



NOAA Technical Memorandum NOS CGS 2

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GPS-ASSISTED PHOTOTRIANGULATION PACKAGE (GAPP)

USER'S GUIDE, VERSION 1.02

James R. Lucas

Rockville, MD

November 1989

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**U.S. DEPARTMENT  
OF COMMERCE**

National Oceanic and  
Atmospheric Administration

National Ocean  
Service

Office of Charting and  
Geodetic Services





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**ABSTRACT.** The GPS-Assisted Phototriangulation Package (GAPP) provides a means for incorporating kinematic Global Positioning System (GPS) observations of the aircraft position into an aerotriangulation adjustment. A floppy disk containing the program and a set of sample data files are provided with this user's guide which provides a description of both program and files. It also provides some guidance in the preparation of data files for a project and prepares the user to respond to decision requests made by the program during execution.

### INTRODUCTION

GAPP is primarily used to perform aerotriangulation adjustments that incorporate observations of the position of a GPS antenna mounted on the aircraft. GAPP can also be used to adjust conventional aerotriangulation data and is often employed in that mode to provide comparisons with GPS-controlled aerotriangulation results.

GAPP, when used in conjunction with the program NAV22 (Mader 1989), provides an Initial Operational Capability for aerotriangulation in which the need for ground control is reduced significantly by the use of GPS observations of the aircraft position. The output from NAV22 is used to generate a set of observations of the position of the aircraft-mounted GPS antenna, which augment the usual image coordinate observations so that precise aerotriangulation is feasible with very little ground control and possible with no ground control at all. Such use of GAPP assumes that the GPS and photo data were acquired in a manner equivalent to that described by Lucas and Mader (1989).

### ENVIRONMENT

The minimum system configuration required to run this version of GAPP is an IBM PC compatible system with 640K of memory, a hard disk, and a math coprocessor. GAPP is written in FORTRAN 77.

In its present form, GAPP has the following limitations where the number of resident ground points is determined by the bandwidth of the banded coefficient matrix of the photogrammetric normal equations.

<u>Parameter</u>	<u>Maximum number</u>
photos	400
ground points	400
images per photo	30
ground control points	50
resident ground points	40

## GETTING STARTED

The distribution disk contains the following files:

GAPP.EXE - GPS Assisted Phototriangulation Package (GAPP), version 1.02.

GETEPH.FOR - FORTRAN source code of a utility program that converts the output of NAV22 into the format required by GAPP.

SYSTCAL.DAT - Data file that provides certain parameters of the data collection system.

ANTENNA.EPH - Data file containing the position of the GPS antenna on the aircraft at a specified time interval during all periods when photography was acquired.

EXPTIME.OBS - Data file that provides the time of exposure of each photo.

CONTROL.DAT - Data file that provides the initial position of the aircraft antenna and the positions of any ground control points to be used in the adjustment.

IMAGECO.OBS - Data file that provides the corrected photo coordinates of all images to be used in the adjustment.

These files are a subset of the data collected during an experiment at Rockdale, TX, and contain all the data needed to exercise the program GAPP. They should be saved and used as models for setting up data files for application by the user.

GAPP.EXE should be copied to and executed from the hard disk. The five data files should be copied to a formatted floppy disk that is to reside in drive A during program execution. During execution, GAPP will create two additional files on the floppy, FRAMEPO.EST and GROUNDPO.EST, that contain results the user may want to save. A file of results to be sent to the printer, GAPP.LST, will be created on drive C which is assumed to be the user's hard disk. In addition, up to seven scratch files will be written to drive D which can be a RAM disk for greater execution speed. If the user does not have sufficient memory to set aside at least 256K bytes as a RAM disk, these temporary files can be directed to the hard disk by using the DOS command "SUBST D: subdirectory name" prior to executing GAPP. See the DOS manual for your system for more details and additional restrictions. The sizes of these scratch files vary with the data set being processed. RAM disk users may have to direct these files to the hard disk when dealing with large projects.

## DATA FILE DESCRIPTION

The following paragraphs provide a brief description of the data files that must be available for the program to execute. This description should be adequate to enable the user to create usable files for a new project. Appendix A contains more information on the contents of these files.

SYSTCAL.DAT must be available whenever any of the functions performed by GAPP are executed. This file must contain at least three records that will be read using the format AS,3X,3F15.3.

- Record 1. Provides a string of up to eight characters used to identify the aerial camera and the camera focal length in millimeters.
- Record 2. Provides the components of the antenna-camera offset vector in meters.
- Record n. Contains only an end-of-data record consisting of eight \*'s and must be the last record in the file.

This file can also be used to supply a number of other data items that apply to a particular project or a particular computer run. Examples are included in the SYSTCAL.DAT file provided on the distribution disk. For a full description of these items see appendix A.

CONTROL.DAT must also be available while executing any of the GAPP functions. This file contains a pair of records for each ground control point, including the initial antenna position, that will be read using the format AS.4F12.3/8X.3F12.3.

- Record 1. Provides a string of up to eight characters used to identify the control point, its longitude, and latitude in degrees, minutes and seconds in the form DDDMMSS.SSS preceded by an optional sign, its orthometric height in meters, and (optionally) its ellipsoidal height in meters.
- Record 2. Provides the a priori standard errors in easting, northing, and elevation, all in meters.

All positions are assumed to be NAD 83 coordinates; all latitudes are assumed to be north latitudes; all longitudes are assumed to be east longitudes. South latitudes and west longitudes must be input with a minus sign. If GPS antenna observations are to be used, the first record pair in this file must be for the initial position of the aircraft antenna, as used in the NAV22 adjustment of the GPS observation data, and the identification character string must be "AIRCRAFT." Additional record pairs associated with (up to 50) ground control points can be included, but are not required when using GPS antenna observations. If the first control point in CONTROL.DAT does not have the name "AIRCRAFT," GAPP will perform a conventional aerotriangulation adjustment using ground control and no antenna observations. This type of adjustment is often used for evaluating the results of GPS-controlled adjustments. However, for day-to-day conventional aerotriangulation the National Ocean Service (NOS) uses and recommends the GIANT program (Elassal 1987).

ANTENNA.EPH must be available if GPS antenna observations are to be used. This file is obtained by stripping extraneous records and columns of records from file NAV22.OUT produced by the program NAV22 (Mader 1989). The distribution disk contains GETEPH.FOR which can produce this file. The source code is provided so the format statement used to read NAV22.OUT can be modified to accommodate any future changes of the format in which that file is produced.

