SLAR Mosaics for Project RADAM

Semi-controlled mosaics made with side-looking radar imagery comprise one of the mapping products of the Amazon and the Brazilian Northeast.

(Abstract on next page)

INTRODUCTION

Until the organization of Project RADAM (for Radar Amazon) in October 1970, the Brazilian Amazon Basin was one of the largest poorly mapped areas in the world. At that time, however, the Brazilian government decided to undertake a reconnaissance survey of the Amazon and the adjacent Brazilian Northeast in a most unconventional manner, namely, by executing the largest commercial side-looking radar (SLAR) remote-sensing project ever undertaken.

The major objective was to collect information on mineral resources, soils, vegetation, and land use; a minor objective was to obtain a standard map product with a certain geometric accuracy.

To date, the minor objective has almost been accomplished: 160 semi-controlled SLAR mosaic sheets have been released for public use. Each mosaic sheet covers a rectangular area of 1 degree latitudinally by 1.5 degrees longitudinally. Preliminary checks have indicated that the geometric accuracy of each sheet and of the overall mosaic can be expected to be well within the contractual requirements, which will be described presently.

Mapping such an extensive area in such a short period required an unconventional
mapping tool, for which only SLAR qualified because of its capability to penetrate clouds. Indeed, the pay-off has been proportional to the high risk taken in the use of a commercially unproven mapping device, to the effect that a good set of reconnaissance maps is now available for all of Brazil north of the 8°S parallel.

In this paper we shall briefly discuss the background of Project RADAM (de Azevedo, 1971) as well as the contractual requirements and the project instrumentation, and we shall then consider in somewhat more detail the specific SLAR geometry, ground control considerations, semi-controlled mosaic compilation and accuracy evaluation.

**PROJECT RADAM**

The project is supported mainly by the Brazilian Ministry of Mines and Energy. The initial plan covered an area of about 1,500,000 km², but the project was gradually extended to cover approximately 4,600,000 km². This extension was made possible by the successful performance of the system. The project area is shown in Figure 1.

For acquisition and processing of the radar imagery and related remotely sensed data, a contract was signed with two associated enterprises: LASA Engenharia e Pesquisas S. A. and Aero Service Corporation. Aero Service’s role was mainly to obtain the radar imagery, whereas LASA provided logistical planning, executed the ground survey and assembled the radar images into mosaics.

Earth Satellite Corporation was contracted by the Brazilian Government to select and evaluate proposals made by qualified contractors, to provide the contractual and technical specifications for the project, and to advise Project RADAM on matters of quality control and imagery interpretation.

**ABSTRACT:** Semi-controlled SLAR mosaics covering most of Northern Brazil (more than 4,500,000 km²) are being compiled as a part of Project RADAM of the Brazilian Ministry of Mines and Energy. These mosaics represent the first large-scale commercial effort to manufacture maps from SLAR imagery. A special combination of SLAR instrumentation and airborne and ground navigation equipment is used for the project, creating special metric problems with respect to ground control, flight configuration mosaic compilation and accuracy estimation.

**IMAGE QUALITY**

- Dynamic range 20 dB; resolution 16 M.

**GEOMETRIC FIDELITY OF IMAGE STRIPS**

- Along-track and across-track scales uniform within 1 percent.

**GEOMETRIC FIDELITY OF SEMI-CONTROLLED MOSAICS**

- Cumulative scale discrepancy in any direction not to exceed 1 km.
- Angular distortion not to exceed 10 mrad within any one swatch.
- Image sidelap average 25 percent but not to be less than 10 percent at any point.
- Corner positions of each mosaic to be accurate to within 1 km with probability of 95 percent and to within 0.5 km with probability of 50 percent.
- Tic mark grid orientation to be correct within 10 mrad.

**INSTRUMENTATION AND OPERATION**

RADAM flights were spaced 15 min of arc apart and were generally flown North-South. The flight spacing provided 25 percent sidelap for the radar strips and 8 percent sidelap for concurrently obtained infrared
photographs which were taken with 66 percent forward overlap. For the initial area all flights were tracked with SHORAN. For the add-on areas, a new and less expensive ground configuration was adopted for which only East-West tie lines were tracked with SHORAN. Figure 1 shows the extent of the initial and the add-on areas, as well as the configuration of ground control points.

