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3.7 REPORT OF THE SUBPANEL ON ERROR CHARACTERIZATION AND ERROR BUDGETS

The subpanel on error characterization and error budgets met in two sessions during November 18 and 19, 1982. The panel consisted of:

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Mr. Charles J. Finley NASA Headquarters	Mr. Eric Beyer General Electric
Dr. Joseph L. Bishop NASA Headquarters	Mr. William Piotrowski NASA Headquarters
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The ultimate objective of this end-to-end error analysis program is to maximize the utility of the data to the user by minimizing the overall positioning error in a cost effective manner. For existing land remote sensing systems, such as Landsat-D, this implies measuring and isolating the key components of error in order to predict errors in inferred output variables, and to modify, if necessary, mission operations and ground processing procedures. For future systems, such as possible multisensor multiresource missions, error analysis starts by modeling and predicting the key error sources and sensitivity in systems performance for specific products in order to assist in the design, fabrication and trade-off phases. The methodology for this error analysis must be in place during the study phase of future systems in order to fully examine both hardware and software approaches to meeting requirements.

The report is organized into two sections. The first reviews our current state of knowledge of both user positioning requirements and error models of current and proposed satellite systems. The second section gives a broad outline of the subpanel recommendations. In addition, there are two appendices. Appendix A details the implications of an assumption that a strawman 1:24,000 scale mapping requirement might be the critical driver for an operational land observing system. Appendix B is a listing of subpanel members.

3.7.1 State of Knowledge

3.7.1.1 User Requirements

Analysis of extensive user surveys on spatial and spectral requirements for an operational land observing system have recently been completed (Barker et al.

1980). There is little if any information in these surveys to quantitatively justify any specific positioning requirement. This is an indication of the need to provide for iterative interaction with informed technical and professional users since a significant mapping requirement was not anticipated. Furthermore, the majority of potential users of map quality digital imagery would not have been surveyed because neither they nor the surveyers recognized the applicability of satellite data to mapping. There were consistent requirements for 2-m data for foresters and others in the USDA. These requirements are about the same size as those needed to meet the most important mapping requirement of 1:24,000 (Barker, 1980) which was identified in a separate initial study of mapping requirements. Informal queries on foreign maps indicate that a scale of 1:50,000 is probably the one most generally used. Actual requirements for mapping from future sensors are part of an ongoing study under the ELOS activities at Goddard Space Flight Center (ERIM, 1981). Appendix 3.7.A details the implied requirements for a strawman 1:24,000 scale map.

3.7.1.2 Generic Error Source Modeling

Spacecraft systems need accurate characterization for error budget development to accuracies commensurate with cartography to NMA standards at 1:24,000 scale. Analytic orbit propagators are not yet adequate to meet the need. Assuming a minimal use of ground control points in the image registration process, the accuracy standards delineated in the following paragraphs must be met.

Ephemeris measurement capability commensurate with GPS capability (10-m position) is essential for geodetic positioning adequate to satisfy the stated user need. The operational processing of GSTDN (Goddard Space Tracking and Data Network) data and the projected processing of TDRSS data do not provide these accuracies.

Knowledge and/or control of platform dynamics to better than 0.001 deg pointing accuracy and 10^{-6} deg/s pointing stability is needed for adequate geodetic position accuracy. Landsat-D pointing control with 0.01 deg pointing control and 10^{-4} deg/s stability represents the present state of the art for nadir oriented platforms.

Sensor dynamics have been modeled to a significant extent for the scanning type instruments as discussed below under "Existing Geometric Error Analysis Models for Landsat-D".

MLA and SAR do not present any obvious dynamics problems and no significant analyses have been done to date. However, the need for continuous alignments to a few arc seconds do not allow ruling out the need for such analyses. Also, pointable imagers such as may characterize an OLOS will certainly necessitate analyses with regard to pointing dynamics and view angle aberrations. Preliminary effects of view angle are indicated by Driver (1982).