ANTENNA.EPH will consist of a sequence of records containing times and antenna positions, relative to the position of "AIRCRAFT" described above. The interval of this "antenna ephemeris" file, usually 1 second, is determined by the GPS receiver used. The data within each record consist of the Greenwich Mean Time in the form HH:MM:SS.SS followed by the WGS 84 coordinates X, Y, Z of the

antenna relative to the initial antenna position, and a scaling factor of the a priori standard errors associated with this position. The scaling factor is usually 1, but a larger number is appropriate if one or more entries in this ephemeris table have to be constructed by interpolation due to missing GPS data. The scaling factor can also have a value of zero or be left blank. In either case, GAPP will substitute a scaling factor of one. The GETEPH program supplies factors that have been determined to be adequate by empirical tests. The format for reading this file is I2,1X,I2,1X,F5.2,3F11.3,2X,I4.

EXPTIME.OBS must also be available if GPS antenna observations are to be used. This file, which must be created by the user, contains the time of exposure of each photograph. Each record consists of: Julian Day (which is not used); hour, minute, and seconds of Greenwich mean time of exposure; and ID string associated with the particular photograph. This file is read using the format 4X,I2,1X,I2,1X,F9.6,2X,A8.

IMAGECO.OBS provides the measured image coordinates, corrected for all known systematic errors (film distortion and lens distortion, both radial and decentering) except atmospheric refraction, for all of the photos to be processed. The first, or header, record for each photograph provides the photo ID string of up to eight characters. The header is followed by one record for each image. These records contain an image ID string of up to eight characters, which is the same as the ID string of the ground point, followed by the x and y coordinates of the image in millimeters. If no decimal point is included in these coordinates, as in the example file, a decimal point will be placed according to the format A8,2X,2F10.3. This set of image records is terminated by a trailer record consisting of a string of eight \*'s in the first eight columns.

#### SAMPLE EXECUTION

Execution of GAPP is initiated by typing GAPP in response to the system prompt or by running a batch file which sets up the proper path to the input data files and output scratch files. The main menu (fig. 1) will soon appear on the screen. Only four of the functions presented are available to the user when GAPP is first initiated. Step 2 cannot be run until step 1 has been completed unless the user chooses not to use GPS antenna observations and provides a file A:FRAMEP●.EST containing estimates of the camera positions and orientations for all exposures. Step 3 is not a valid choice, because it cannot precede step 2, and neither step 4 nor step 5 can precede step 3.

#### Review/Revise Options

If any of the basic option data are to be changed from their default values, this should be done first. Hence, this description will begin with the user typing 7 followed by **ENTER** so that the Options menu (fig. 2) will appear on the screen. All user input must be followed by **ENTER** (the key that produces a carriage return and line feed; the label varies on different computer systems), so this detail will not be repeated hereafter.

GPS - ASSISTED  
PHOTOGRAMMETRIC NETWORK ADJUSTMENT

Version 1.02 - 21 Jun 1989

```
*****
*   1 - ESTIMATE CAMERA POSITIONS AND ORIENTATIONS   *
*   2 - ESTIMATE GROUND POINT POSITIONS             *
*   3 - PREPARE DATA FOR AEROTRIANGULATION         *
*   4 - PERFORM AEROTRIANGULATION ADJUSTMENT       *
*   5 - SOLVE ONLY (NO COVARIANCE PROPAGATION)     *
*   6 - BATCH MODE                                  *
*   7 - REVIEW/REVISE OPTIONS                       *
*   8 - TERMINATE                                   *
*****
                        SELECTION:
```

Figure 1.--Main menu for GAPP as it appears on the user's screen.

```
*****
*                                     OPTIONS         *
*****
*   1 - A PRIORI STANDARD ERRORS                   *
*   2 - OUTPUT OR RESIDUALS                        *
*   3 - SYSTEM CONSTANTS                           *
*   4 - MISCELLANEOUS OPTIONS                      *
*   5 - RETURN TO MAIN MENU                        *
*****
                        SELECTION:
```

Figure 2.--Options menu.

The Options menu is self explanatory. However, the beginner may want to bring up the secondary screens in order to learn what default values are applied by GAPP.

From the Options menu, enter 1 to bring the A Priori Standard Errors of Observation menu (fig. 3) to the screen. From this menu, the user can revise the a priori standard errors associated with the antenna observations by entering 1 or the image coordinate standard errors by entering 2. The a priori standard errors associated with ground control points are included with the position data in file CONTROL.DAT so revision of these quantities is not an option available from this menu. If the user chooses to revise the a priori standard errors of the antenna observations, the program will ask for new values for all four of them. Any of the default values can be retained without typing them by merely entering "/" when asked for a new value.

If either 1 or 2 is chosen and new values entered, the menu will reappear with the revised values for the user's inspection, and the opportunity is then available for these values to be corrected. When satisfied with the values chosen, enter 3 to return to the Options menu.

```

*****
*          A PRIORI STANDARD ERRORS OF OBSERVATIONS          *
*****
*
*          ANTENNA OBSERVATIONS                               *
*
*          Sigma Easting =      .020 meters                 *
*          Sigma Northing =     .020 meters                 *
*          Sigma Elevation =    .040 meters                 *
*          Sigma Time =        .00085 seconds              *
*
*          IMAGE OBSERVATIONS                                 *
*
*          Sigmax = Sigmay =    .005 millimeters           *
*
*          1 - REVISE ANTENNA OBSERVATION STANDARD ERRORS   *
*          2 - REVISE IMAGE OBSERVATION STANDARD ERRORS     *
*          3 - RETURN TO OPTIONS MENU                       *
*****
SELECTION:

```

Figure 3.--A priori standard errors of observations menu.