The remote-sensing platform was a twin-jet Caravelle flying at an altitude of 12 km with a speed of approximately 690 km/hour. On board were the following remote sensing and navigation devices:

- Side-looking radar—Goodyear Mapping System 1000 (GEMS). Optically correlated, coherent, and focused beam. Ground range presentation. Operational parameters—scale 1:400,000, ground range delay 11 km, ground sweep 37 km, swath overlap 25 percent.
- Video tape system—3 cameras Javelin SC-950 with Sony videotape recorders.
- Inertial guidance platforms—2 Litton LTN-51 systems, indicating present position, attitude, heading, drift angle, and ground velocity.
- Radar altimeter—Stewart Warner APN/195. Accuracy ± 50 m.
- Barometric differential altimeter—Rosemount 803C.
- SHORAN master station—RCA APN-84.
- Digital data handling equipment—Lancer digital data system, Kenedy tape recorder, Monroe datalog printer.

The digital-data system integrates the inertial velocity signal and triggers the cameras and the fiducial marks on the SLAR imagery for every 10 kilometers. On digital tape are recorded the SHORAN ranges, the LTN-51 outputs, the radar altimeter outputs and the time, one record per km.

To provide ground support for the SHORAN system, accurate point positions for 45 ground points were determined using TRANSIT satellite locating equipment. The Magnavox MX-702 provides coordinates accurate to within ± 15 meters. A few observations were on points of known coordinates adjusted to the Brazilian Corrego Allegre datum (Hiran points). The discrepancies due to the differ-
ences between the Brazilian and satellite ellipsoids were almost constant, namely, 1 second for latitude and 3 seconds for longitude (da Rocha, 1971).

The SHoran system was not used in the usual manner, namely for the determination of base distances between ground stations, but instead the recorded ranges to two ground stations with known coordinates were used to intersect the air-station positions.

Logistics plans called for the operation of four SHoran transponders at a time so that one spare transponder was always available. Considering that a great number of ground stations were located in uninhabited regions, and that flight operations were almost continuous, the small amount of untracked flight lines (16 percent) indicates a high performance level of the SHoran system and its operating crew.

In all, 300 flight missions were made, accounting for a total of 1,500 hours of flight time.

**SLAR Geometry**

It was the task of the Apoio Técnico team to monitor the quality and geometric fidelity of the incoming images and also to advise on the implementation of mosaic compilation methods. To accomplish this task, the members and advisors of the team had to gain some insight in the relevant SLAR geometry.

For the purpose of controlled mosaic construction two types of control points were specified in the contract. The primary geopoint (G1 point) was mainly a point determined by the TRANSIT equipment. The secondary geopoint (G2 point) was specified as any radargrammetrically or photogrammetrically derived point. For the semi-controlled mosaic (henceforth referred to as MSC) radargrammetric G2 points proved to be of prime importance as the image strips were matched at the G2 points with the plotted positions of these points.

Analytically, G2-point coordinates can be computed from the known slant range and the air station coordinates. Air station coordinates can in turn be computed from the recorded SHoran ranges.

In Figure 2 the antenna axis system X', Y', Z' is at the air station C, whose coordinates X', Y', Z, are expressed in the XYZ-system. The slant range from C to P is r. As many authors (Leberl, 1970; Rosenfield, 1968; Konecny, 1970) have indicated before, the slant range can be considered as the radius of a sphere with the equation:

\[(X-X_c)^2 + (Y-Y_c)^2 + (Z-Z_c)^2 = r^2. \quad (1)\]

At the same time the slant range \(r\) is situated in the \(X'Z'\)-plane for which we can write the following equation:

\[A'(X - X_c) + B'(Y - Y_c) + C'(Z - Z_c) = 0 \quad (2)\]

where

\[A' = \sin \kappa \cos \phi + \sin \phi \cos \kappa \sin \omega,\]

\[B' = \cos \kappa \cos \omega\]

\[C' = -\sin \phi \sin \kappa + \cos \kappa \sin \omega \cos \phi\]

with \(\kappa, \phi, \text{ and } \omega\) representing the yaw*, roll and pitch angles, respectively, of the antenna pod.

If we assume that \(Z_c\) is the flying height above the plane in which \(P\) is situated, then \(Z = 0\), so that Equations 1 and 2 reduce to two equations with two unknowns, from which we can solve for \(X\) and \(Y\), namely

\[X = A'C'Z_c \pm B'.\]

and by permuting \(A'\) and \(B'\) in Equation 3 we obtain the expression for \(Y\). Considering the look direction, there is no difficulty in identifying the proper solution.

