AVHRR Image Navigation: Summary and Review

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ABSTRACT: The navigation of imagery from polar orbiting weather satellites includes the correction for geometric distortions due to Earth shape/Earth rotation, satellite orbit variations, and satellite attitude along with the resampling of the satellite image to a selected geographic map projection. The routine image navigation procedure also compensates for the distortion of the satellite imagery due to the nonliear scanning of the sensor system. We review general methods for performing this image navigation ranging from a method that assumes no orbital information, and thus relies on nominal orbital parameter values and image corrections computed by matching ground control point (GCPS), to a method that uses high quality satellite ephemeris data to make the correction with a limited number of GCPs. A procedure to optimize the image navigation by using a spatial remapping, or interpolation, is introduced and outlined. Recommendations are made for people interested in the processing of AVHRR imagery.

INTRODUCTION

S INCE ITS FIRST DEPLOYMENT on the TIROS-N satellite in 1978, the Advanced Very High Resolution Radiometer (AVHRR) has become one of the most widely used satellite sensor systems. The direct broadcast capability of TIROS-N satellites makes it possible for interested parties to directly receive and process AVHRR data. In order to work with AVHRR image data, it is necessary to correct the images for distortions due to Earth shape, Earth rotation, variations in satellite orbit, and satellite attitude. One needs to decide whether the geographic grid will be distorted to match the satellite image projection (also called direct image referencing (Ho and Asem, 1986)) or if the image will be corrected and resampled to fit a desired geographic map projection (called inverse image referencing by Ho and Asem (1986)).

This latter procedure has become widely known in the remote sensing community as image navigation because it performs the dual function of correcting the image and transforming it into a known map projection, thus locating each pixel at the appropriate geographic location much as you would in navigating a ship or aircraft. This processing step is common to all polar orbiting satellites, and there is a considerable body of literature that discusses the specific methods for carrying out this processing particularly for the Landsat satellites (Bernstein, 1976; Bernstein, 1983; Duck and King, 1983; Friedmann et al., 1983; Forrest, 1981). While the fundamental principles apply to the AVHRR as well, the tracking accuracy and the availability of high-quality ground control points (GCPs) is much more limited for the AVHRR. A number of papers addressing AVHRR navigation have, however, appeared (Brush, 1988; Brunel and Marouin, 1987; Ho and Asem, 1986; Brush, 1985; Emery and Ikeda, 1984; Legeckis and Pritchard, 1976) that discuss particular methods for navigating AVHRR images.

It is the purpose of the present paper to review these and other techniques for image navigation, to introduce some recent improvements to these procedures, and to make specific recommendations for the navigation of AVHRR images, particularly for those scientists just starting to work with digital AVHRR data. We hope to provide a basic reference for new groups starting to acquire and process AVHRR images for a variety of applications in meteorology, oceanography, and terrestrial physics. Because computer systems, image display systems, and other hardware related functions are expected to continually evolve, the treatment and approach will be general in nature so as to be adaptable to future computing environments. An emphasis will be placed on general understanding; detailed aspects of the navigation methods are left to the original papers or are relegated to a separate appendix.

AVHRR IMAGE NAVIGATION TECHNIQUES

In the discussion that follows, we will only address the navigation of AVHRR imagery as it has been defined above. That is, we will only discuss the correction and registration of the image to a known geographic reference map. This amounts to what other investigators have called inverse image referencing (Ho and Asem, 1986). Direct image referencing, where the latitude and longitude locations of each image pixel are calculated, produces geometrically unique images that cannot be sequenced or registered with other images. Thus, the navigation approach is much more useful in the combination of AVHRR imagery (and derived results) with other satellites images, *in situ* measurements, and numerical model results. We will concern ourselves only with the navigation of AVHRR imagery.

There are essentially two different approaches to the problem of polar orbiter image navigation. The first assumes only a very rudimentary knowledge of the satellite orbit and relies on known geographic features clearly visible in the images (called Ground Control points, GCPs) to correct for errors in Earth shape, scan geometry, satellite orbit, and satellite attitude. The second method uses highly accurate satellite ephemeris data (orbital parameters) to locate the satellite as a function of time and only requires ground control points to correct for possible timing errors and satellite altitude. The first of these two methods is considerably more time consuming because the operator must interact with the image and a map (unless pre-selected points are always used) to locate the satellite view of the selected ground features used as reference. This assumes that these features are clearly visible in the image which, in the presence of cloud cover, may not always be the case for an optical system. Also, a GCP approach only works when land is present in the image; there are very few GCPs in the open ocean.

The selection of which method to use for navigation depends on a number of factors. First, does the investigator have ready access to accurate ephemeris data for the period of the image?

