure for a typical geometric processing, including registration, UTM projection, and resampling. The relative increment in CPU time required by different interpolation algorithms applied in the resampling varies only few percent for “standard” interpolation approaches: bilinear (1.02), cubic convolution (1.07), cubic B spline (1.10). However, if sensor-specific optimum-interpolation approaches are used (see Refs. 18 and 20), CPU time increases drastically: analytical optimum interpolation (7.7), fully numerical optimum interpolation (360.5). Even with more sophisticated processing to achieve more accurate results, an increase in CPU time by a factor of 360 is not acceptable for operational use. Analytical simplifications are more practical but still give reasonable accuracies (18). Resampling considerations become only critical for multisensor studies, especially when very different spatial resolution data have to be merged. In all optimum interpolation methods, the basic idea is not to increase the apparent resolution, but to provide interpolated values for new pixels resulting from geometrical transformations.

Another type of resampling is specifically oriented to create “super-resolution” products by enhancement of the high-frequency content of the image. This is possible with the help of at least two resolution data. However, some recent approaches use many different low-resolution images of a given area, each acquired under a slightly different viewing geometry (only partial overlaps among IFOVs in each different images or images shifted one with respect each other by a small fraction of the IFOV). In this way high-resolution information is reconstructed by iterative processing of the multiple views (21,22). Super-resolution resampling techniques have been intensively used to increase usefulness of low-resolution passive microwave or scatterometer data, for which spatial resolution is typically very poor but many views are available for each area. Although these techniques are still in early stages of development, they appear to be really successful only in areas with highly contrasted spatial substructures.

CALIBRATION AND REMOVAL OF TECHNICAL ANOMALIES

Several sensor-specific technical anomalies have to be considered in the geometric processing (23). Calibration typically refers to radiometric calibration. In the case of SAR data, calibration refers not only to radiometric but also some geometric aspects. Correct interpretation of SAR data requires deconvolution of the signal from artifacts due to antenna gain pattern and then directly related to local variations in incidence angle for each observed area.

Calibration also means intersensor normalization. Only few sensors acquire the images on a strictly pixel-by-pixel basis (AVHRR (Advanced Very High Resolution Radiometer) is a typical example). In the case of the Landsat Thematic Mapper (TM), 16 lines are simultaneously acquired by an array of detectors. In the case of the Satellite Pour l’Observation de la Terre (SPOT), each whole line is acquired simultaneously by charge-coupled device (CCD) arrays. Electrooptical multidetectors, with CCD technology and advanced optical fiber devices, will be the common technology for sensors in the near future. Since the behavior of multiple detectors composing the final image is not the same, intersensor normalization or recalibration is strictly required to avoid artifacts in the image (different intensity vertical strips, horizontal stripping, and nonregular spatial noises). Additional problems are due to the scanning devices, especially for dual-scan systems (forward and reverse) such as Landsat TM. Nonlinear figure-8-shaped distortions in line geometry must be optically compensated, but local geometric distortions resulting in the images are quite difficult to remove.

SPATIAL MOSAICKING

Satellite data acquisitions are typically done along strips of limited width. The width varies from hundred of meters, for very-high-resolution systems, to thousands of kilometers, for low-resolution systems. The reason for this variation is mainly the limited capabilities of data transmission from sat-