Formula 3 and its \(Y\) equivalent can be used to handle any orientation of the antenna pod. However, recorded antenna pod orientation parameters were not available for Project RADAM, even though the orientation param-
eters of the aircraft were recorded on magnetic tape. Unfortunately, these parameters could not be used as the antenna pod had an independent motion compensation system (drift angles of as much as $6^\circ$ could be accounted for by orienting the antenna in the direction of zero Doppler shift). Thus, for Project RADAM, Equation 3 and its Y equivalent could be simplified for general flight directions by assuming zero pitch and roll, so that $\lambda' = \sin \kappa$, $B' = \cos \kappa$, and $C' = 0$, yielding $X = G \cos \kappa + X_c$ and $Y = -G \sin \kappa + Y_c$, where $G$ represents the ground range ($G = (r^2 - Z_e^2)^{1/2}$). A further simplification could even be made for north-south flights for which $\kappa$ can be assumed equal to zero, so that $X = G + X_c$ and $Y = Y_c$.

Incidentally, this same solution is obtained for $\kappa = 0^\circ$, $\phi = 0^\circ$, but $\phi \neq 0^\circ$, as can be seen from the expression for the orientation matrix elements and Equation 3 and its Y equivalent. Thus, for small yaw and pitch angles, roll can be neglected and this is logical as the position in the Y plane is determined by the radar system in the time domain.

For the USC compilation, the $X = G + X_c$ equation was simply implemented by offsetting the ground range from the plotted air station perpendicular to the flight path.

After correlation, seven slant range marks are visible at every 10-km fiducial on the radar film. The time delay for each range mark can be calculated from, the fact that there is a 30.88 microsecond increment for each pulse. Then, knowing the speed of light and the atmospheric refractive index, accurate slant ranges can be determined from the time delays. The slant ranges in turn can be converted to ground ranges reflecting the height of the aircraft. The seventh slant range mark in the far range channel was selected for the computation of G2 points. They were generally spaced 50 km apart both in the along-track and across-track direction.

Throughout the course of the image acquisition phase there was a concern for the consistency of along-track and across-track scale. In the initial contract a clause was included calling for daily overflight of a geometric test area. As work began, however, it soon became apparent that it would be more feasible to fly a series of east-west (E-W) tie lines (not to be confused with the aircraft controlled tie lines for the add-on areas). Such lines were flown and served a two-fold purpose, namely, to provide insurance against a total collapse of the ground-control system and to facilitate transversal scale checking of the north-south (N-S) lines. The E-W tie lines in the original area were flown over identifiable ground stations, so that their along-track scale could readily be computed and used to evaluate the across-track scale of the N-S lines.

Under the flat-ground assumption, however, we discovered that there exists a simple method to compute the across-track scale directly from the recorded radar altimeter readings. Across-track scale variation mainly results from the difference between the assumed mean terrain clearance used in the slant range to ground range conversion function and the actual terrain clearance. Slant range mark spacing as a function of the assumed mean terrain clearance can be expressed as follows:

$$d_i = \frac{1}{E} \left[ (r^2_{i+1} - \bar{h}^2)^{1/2} - (r^2_i - \bar{h}^2)^{1/2} \right]$$  (4)

where $d_i$ is the distance between range marks $i$ and $i+1$, $\bar{r}$ is the assumed mean terrain clearance, $r_i$ is the slant range of range $i$, and $E$ is the representative fraction of the nominal scale (400,000). For the same distance on the ground a similar expression can be written in which the term $1/E$ is omitted and $\bar{h}$ is replaced by $h$, the actual terrain clearance. Division of the two expressions then gives the representative fraction of the actual average scale between the two marks:

$$E_x = E \frac{(r^2_{i+1} - \bar{h}^2)^{1/2} - (r^2_i - \bar{h}^2)^{1/2}}{(r^2_{i+1} - h^2)^{1/2} - (r^2_i - h^2)^{1/2}}$$  (5)

By rearranging Equation 5 and using truncated series developments, an expression can be developed in which $r_{i+1}$ has been replaced by $r_i + d_i$. Then by obtaining the limit of this expression for $d_i \to 0$, we can derive the following continuous expression for the across-track scale:

$$E(r) = \frac{8r^4 + 4r^2h^2 + 3h^4}{8r^4 + 4r^2h^2 + 3h^4}$$  (6)

Equation 6 presented in graphical form shows a series of hyperbolic curves with maximum scale distortion closest to the aircraft ground track and minimum distortion in the far range. These graphs prove to be extremely useful in assessing transversal scale variation by examining radar altimeter records. For instance, it was found for one extremely long tie line flight that the error around the mean terrain clearance was 128 m, and that a maximum deviation of 422 m occurred. Using Equation 6 we determined that this corresponded to a 1-percent scale variation in the near part of the near range and to less than 0.25-percent scale variation in the farthest part of the far range.
On mapping missions, the aircraft was always guided by an inertial guidance platform. Two Litton LTN-51 systems were on-board; one situated in the cockpit, the other system located in the middle of the plane. The two systems were interchangeable.