Error sources not subject to control such as earth rotation, curvature, and topographic variability have significant impact on potential geodetic position accuracy and must be modeled and compensated for error minimization.

Surface velocity and image configuration on a rotating triaxial ellipsoid must be modeled and analyzed and methods sought for error minimization.

Ground control pattern utilization is common for obtaining high-accuracy geodetic position. However, this is a costly and slow method for image registration and rapidly becomes untenable for rapid repeat coverage on a global scale, particularly for inadequate a priori estimate of geodetic position. Furthermore, adequate ground control does not exist in many parts of the world. Tentative error-compensation options have been advanced for the major sources (Driver, 1982). Significant work is needed to determine the feasibility of such compensation options or others which will enable acquisition of images with inherently accurate geodetic position on a global scale. The projected 5-10 year time scale for the development of a TM GCP (Ground Control Point) library indicates that future sensor systems of high spatial resolution must place a greatly reduced reliance on GCPs.

3.7.1.3 Existing Geometric Error Analysis Models for Landsat-D

A number of error analysis models and simulations currently exist for the Landsat-D TM image processing. These techniques can be categorized into TM sensor, attitude measurement, attitude control, spacecraft structural dynamics, Systematic Correction Data Generation, and control point error dynamics.

The TM sensor models include a dynamic simulation of the TM scan mirror assembly (including open loop and closed loop structural interaction effects), a scan line corrector dynamic simulation, and a TM optical model which categorizes off-axis pointing of each detector as a function of detector location and optical misalignments.

The attitude measurement models include jitter response (above 0.01 Hz) and models of the Attitude Control DRIRU (gyro.) and the angular Displacement Sensors (ADS). These models are incorporated into a simulation which imparts attitude motion into the sensors, processes the data through prototype Attitude Data Processing software and evaluates the accuracies of the processing system. This simulation is used to determine the effects of DRIRU or ADS calibration error on overall system performance.

The attitude control model is a detailed simulation of the Attitude Control System and low-frequency (less than 7-Hz) structural dynamics. Included in this simulation are effects of the solar array drive and TDRSS antenna drive. This model has been used to estimate the attitude control pointing accuracy and the low-frequency spacecraft jitter.

The structural dynamics model is a detailed NASTRAN model of the Landsat-D spacecraft from which modal analysis is performed. This model has been verified by performing component modal tests of the TDRSS Antenna and boom, the solar array, the Instrument Module Center body (including TM and MSS Mass Simulators), and Multimission Spacecraft. This model is used to predict on orbit high-frequency (greater than or equal to 7-Hz) jitter caused by the TM and MSS mirror impacts.

The accuracy of Systematic Correction Data Generation is tested by comparing the outputs of prototype software to those of a high precision earth look point and map projection models.

The control point error dynamics analysis includes an 18-state covariance analysis and a detailed simulation of control point location errors (this simulation is currently in development). The covariance analysis and simulation include dynamic error models for ephemeris, alignment, and low-frequency attitude. The covariance analysis has been used for system studies to determine processing feasibility and the simulation will be used to test the operational control point processing software.

In addition to the above error analysis, the effects of gap resampling have been studied using simulated TM edge responses and small sections of analytically generated TM imagery. The entire resampling processing has been developed in a prototype software simulation which includes a bit-by-bit emulation of the resampling hardware.

It must be noted that these analysis models and simulations are not currently deliverable software packages. They are analysis tools used by General Electric to design and analyze the TM processing system.

3.7.2 Recommendations For Position Error Modeling Research

Four specific recommendations were made by the panel in the limited time they had to collectively discuss the issues. These are summarized below and are discussed in more detail in Sections 2.1 thru 2.4. In addition, a very preliminary assessment was made by several of the panel members of the resources that may be required to carry out the recommended research. Due to lack of time at the workshop, the full panel was not able to be consulted onto the required resources.