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What is the desired image accuracy for the study in question? How much processing time can be allocated to each image? Answers to these questions will determine just what approach is taken. If no ephemeris data are available, some method using GCPs must be used. For highest accuracy (single pixel RMS differences), a number of GCPs will be necessary (Emery and Ikeda, 1984; Wong, 1984); at the same time, the processing time will increase because each GCP must be precisely located by an operator. In addition, the location error resulting from GCP navigation is a function of the points selected and may not be uniform over an image. A procedure using a single GCP was developed by Ho and Asem (1986) to correct satellite attitude and inclination. They report RMS accuracies of about 2 pixels for ten AVHRR images of western Europe.

The ephemeris image navigation method is much faster than that using GCPs because the orbital model is fast to run and requires no operator intervention to compute the geometric corrections and projection resampling needed for the navigation. As mentioned above, one of the largest sources of error in this method is inaccurate timing at the ground station where the data are collected and/or on the satellite that is broadcasting the information. Unfortunately, the clock on the TIROS-N satellites drifts significantly (70 ms per day) and, therefore, is not a reliable absolute time source. Thus, when receiving data, one needs an accurate time standard to know exactly when the data were collected. Without this information, the satellite position along its track will be slightly off, producing shifts in the image along the satellite orbit path. Corrections for this along-track shift in the image have been named the "nudge" by most users of these image data. In this nudge the whole image is moved up or down along the nadir track-line until whatever geographic features in the image are lined up best. Thus, it is often the practice to use a single GCP to define this along-track nudge, which means that even the ephemeris navigation routine has options for further corrections to match know GCP locations.

Even with the ephemeris technique, image location errors that result from satellite attitude pointing errors may need to be corrected. The attitude of the NOAA polar orbiters is controlled to better than 0.1 degree in each of the roll, pitch, and yaw axes, and in most applications experience has shown that these attitude variations can be neglected to achieve image location accuracies on the order of the 1 km AVHRR resolution. If attitude variations are to be compensated for, one needs to have at least three ground control points to correct the image. This is not a problem for most land and coastal images but can be a significant problem for open ocean imagery where landmarks are generally non-existent. In these geographic areas the ephemeris navigation must be relied on to produce navigated images with an accuracy of a single pixel. This improvement over the RMS accuracy reported by Ho and Asem (1986) reflects the greater accuracy possible with ephemeris satellite navigation methods.

IMAGE NAVIGATION WITHOUT SATELLITE EPHEMERIS DATA

Because the NOAA series of satellites are launched into nearly circular polar orbits, a good assumption to make, if one does not have access to the current ephemeris data, is that of a circular orbit about a spherical Earth, with the appropriate altitude giving the radius of the circle out to the satellite. In reality, the satellite is in a retrograde, slightly elliptical orbit about a rotating oblate Earth. Differences between this reality and the circular orbit, spherical Earth assumptions lead to image navigation errors of about 10 km for each of the above effects. Legeckis and Pritchard (1976) used a simple algorithm with a circular orbit and a spherical Earth to achieve image navigation accuracies of about 5 km for NOAA-4 data. A modified version of this same procedure is presently used by NOAA/NESDIS (National Environmental Satellite and Information Service) at 51 equally spaced intervals along each AVHRR scan line. In a study of oceanic fronts, Clark and LaViolette (1981) examined the accuracy of the NESDIS navigation and found position errors of between 2 and 4 pixels. Similar procedures used by the CMS (Centre Meterologie Spatiale) receiving station in Lanion, France result in image errors of about 5 km. Thus, simple automated navigation systems, using circular orbit geometry and a spherical Earth, are capable of routinely correcting AVHRR imagery to within 5 pixels.

More recently Ho and Asem (1986) reported on a model with similar geometry having image navigation accuracies of about 2 km. One improvement in the model is the consideration of the Earth as an oblate spheroid (Duck and King, 1983). They also include corrections for image distortions due to scan skew and variations in satellite altitude and inclination. Corrections in the latter two quantities are computed using a single GCP as reference. Scan skew corrections are necessary to adjust for the fact that, due to the rotating scan mirror scanner, pixels are larger away from nadir (Brush, 1988). While pixels remain uniformly large away from nadir, near the sub-satellite point pixel sizes change rapidly, providing a non-linear sampling of the Earth's surface. This image error can be compensated for by linearizing the scan geometry.

NOAA SATELLITE ORBITAL GEOMETRY

The NOAA polar orbiters (TIROS-N satellites) that carry the AVHRR are deployed in nearly polar, sun sunchronous orbits. The orbital plane of a sun-synchronous satellite remains fixed in space relative to the sun-Earth vector, precessing at one revolution per year relative to an inertial coordinate system. Within the limits of this precession, a sun-synchronous satellite will cross the equator at the same (local) time every day. The present constellation of two operational NOAA satellites means that, for most locations on the Earth, a satellite passes every 6 hours. At polar latitudes, however, the approximately 2000 km AVHRR scans overlap considerably, creating much more frequent coverage.