In the initial stages of the project, inertial platform behavior was of concern because of its effect on scale variation in the image strips. At a later stage, knowledge of this behavior became crucial in considering ground support methods for an add-on area known as RADAM North. In this area SHoran support of every strip became impractical due to the scarcity of qualifying airports in the remote northern jungle areas. Thus, a decision had to be made as to whether to continue solely with LTN-51 position data or to develop a ground support system with partial SHoran control. After the LTN-51 performance data had been considered, the latter course of action was taken and a series of East-West SHoran-controlled tie lines was flown.

We could evaluate the LTN-51 behavior in two ways. When the aircraft returned to its point of departure, the inertial positions were read from the displays and the differences between them and the starting positions were noted. These closure errors provided insight into the secular drift of the platforms. Histograms of latitude and longitude closure errors are presented in Figure 3, which were compiled from 80 flight missions of an average duration of 5 hours. Absolute values of the closure errors were used to make the histograms. Root Mean Squared Errors (RMSEs) were computed from these data, which
proved to be 1.10 minutes of arc (1.9 km) in longitude and 2.56 minutes of arc (3.4 km) in latitude. The second platform was less accurate with rmses of 2.35 and 4.60 minutes of arc (4.3 and 8.3 km) in longitude and latitude, respectively.

Perhaps due to the predominant N-S flight directions with mostly changes in latitude, LTN-51 indicated latitudes were more subject to error than longitudes. However, on the relatively predominant E-W flights larger closure errors for latitude than for longitude were also observed.

The second method to evaluate the LTN-51 behavior was to compare the platform indicated latitude and longitude with the position data computed from the recorded shoran ranges. This method provided us with a continuous evaluation of the inertial platform error over some very long flight lines.

The latitude and longitude differences for an E-W tie line are presented in Figure 4. For both graphs the abscissa indicates the position difference in minutes of arc, whereas the ordinate indicates the fiducial number. The fiducials were spaced approximately 0.8 km apart (not 1 km, due to system error). The line was about 1100 km long and accounted for about 93 minutes of flight time. It was flown in the southeastern part of the original radam area with the plane taking off from Belem and landing in Fortaleza. Inspection of the curves shows the latitude error to be larger than the longitude error most of the time, consistent with the closure errors of this flight and the data of the closure error histograms.

An important feature of the error curves of Figure 4 is the periodicity of the position errors. This phenomenon is sometimes referred to as the Schuler period. The periodicity is caused by initial misalignment of the platform and is further a result of the complexities of unscrambling the acceleration in spherical coordinates on a rotating earth while accounting for the earth's nonsphericity and gravitational variations.

In its oscillating state the platform seems to behave much like a Foucault pendulum (Broxmeier, 1964). The period of oscillation in the plane of oscillation is \( T = \frac{2\pi}{\Omega \sin \lambda} \), where \( \Omega \) is the rate of rotation of the earth axis and \( \lambda \) is the latitude. If the pendulum is observed with respect to a geographic reference system, the projection of its oscillations on the \( x \) and \( y \) axes will have the appearance of beat waves with the period \( S = \frac{2\pi R g}{4 \pi R g} \approx 84 \text{ min} \), where \( R \) is the earth radius and \( g \) is the gravitational constant. The same period is also the predominant period in the error curves of Figure 4. (The Foucault period is much larger than 5 hrs.)

Brown has suggested the following error model to describe the error curves:

\[
s(t) = a_0 + a_1 t + a_2 \sin \frac{2\pi t}{5} + a_3 \cos \frac{2\pi t}{5}
\]

(7)

where \( s(t) \) represents the latitudinal or longitudinal error as a function of flight time. In Table 1 the least squares fitted coefficients of Equation 7 are listed as computed from the data of Figure 4.

Time \( t = 0 \) was assumed at the beginning of the curves of Figure 4 at fiducial 110 and the units of the fitted data were minutes of arc.