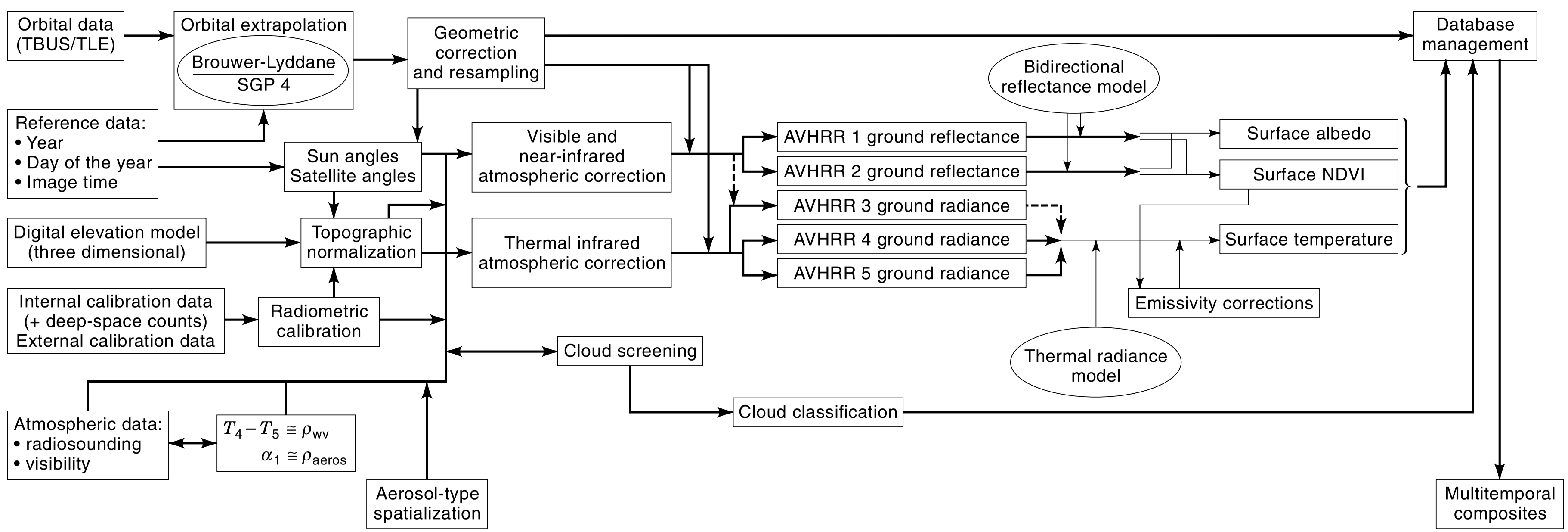

Figure 3. Schematic diagram illustrating the whole processing chain for NOAA AVHRR data. Similar processing schemes are used for most remote-sensing data systems. SGP = simplified general perturbation; nDVI = normalized difference vegetation index; wv = water vapor; aeros = aerosols.

ellites to Earth. Since the whole data volume is limited, an increase of spatial coverage is done at the expense of reduction in spatial resolution. For many applications, mainly those requiring high-resolution data, a single strip is not enough to cover the study area, and several images have to be "mosaicked" to make a single image of the area. A large image area is defined and all pixels are set to zero values. Then, each single image is reference over the large frame background. When two single images overlap each other, a decision has to be made about how to combine both pixels to define the unique value in the mosaic.

Accurate geometric registration of each single image forming the mosaic is not enough to make the mosaic look like a single image. Single images are acquired under different viewing geometries, and illumination corrections are needed in order to avoid artifacts in the boundaries between original single images. Since images are acquired at different times, motions or changes in targets (i.e., clouds) can result in discontinuities. Simple image-processing techniques are often used (local histogram equalizations plus local cross-correlation and linear composites across overlaps) to improve appearance. However, physically based methods are preferred to compensate for perturbing effects, especially if the data have to be used in numerical studies or as input to physical models after the mosaic images have been produced.

MULTITEMPORAL COMPOSITING

Monitoring the surface condition by remote sensing implies the use of multitemporal data. Obviously, geometric registration among all the multidate images must be set within one pixel to make sense of the use of the composites.

A critical issue is the necessity of accounting for the illumination dependence on the measured data. It is therefore necessary to keep track during the geometric processing about the observation angles but also the illumination angles, absolutely critical in the case of passive optical data.

In the case of SAR data, this is no longer a serious limitation. This illumination independence of SAR data and also the cloud-transparency properties are the two major reasons for the superior capabilities of SAR remote sensing over optical systems for operational all-weather monitoring capabilities. However, proper corrections of antenna gain pattern effects that vary with local incidence angle are needed, especially over topographically structured areas, to avoid artefacts simply due to changing illumination conditions in multitemporal studies.

OPERATIONAL PROCESSING AND DATA VOLUME CONSIDERATIONS

Since remote-sensing data are used in practical applications, operational constraints limit the use of sophisticated algorithms, which in many cases represent an unacceptable amount of computer time or memory management. Most of the considerations previously noted are highly limited by the amount of data to be processed, which points to the subsequent need for simplified algorithms and numerically optimized techniques. Although it is true computer techniques have experienced tremendous improvements in processing speed and memory capabilities, the increase in the amount of remote sensing data to be processed, as well as in the sophistication of the algorithms used for the processing of the data, has increased also in such a way that limitations exist. The optimum compromise between accuracy requirements and practicality should be achieved in each particular application by optimization of the codes and advanced memory management in processing facilities.

The case of AVHRR data has become a typical example, partly due to the many applications of these data due to low cost and global availability, and also due to the peculiar characteristics of the system with highly nonlinear geometric distortions due to panoramic view and circular scanning. Figure 3 indicates the many steps involved in the whole AVHRR data-processing scheme. Most other data-processing schemes for other sensors or systems follow similar steps. The developments in AVHRR data processing (3,12) have become a good example of how improvements in data-processing techniques can drastically increase the usefulness of data in many new potential applications.

However, the future is really challenging. The Earth Observing System (EOS) platforms will provide data at the rate of 13.125 Mbyte/s for the first EOS platform and slightly higher for the posterior series. Similar or even higher rates are expected for other systems, especially for those using active sensors like SAR. These data rates represent a real challenge for current computational algorithms and hardware technologies (24).