The selection of a sun-synchronous orbit for these primarily weather satellites was made to standardize the sun-satellite geometry, provide consistent ground illumination, and simplify the design of the satellite cooling systems. This selection has proven to be most advantageous for a number of AVHRR applications, including the monitoring of terrestrial vegetation with the repeated afternoon passes. The standardization of the solar illumination is an important constraint for many studies of temporal variability.

The orbital geometry of the NOAA satellites, in a geocentric reference systems, is shown here in Figure 1; the symbols are defined in Appendix A. The constants and nominal values are those specified in the NOAA Technical Memorandum 95 (Schwalb, 1978) and can also be found in Brush (1982).

SCAN GEOMETRY

The AVHRR scanner uses a rotating mirror fixed at a 45° angle with respect to the Earth and the axis of the optical observing telescope. The telescope is aimed at the center of the scan mirror in such a way that the resulting scan pattern describes a great circle on the surface of nonrotating Earth perpendicular to the satellite's direction of motion. The mirror rotation rate is set so that consecutive scan lines are spaced one pixel apart at nadir. Data sampling is restricted by field stops to the intervals that the scanner views the Earth's surface. The data collection module, using Earth limb and satellite attitude information, generates a nadir reference mark. Thus, every scan line collected by the satellite has an associated time from which the satellites orbital location can be precisely determined.



FIG. 1. Satellite orbit geometry.

Off nadir viewing, however, is nevertheless distorted due to the curvature of the Earth's surface and the slant path of the scan mirror. Using the Earth-satellite geometry of Figure 1, with the symbols as defined in Appendix A, we can write the relationship between the scan mirror angle δ and the geocentric angle ψ from nadir as

$$\psi = \sin^{-1} \left\{ \left[(R_e + h_s) / R_e \right] \sin \delta \right\} - \delta \tag{1}$$

where R_e is the Earth radius and h_s is the satellite altitude. This equation can be rearranged to solve for mirror scan angle δ as (Brush, 1988)

$$\tan \delta = \sin \psi / \left[(R_e + h_s) / R_e - \cos \psi \right]$$
(2)

Equation 1 can be used to compute the geocentric angle ψ that corresponds to the known maximum mirror scan angle from which the direct relationship between pixel location (defined by the geocentric angle along the scan line) can be computed for each step in the mirror scan. For large values of ψ , the pixel number remains the same for a large number of samples while, for values of the geocentric angle near nadir, the samples change rapidly. This technique resamples the scan data so that samples near the edge of the scan are repeated many times whereas samples near the center may not be repeated at all. This linearizes the scan geometry to account for differences in mirror viewing angle. No correction is attempted for possible changes in satellite altitude during the maximum 15 minutes of AVHRR image data collection.

MODEL TRANSFORMATIONS

The most important aspect of navigating satellite imagery is the transformation between the geocentric coordinate system of the model satellite orbit to the geographic coordinate system used for locations on Earth. For example we can write this transformation for latitude as

$$\tan \left(\varphi_{\text{geographic}}\right) = \left[\left(R_{\text{equa}}\right)^2 / R_{\text{pole}}\right)^2\right] \tan \left(\varphi_{\text{geocentric}}\right) \tag{3}$$

Using the appropriate spherical trigonometry, similar expressions can be written to accurately transform between satellite image coordinates and geographic Earth locations. This transformation can be set up either to transform from the line and pixel units of the satellite image to the corresponding geographic coordinates (called direct image referencing by Ho and Asem, 1986) or to transform from known geographic coordinates to the appropriate image pixel and line (called inverse referencing by Ho and Asem (1986)). The direct procedure can be done analytically while the second is a more complicated iterative procedure that is accomplished using numerical techniques. This iteration is due to the fact that the time, *t*, from the ascending node of the satellite orbit to the pixel and scan line is not known and must be solved for iteratively.

The first of these two options would allow us to distort the geographic grid to match the image projection of the AVHRR; this is called the direct transformation or direct referencing. We would instead like to resample the image to match our selected geographic projection, so we are interested in what is called the inverse transformation (inverse referencing) which will allow us to compute the pixel and scan line that corresponds to each map location in our chosen projection. Thus, we will restrict our mathematical description to the computation of satellite image locations to match our known geographic map positions. Readers interested in the direct computation are referred to Ho and Asem (1986) for a description of the direct transformation. In the following derivation we follow the development given by Ho and Asem (1986) for direct referencing under the assumptions of a circular orbit around a spherical Earth.