A significant spin-off of the evaluation of the Schuler-periodic error curves was that we could estimate the accuracy of the shoran system. The random variation exhibited in the error curves of Figure 5 is due to shoran operator error, atmospheric conditions and ground station geometry. Theoretically, it would be difficult to propagate all the error sources through the complicated procedure used to derive the air station coordinates. However, the knowledge that the error curves should be smooth, as there are no high frequency oscillations in the platform, provided us with the unique opportunity to estimate the combined shoran errors. The estimated standard deviations of latitude and longitude computed from the fitting of Equation 7 were 236 and 138 meters, respectively. These numbers are very good estimates for the accuracy of the computed air station coordinates.

The Schuler-period error curves became further important in the course of the project, as the Apoio Técnico team could use them as a device to trace errors in the shoran computations due to faulty programming, errors in ground station coordinates, tracking, etc. Three different ground station combinations were used for the flight of Figure 4, as indicated by the Roman numerals, yet no jumps in the error curves can be detected.
indicating good computational results (a part of the curves is missing due to shoran failure). The model of Equation 7 might even be used to smooth the computed air station coordinates. Such a procedure and its potential benefits are outlined in “Geometric Evaluation of Radar Mosaics” (van Roessel, 1972).

**Semi-Controlled Mosaic Compilation**

Initially, mosaic compilation was begun with the manufacture of uncontrolled mosaics. At a later stage MSC compilation was started and at that time it became an important responsibility of the Apoio Técnico team to monitor and advise on compilation methods.

**Mosaic Compilation with Full Shoran Control**

The first step in the MSC production is the establishment of a geometric base by computing the coordinates of the G2 points to be plotted on a stable base overlay. The procedure begins with the processing of a paper tape, produced by the transit equipment, containing satellite range information from approximately 20 satellite passes. Computer processing of this tape provides the coordinates of the shoran ground stations. Also, the magnetic tape with the data logged in the aircraft is cleaned up and standardized. The standardized tape is used as input to the shoran program together with the ground station coordinates; then, geographic and utm coordinates are computed for air stations 10 km apart along the flight line.

The air stations are plotted on a stable base overlay at a scale slightly larger than the final mosaic (1:200,000) with the help of an invar grid plate and a small coordinograph. The G2 points are then plotted by off-setting their ground range from the plotted air stations, perpendicular to the flight track, as judged from adjacent air stations. The ground range to the G2 points used for off-setting is pre-computed as a function of the mean terrain clearance.

The actual mosaic compilation is then begun. Based on the overlay, overlapping pieces of the same radar strip negative are enlarged through an anamorphic lens. This lens is capable of differential enlargement in two orthogonal directions. However, only the along-track scale is adjusted whereas the across-track scale is left unchanged. An analysis of across-track scale variation based on radar altimeter data and using Equation 6 convinced us that this practice (at least in the eastern part of the original area) would not cause across-track scale errors outside of the contractual specifications. This was especially true considering that 25 percent of the near range, where across-track scale distortions are most significant, was not used for the mosaic compilation.

The prepared copies of the radar strips are assembled on a piece of Masonite hardboard. The strips are glued down and when the glue has dried they are inspected to see that linear features such as roads and rivers are continuous and that the G2 points coincide with their plotted positions on the overlay. The Masonite boards cover 1.5 degrees in longitude (one mosaic width) and up to 8 to 10 degrees in latitude. The breakaway method is used to provide continuity from column to column. After the mosaic column has been inspected for image quality and general assemblage, individual mosaics are cut from the column. These are annotated with place names and tic marks and are then copied onto a negative at a scale of 1:250,000. This negative is joined with a standard border to form the final negative from which the final mosaic copies are made.

As an example of the final product, a portion of semi-controlled mosaic in the vicinity of the city of Manaus, is shown in the Fronispiece.

**Mosaic Compilation with Partial Shoran Control**

Outside the original area, only shoran-controlled tie lines were available to produce mscs. In this instance, the tie lines are glued down on the masonite board with the help of the tie line G2 points which are similarly plotted on an overlay. A study of the tie-line intersections with a selected number of N-S lines is then made and the along-track scale of these N-S lines is then adjusted piece by piece, such that the E-W and N-S images will coincide at the tie lines. The N-S lines are then glued down and their scale is transferred to other N-S lines. After all lines have been put into position, the tie line has become completely covered.

**Mosaic Accuracy**

Another task of the Apoio Técnico team was to evaluate the accuracy of the mosaics. For this task three potential methods were considered.