BIBLIOGRAPHY

1. P. Meyer, A parametric approach for the geocoding of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data in rugged terrain, *Remote Sens. Environ.,* **49**: 118–130, 1994.
2. H. De Groof, G. De Grandi, and A. J. Sieber, Geometric rectification and geocoding of JPL's AIRSAR data over hilly terrain, *Proc. 3rd Airborne Synthetic Aperture Radar Workshop,* J. J. van Zyl (ed.), NASA JPL Pub. 91-30, 1991, pp. 195–204.
3. J. Moreno and J. Meliá, A method for accurate geometric correction of NOAA AVHRR HRPT data, *IEEE Trans. Geosci. Remote Sens.,* **31**: 204–226, 1993.
4. R. R. Bate, D. D. Mueller, and J. E. White, *Fundamentals of Astrodynamics,* New York: Dover, 1971.
5. K. I. Duck and J. C. King, Orbital mechanics for remote sensing, in R. N. Colwell (ed.), *Manual of Remote Sensing,* 2nd ed., Falls Church, VA: American Society Photogrammetry, 1983, vol. I, chap. 16, pp. 699–717.
6. A. E. Roy, *Orbital Motion,* 3rd ed., Bristol: Hilger, 1988.
7. F. R. Hoots and R. L. Roehrich, *Models for propagation of NORAD elements sets,* Spacetrack Rep. No. 3, NORAD, Aerospace Defense Command, Peterson AFB, CO, 1980.
8. D. Brouwer, Solution to the problem of artificial satellite theory without drag, *Astron. J.,* **64**: 378–397, 1959.
9. P. R. Escobal, *Methods of Orbit Determination,* New York: Wiley 1965.
10. E. D. Kaplan (ed.), *Understanding GPS: Principles and Applications,* Norwood, MA: Artech House, 1996.
11. J. Morrison and S. Pines, The reduction from geocentric to geodetic coordinates, *Astron. J.,* **66**: 15–16, 1961.
12. G. W. Rosborough, D. G. Baldwin, and W. J. Emery, Precise AVHRR image navigation, *IEEE Trans. Geosci. Remote Sens.,* **32**: 644–657, 1994.

13. W. H. Press et al., *Numerical Recipes,* Cambridge, UK: Cambridge Univ. Press, 1986.
14. J. Dozier and J. Frew, Rapid calculation of terrain parameters for radiation modeling from digital elevation data, *IEEE Trans. Geosci. Remote Sens.,* **28**: 963–969, 1990.
15. R. Bernstein, Digital image processing of Earth observation sensor data, *IBM J. Res. Develop.,* **20**: 40–57, 1976.
16. R. Bernstein et al., Image geometry and rectification, in R. N. Colwell (ed.), *Manual of Remote Sensing,* 2nd ed., Falls Church, VA: American Society Photogrammetry, vol. I, chap. 21, pp. 873–922, 1983.
17. R. G. Keys, Cubic convolution interpolation for digital image processing, *IEEE Trans. Acoust. Speech Signal Process.,* **29**: 1153–1160, 1981.
18. J. Moreno and J. Meliá, An optimum interpolation method applied to the resampling of NOAA AVHRR data, *IEEE Trans. Geosci. Remote Sens.,* **32**: 131–151, 1994.
19. S. K. Park and R. A. Schowengerdt, Image reconstruction by parametric cubic convolution, *Comput. Vision Graphics Image Process.,* **23**: 258–272, 1983.
20. G. A. Poe, Optimum interpolation of imaging microwave radiometer data, *IEEE Trans. Geosci. Remote Sens.,* **28**: 800–810, 1990.
21. D. Baldwin, W. Emery, and P. Cheeseman, Higher resolution Earth surface features from repeat moderate resolution satellite imagery, *IEEE Trans. Geosci. Remote Sens.,* **36**: 244–255, 1998.
22. P. Cheeseman et al., *Super resolved surface reconstruction from multiple images,* NASA-AMES Tech. Rep. FIA-94-12, 1994.
23. P. N. Slater, *Remote Sensing Optics and Optical Systems,* Reading, MA: Addison-Wesley, 1980.
24. M. Halem, Scientific computing challenges arising from spaceborne observations, *Proc. IEEE,* **77**: 1061–1091, 1989.

JOSE F. MORENO
University of Valencia

RENDERING (COMPUTER GRAPHICS). See GLOBAL ILLUMINATION.

RENEWABLE ENERGY. See OCEAN THERMAL ENERGY CONVERSION.

RENEWABLE SYSTEMS. See REPAIRABLE SYSTEMS.