The recommendations are:

1. Obtain and evaluate the existing error models for Landsat-D/TM (see Section 2.1 for discussion). Expected resources required: \$0.5M over 3 years with 5 MY civil service.

2. Provide iterative user involvement in system error budgeting and error model development and verification on real and synthetic data sets (see Section 2.2 for discussion). Expected resources required: \$2.0M over 5 years with 20 MY civil service.

3. Develop error models for future system definition and trade-off studies on: a) sensors (MLA Advanced scanner SAR) b) spacecraft/shuttle c) processing/information (see Section 2.3 for discussion). Expected resources required: \$0.5M over 3 years with 5 MY civil service.

4. Create a Positioning Error Budget Study Group (see Section 2.4 for discussion) Expected resources required: \$0.1M over 5 years with 2 MY civil service.

3.7.2.1 Needed Geometric Error Analysis Model for TM

A number of potential error models may be needed to more fully characterize TM sensor and processing errors. These include:

- A TM dynamic structural model to evaluate the critical rigid body assumption between the ADS mounting location and the TM optical axis.

- Effects of topological variation resulting from the orbit and attitude control on the Landsat-D geodetic and temporal registration accuracies. Examination of the feasibility and desirability of developing and appending a quantitative measure of topographic variability within a TM scene as a direct or surrogate estimate of misplacement of pixels within the scene due to topography.

- Analyses of the correlation location accuracy which can be expected from TM resolution imagery.

RECOMMENDATION - Obtain and evaluate the existing TM processing error models. This may require upgrades of the software documentation to deliverable status.

3.7.2.2 Create Interactive User Involvement In System Error Budgeting and Modeling and Verification on Real Data Sets

User "requirements" have been solicited from a variety of users, generally without consideration of costs of obtaining them, without verbalized consideration of any losses in utility if they are not met, and without verbalized consideration of parameter tradeoffs. This prevents the system engineer or scientist from being able to iterate potential system designs with the users.

To solve this problem, it is recommended that specific efforts be planned to involve the users iteratively in the generic development of error budget methodology prior to and during the mission designs.

One possible mechanism for facilitating cooperative involvement of the user and system engineer in the translation of user requirements into system performance specification, subsystem allocations, error budgets, and error models would be the use of mission system analytical models which are capable of producing an output which simulates the actual data that the user would get from the mission. A capability could be generated for processing undistorted input scenes (real and synthetic) and creating distorted output scenes in the users data format. The analytical processing would be done using system models for the mission and would include distorting estimates due to all sources of error that the platform, instrument, and ground and flight data processing systems would introduce. In the early stages of mission definition and instrument conceptual design, these analytical studies could be based on simple models of the mission and the distortions. As the instrument and mission design forms up, the models and analysis could be updated and take on more complexity if required. If the models also contained representatives of the other electro-optical imaging characteristics of the instrument, the analysis would produce an output image containing representations of all radiometric, spatial, and geodetic instrument data degradations. A byproduct of this capability would be that analytically produced data products would be obtained which could be used to aid in the design and testing of ground data processing systems. The expected result of an effort to produce this overall mission analytical simulation would be to provide a systematic, highly visible, interactive approach for establishing optimum instrument performance specifications and error budgets which could also be used to assess expected instrument system performance including ground data processing algorithms.

Before embarking on extensive data collection schemes, however, a study should be conducted to see if synthetic scenes can contribute to the understanding of positioning errors for future systems.

3.7.2.3 Identify Strawman Mission For Modeling Key Error Sources And Identify Hardware and Software Methods For Minimizing Errors

In order to identify the hardware and software technology needed to obtain the registration and rectification requirements expected of advanced spaceborne imaging systems, complete end-to-end system trade-off studies need to be performed. These can be accomplished by identifying several strawman missions which are expected to drive image registration/rectification technology and by performing system studies on these missions. The system studies would identify the error budgets for the missions which would include errors due to the orbit, platform, sensor dynamics, scene variability, as well as errors introduced due to any processing of data on-board or on the ground. Trade-off studies could then be performed using system registration/rectification models for the missions with all sources of error modeled. Trade-offs involving hardware and software improvements for positioning error minimization could be made in the areas of:

1. Platform attitude and ephemeris measurements/estimation/control
2. Instrument pointing and alignment measurement/estimation/control
3. On-board or ground processing of the data, including GCPs. To register and rectify the images both within one mission data set as well as with other data sets.

