Feasibility of Balloon Trajectory Analysis Utilizing Analytical Photogrammetry

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Submitted to:
Officer-in-Charge
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Contract Number: N 189(188)55120A
Project Leader: Elmar R. Reiter

Technical Paper No. 45, Part II
Department of Atmospheric Science
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Fort Collins, Colorado

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INTRODUCTION

This report covers the work undertaken as an extension to Contract Number N 189(188) 55120A with Navy Weather Research Facility, Norfolk, Virginia. The extended effort was in the manner of a feasibility study to determine whether photogrammetric methods and equipment developed under the original contract could be used to study the trajectory of a ground-released balloon for some miles into the atmosphere. It is thought such data would be of high value in determining the detailed structure of wind shear phenomenon, as a function of altitude.

The investigators were successful in photographing a 1200 gm. balloon and defining its space position to a precision of around 1 part in 3000, under working conditions. However, complete trajectory data were not secured, due to the limitations of available equipment.

This report discusses the equipment and procedures used and the problems that were encountered in attempting to secure balloon trajectory data.

GENERAL

The methods of analytical photogrammetry provide a direct and feasible means of locating a moving object at any instant of time. Basically, this scheme amounts to a geometrical triangulation performed from the two end points of a precisely surveyed base line. Two K-24 aerial reconnaissance cameras were located at the end points of the base line and directed toward the balloon. Each camera was equipped with a 30 X sighting telescope through which the balloon was easily tracked. A picture may be simultaneously exposed at each camera site at any desired time interval, thus recording the position of the balloon as a function of time. The conversion of picture image to space coordinate description may take place at any convenient later time. The amount of data which must be directly gathered in the field is a minimum; the data that is required is simple enough to secure and relatively inexperienced field personnel can operate the system quite reliably.

To determine the space position of the balloon, two pictures are required; one from either end of the base line. An additional requirement is that both pictures should have been exposed as close as possible to the same instant of time. The photographic image position of the balloon is measured on each picture, using a .001 mm Mann Comparator, and the direction lines to the balloon may be calculated. Knowing the space coordinates of each camera station and the direction lines from camera to balloon, the space coordinates of the balloon are easily calculated.

A detailed description of the camera and the mathematical reduction methods are to be found in the final report of the original contract (Reiter and Hayman, 1962), and will not be reported here.

RESECTION ORIENTATION OF TRACKING CAMERAS

In order to accomplish the mathematical conversion of photographic image to space coordinate description, it is necessary to know the orientation, in space of the principal axis of each camera, at the instant of picture exposure. In the initial measurement program, the angular attitude of the principal axis of each camera had been controlled and recorded by reference to a counting system included in the camera mounts. The success of this practice required that the cameras be maintained in perfect adjustment and that field operators devote much time and care in manipulating the equipment as the balloon followed its course. The general operational environment imposed conditions that normally prevented camera operation according to these prerequisites. In addition, since the angle-dials must be read rapidly during the course of other activities, there existed a large possibility for human error and subsequent loss of large portions of the trajectory. In fact, if the camera attitude is to be changed quite rapidly and if the period of operation during any one series of observations is long, any similarity between observed camera attitude and actual camera attitude is only approximate, with the equipment that was being used. Literature reveals that these problems are typical of optical measurement systems (Rosenfield, 1961).

To circumvent these problems, a modified resection technique was developed which allowed the recovery of the camera attitude data from each individual picture of the balloon. This technique works on the premise that if the theoretically true camera orientation is known, then the directions to selected objects in the picture could be determined and would contain only the random errors suffered as the photographic image positions are measured. Conversely, if the true directions were known from the camera station to a selected number of control points, then the characteristics of the camera lens and direction of the camera axis could be recovered and would contain only the random errors introduced in the image measurement process. Further, if enough control points were available, the random error of camera orientation could be made as small as one would like.