For our inverse calculation we first assume the time of the scan line and pixel of interest are given by

$$t = t_f - t_c \tag{4}$$

From *t* we calculate the static Earth longitude (λ_D) from the selected geographic longitude (λ_D) using

$$\lambda_D = (\lambda_D - V_c t) (180/\pi) + \lambda_c \tag{5}$$

It should be noted that this equation ignores the motion of the ascending node which can contribute an error of a few kilometres in longitude over large orbital segments due to across track skews. This equation relates geographic longitude in degrees to static (non-rotating) longitude (radians); a similar expression can be written that relates Earth latitude to static latitude, i.e.,

$$\phi_D = \phi_{D'} (180/\pi) \tag{6}$$

Using spherical trigonometry, we can set up the relation

$$\cos \lambda_{D'} = \cos \beta / \cos \phi_{D'} \tag{7}$$

from which we solve for β knowing $\lambda_{D'}$ or $\phi_{D'}$. We now calculate *j*, ψ , and θ using the following three spherical trigonometric relations:

$$\sin \phi_{\rm D'} = \sin \beta \sin j \tag{8}$$

$$\sin(i - i) = (\sin \psi \sin \gamma) / \sin \beta$$
(9)

$$\cos \beta = \cos \psi \cos \theta + \sin \psi \sin \theta \cos \gamma \tag{10}$$

The inverse referencing that is done as part of AVHRR image navigation is an iterative process rather than a direct mathematical transform. We had started this calculation by assuming time *t* was given by Equation 4. We now improve our time estimate using the relationship relating time to θ , the Earth angle from the ascending node to the subsatellite point

$$\theta = t \; (\mu/r^3)^{1/2} \tag{11}$$

where $r = R_e + h$. Using this new time estimate, we compute the time difference Δt between it and the time computed from Equation 4 above. If this Δt is smaller than some arbitrarily small value (i.e., $\epsilon = 0.001$), then this is taken to be the correct time and the computation is continued. If $\Delta t > 0.001$, then return to Equation 5, take $t = t + 0.5\Delta t$, and repeat the following steps until $\Delta t < \epsilon$.

We now calculate the appropriate off-nadir scan angle δ from ψ using

$$\arcsin\left[\left(r/R_{e}\right)\sin\delta\right] = \psi + \delta \tag{12}$$

(see triangle SOD' in Figure 1). From the scan angle we can compute the corresponding pixel number (p) from

$$\delta = p \, \delta_i \tag{13}$$

where δ_i is the scan step angle in radians which for the AVHRR is 0.955×10^{-3} rad. The corresponding AVHRR scan line number (*L*) can be computed directly from the correct time *t* as

$$L = (t - t_f) \Delta L + 1 \tag{14}$$

where t_f is the time of the first scan and ΔL is the scan line rate (determined by the orbital velocity of the satellite).

Ho and Asem (1986) supplement this procedure using a single GCP of known latitude and longitude at image coordinates (L,p) to correct for the effects due to variations in satellite altitude and orbital inclination (note this still assumes a locally circular orbit and corrects only for the mean altitude at the scene of interest). Knowing the geographic latitude and longitude of the pixel (L,p) at the GCP allows one to recompute both δ and t using Equations 13 and 14. Then, to begin the solution, the inclination i is taken as the nominal for the respective satellite as is the altitude h. The angular speed of the satellite (V_s) is given by

$$V_s = \sqrt{(\mu/r^3)} \tag{15}$$

from which we now calculate V_s using the new satellite altitude. Similarly, we use our new V_s to compute the satellite azimuth angle γ from

$$\gamma = \arccos\left(V_s t_{1/2}/\psi_{\max}\right) \tag{16}$$

where $t_{1/2}$ is one-half the scan line time.

The next step is to compute V_e and $\lambda_{D'}$ from

$$V_e = 2\pi/D_s - P_e \tag{17}$$

and Equation 5. Now β , *j*, ψ , and θ are calculated from Equations 7, 8, 9, and 10. Now we have two alternatives for computing the corresponding satellite altitude to match these conditions. We first calculate h_1 from δ and λ using Equation 12; at the same time we compute h_2 from θ with Equation 11. We now return to Equations 12 and 9 to compute ψ and the inclination (*i*). This calculation is repeated from the computation of V_e in Equation 15 until $abs(h_1 - h_s) < 0.5$ km. This correction in satellite altitude adjusts for image distortions due to the oblateness of the Earth and the ellipticity of the satellite orbit.

Emery and Ikeda (1984) also review the problem of image correction using the above assumptions of a circular orbit around a spherical Earth. They subsequently introduce the concept of modifying the results using a set of GCPs rather than a single GCP as suggested by Ho and Asem (1986). The procedure is very much the same as that given above for a single point with the exception that the equations for the corrections in inclination and altitude are now a function of more than a single point. For each GCP we have two independent pieces of information and thus, as discussed in Emery and Ikeda (1984), the unknowns are expressed in a power series expansion which can be solved using the differences between the image features and the corresponding GCP locations. For the example discussed in Emery and Ikeda (1984), the solution of the image offset required three separate GCP offsets to determine the proper x and y locations for the image lines and pixels. Instead of using the required three GCPs for a complete solution, a least-squares fit procedure was employed so that more GCPs (a total of seven were used) could be used to set the image corrections.