3.7.2.4 Develop Error Models for Future System Definition and Trade-off Studies

3.7.2.4.1 Sensors

a) MLA: The MLA sensor operates in an integrating mode where the cross-track scene is simultaneously imaged with fixed geometry and perspective. Unlike a scanner, any spacecraft or sensor induced jitter or other disturbance will affect all detectors equally. No pixel-to-pixel high-frequency jitter correction will be necessary.

The fixed nature of the detectors and the simultaneous imaging in the cross-track direction should substantially reduce the processing required to produce geometrically correct images.

Studies should be conducted to investigate the geometric effects which are unique to an MLA-type sensor and its impact on rectification. One-dimensional dewarping algorithms to simplify geometric rectification and the residual errors resulting from attitude and ephemeris uncertainties should be investigated. In order to realize the advantage of the smaller pixels and higher resolving capability provided by an MLA sensor, concurrent improvements in the capabilities of the spacecraft attitude and ephemeris system will be required.

Models and sensor simulations need to be developed to investigate and identify the trade-offs between sensor ACS and ephemeris determination improvements and sensor performance for various pixel size. Semiempirical models of the sensor/spacecraft interface including dynamic effects should be developed to determine whether some form of active jitter or image motion compensation will be needed to realize the 10-m baseline resolution of MLA.

A potential pushbroom sensor containing a central segment(s) of higher resolution end segments could provide the possibility of obtaining high-resolution data for mapping and ground control point location concurrently with acquisition of the "normal" multispectral data.

The added high-precision data allows the possibility of minimizing geometric errors related to ground point locations (as well as providing the possibility for subpixel texture information). This also provides data which can be used to iterate spacecraft attitude models, at higher precision than would the normal lower resolution data.

b) Advanced Scanner: Scanning instruments such as MSS and TM create unique problems with error budgeting and modeling. There is a suggestion that TM could be modified to more than double its IFOV by increasing the number of detectors in the focal plane and putting on more scan mirror monitors (to better identify the scan profile).

Due to the torques involved in the scanning process, especially for highly efficient scanning techniques, high-frequency positioning errors (jitter) can result from flexible body effects in the instrument as well as in the platform to which it is attached. Techniques need to be developed, beyond those which exist in the Landsat-D/TM, for budgeting and modeling these errors. This would include the possibility of having to measure the instrument boresight including effects of individual optical element motions.

In addition, techniques need to be developed to reduce the magnitude of the positioning errors through the use of actively controlled optical elements and the isolation of instrument dynamics from those of the platform.

c) SAR: Unlike the scanning and MLA sensors, a significant amount of geometric distortion can result in the signal processing segment. The purpose of such segments is to convert from a raw image into a slant range/azimuth image.

Processing errors include: a) estimation of FM rate, b) azimuth compression technique (time domain, frequency domain), c) range cell migration correction and associated interpolation, d) block processing techniques, e) doppler centered tracking accuracy, and f) terrain variation effect on point target locations.

To map the slant range/azimuth image to a certain map projection, remapping and resampling errors are introduced. Remapping does not require attitude information. Remapping errors include: a) ephemeris, b) earth curvature, c) GCP accuracy, d) terrain variation, and e) atmospheric refraction (very severe for VOIR).