From the Options menu enter 2 to bring up the Listing of Residuals menu (fig.4) to the screen. The default is to list none of the residuals. If the user enters 1, 2, or 3, the menu will reappear with the appropriate item changed from "NoList" to "List" and that particular set of residuals will be listed (on the last iteration, only) when the aerotriangulation adjustment is run. After selections are completed, enter 4 to return to the Options menu.

```

*****
*          LISTING OF RESIDUALS                               *
*****
*
*          1 - LIST IMAGE RESIDUALS      ( = NoList )      *
*          2 - LIST GROUND CONTROL RESIDUALS ( = NoList ) *
*          3 - LIST ANTENNA RESIDUALS    ( = NoList )      *
*          4 - RETURN TO OPTIONS MENU     *
*****
SELECTION:

```

Figure 4.--Listing of residuals menu.

```

*****
*                               SYSTEM CONSTANTS                               *
*                               *                                             *
*   STATE PLANE ZONE CODE =      4203                                       *
*   GEOID HEIGHT =                -24.859 meters                             *
*   ANTENNA EPHEMERIS INTERVAL = 1.000 seconds                             *
*   OBSERVATION REJECTION CRITERION = 3.0*Sigma                             *
*                                                                           *
*   1 - REVISE STATE PLANE ZONE CODE                                         *
*   2 - REVISE GEOID HEIGHT                                                  *
*   3 - REVISE ANTENNA EPHEMERIS INTERVAL                                    *
*   4 - REVISE OBSERVATION REJECTION CRITERION                              *
*   5 - RETURN TO OPTIONS MENU                                              *
*****
                               SELECTION:

```

Figure 5.--System constants menu

From the Options menu, enter 3 to bring up the System Constants menu (fig. 5). The first item on this menu is the State plane zone code for which the default is 4203, the Texas Central zone which applies to the data files provided on the distribution disk. The results from an aerotriangulation adjustment will be provided in latitude, longitude, and height, and also in State plane coordinates and elevation, so it is necessary to set the appropriate zone code. If this item is selected for revision, the following note "<< Enter "H" for a listing of the State Plane Zone Codes >>" will appear on the screen. Entering H will provoke a list of all 133 zone codes and associated zones. The user is then asked again for a selection.

The second item in this menu is the geoid height of the project area. This value is needed to resolve the difference between the ellipsoidal heights associated with the GPS data and the orthometric heights of ground control points that have been determined by spirit leveling. The relationship between these quantities is orthometric height equals ellipsoidal height minus geoid height. If the geoid height of the project area is unknown, an approximate value can be obtained from the National Geodetic Information Branch, N/CG174, Charting and Geodetic Services, National Ocean Service, NOAA, Rockville, MD, 20852.

The third item, the antenna ephemeris interval, is a function of the GPS receiver used. The ANTENNA.EPH file provided on the distribution disk has an interval of 1 second, as the default value indicates, but this value may need to be changed to match the data provided by the user's receiver.

The last item in this menu is the critical value used in the process of rejecting observations as possible blunders. The test statistic to be compared to the critical value is the ratio of the weighted residual from an observation to the square root of the reference variance (sometimes called the variance-of-unit-weight). The default value of the critical value is 3, which corresponds approximately with the 95 percent confidence level. In some instances, it may

be advisable to set this value to a larger number to avoid rejecting so many observations that the adjustment cannot proceed due to a singular least squares coefficient matrix. This device is provided as a diagnostic tool and should only be used to obtain information with which to identify and correct the problem. The default value of 3 should be satisfactory for any data set with realistic weights and a small percentage of blunders.

The first three items on this menu can also be modified for all executions with a particular data set by including records in the SYSYCAL.DAT file as described in appendix A.

The menu will reappear after each change, showing the results of the change, and the user will have an opportunity to revise any erroneous entry before entering 5 to return to the Options menu.

Entering 4 from the Options menu will bring up the Miscellaneous Options menu (fig. 6). This menu provides four items that can be toggled YES or NO by entering the appropriate number.

The first item determines whether or not atmospheric refraction corrections will be applied. When an aerial camera is operated in a pressurized aircraft with a glass port in front of the lens, the refraction of light rays through these elements may nearly compensate for atmospheric refraction. Therefore, it is sometimes convenient to compare the aerotriangulation results with and without correcting for refraction. Also, some analytical plotters used for mensuration of photos automatically apply a correction for atmospheric refraction. Therefore, the user will want to avoid applying the correction a second time.

```

*****
*                                     *
*                               MISCELLANEOUS OPTIONS                               *
*                                     *
*                                     *
*                                     *
* 1 - APPLY REFRACTION CORRECTION           ( = YES ) *
* 2 - LIST PHOTO PARAMETER STANDARD ERRORS ( = NO  ) *
* 3 - USE GPS OBSERVATIONS, IF AVAILABLE    ( = YES ) *
* 4 - USE GROUND CONTROL, IF AVAILABLE      ( = YES ) *
* 5 - RETURN TO OPTIONS MENU                *
*                                     *
*****
SELECTION:

```

Figure 6.--Miscellaneous options menu.

The second option, LIST PHOTO PARAMETER STANDARD ERRORS, will cause the propagation of covariance for the adjusted camera position coordinates and attitude angles and the inclusion of the standard errors of these estimates in the printed output. The use of this option will significantly increase the

computer time required for an adjustment and should, therefore, be used only for diagnostic purposes or when a complete record of the adjustment is desired.

The third option, USE GPS OBSERVATIONS, IF AVAILABLE, will have a default of YES if the first record in the CONTROL.DAT file has an ID string of AIRCRAFT, otherwise it will be set to NO. This is because GPS observations cannot be used if the initial position of the antenna is not available. On the other hand, if both GPS observations and a sufficient set of ground control are available, this option can be used to prevent the use of GPS observations should the user want to perform an adjustment with ground control only.

In the same manner, the user can toggle the USE GROUND CONTROL, IF AVAILABLE option to NO in order to perform an aerotriangulation adjustment without ground control, using GPS observations only.

Only the first item on this menu can be modified by records in the SYSYCAL.DAT file. All other options described in this menu are intended to be used during a particular computer run.

#### Estimate Camera Positions and Orientations

The first item on the main menu screen (fig. 1) is a very abbreviated description of what takes place when this function is chosen. For each exposure time provided in file EXPTIME.OBS, a set of five consecutive antenna positions is obtained from file ANTENNA.EPH such that the central time is within half an ephemeris interval of the exposure time. The components of the antenna position and velocity vectors are then computed by fitting a third-order polynomial to the five tabular entries of each of the components of antenna position. Next, the a priori covariance matrix associated with this antenna position is formulated and this set of data is written to a temporary file called ANTENNA.OBS.

Then the position and attitude of the camera are estimated. Starting with the antenna position as a good initial approximation of the camera position, an orientation matrix (geocentric-to-photo) is estimated using the latitude and longitude of the camera and the assumption that the photo is vertical with its x-axis aligned with the horizontal projection of the antenna's velocity vector. An improved camera position is then computed using this orientation matrix and the antenna-camera offset vector obtained from file SYSTCAL.DAT. The estimated camera position and attitude are then written to file FRAMEPO.EST.