ADDING EPHEMERIS DATA

All of these computations have been carried out for a spherical Earth and a circular orbital geometry, thus neglecting the oblateness of the Earth and the elliptical nature of the satellite's orbit. These assumptions have been initially necessary because we have assumed no direct knowledge of the precise orbital parameters for our satellite. With access to regularly updated ephemeris data, we can use an elliptical model for our computation of the line and pixel locations that correspond to the map location on our geographic grid.

This can be done in a number of ways, each of which has important implications for the speed and accuracy of navigating images. At the Rosenstiel School of Marine and Atmospheric Sciences (RSMAS) of the University of Miami, the elliptical corrections are carried out (Brown, 1988) every 300 scan lines by computing the satellite position and using this location vector when converting between scan line and along track position of the satellite. This corrects for orbital ellipticity because the alongtrack velocity varies in a periodic fashion from the mean orbital velocity due to the elliptic orbit. Thus, correcting the satellite position each 300 scan lines compensates for the effects of the elliptical orbit which can be as great as 20 km in satellite altitude for an orbital eccentricity of 10⁻³. At the same time, the computation of the satellite height every 300 scan lines can be used to correct for the across track distortions due to the effects of the Earth's oblateness.

Another approach is to use the full elliptical orbital model, and including the effects of deviations from sphericity of the Earth, to compute the transformation between geographic coordinates and satellite image line and pixel locations. Brush (1988) found that the method of Ho and Asem (1986), outlined above, was not sufficiently accurate for the gridding of data over large areas. He therefore recommended the use of a fully elliptical orbital model of relatively low eccentricity (Keplerian) where the orbital parameters were specified by a set of accurate orbital elements computed from the tracking of the satellites (NOAA/TBUS, etc.).

Following Emery and Ikeda (1984), the orbital parameters computed from the current ephemeris data are the orbital inclination (*i*), the local satellite angular velocity (V_s), the local satellite altitude (h_s), the time of equatorial crossing (T_{eq}), and the equator crossing longitude (referred to above as the static Earth longitude, $\lambda_{D'}$). The angular velocity, V_s , is now computed from

$$V_s = (\sqrt{\mu} \sqrt{a} (1 - e_0^2)^{1/2}) / (R_e + h_s)^2$$
(18)

where the appropriate satellite altitude (h_s) is given in the ephemeris data set. The equatorial crossing time and the equatorial longitude are given in the ephemeris data along with the orbital inclination, the eccentricity, the mean orbital motion, the

orbital decay rate, the argument of perigee, and the mean anomaly at Epoch (midnight GMT).

With these orbital parameters, the procedure given above can be repeated to find the line and pixel values that correspond to the geographic map coordinates desired for the final image. This array of pixel and line locations is used to resample the original image data to compose the navigated final image. As part of this resampling the pixel, line locations are simultaneously transformed to the desired geographic map projection so that an appropriate latitude-longitude grid can be added along with any geographic boundaries that may be present in the image. Where appropriate, pixels are repeated to fill in regions stretched by the navigation while other pixels may be deleted in those areas where the required shrinking of the image makes the pixels redundant.

This approach assumes a fully elliptical orbit for the entire computation of the image correction and registration that we have combined here in the process of image navigation. When compared to the circular assumption discussed above, this computational procedure will be slightly more time consuming in terms of CPU time. One time savings variation is to use the fully elliptical orbit to initially locate the center location of the image and then to apply a locally circular orbit assumption (i.e., use Equation 15 for V_s) to the computation of the image corrections themselves. This saves the time-consuming repeat precise calculations required of the fully elliptical solution. As will be shown by example later for many applications, this locally circular assumption is adequate in providing sufficient image navigation accuracy.

The formulation of the fully elliptical image navigation is slightly different from that given above for the navigation without ephemeris data and follows the outline given in Emery and Ikeda (1984). Here we assume that accurate and precise ephemeris data are available for the computation of the satellite orbital parameters as close in time as possible to the time of image data collection. Thus, we first compute V_s from ephemeris information on the mean orbital motion and the eccentricity of the orbit using

$$V_{s} = M_{1}' \left(1 + e_{0} \cos A\right) / \left(1 - e_{0} \cos E\right)$$
(19)

where

$$A = M^* + 0(e_0^2)$$
; (for most cases $A = M^*$) (20)

$$M^* M_0 + M_1 (t^* - T_0) + M_2 (t^* - T_0)^2$$
(21)

$$E = M^* + e_0 \sin M^*$$
 (22)

$$\sin \theta_{1} = \sin (\omega + A) \sin i \qquad (23)$$

$$\omega = \omega_0 + \Delta \omega N \tag{24}$$

$$N = M_1 \left(t^* - t_0 \right) / 2\pi \tag{25}$$

$$M_{1}' = M_{1} (1 + \Delta \omega / 2\pi)$$
(26)

$$t_0 = t * - (\omega + A)/V_s$$
 (27)

Note: M_1 is measured relative to perigee while M_1' is measured relative to the equator. The time t^* is the time at the center of the image of interest. Equations 19 to 25 are iterated with increasing t^* until θ_1^* is close to the latitude of the center of the image of interest.