First, one could think of performing a complete theoretical error propagation, taking into consideration errors in ground station positions, errors in shoran range measurements and reduction, terrain distributions, flying altitude and attitude distributions, plotting and mosaicking errors, etc. However, there is no need to study these aspects thoroughly before deciding whether this

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method would be prohibitively complex and tedious.

The second method is one in which the coordinates of measured mosaic points are directly compared with the coordinates of ground points established by astronomical observation, TRANSIT determination, HIRAN survey, etc.

The objection against this method is that these points are often difficult to locate on the radar imagery, as they are often not marked on any kind of image. However, Project RADAM was lucky to have available a set of 16 astronomically derived points furnished by the Brazilian Navy (Diretorio de Hydrografia e Navegaçao), which were well marked on aerial photographs.

The points were identified on the radar mosaics and their coordinates were then determined by the multi-laterative method (Wolf, 1967), for which only an accurate scale is needed. Differences in Easting and Northing with the known UTM coordinates were computed. Histograms of the differences are shown in Figure 5. In all, 16 points were used, situated on the North-East coast of Brazil. A positive bias of 150 meters was present in Easting, whereas a negative bias of 133 meters was present in Northing. RMS errors were 190 and 306 meters in Northing and Easting, respectively.

One has to keep in mind that these results are obtained from a small set of points clustered in a small area and are therefore subject to small-sample variation. A third method of accuracy evaluation is available, however, part practical, part theoretical, that is applicable to larger areas.

With this method, the compilation procedure is considered step by step, with an appropriate practical or theoretical error estimation for the coordinates at the end of each step, given the coordinates of the previous step. For the msc compilation process the steps are as follows:

1. TRANSIT ground station coordinates. Some TRANSIT determined points were also part of a HIRAN triangulation net. The HIRAN coordinates could be compared with the TRANSIT coordinates and the differences could be used to provide error estimates.

2. SHORAN air-station coordinates. Random variation around the Schuler-periodic error curves of the LTN-51 platforms could be used to provide extremely good estimates of the accuracies of the SHORAN air stations, given a set of ground station coordinates.

3. G2 point coordinates. Here we could use theoretical error propagation methods using the partial derivatives of Equation 3 and its Y equivalent. The error sources used as input to the derived error equations were (a) the variation in flying height (from radar
### Table 2. Error Budget for Semi-Controlled Mosaics

<table>
<thead>
<tr>
<th>Intermediary Coordinates</th>
<th>ERMSE E</th>
<th>Bias</th>
<th>ERMSE N</th>
<th>Bias</th>
<th>Error Estimation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRANSIT coords.</td>
<td>76</td>
<td>74</td>
<td>30</td>
<td>29</td>
<td>Comparison with triangulation net.</td>
</tr>
<tr>
<td>Air station coords.</td>
<td>138</td>
<td>—</td>
<td>236</td>
<td>—</td>
<td>Use of random variation around fitted Schuler period error curve.</td>
</tr>
<tr>
<td>computed from SHORAN ranges.</td>
<td>32</td>
<td>—</td>
<td>311</td>
<td>—</td>
<td>Theoretical error propagation. Stdv flying height = 128 m; stdv azimuth = 0.4°; stdv pitch = 0.1°.</td>
</tr>
<tr>
<td>Analytically determined G2 point coords.</td>
<td>133</td>
<td>—</td>
<td>164</td>
<td>-97</td>
<td>Comparison of analytic with plotted coords.</td>
</tr>
<tr>
<td>Coords. of plotted G2 points</td>
<td>178</td>
<td>—</td>
<td>284</td>
<td>—</td>
<td>Comparison of plotted with mosaicked coords.</td>
</tr>
<tr>
<td>Estimated accuracy at the mosaicked G2 points</td>
<td>274</td>
<td>74</td>
<td>510</td>
<td>-68</td>
<td>Combining the above error estimates with (8)</td>
</tr>
<tr>
<td>Estimates from Navy points for comparison</td>
<td>(340)</td>
<td>(150)</td>
<td>(230)</td>
<td>(-132)</td>
<td></td>
</tr>
</tbody>
</table>

An error budget resulting from such a stepwise analysis made for a column of mosaics in the Eastern part of the original RADAM area is presented in Table 2.

In Table 2, ERMSE stands for Estimated Root Mean Squared Error. The ERMSE is equal to the variance plus the bias squared, so that the errors for two error sources are combined as follows:

$$\text{ERMSE}_{12} = (\text{ERMSE}_1^2 + \text{ERMSE}_2^2 + 2 \text{bias}_1 \text{bias}_2)^{1/2}. \quad (8)$$

Of course, the implicit assumption of independent error sources is present in the above process, and also errors in Easting and Northing are assumed uncorrelated. These assumptions are quite reasonable because the five steps mentioned are independent and most operations are either performed in Easting or Northing. The bias product term of
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FIG. 5. Linear scale and position adjustment of N-S lines to E-W lines; estimation of error component due to Schuler periodic variation.