When 1 is entered, the program will respond with

```
Computing Antenna Positions and  
Estimating Camera Positions & Attitudes . . .
```

When this task is completed, the program will report the number of exposure time read from the EXPTIME.OBS file, and the user is instructed to press RETURN to return to the main menu. The user can then terminate the task by entering 8 or continue to the next step. If this first step was executed before mensuration of the photography, the user must terminate at this point or the run will be aborted due to the absence of an IMAGECO.OBS file. It is advantageous to run the first step prior to mensuration in order to provide the mensuration technician a listing of the FRAMEPO.EST file to aid in performing the mensuration.

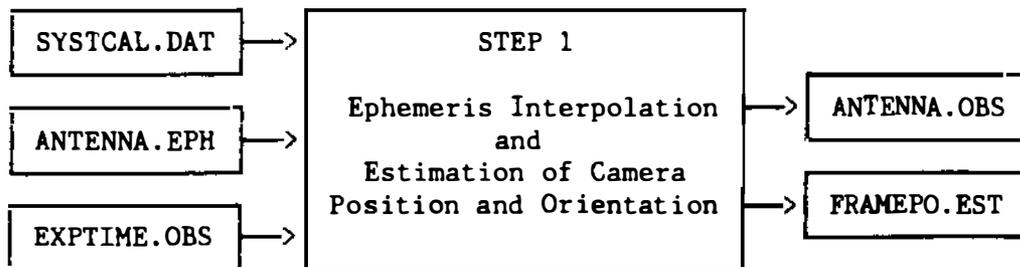


Figure 7.--Files involved in the execution of step 1.

### Estimate Ground Point Positions

The next item on the main menu requires the IMAGECO.OBS file, generated after the photography has been measured, and the FRAMEPO.EST file produced by step 1. If antenna observations are not available and the user chooses to use this program for a conventional aerotriangulation adjustment, a file of camera position and attitude estimates can be created by some other means and the program started at this step.

The purpose of this step is to provide initial estimates, required by the least squares adjustment, of the positions of all ground points. Figure 8 shows the input and output files involved. Control point positions, if any, are merely read from the CONTROL.DAT file, but the positions of pass points are estimated by the "single ray intersection" method. Using the estimated camera position and attitude and the known image coordinates of a pass point, a line (ray) through the perspective center and the image is extended analytically to the point where it intersects an ellipsoid that is parallel to the Earth ellipsoid and above it by a computed mean elevation for the project area. The computed latitude, longitude, and elevation of all ground points are then written to the direct access file GROUND.P.DAF so they can be recalled in the sequence in which they will be used in the adjustment.

For this estimation process to take place, the image coordinate observation file must be searched for pass points that still have to be estimated. While this is taking place, it is convenient to perform a number of other tasks that must be completed in preparation for the aerotriangulation adjustment. The set of all image coordinates for each photo is written to a direct access file called IMAGECO.DAF and the antenna observations, if any, associated with each of the photos are written to a direct access file called ANTENNA.DAF.

As the observation file is examined, the connections between all ground points imaged on a particular photograph and the connections between those ground points and the photograph are recorded in a "Neighbor List" that will be used in determining the optimum order of the photos in the adjustment.

The last task in this step is to compute the bandwidth that the normal equations coefficient matrix would have, if the order of the photos remained the same as in IMAGECO.OBS. The computed bandwidth is displayed as the number of resident ground points (number of ground points in the portion of the normal equation coefficient matrix that must reside in memory).

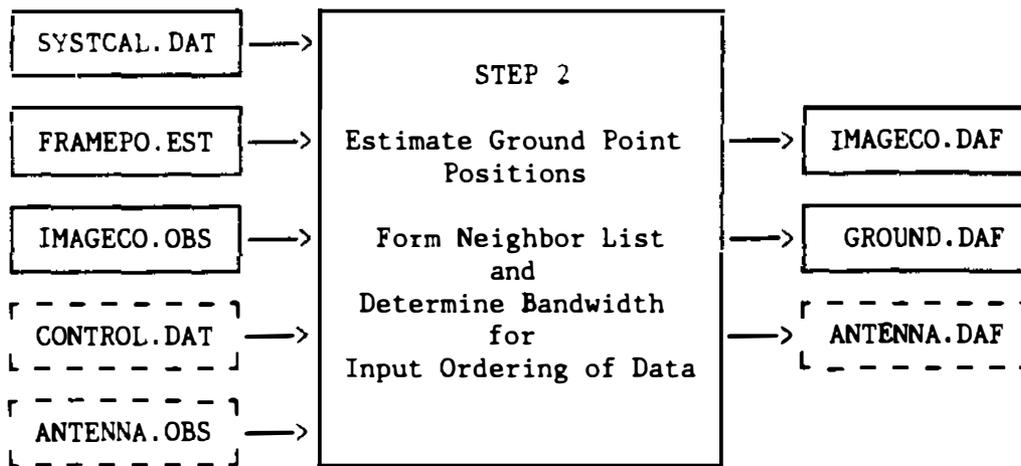


Figure 8. Files involved in the execution of step 2.

When the user selects 2, the program will respond with

Estimating Ground Point Positions . . .

After some time, perhaps several minutes for large data sets, the program will report the number of ground points and number of photographs. The values for the data set on the distribution list should be 43 and 18, respectively. The user will then be informed:

Building Neighbor List . . .

When this task is complete, the number of resident ground points will be reported and the user instructed to press **RETURN** to return to the main menu.

#### Prepare Data for Aerotriangulation

When Step 2 has been completed (and not before), the user can select 3 which will cause the program to compute an ordering of the data that usually provides a smaller bandwidth for the banded coefficient matrix of the normal equations. The algorithm used is empirical in nature. It has been shown to produce "cross-strip numbering," which is thought to provide the minimum bandwidth for very regular cases. For the general case, however, it can only be said that this algorithm performs as well or better than any other algorithm tested, but requires more computer time than most (Lucas 1985). The time required to perform this reordering is significant only when dealing with very large data sets, and then it is worth investing the time at this point, because considerably more time will be saved during the adjustment.

When a near optimum order for the ground points and photographs has been determined, the observations and initial estimates of the parameters are retrieved from the appropriate direct access files and written in the optimum order to a sequential observation data file called OBSVATN.DAT and a direct access parameter estimate file called PARMEST.DAF. A direct access file is used for the parameter estimates because these estimates will be updated during the

adjustment, and the new estimate records will be written to the file in reverse order. Figure 9 shows the input and output files involved.