The parameter *E*, as solved for above, is also used to compute the satellite altitude as

$$h = a(1 - e_0 \cos E) - R_e \tag{28}$$

where

$$a = (\mu/M_1^2)^{1/3} \tag{29}$$

The equatorial crossing longitude (λ_o) is computed as

$$\lambda_0 = \lambda_0' + M_1 \Delta \lambda_c / 2\pi - (t_0 - T_0) - V_c(t_0 - T_0)$$
(30)

We now use these parameters to compute the line and pixel locations that match with our desired geographic map projection. We use a procedure similar to that given above but now the orbital parameters such as satellite altitude (h), geocentric latitude and longitude, etc., are now computed from the ephemeris data rather than assumed from nominal values and later adjusted to meet the requirements of known GCP locations.

The fully elliptical calculation is also reviewed by Brush (1988), but his final output conversion is to the specific characteristics of the facsimile machine used for hard-copy output. If this output device were replaced with another, a similar transform will have to be carried out to provide the appropriate navigation. We have tried to avoid specifics regarding data input and output in our review of AVHRR image navigation methods and instead have tried to generally describe and mathematically outline the available methods and their application.

INTERPOLATION

One method of speeding up the navigation computation is to navigate only a limited portion of the pixels in the image and then to use an efficient interpolation scheme to adjust the remainder of the pixels in the image. Here we introduce a method using continuous, piecewise-biquadratic remapping functions to greatly accelerate the navigation of AVHRR images. This interpolation procedure saves from 20 to 40 percent on the CPU time needed to navigate images.

To discuss the details of this method, we introduce the descriptions of the input and output planes in Figures 2a and 2b. Here the axes are in terms of pixel location corresponding to line and pixel designations. We also introduce the real valued coordinates (x,y) and (u,v) which correspond to the input and output planes, respectively. Because we are now going to geometrically transform only a limited number of the input pixel array, the image rectification scheme must also interpolate the intensities of the intervening pixels.

We can write the geometric transforms simply as

$$u = AA(x, y), \tag{31}$$

$$v = BB(x, y) \tag{32}$$

The mapping functions AA and BB depend on the scan geometry of the sensor (as discussed earlier), on the orbital behavior of the satellite, and finally on the selected map projection to be used for the final image display. These functions are derived as outlined above for the orbital characteristics of the appropriate NOAA satellite either using the nominal orbital



FIG. 2. Input and output image planes for remapping.

parameters or by using precise ephemeris information (Murphy *et al.*, 1978); Wong, 1984). Also, as discussed above, these transformations can be adjusted to minimize the errors in position at a number of GCPs.

For our purposes, we assume that functions AA and BB are given and are assumed to be smooth; the problem is that their repeated application is time consuming in terms of the navigation computation. In order to save computational time, we perform a remapping procedure whereby we approximate the transformations AA and BB with bilinear polynomials (Bernstein, 1976; Friedman *et al.*, 1983). A consequence of this remapping is that the pixel radiances must be interpolated, for which we use nearest neighbor interpolation. Other investigators (Bernstein, 1976; Wong, 1984) have suggested, as an alternative, the use of cubic spline interpolation to fill in the radiance values.

REMAPPING PROCEDURE

For the remapping, the output plane is divided into cells of an auxiliary grid as shown for example in Figure 2b. The values of the original mapping functions AA and BB are calculated at the grid nodes, the cell edges, and the cell centers. The continuous remapping functions *a* and *b* are defined by fitting biquadratic polynomials to the nine available values of AA and BB for each 2 by 2 auxiliary grid cell. For example, if a pixel center x = i, y = j belongs to the cell $\{m, n\}$, the biquadratic interpolation can be written as

$$a(i,j) = (a_{mn}^{00} + a_{mn}^{01|} + a_{mn}^{02|2}) + (a_{mn}^{10} + a_{mn}^{11|} + a_{mn}^{12|2}) + (a_{mn}^{20} + a_{mn}^{21|} + a_{mn}^{22|2})$$
(33)

where the terms a_{mn} are cell dependent coefficients which are determined from the radiances at the corners of the output pixels in Figure 2b. A similar relation can be written for b(k, l).

Thus, the remapping procedure can be separated into two phases:

Phase 1: The calculation of an array containing all of the values to be interpolated for all of the cells $\{m, n\}$; and

Phase 2: The calculation of the biquadratic interpolation functions.

This reduces the number of computations to the multiplications and additions given here in Equation 33. In addition, if the remapping is carried out along horizontal lines (j=constant), the array sizes can be kept small, reducing the computer memory required.