The resection process provides the additional advantage of relieving the camera operators of the responsibility of trying to keep records of the camera orientation and of having to keep the camera azimuth axis perfectly vertical. The mathematical details of the complete resection process are to be found in any good analytical photogrammetry reference, for example (Merritt, 1958). The complete details of this process are not, therefore, included in this report. The modified process, used in this work is, however, included as part of the complete image point analysis program shown, in Fortran Code, in the appendix to this report.

Obviously, a requirement for the use of the resection scheme to describe camera orientation is that a given number of control points be included in each picture. To this end, numerous physical features, surrounding each of three camera stations, were picked and their directions were measured several times with a precise theodolite. In an extended operation of this type, it would be advisable to erect target boards for this purpose to insure that well defined and unique objects be available in all areas of interest.

A complete analysis of errors involved in the total system was not undertaken in this preliminary study but error evaluations of a limited number of test cases seem to indicate that the camera axis was oriented with a probable error of 15 to 20 seconds of arc. This should mean that direction rays to the balloon images were computed with an error of about the same magnitude.

FIELD PROCEDURE

The actual process of photographing the balloon was quite simple; a number of fundamental operational problems arose, however, which prevented the acquisition of a very complete single history of balloon position.

Initially, a 100 gm balloon was launched and observed for several minutes to determine the general trend of its flight. This was necessary so that a pair of camera stations could be selected with the general objective that the balloon should be as near as possible to the perpendicular erected from the mid-point of the camera base line. In such a location, the balloon occupies the optimum mathematical position for its location by triangulation.

A 1200 gm balloon was then launched from such location as to satisfy the above mentioned condition during as much of the flight as possible. The balloon was inflated to such capacity that it rose at approximately 1500 ft. per minute.

During the course of a given flight, pictures were taken at the rate of 5 and 10 seconds per frame. To secure usable trajectory data, the exposure rate should probably be increased, at least during given periods, to perhaps one frame per second. The K-24 camera is not particularly well suited to such a rapid fire rate and considerable maintenance problems were encountered in keeping the cameras operating for an extended period at the 5 and 10 second rate.

Time of picture exposure was recorded by a stop watch mounted in front of each camera lens. Radio communications between each camera provided the means of synchronizing the time element to a fairly satisfactory degree.

LIMITATIONS AND PROBLEMS

One of the main problems connected with this study was the inherent limitation imposed by the resection solution. As was stated earlier, this process requires that a number of control points be visible in each photograph. This means that the camera can only be inclined to a limited extent before the horizon passes out of the picture. In the case of the K-24 camera, equipped with a 178 mm lens, the limiting angle of inclination was 20 degrees. This means that the balloon could only be tracked for 40 degrees above the horizontal, or only a limited portion of its flight. The fraction of the flight which could be tracked depended on how close the balloon was to a given camera. A circle of limitations was thus established: if the balloon were launched a sufficient distance from the camera so that it might be tracked for a reasonable lenght of time, then the balloon was not visible on the photograph; if the balloon were brought close enough to be photographed, then it could only be tracked for a short time. No optimum combination of events was realized in this preliminary study, even though satisfactory data was acquired for the initial phases of several flights.

To have increased the picture magnification by using a longer focal length lens would have further reduced the photographic lens angle, and thus have introduced further restrictions to camera elevation angle.

At this point, the investigators contacted personnel at the RCA Missile Test Project, Atlantic Missile Range, Patrick Air Force Base, Florida. Literature published by this group (Rosenfield, 1961) and (Smith, 1960) had indicated that problems such as those mentioned herein were being circumvented in missile tracking operations, at the Atlantic Missile Range, Subsequently, a visit was made to the

Atlantic Missile Range for the purpose of observing tracking equipment and discussing capabilities and limitations. As a result of these discussions, and through the overall efforts of this study, several recommendations are presented for any future work which may be contemplated in studying balloon trajectories.

RECOMMENDATIONS FOR FURTHER STUDY

1. The use of special pieces of commercially available photographic equipment should be considered. Such a system as the Askania Cine Theodolite will provide camera orientation data to a theoretical accuracy of 5 to 10 seconds of arc, independent of a resection process. Operating accuracies of such a system are commonly in the range of 30 to 40 seconds of arc. Such systems are specifically designed to operate as tracking equipment; the object being tracked may be kept at the optical center of the photograph by reference to a powerful viewing telescope whose axis is concident with that of the camera lens. Taking advantage of this feature, the object need not be continuously visible on the photograph itself; as the direction to the object will be identical to the direction of the camera axis. The camera orientation is automatically and continuously recorded on the photograph, along with the time of picture exposure.