Equation 8 contributed only to the overall ERMSE when all error sources have a bias term, which is not the case in Table 2. An estimate of the overall bias term is obtained simply by adding individual bias terms.

The estimates of Table 2 apply only to the G2 points. A further analysis is necessary to gain insight into the variation at other mosaic points, but at least the variation at those points is bounded by the expected values of the estimates at the G2 points.

It is interesting to compare the results of Table 2 with the analysis of the Navy points, the results of which are included in Table 2 in parentheses. The ERMSEs for Easting are in good agreement but the values for Northing differ by a factor of 2, as do the bias terms. The signs of the bias terms are in correspondence, however.

MOSAIC ACCURACY FOR AREAS WITH REDUCED SHORAN CONTROL

The above estimates are probably also valid for the G2 points on the tie lines of the area with reduced SHORAN control. However, for the N-S lines in these areas, additional inaccuracies will be present.

We debated whether the Schuler-periodic error would be a significant error source. This periodic variation causes the film scale to vary periodically and also causes a wandering terrain effect in the across-track direction. The following analysis gave us insight into the significance of the Schuler period in terms of point inaccuracy, and also provided us with criteria for E-W tie-line spacing.

A periodic error curve, to which a straight line is fitted such that it coincides with the error curve at two points, is shown in Figure 6. This adjustment is in fact what happens when the scale of the N-S line is changed by a constant and its position is changed by a simple rotation to make the strip coincide with the E-W strips at the crossing points (points A and B in Figure 9).

Let the error curve be \( s(t) \) of Equation 7. Also \( s(t_i) = s_i \) and \( s(t_{i+k}) = s_{i+k} \), where \( t_{i+k} \) and \( k \) is the flight duration from one tie line crossing to the next crossing. The distance between A and B on the straight line X is designated \( l = s_i - s_{i+k} \).

We are interested in the deviations of \( s(t) \) from X as given by the function which we will call \( q(t,t_i) \) for various positions of \( t_i \) and various values of \( k \).

The phase of the curve \( s(t) \) is randomly determined and different for every flight, so that \( t_i \) can be considered a random variable with a uniform distribution. The time \( t \) is also considered a random variable with uniform distribution as we are interested in the error along the N-S strips at randomly selected points with no preference for certain locations. Under this assumption, probabilities for \( t \) and \( t_i \) will be \( \frac{1}{S} \) and \( \frac{1}{k} \), respectively.

Then we can express the contribution to the RMSE of the position of the points in the N-S strip due to the Schuler-periodic variation as follows:

\[
RMSE_s = \left[ \frac{1}{S} \sum_{i}^{S} \int_{0}^{t_i} [q(t,t_i)]^2 dt \right]^{1/2}.
\]

The expression \( q(t,t_i) \) can easily be found by rotating from the \( X'Y' \) system to the \( XY \) system, namely:
TABLE 3. EXPECTED CONTRIBUTION TO ERMSEs FOR POINTS ON N-S STRIP FITTED BETWEEN E-W TIE LINES DUE TO SCHULER VARIATION (Flight 33)

<table>
<thead>
<tr>
<th>Contribution to ERMSE</th>
<th>Distance Between Flight Time (sec)</th>
<th>Tie Lines Distance (km)</th>
<th>(min. of arc) Lat.</th>
<th>(meters) Long.</th>
<th>(meters) Lat.</th>
<th>(meters) Long.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>96</td>
<td>0.0137</td>
<td>0.0235</td>
<td>25</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>1000</td>
<td>192</td>
<td>0.0536</td>
<td>0.0917</td>
<td>98</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>288</td>
<td>0.1155</td>
<td>0.1978</td>
<td>211</td>
<td>362</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>384</td>
<td>0.1934</td>
<td>0.3312</td>
<td>354</td>
<td>607</td>
</tr>
<tr>
<td></td>
<td>2500</td>
<td>480</td>
<td>0.2796</td>
<td>0.4787</td>
<td>512</td>
<td>877</td>
</tr>
</tbody>
</table>

\[ q(t,t_i) = \frac{1}{2} (s(t) - s(t_i)) + \frac{1}{2} (t - t_i). \quad (10) \]

The integration was performed numerically using the fitted coefficients of Table 1 for the coefficients of \( s(t) \). The results are presented in Table 3.