An additional advantage of this remapping procedure is that, by dealing with the larger grid, it is possible to achieve subpixel remapping accuracies. For example, with the typical 512 by 512 AVHRR image, this subpixel accuracy is achieved when the auxiliary grid contains $M^*N=4^*4$ grid cells. In order to ensure even greater accuracy, we choose $M^*N=8^*8$. This remapping procedure is superior to the piecewise bilinear interpolation which requires high resolution auxiliary grids, especially near the edge of the image in the off-nadir viewing region. In addition, for sensors where the scan lines are circular (conical scanners), the present remapping procedure is again superior when compared with linear methods.

IMAGE NAVIGATION USING INTERPOLATION

Now, with our remapped image data, we are ready to navigate the image by rectifying it with the desired map projection. This rectification can be separated into three steps:

Step 1: The geometric transformation from the output plane (desired map locations) to the input plane (the remapped satellite image), Step 2: image data input and selection, and

Step 3: assembly and calibration of the output image.

The first step can be further broken into two procedures, the first of which is calculating the array of nearest scan line numbers for the output map using the above interpolation techniques; the second step amounts to finding the sequence of pixel numbers for the nearest along-scan locations.

As an example, consider the array shown here in Figure 3 which relates the nine output pixels to the appropriate input pixels using the nearest neighbor interpolation assignment. The selection of values in this array is essentially arbitrary, and the only limitation on matrix values is that they must be between 1 and 6 for the input array shown in Figure 2a. Note here that we have corrected for both Earth curvature and rotation as indicated by the skewed arrangement of the input pixels on the output matrix. The (x, y) values shown in Figure 3 are the a's and b's computed from the biquadratic resampling. Thus, rather than navigating every line and pixel location, we have reduced the computation to a definite matrix of locations. The second and third steps in this procedure are concerned with the bookkeeping that selects the input data for transform to the output image.

This rectification procedure can be generalized to simultaneously navigate all of the AVHRR channels at the same time rather than to do each channel separately. Obviously, by doing all of the channels at the same time, the memory requirements for the transformation increase significantly to be able to store the scan line and pixel location arrays. One can take advantage of the fact that the steps follow sequentially and memory used at a early stage can be released and used for subsequent computations.

SAMPLE APPLICATION

In order to demonstrate the effects of the AVHRR image navigation techniques discussed above, we present here an unnavigated AVHRR image of the U.S. west coast in Figure 4. The data were collected from a direct readout station at the University of British Columbia in Vancouver, B.C. In Figure 4, we have added the appropriate map with coastal boundaries as well as the individual state boundaries for reference. The distortions of the image are clearly displayed by the lack of correspondence between the satellite image and the reference map grid. Both the effects of Earth curvature and Earth rotation are clearly exhibited by this comparison.

Using the elliptical model to locate the center point of this image, we then applied the circular orbit approximation to a spherical Earth to produce the navigated image in Figure 5. Here there continues to be an offset along the center of the image (nadir track) which is due to the lack of accurate time at the receiving site. This is corrected for with a "nudge" along the track line to bring the coastal boundary into agreement with the image.

A slight improvement in pixel location is possible by using a fully elliptical model for the entire navigation calculation, as we mentioned earlier. The navigated results of the fully elliptical computation are shown here in Figure 6, which looks very sim-



FIG. 3. Relationship between output image and input pixel locations for Figure 2.



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 $\mathsf{F}_{\mathsf{IG.}}$ 4. Unnavigated image of the U.S. West Coast. Note distortions from map overlay.

FIG. 6. Navigated and nudged version of Figure 4 using the fully elliptical orbit model.





FIG. 7. Difference image between Figures 5 and 6.

FIG. 5. Navigated version of Figure 4 using the elliptical orbit to locate the image center and a locally circular assumption to compute the image rectification.

ilar to Figure 5. Both of these computations utilized the memory management scheme outlined in the sections on interpolation. Earlier computations, which did not take advantage of this time saving technique, produced very similar results in terms of the accuracy of the navigation. As reported in Emery and Ikeda (1984), navigation accuracies of about 1.5 km (approximately 1 pixel) are regularly possible with these techniques.

To display the differences between these two navigation strategies, the elliptical image in Figure 6 was subtracted from the locally-circular image in Figure 5, as shown here in Figure 7. Due to the use of the elliptical model to locate the image center in Figure 5, the differences are greatest in the four image corners. To quantify this location, offset windowed cross correlations were computed between Figure 5 and 6 and the results are presented here in terms of pixel offset in Figure 8. Maximum offsets are a few pixels, with the average being about 3 pixels.

RECOMMENDATIONS

One of the primary purposes for writing this review paper was to bring together information on the presently used techniques for AVHRR image navigation and to recommend to potential users the approach they might take. Clearly, it is no longer necessary to reinvent these procedures as the software can be acquired from a variety of sources. Thus, new users of AVHRR data should make contact with those active in the processing of these data who can provide guidance and expertise, along with software, to carry out the important processing steps, including that of image navigation.