A focus of the study on the following is recommended: a) Study various signal processing algorithms on the raw image and their tradeoffs. Develop error models. Investigate how error propagates from one processing stage to the another. b) Develop remapping/resampling error model. c) Develop an error model for using DTM for rectification/registration. In SAR imagery, terrain distortion is more severe than it is in the scanner imagery. d) Study the effect of terrain variation on processing algorithms, since terrain affects the target trajectory in the raw image. e) For planetary missions, no GCPs will be available. Study whether automatic focusing on strip-to-strip registration can be used to replace ephemeris parameters. Develop an error model.

3.7.2.4.2 Spacecraft/Shuttle

Spacecraft and Shuttle models for future systems should include advanced sensor and system models which would provide increased knowledge of spacecraft induced error sources which are commensurate with increased resolution expected from advanced sensors. Spacecraft subsystems which must be modeled include: a) attitude measurement systems, b) attitude control systems, c) orbit determination systems, d) orbit control systems, e) sensor alignment measurement systems, f) time and frequency standards.

Examples of future spacecraft systems which must be modeled are: advanced star trackers, advanced horizon sensors, fine pointing sun sensors, and ultra-stable gyro systems. The above system models are components of the attitude measurements and control systems.

An instrument could be provided which, through repeated overlapping images of the ground, can provide the data to allow generation of attitude history without reference to maps or other surveyed ground points. This will be of particular use in shuttle or aircraft systems. This data, in turn, allows image line-by-line data to be positioned properly in the rectified image. This will allow modifications of the error budget by providing images with greater geometric accuracy.

For orbit measurement and control systems, on-board orbit determination using Global Positioning System (GPS) data or utilizing Tracking and Data Relay Satellite System (TDRSS) data must be modeled. Accelerometer packages to measure nonconservative accelerations could be modeled along with on-board actuators for orbit control. Ephemeris data resulting from precision ground based orbit determination must also be modeled.

Time maintenance and time transfer systems to be modeled include GPS and TDRSS time transfer and/or flying with stable oscillators.

Studies resulting from the development of the above models would be the generation of error budgets for varying system configuration and performing end-to-end trade-off studies such as cost impacts and enabling technology impacts of improving spacecraft system knowledge such that GCP processing can be either eliminated or substantially reduced.

3.7.2.4.3 Processing/Information

Often in the design and development of processing systems there are not strong and specific identifications as to what function must be performed to insure that the end product is most beneficial to the user needs. The functions may be isolated to hardware or software components but must include/reflect algorithms that eliminate/reduce errors from the data source, sensor/spacecraft.

The development of supporting processing system should begin concurrent with the development of the sensor/spacecraft at or during the phase A/B studies. If the processing system was designed with the understanding of possible error enhancement to this data source, then data recovery, correction, and error removal procedures should be considered in the design.

Some factors that must be considered in this processing system to eliminate/minimize errors are: a) ephemeris accuracy/variations, b) sensor alignment, c) data translation, d) geometric errors and systematic correction (orbit/attitude), e) scanning sensor's rates, gaps, and profile, f) lessons learned from historical sensors, g) image corrlation/matching techniques, h) temporal processing/data translation, i) pixel errors, j) cartographic and mosaic errors, k) integration of multisensor data, l) ground control point/pointing tolerances, m) edge detection/image sharpness/filtering, and n) image warping.

The processing system should also give the users some information about what corrections, algorithms, filters, etc., were used in correlating the product. This data will facilitate the user understanding and use of the final product.

3.7.2.4.4 Study Group

It is recommended that a permanent Ad Hoc Earth Observing System Error Analysis Working Group be established at the NASA Headquarters level. The purpose of this working group is to advise the NASA Program Manager on technical requirements and limitations relating to error characterization, error budgets, and system verification.

Establishment of this working group is imperative to preserve continuity in the Earth Observing Systems Techniques and Data Processing Development Program. The working group members should be comprised of system designers and system users and be representative of the government, industry, and university communities.