When 3 is selected, the program will respond with:

Reordering Ground Data . . .

When this task is complete, it will report the number of resident ground points for the computed ordering of ground points and state:

Reordering Photo Data . . .

followed almost immediately by:

Writing Estimate and Observation Data Files . . .

This task, the physical reordering of data, will take considerably longer than the computation of what the order should be. The user will then be advised to press **RETURN** to return to the main menu.

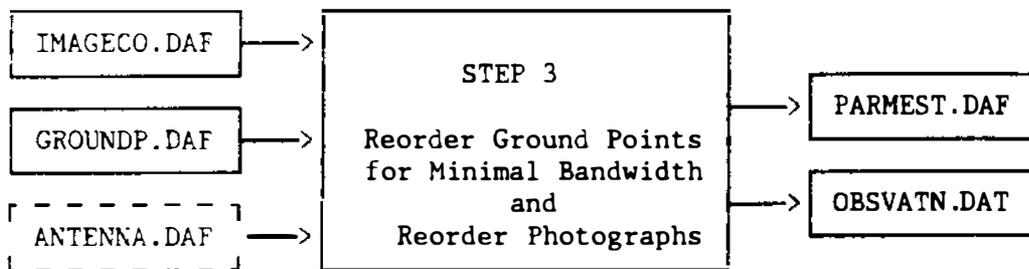


Figure 9. Files involved in the execution of step 3.

#### Perform Aerotriangulation Adjustment

When 4 is selected, the program responds with:

Iteration No.	Sigma Zero	Observations Rejected	Ground Point mean	Corrections max
0				

The cursor is positioned after the zero, indicating that the zeroth iteration is in progress.

When the forward reduction has been completed, the "Sigma-Zero" and "Observations Rejected" columns of this table will be filled. Sigma-zero is the square root of the current estimate of the variance-of-unit-weight, sometimes called reference variance. The reference variance is computed from the sum-of-squares of the weighted residuals divided by the degrees of freedom. If

there are no uncorrected systematic errors, if the mathematical model employed is a good approximation of the physical circumstances, and if the weights assigned to the observations are correct, the reference variance should be equal to one. A more realistic expectation is that the reference variance, and therefore sigma-zero, will approach unity as the iterations continue. During the zeroth and first iterations, no observations will be rejected so that column should be zero.

After the back-solution has been completed, the mean and maximum ground point corrections will be displayed. These values are in meters and may be rather large on the zeroth iteration, because initial approximations for pass points are only rough estimates. As the iterations progress, both the mean and the maximum should approach zero.

During the iteration process, parameter estimates and observations are read from their respective files when they are needed in the formation of the "resident" normal equations. When all observations that affect particular rows of the resident normal equations have been processed, those rows are forward reduced using Gaussian elimination and then written to a temporary storage file COVMATX.DAF (fig. 10). These rows are then read back into memory in reverse order during the back solution.

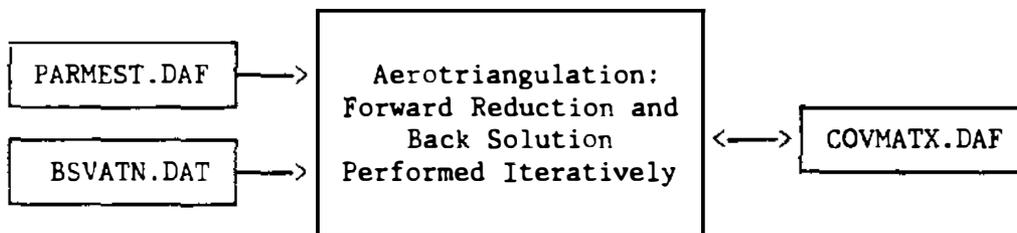


Figure 10.--Files involved in the execution of aerotriangulation.

When the maximum correction falls below 5 cm, or when iteration number 5 has been completed, the iteration process is terminated and GAPP will automatically move on to the covariance propagation step and will display the message:

Performing Covariance Propagation . . .

The message will be displayed until this step is completed, usually about twice the time required for each iteration in the solution phase. During covariance propagation, the forward-reduced "resident" normal equation rows are brought back into memory in reverse order and used in computing the sparse inverse of the normal equation coefficient matrix. The portions of the inverse matrix that are needed to compute the a posteriori estimate of the standard errors of the ground point coordinates (and camera positions and attitude parameters, if that option was selected) are then scaled by the variance-of-unit-weight, transformed into an East-North-Up coordinate system, and written to the parameter estimate file PARMEST.DAF (fig. 11).

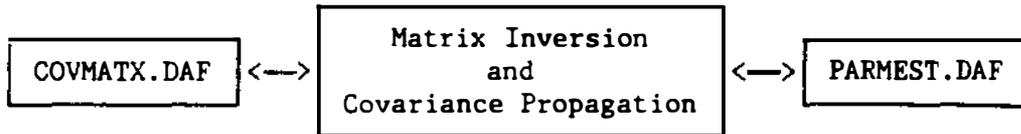


Figure 11.--Files involved in the execution of covariance propagation.

When covariance propagation has been completed, GAPP will display the message:

Printing Results . . .

while it is actually writing the output to a file on the C drive called GAPP.LST, which can be printed later. The program will then complete a normal termination with no further action required of the user.

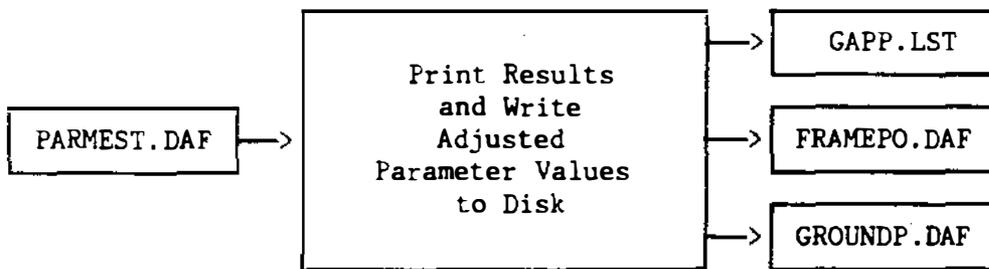


Figure 12.--Files involved in the execution of step 6.

#### Solve Only

When 5 is selected, the sequence of events is exactly the same as in Step 4 except that the covariance propagation is omitted.