Specific recommendations depend on the level of capability of the user and his/her respective needs in terms of processing. While it is not difficult to arrange for the reception of some form of NOAA ephemeris data, not all users may have opportunities to establish a link to these data. In that case, they may opt for the navigation of AVHRR images using the nominal orbital parameter values for the appropriate NOAA satellite and perhaps correcting the resultant imagery to a single or set of recognizable GCPs. While this is time consuming, it may be the only image navigation method available to some users of these data.

If at all possible, the AVHRR image analyst should locate and acquire the NOAA satellite ephemeris data for the period in question. A number of sources of these data merit mention at this point. First, there are the NOAA TBUS messages which are put out daily by NOAA, the same agency that operates the satellites. These messages are the ephermeris data generated by an orbital model, corrected primarily with satellite tracking information provided by NORAD. These ephemeris messages come in the form of a three-day predict and are valid at least for a couple of days. Another potential source of these data is the U.S. Naval satellite tracking facility called NAVSPASUR. They integrate a set of U.S. satellite tracking station data with those from a global military network of tracking stations and use these tracking data, along with an orbital model, to generate these ephemeris data.

The "navy model" is slightly more accurate than the model used for the TBUS messages and is very similar to the model used by the French data collection system called ARGOS. The ARGOS system uses the Doppler shift of Earth-based radian transmitters to accurately locate these radio beacons on the Earth. This system therefore requires a very accurate orbital model to determine precisely the location of the Earth platform at the time of radio reception. It is this orbital model that we have actually used in the computations that produced Figures 5 and 6. This model is almost identical to the U.S. Navy model, which also has a requirement for very high accuracy because they are tracking operational navigation satellites as well. These Navy data can only be acquired if the group is in some way supported by the U.S. Navy. Any investigator with funding from the U.S. Office of Naval Research (ONR) can have his project monitor make a written request to NAVSPASUR who will provide the data for him. These data can be received in the mail or by telex. The latter has the advantage that it is then in digital format and can thus be easily used in image navigation computations. NOAA/ TBUS data are also available on line as they are regularly broad-





FIG. 8. Pixel displacements between Figures 5 and 6.

ψ

R,

S

 T_0

 $t_{1/2}$

t_f

t,

t*

 θ

 θ_1^*

 θ_1

V

 V_s

t

cast over the normal weather circuits. Most people don't even know about the existence of these TBUS messages because they are not often concerned with operating a NOAA ground station.

CONCLUSIONS

NOAA AVHRR images must be navigated to correct for the effects of Earth curvature and Earth rotation by using the nominal satellite orbital parameters (when the satellite was first launched) and correcting the resultant navigated images for offsets between the image and well identified Ground Control Points. An alternative approach is to acquire accurate satellite ephemeris data and to use these data to allow image navigation with a fully elliptical model. With these corrections, it is possible to achieve image navigation accuracies of about 1.0 to 1.5 km.

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APPENDIX A. SYMBOL NOTATION

- = semi major orbital axis a
- Angle formed by the arc from the pixel to the ascend-= α_{c} ing node and the equatorial plane (rad)
- Angle from ascending node to the pixel (rad) β =
- δ Off-nadir viewing angle (rad)
- Scan step angle (rad) δ_i =
- Ď Position at the end of the scan line =
- Orbital eccentricity e_0 =
 - =
- $\gamma h i_s i_s j$ Satellite altitude (km) =
 - Orbital inclination angle (degrees) =
 - Counters in image arrays =
- Earth oblateness coefficient (0.00108263) J_2 =
- Longitude of equator crossing computed from T_0 , e_0 , λ_0 = and i.
- $\lambda_{\rm D}$ Geographic Earth longitude (degrees) =
- Static Earth longitude (rad) $\lambda_{D'}$ =
- Nodal longitude or longitude of equator crossing (de-= λ_e grees)
- Mean anomaly M_0 =
- = Mean orbital motion M_1
- = Equivalent mean orbital motion M_1
- = Orbital decay rate M_2
- = Earth gravitational constant ($3.98603 \times 10^{14} \text{ m}^3 \text{s}^{-2}$) μ
- Argument of perigee ω =
- Daily average orbit-to-orbit fluctuation in ω $\Delta \omega$ =
- ϕ_D Geographic Earth latitude (degrees)
- $\phi_{D'}$ Static Earth latitude (rad)

- Arc between the viewing pixel and the subsatellite point (rad)
- Earth radius (6,378,160 m) =
- Subsatellite point =
- Epoch (midnight GMT) =
- Time from the ascending node (equator crossing, s) =
- Half scan line time (s) =
- Time of first scan line (s) =
- Nodal time or time of equator crossing (s) =
- Time of image center (s) =
- Geocentric angle from the ascending node to the subsatellite point (rad)
- Latitude of image center (rad) =
- Geocentric latitude of nadir on the scan line of interest = (degrees)
 - Earth angular velocity (rad/s) =
- Satellite angular velocity (m/s)

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