3.7.3 References

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3.7.4 Appendices to Error Characterization and Error Budgets Subpanel

APPENDIX A

POSITIONING REQUIREMENTS COMPATIBLE WITH NMAS FOR 1:24,000 TOPOGRAPHIC MAPS

The basic assumption in this exercise is to set-up a "straw-man" mission designed to provide data suitable for meeting National Map Accuracy Standards NMAS for 1:24,000 scale topographic and planimetric map products. This is a geometric requirement rather than a nonmetric informational requirement. In addition, the change is to produce these x, y, z earth system coordinate data with minimal reference to ground control. The geometric requirements will, in turn, define the IFOV of the system. As will be noted, an IFOV of about 3-4 m will be required to meet the accuracy standards. The following statements are not meant to advocate this system, but rather to consider its feasibility in terms of error budgets and error budget modeling methodology.

I. National map accuracy standards (NMAS) for 1:24,000 scale map products require:

a. 90% of horizontal positions (for well defined points) be established to ± 12 m of their correct location. The acceptable $RMSE_{X,Y}$ (68%) is approximately ± 7 m.

b. 90% of elevations interpolated from contour lines will be correct to within 1/2 the contour interval (CI). The acceptable RMSE will therefore be equal to the C.I./3.3. As most 1:24,000 scale maps have C.I. of 5, 10, 20, or 40 feet (depending on the terrain), the RMSE requirements are approximately ± 0.5, 1, 2, and 4 m respectively. Because elevation standards are the most stringent requirement, they will control system design.

II. System Design Assumptions

a. The assumed imaging system consists of three line-array cameras operating in the pushbroom mode. Two of the cameras will be oriented approximately 24 degrees from the vertical in a convergent arrangement in order to provide fore and aft coverage while the third camera is aligned vertically so as to produce near orthographic coverage of the terrain. This configuration results in potential base-height (B/H) ratios of 1.0 for fore and aft stereopairs and 0.49 when the vertical is employed with either fore or aft coverage.

b. Altitude - set between 5[illegible] and 1000 km, e.g., 713 km or 919 km

c. IFOV ≤ 5 m: to be determined by NMAS, geometric and correlation requirements, rather than by nonmetric information requirements

d. Swath - TBD in the range 60-185 km

e. The feasibility of a mission designed to most of the above NMAS requirements remains to be demonstrated.

III. Error Considerations and Sources

a. Maximum RMSEs
   1. Horizontal (X,Y) = $\pm$ 7 m
   2. Vertical (Z) = $\pm$ 3 m (for 10 m C.I.)

b. Error Considerations

   1. General

      The mission must provide essentially error-free geometric and radiometric data if accurate map products are to be developed. In theory, the spacecraft and sensor systems can be controlled so as to preclude any special ground based computer processing (to correct the errors), which is both expensive and subject to delay.

      The parameters which influence the geometric fidelity of the image data include pointing control rate motion stability and jitter. The satellite line-array sensor system (which is recording the terrain as a series of cross-track strips) must be pointed correctly and held stable for approximately 100 seconds to produce error-free stereo imagery. Any perturbation of the sensor system during the recording period will cause displacements/errors in the data which, in turn, may require geometric correction and resampling at a ground receiving station. Rotation of the spacecraft about the X, Y, and Z axes (roll, pitch, and yaw, respectively), although constrained, will cause deformations of the nominal image format as will changes in spacecraft altitude and oblateness of the Earth.

   2. Earth Rotation

      The basic imaging concept is straightforward, however, because of Earth rotation, the satellite ground track is no longer a simple great-circle route, and the vertical, fore, and aft cameras will not automatically image the same ground area, even with a perfectly stable satellite. In order to obtain ground coverage common to any two cameras, a yaw motion must be introduced into the camera/spacecraft. This motion is not constant, but must vary with latitude to maintain image registration.

   3. Oblate Earth

      The basic imaging concept assumes a spherical Earth and a circular satellite orbit so that a constant satellite altitude is maintained. In practice, however, we must consider an oblate spheroid and an orbit which only approximates to a circle due to variations in the gravitational effect of the Earth. These deviations from the ideal situation create increases in slant range and altitude which in turn cause scale variations as the satellite increases its distance from the equator.