#### Batch Mode

When the user selects Batch Mode by entering 6, GAPP responds with STARTING WITH:.. The correct response is to enter the number of the first function to be performed, which will probably be 1 or 2, depending on what has been accomplished in a previous execution of the program. GAPP then asks INCLUDE COVARIANCE PROPAGATION? (Y/N):, and waits for the user to respond. If 1 is selected as the starting point, the software will automatically perform steps 1, 2, 3, and either 4 or 5, depending on whether or not covariance propagation is selected. It will then continue through the printing of the results and normal termination, all without any further action by the user.

Batch Mode is the most efficient way to proceed through an aerotriangulation adjustment from the first, or any intermediate, step as long as there is no need to stop along the way. When the steps are performed under user control, the process can be stopped by selecting 8 at any time the user is asked to make a selection from the main menu. Processing can then be resumed at some later time because GAPP saves certain information about the data it has been processing. Once the batch mode has begun, the processing can only be interrupted by the user pressing Control-C or Control-Break which does not save these data. The computer run will then have to be restarted from the first step performed under batch mode.

#### REFERENCES

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- Lucas, J.R., 1985: Automated data ordering in photogrammetry, Vermessung Photogrammetrie Kulturtechnik, 83, pp. 335-339.
- Lucas, J. R. and G. L. Mader, 1989: Recent advances in kinematic GPS photogrammetry, Journal of Surveying Engineering, 115 (1), pp. 78-92.
- Mader, G. L., (National Geodetic Survey Division, Charting and Geodetic Services, National Ocean Service, National Oceanic and Atmospheric Administration, Rockville, MD 20852) 1989: NAV22 program (unpublished manuscript).



APPENDIX A. -- SAMPLE DATA FOR FIVE FILES

Exhibit A: Sample Data for File A:SYSTCAL.DAT

	1	2	3	4	5	6	Record No.
12345678901234567890123456789012345678901234567890							
TX_SDHPT		153.280					1
		-1.740	0.060		0.640		2
PROJECT	GPS TEST - Rockdale, TX - Sept 1986						3
ICODE	4203						4
GEOIDH	-24.859						5
EPHINT	1.0						6
USEREF	.TRUE.						7
ASIGE	0.02						8
ASIGN	0.02						9
ASIGH	0.04						10
ASIGT	0.000015						11
ASIGM	0.005						12
*****							13

Record No.	Description	Units	Format	Comment
1	Focal Length	mm	(A8,3X,F15.3)	Required
2	Antenna-Camera Offset Vector	meters	(A8,3X,3F15.3)	Required
3	Project Title	-	(A8,2X,A40)	Optional
4	State Plane Zone Code	-	(A8,2X,I4)	Optional
5	Geoid Height	meters	(A8,2X,F10.3)	Optional
6	Antenna Ephemeris Interval	sec	(A8,2X,F10.3)	Optional
7	Apply Atmospheric Refraction	T or F	(A8,2X,L7)	Optional
	A Priori Standard Error in:			
8	Antenna Easting	meters	(A8,2X,F10.3)	Optional
9	Antenna Northing	meters	(A8,2X,F10.3)	Optional
10	Antenna Elevation	meters	(A8,2X,F10.3)	Optional
11	Exposure Time	sec	(A8,2X,F10.3)	Optional
12	Image Coordinates	mm	(A8,2X,F10.3)	Optional
13	End-of-Data Record		(A8)	Required

Exhibit B: Sample Data for File A:CONTROL.DAT

	1	2	3	4	5	6	Record No.
12345678901234567890123456789012345678901234567890							
AIRCRAFT-965823.4749	305244.5997		123.652		98.503		1
AIRCRAFT	0.010	0.010	0.010				2
H58 -970035.6840	303906.1039		144.097				3
H58	0.030	0.030	0.030				4
H58L	0.000	0.000	146.530				5
H58L	100.000	100.000	0.030				6
H58R	0.000	0.000	145.033				7
H58R	100.000	100.000	0.030				8
H60 -970016.8954	303914.5872		134.932				9
H60	0.030	0.030	0.030				10
H60L	0.000	0.000	135.258				11
H60L	100.000	100.000	0.030				12
H60R	0.000	0.000	134.216				13
H60R	100.000	100.000	0.030				14

Notes:

1. Pairs of records are read using the format A8,4F12.3/8X,3F12.3 and the items read are: name, longitude, latitude, orthometric height, ellipsoidal height, and a priori standard errors in easting, northing and height. Angles are in the form DDDMMSS.SSS and all other quantities are in meters.
2. The name of the first point in the file must be "AIRCRAFT" and must provide the starting (and ending) position of the antenna, if GPS observations are to be used.
3. In records 5 and 6, 7 and 8, etc., the longitude and latitude of elevation only control points can be set to zero, because a standard error of 100 meters directs GAPP to use the longitude and latitude computed by the single ray intersection method.
4. The number of ground control points is limited to 50 in the present version of GAPP.

Exhibit C: Sample Data for File A:ANTENNA.EPH

	1	2	3	4	5	6
123456789012345678901234567890123456789012345678901234567890						
19:20:25.74	-6753.157	-13045.586	-22111.492			1
19:20:26.74	-6700.160	-13037.909	-22085.425			1
19:20:27.74	-6647.062	-13030.484	-22060.090			1
19:20:28.74	-6593.932	-13022.505	-22035.249			1
19:20:29.74	-6540.793	-13014.752	-22010.424			1
19:20:30.74	-6487.648	-13006.547	-21985.469			1
19:20:31.74	-6434.544	-12998.250	-21960.567			1
19:20:32.74	-6381.236	-12989.967	-21936.069			1
19:20:33.74	-6327.755	-12981.411	-21911.964			1
19:20:34.74	-6274.198	-12972.926	-21887.709			1
19:20:35.74	-6220.517	-12964.389	-21863.449			1
19:20:36.74	-6166.680	-12956.450	-21839.453			1

Notes:

- Records are read using the format 1X,I2,1X,I2,1X,F5.2,3F11.3,2X,I4 and the items are: hour, minute, seconds, DX, DY, DZ, and scaling factor. The time is GMT and coordinate data are WGS-84 in meters, relative to the position of "AIRCRAFT" given in file CONTROL.DAT.
- The scaling factor should be 1 unless some data were missing from the NAV22.OUT file due to the receiver failing to record one or more observations. In this case, the entry must be estimated by interpolating and a scale factor entered to reflect its uncertainty. A rule-of-thumb is given in the following table of scale factors for number of consecutive entries missing:

Number of Missing Table Entries	Scale Factor(s)
1	15
2	25, 25
3	28, 40, 28
4	28, 44, 44, 28
5	28, 46, 185, 46, 28
6	28, 46, 200, 200, 46, 28
7	28, 46, 200, 500, 200, 46, 28
8	28, 46, 200, 500, 500, 200, 46, 28
9	28, 46, 200, 500, 2000, 500, 200, 46, 28

- Program GETEPH is designed to produce ANTENNA.EPH from NAV22.OUT. The source code of the program is provided on the distribution disk.