2. Consideration should be given to photographing an illuminated object carried by the balloon during a night flight. Such a procedure would allow the stars to be used as objects for the space resection recovery of the camera attitude. A long focal length lens could be used and thus guarantee that the illuminated object be continuously visible on the photograph. Multiple exposures could be made on one

picture frame to record a good portion of the trajectory on that single frame. This procedure would simplify the data reduction process as well as make it less time consuming and less costly. Glass plate film could be used which would cut down, significantly, on the problem of film shrinkage. Random atmospheric light refraction would be reduced as the atmosphere is generally more stable during the night. This type of program offers, perhaps, the highest potential of absolute accuracy of any of the photogrammetric processes available.

3. Consideration should be given to linking the companion cameras together so that they may be fired at exactly the same instant of time in response to a master time element.

REFERENCES

1. Reiter, E. R. and R. W. Hayman, 1962: On the nature of clear-air turbulence. Atmospheric Science Technical Paper No. 28, Scientific Interim Report prepared for Navy Weather Research Facility. Colorado State University Research Foundation.
2. Rosenfield, G. H., 1961: Present and future capability of optical systems with emphasis on the ballistic camera operation. Photogrammetric Engineering, March 1961.
3. Merritt, E. L., 1958: Analytical photogrammetry. New York, Toronto, London. Pitman Publishing Corporation.
4. Smith, E. S., 1960: Askania Cine-Gheodolite Reduction Manual. RCA data processing technical report No. 56. AFMTC-TR, ASTIA Document No. 60-1.

APPENDIX

GENERAL

The computer program, written in FORTRAN II code, was designed to solve, by spacial triangulation, for the location of any desired object which appears on each of two separate photographs; the two photographs having been taken by any two of four specially mounted K-24 cameras available to the project. The program is not a completely general photographic triangulation solution but is contrived to accept input data in a form most convenient to the specific pieces of equipment available to the project. The program corrects the image position for lens distortion and automatically assigns the correct focal length, (steps 21 + 1 through 22), according to an input code (ICAM) designating which of several cameras were used. Since the focal length and lens distortion patterns vary from camera to camera, this part of the program would have to be revised before it could be used with other equipment.

As an optional feature of the program, the spacial attitude of the cameras may be reported as input data, rather than relying on the resection process to provide this information. The use of an extra input card, called a code 4 card, converts the program from automatic resection to use of assigned camera orientation.

A sample data sheet, showing the input data and its arrangement on the input cards, is shown in Table I. One each of code 1 and 2 cards is required per photo pair. The code 3 cards come next in order; the program will accommodate any number of code 3 cards, up to 100. The first of the code 3 cards relate to reference points which are used in the resection process. The reference points are fully described by giving the direction of each point from the appropriate camera station and the photographic image position of the reference point. The reference points used need not be common to the two photos being analyzed. A maximum of ten of the code 3 cards may be used to describe the reference points; the remainder of the code 3 cards are reserved for the photographic image descriptions of those objects being measured. One code 4 card is included only if the camera orientations are to be offered as input data. The code 4 card, if needed, immediately precedes the code 3 cards.

In operation, the program is a one-pass system with output being punched on standard IBM cards. The standard library subroutines for the trigonometric functions and the square root must be added to the object deck before processing.data. A listing of the source program statements for the entire problem is included in a later portion of this appendix.