4. Resampling Considerations

Any image deformations which are not maintained within specified limits must be removed in the ground data processing. The pixels may be resized, reshaped, realigned, and new grey level values determined to provide the necessary image quality. An objective of the mission is to acquire error-free data which will eliminate the need for resampling (and minimize geometric corrections).

5. Spacecraft Performance

In order to reach some conclusions regarding the geometric accuracy, it is necessary to consider the pointing, stability, and jitter of the spacecraft and its sensors. Pointing accuracy is the factor most often quoted as a measure of geometric performance. For example, the Multimission Modular Spacecraft (MMS) which will be employed for Landsat-D has a pointing accuracy specification of ± 0.01 degree (one sigma). Thus, by design, the summation of all factors that include the attitude control subsystem should have a root-mean-square value of less than the design specification. In addition, other factors such as orbit determination, timing, sensor alignment with the attitude control system (including the effects of thermal instabilities), and the torquing motions of a tape recorder (if used) influence the pointing geometry. Satellite stability is an important consideration. Extremely tight tolerance will be required (e.g., 10^{-6} deg/sec at the 3T level or better).

The third problem is jitter. The satellite will respond to dynamic disturbances caused by antenna or solar panel motions as would a tuning fork. Response is frequency dependent because of structural qualities. No moving parts are desired.

IV. Error Sources Influencing the Mapping Potential

From a cartographic viewpoint, the most significant problems are likely to be of a geometric nature. Consequently, it is desirable to determine the accuracy to which X, Y, Z terrain coordiantes can be recovered from image data recorded by the proposed line-array system.

Major factors which appear to determine the accuracy to which X, Y, and Z terrain coordiantes can be recovered are listed below: An attempt is made to estimate quantitatively the magnitudes of the starred error sources in terms of root-mean-square error (RMSE).

1. Position of S/C Error Sources
2. Pointing of sensors and attitude control
3. Satellite velocity
4. Precision of measurement
5. Reliability of ground control
6. Earth curvature, atmospheric refraction, etc.
7. Processing equipment and procedures
8. Adjustment Procedures

a) Position of S/C

The positional determination of the S/C must be within 10 m for all three axes.

b) Sensor Pointing and Attitude Control

Nominal correction values for a constant bias can be determined with the aid of ground control. In many areas of the world, however, ground control is inadequate for mapping tasks, and alternative methods of establishing corrections for pointing errors must be made available.

Attitude stability and maintenance of controlled yaw are critical parameters. In order to achieve acceptable coordinate values with reasonable consistency, a worst-case correction rate value of 10^{-6} deg/sec at the 3-sigma level of confidence is required. This equates to ± 4 m (approximately 1 pixel) over the 10-minute time interval and should provide an epipolar condition.

The overall requirement for pointing determination accuracy is better than one arc sec (~4 m from 800 km). This will be a major source of error.

c) Satellite Velocity

Variation in satellite velocity can be accounted for if accurate timing marks can be incorporated in the data. GPS is a source for time data.

d) Measurement Error

Measurement or correlation error must be limited to well within one-half the $RMSE_{X,Y}$ value in order to meet vertical accuracy requirements. Thus, RMSEs in horizontal measurem must be on the order of 1-2 m.

e) Reliability of Ground Control

It is anticipated that a minimum number of ground control points will be required. However, they will have to be accurate to 1-2 m. Possibilities for autotriangulation exist, but error figures cannot be determined at this time.

f) Earth Curvature and Refraction

Errors due to Earth curvature and refraction are systematic and can be corrected during processing. The influence of variations in refraction is negligible for a narrow (5^{o}) field-of-view.

There are other error sources which will need to be considered. However, the magnitude of the above errors in relation to NMAS can be estimated.