Exhibit D: Sample Data for File A:EXPTIME.OBS

1	2	3	4	5	6
123456789012345678901234567890123456789012345678901234567890					
286	19 21	6.291469	51C0295		
286	19 21	9.830104	51C0296		
286	19 21	13.369570	51C0297		
286	19 21	16.906830	51C0298		
286	19 21	20.584096	51C0299		
286	19 21	24.119783	51C0300		
286	19 25	29.017413	52N0316		
286	19 25	32.412722	52N0317		
286	19 25	35.524305	52N0318		
286	19 25	38.775806	52N0319		
286	19 25	42.027035	52N0320		
286	19 25	45.703901	52N0321		
286	19 29	54.606430	53S0338		
286	19 29	58.168333	53S0339		
286	19 30	1.587019	53S0340		
286	19 30	5.148653	53S0341		
286	19 30	8.708367	53S0342		
286	19 30	11.981909	53S0343		

Notes:

1. Records are read using the format 4X,I2,1X,I2,1X,F9.6,2X,A8 and the items are: day of year (which is skipped over), hour, minute, seconds, and photo ID string.
2. A camera position and attitude estimate will be computed for each exposure in this file, but only those photos for which a set of image coordinates are provided in file IMAGECO.OBS will be used thereafter.

Exhibit E: Sample Data for File A:IMAGECO.OBS

1 2 3 4 5 6  
 123456789012345678901234567890123456789012345678901234567890

-----  
 51C0296

31!	-65416	-89346
H60R	-95757	-37092
H60	-86685	-7628
33!	-75595	-4004
H60L	-89323	29805
35!	-66562	95596
36!	1601	92629
H61L	-11824	42649
H61	-7700	1426
H61R	-7461	-44772
H62R	61181	-30782
H62	61101	4878
H62L	57202	44624
13!	85709	97806
15!	93097	1615
68!	17319	-85638
73!	88706	-86246

\*\*\*\*\*

51C0297

36!	-63213	91629
H61L	-78319	42218
H61	-75831	937
H61R	-76876	-45133
H62R	-8214	-33592
H62	-7474	1945
H62L	-10327	41702
13!	19785	93693
15!	24322	-2431
16!	93129	1176
18!	84343	97710
68!	-53485	-86697
73!	17990	-89728
78!	86385	-74043

\*\*\*\*\*

-----  
 Notes:

1. Records are read using the format A8,2X,2F10.3. The first, or header, record for each photo contains only the photo ID string. This record is followed by up to 30 image coordinate records that consist of ground point ID string and the x- and y-coordinates of the image in millimeters (when the decimal point is inserted according to the format statement). The last, or trailer, record of each photo consists of a string of eight \*'s.
2. The present version of GAPP is limited to 400 photos and 400 ground points.



## APPENDIX B. -- ERROR MESSAGES

The following list of error messages is presented in alphabetical order and includes all such messages that the user of GAPP may encounter. The errors cited by these messages are fatal to execution of the program. There are a few exceptions which are noted.

### \*\*\* Antenna-Camera Offset Vector not on System Calibration Data File \*\*\*

The second record of file SYSTCAL.DAT must provide the components of the camera-to-antenna offset vector. If GPS observations are not going to be used, a record can be inserted with all components zero.

### \*\*\* Antenna Observation for Photo cccccccc Out of Sequence \*\*\*

If GPS antenna observations are used, there must be an observation for every photo, which means that every photo with an image coordinate data set on file IMAGECO.OBS must have an exposure time record on file EXPTIME.OBS. If a full set of GPS observation data is not available, dummy exposure time records must be inserted. If this is done, the standard error scale factors for the five antenna ephemeris records nearest to the dummy time should be set equal to 9999 so that this false pseudo-observation does not affect the adjustment.

### \*\*\* END-OF-FILE READING RECORD NO. nnn FROM IMAGE OBSERVATION FILE \*\*\*

Image coordinates appear on file IMAGECO.OBS as sets associated with a particular photo and terminated with a record having 8 \*'s in the ID field. GAPP encountered an end-of-file on that file before reading the termination record. Check the last photo on the file for a valid termination record.

### \*\*\* ERROR nnnn OPENING cccccccccccccc \*\*\*

Error number nnnn was returned by the system when processing a request to open a file named ccc..., where nnnn is an integer and ccc... is a string of up to 14 characters.

### \*\*\* ERROR nnnn READING cccccccccccccc (Record No. mmmmm) \*\*\*

Error number nnnn was returned by the system when processing a request to read from a file named ccc..., where nnnn is an integer and ccc... is a string of up to 14 characters.

### \*\*\* ERROR nnnn WRITING cccccccccccccc (Record No. mmmmm) \*\*\*

Error number nnnn was returned by the system when processing a request to write to a file named ccc..., where nnnn is an integer and ccc... is a string of up to 14 characters.

\*\*\* FATAL ERROR: TOO MANY GROUND POINTS \*\*\*  
\*\*\* Parameter NGPmax must be > or = nnn \*\*\*

The current adjustment involves more than the maximum number of ground points (400) allowed in the current version of GAPP. In order to continue with this data set, GAPP must be recompiled with the parameter NGPmax increased to at least the integer specified by nnn. Alternatively, the total number of ground points can be reduced to 400 or fewer by deleting all images of certain ground points from the image coordinate file IMAGECO.OBS.

\*\*\* FATAL ERROR: TOO MANY PHOTOS \*\*\*  
\*\*\* Parameter NFRmax must be > or = nnn \*\*\*

The current adjustment involves more than the maximum number of photographs (400) allowed in the current version of GAPP. In order to continue with this data set GAPP must be recompiled with the parameter NFRmax increased to at least the integer specified by nnn. Alternatively, the total number of photographs can be reduced to 400 or fewer.