From Table 3 we can see that the contribution to the ERMSE increases exponentially with the tie line spacing. For Project RADAM the tie line spacing varied from 200-300 km. Combining the 1,500-sec flight time estimates (211 and 362 m) with the ERMSE values from Table 2 (upon interchanging latitude and longitude as the values apply to tie lines) we obtain values of 450 m and 550 m for latitude and longitude, respectively, as preliminary ERMSE estimates for areas with reduced SHORAN control. To obtain more realistic estimates, several other minor error sources would have to be considered but it seems that the 1 km requirement would not be violated.

To test the accuracy of the tie-line controlled areas, the Brazilian author of this paper conducted an additional test in which 46 points were measured, some of which were established with the TRANSIT satellite locating equipment. The results of the test are ERMSE of 310 and 393 meters in Easting and Northing, respectively, a slightly better result than expected from the above considerations.

**Summary and Conclusions**

Project RADAM is a project of the Brazilian Ministry of Mines and Energy. It was established with the objective to map the Amazon and the Brazilian North-East with side-looking radar.

A technical support team was formed to monitor image quality and to advise on the implementation of semi-controlled mosaic compilation methods. This team had to understand the project instrumentation, the contractual requirements and the relevant SLAR geometry, as well as the navigational methods used.

Special problems arose with respect to scale estimation, mosaic compilation techniques and mosaic accuracy evaluation. Solutions to these problems were discussed and methods used were outlined. In particular, an evaluation of the behavior of the inertial guidance platform LTN-51 was made and the results were used to specify a modified ground control system, relying on SHORAN controlled E-W tie lines. Accuracy estimates for both the full and partial control systems were made (± 200-300 m, and ± 500-600 m, respectively).

Our preliminary conclusion is that, certainly for the fully controlled area, the mosaic accuracy will be well within specifications. For the tie line controlled areas this is probably true also, but additional study is required to produce estimates based on more extensive samples.

In general, however, we can conclude that the initial requirement, namely, to produce a set of reconnaissance maps with some geometric consistency, has been more than satisfied.

**References**

3. Leberl, F., *Metric Properties of Imagery Pro-


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**New Sustaining Members**

**Aero-Metric Engineering, Inc.**

Aero-Metric Engineering, Inc., was founded in 1969 to provide complete photogrammetric services to the engineering profession. In the first two years, production was mainly concentrated on producing large-scale topographic maps. The corporation has grown to its present staff of 38 professional and technical photogrammetric personnel. Aero-Metric Engineering currently has its operations and production in Sheboygan, Wisconsin in a completely new and modern plant and office building. The Photogrammetric Engineering Department is equipped with first-order Stereometrographs, second-order Topocarts and Jena Orthophot Systems. In addition, we use the Wild PUG point transfer device. Data processing and computations are performed with an in-house IBM 1130 System, and Auto-Trol Digitizer.

Photo laboratory production utilizes the Durst V-184 Color Enlarger and Brown Copy Camera. Aero-Metric performs all mapping utilizing color photography. The LogEtronic Printer and Kodak Color Enlarger, in addition the LogEtronic Strip Printer, round out the photo lab equipment.

Aero-Metric Engineering also performs land surveying and sub-division planning in addition to photogrammetric control utilizing the latest in survey instruments and E.D.M. equipment.

The area of operations has increased to cover most parts of the United States with a heavy emphasis on State and Federal Mapping Programs.

**DICOMED Corporation**

DICOMED Corporation manufactures a complete line of digital equipment for use in computer-based image processing systems. The product line includes digitizers for converting photographic film images to computer-compatible images, and digital film recorders for converting digital image data to high-quality color (and black-&-white) film images. Other products include digital tape units, computer interfaces and channel expanders to facilitate the interconnection of DICOMED peripherals with a wide variety of computers and to provide modular flexibility in system configurations. DICOMED also maintains a well-equipped Data Services operation for converting film images to computer mag-tape and also for converting mag-tape to color or black-&-white film images.

In addition to its standard product line, DICOMED develops and supplies specialized digital image peripherals to original equipment manufacturers of various systems.

DICOMED maintains a well-staffed Customer Service Department for close support in field maintenance and, in addition, offers training courses in the operation and routine maintenance of its standard equipment. Demonstrations of standard peripherals are conducted by appointment at the Corporate headquarters in Minneapolis, Minnesota.