\*\*\* FATAL ERROR: TOO MANY CONTROL POINTS \*\*\*  
\*\*\* Parameter NGCmax must be > or = nnn \*\*\*

The current adjustment involves more than the maximum number of ground control points (50) allowed in the current version of GAPP. In order to continue with this data set GAPP must be recompiled with the parameter NGCmax increased to at least the integer specified by nnn. Alternatively, ground control points can be converted to pass points to bring the total number to 50 or fewer.

\*\*\* FATAL ERROR: TOO MANY IMAGES/PHOTO \*\*\*  
\*\*\* Parameter NIMmax must be > or = nnn \*\*\*

The current adjustment involves at least one photo that has more than the maximum number of images per photo (30) allowed in the current version of GAPP. In order to continue with this data set, GAPP must be recompiled with the parameter NIMmax increased to at least the integer specified by nnn. Alternatively, the number of images on every photo can be reduced to 30 or fewer.

\*\*\* FATAL ERROR: INSUFFICIENT STORAGE \*\*\*  
\*\*\* Parameter Lngmax must be > nnn \*\*\*

The current data set will produce a normal equation coefficient matrix with bandwidth too large to fit the array available. This message indicates that in order to continue with this data set, GAPP must be recompiled with the parameter Lngmax increased to at least the integer specified by nnn. However, increasing Lngmax to a value larger than 16384 is not recommended. It would be preferable to reduce the number of images per photo, especially in areas where strips of photos overlap.

\*\*\* First record in Ground Control Data File must be "AIRCRAFT"

Estimation of camera positions and orientations, function 1 from the main menu, has been chosen indicating that camera positions are to be estimated using the GPS antenna observations, but to do so requires that the first record of file CONTROL.DAT provide the initial position of the antenna. This error is not fatal, after pressing "ENTER" the main menu will reappear. If function 1 was selected by mistake, another selection can be made. If function 1 was intended, make sure that the first record of CONTROL.DAT has the ID string of "AIRCRAFT."

\*\*\* Ground Point ccccccc Appears on Only One Photo \*\*\*

The ground point whose ID string is cc... (a string of up to 8 characters) will not be used in the adjustment because it appears on only one photo. This message is only a warning and does not terminate execution.

\*\*\* GROUND POINT POSITION ESTIMATES MUST PRECEDE REORDER \*\*\*

Preparation for Aerotriangulation, function 3 from the main menu, has been chosen before the estimation of the ground point positions, function 2, has been performed. This error is not fatal, after pressing "ENTER" the main menu will reappear and function 2 can be selected.

\*\*\* Imaginary roots in single ray intersection \*\*\*

Estimation of a ground point position has failed because the ray from its image through the estimated position of the camera's perspective center does not intersect the Earth's spheroid. The camera position or orientation estimate obtained from file FRAMEPO.EST may be grossly in error due to an erroneous antenna position obtained from file ANTENNA.OBS. If this is found to be the case, check to see that the position of "AIRCRAFT" on file SYSTCAL.DAT is correct. Is the longitude measured west, but entered without the minus sign? Is the focal length being read from SYSTCAL.DAT correctly? It should be in millimeters with 3 digits after the decimal point and there should not be a minus sign. Are the image coordinates being read correctly from file IMAGECO.OBS? They should also be in millimeters with 3 digits after the decimal point, which need not appear in the record.

\*\*\* Insufficient Constraints for Aerotriangulation Adjustment \*\*

The minimum number of constraints for aerotriangulation are two in latitude, two in longitude, and three in elevation. This minimum can be satisfied with any combination of ground control points and/or GPS antenna observations.

\*\*\* Less than Three images on Photo ccccccc \*\*\*

There must be at least three images on every photo in order to perform an aerotriangulation adjustment. The coordinates of fewer than three images were found on file IMAGECO.OBS for the photo whose ID string is cc... (a string of up to 8 characters).

\*\*\* MORE THAN 30 PARAMETERS HAD TO BE FIXED TO AVOID SINGULARITY

Before beginning an adjustment, GAPP makes a check to see that there are sufficient constraints so that singularity of the normal equation coefficient matrix is not a problem. When observations are rejected as suspected blunders because of large residuals, there is a potential for the matrix to become singular, causing the results of the nearly completed adjustment to be lost. GAPP prevents this loss of information by fixing the parameter(s) involved at their current values so that the matrix will not become singular. The user is informed of this action and warned of the unreliability of the parameter(s) on the printer output. If more than 30 parameters have to be fixed in this manner, this means something is seriously wrong, so the adjustment is terminated and this message is displayed.

\*\*\* PHOTO ccccccc NOT FOUND ON CAMERA POSITION & ORIENTATION ESTIMATE FILE \*\*\*

The photo ID string cc..., a string of up to 8 characters, associated with a set of image coordinates found on file IMAGECO.OBS does not appear on the file FRAMEPO.EST, which was constructed using the names associated with exposure times given on file EXPTIME.OBS. Compare the name on IMAGECO.OBS with that on EXPTIME.OBS column by column; blanks are significant.

\*\*\* Premature End-of-File on cccccccccccccc \*\*\*

End-of-file was encountered while attempting to read from file ccc... (where ccc... is a string of up to 14 characters) and more records are expected from this file.

\*\*\* Record No. nnnn of Estimate Data file is not a ground point

The estimate data file has somehow been contaminated. Restart the adjustment from the beginning.

\*\*\* REORDER OF DATA MUST PRECEDE AEROTRIANGULATION ADJUSTMENT

Aerotriangulation, function 4 or 5 from the main menu, has been chosen before the preparation step, function 3, has been performed. This error is not fatal, after pressing "ENTER" the main menu will reappear and function 3 can be selected.

\*\*\* Too Many Resident Ground Points for MicroComputer \*\*\*

The maximum number of resident ground points that can be accommodated by GAPP is 40, and this number has been exceeded. This condition can often be corrected by reducing the number of images per photo where there are overlapping strips of photography.

\*\*\* THE ZONE CONSTANTS ARE NOT YET AVAILABLE FOR -nnnn

GAPP uses subroutines taken from program SPCS83 (also available from the National Geodetic Survey) for computing State plane coordinates and the constants needed to compute State plane coordinates in the zone specified by nnnn are not available. At the time GAPP 1.02 was completed, zone 5001 (AK 1) was the only zone for which constants were not available.

\*\*\* Vital Antenna Ephemeris Data Missing \*\*\*

Interpolation of the antenna ephemeris requires five consecutive ephemeris entries: the table entry nearest to the time of exposure and the two before and the two after it. One or more of these points is missing from the file. This condition can be avoided by using program GETEPH to construct the antenna ephemeris data file