Data Input Form for Stereophotography Program

Code 1 Card - Basic Information

Item	IYR	MON	IDAY		INIT		INIO	J	K	ICAM(1)	ICAM(2)	D →
Data												
Column	1 3	4 6	7 9		11 17		19 21	22 24	25 28	29 30	31 32	33

Item	D	ROTB	XC	YC	ZC
Data					
Column	39	40 49	50 58	59 66	67 72

Code 2 Card - Centerline and Shrinkage

Item	XLC	ZLC	XRC	ZRC	
Data					
Column	1 8	9 16	17 24	25 32	33 36

Item	SFX(1)	SFZ(1)	SFX(2)	SFZ(2)
Data				
Column	37 45	46 54	55 63	64 72

Code 4 Card - Camera Orientation (If Needed)

Item	AZ(1)	AZ(2)	VANG(1)	VANG(2) →
Data				
Column	1 10	11 20	21 29	30

Item	VANG(2)	
Data		
Column	38	39

Code 3 Cards - Point Coordinates

Item	X(L)	Z(L)	AZCO(L)	VERCO(L)	X(R)	Z(R)	AZCO(R)	VERCO(R)
Columns	1-8	9-16	17-26	27-35	36-43	44-51	52-61	62-70
Data:Pt.1								
etc.								
100								

PROGRAM DOCUMENTATION

I. Variable Names, Descriptions, and Data Sizes

X : Horizontal coordinate on photograph; input, size ± XXX. XXX millimeters; dimensioned (2, 100) -- number 1 in first subscript position refers to data from left-hand photograph and number 2 refers to data from right-hand photograph; number 100 in second subscript position indicates that up to 100 photographic objects may be referred to per photographic pair.

Z : Vertical coordinate on photograph; input, size ± XXX. XXX mm; dimensioned (2, 100).

XLC: Horizontal location of optical center on left photo with respect to X, Z coordinate origin; input size ± XXX. XXX mm.

ZLC: Vertical location of optical center on left photo with respect to X, Z coordinate origin; input size ± XXX. XXX mm.

XRC: Horizontal location of optical center of right photo with respect to X, Z coordinate origin; input size ± XXX. XXX mm.

ZRC: Vertical location of optical center of right photo with respect to X, Z coordinate origin; input size ± XXX. XXX mm.

F: Camera focal length, F(1) left camera, F(2) right camera; size ± XXX. XXX mm.

IYR: Year of photograph pair; input size XXX.

MON: Month of photograph pair; input size XXX.

IDAY: Day of photograph pair; input size XXX.

INIT: Time of exposure; input size XXXXXXX.

INIO: Photo pair sequence number; input size XXX.

J: Maximum number of control points in either photo pair used for resection to find camera axial orientation.

K: Number of object points common to both photos whose spatial location is desired.

I: Sum of J and K (limited to 100).

ICAM: Number (1, 2, 3, or 5) assigned to each of the four K-24 cameras available for the study; ICAM(1) designated left camera; ICAM(2) designated right camera; input, size XX.

ICAN: Temporary location for ICAM.

D: Length of camera triangulation base line; input size XXXXX. X feet.

ROTB: Clockwise rotation of triangulation base line needed to make perpendicular to base line point north; input, size ± XXX. XXXXX degrees.

XC, YC, ZC: The spatial position of the left hand camera in which grid system the spatial location of the targets will be computed by the program (this study used the Northern Zone of the Colorado State Plane Coordinate System and elevation above mean sea level as the reference system); input, sizes ± XXXXXXX. feet, ± XXXXXX. feet, and ± XXXX. feet respectively.

SFX: Horizontal shrinkage of film from exposure to data reduction: ratio of photographic reference dimension to comparable glass plate dimension. SFX(1) - left photo shrinkage, SFX(2) - right photo shrinkage; input, size ± X. XXXXXX.

SFZ: Vertical shrinkage of film from exposure to data reduction: ratio of photographic reference dimension to comparable glass plate dimension. SFZ(1) - left photo shrinkage, SFZ(2) - right photo shrinkage; input, size ± X. XXXXXX.

E: Conversion factor from degrees to radians.

AZCO: Known azimuth from camera to control point used in resection process -- assumed zero for input of object points whose location is desired; input, size ± XXX. XXXXX degrees.

VERCO: Known vertical angle from camera to control point used in resection process -- assumed zero for input of object points whose location is desired; input. size ± XX. XXXXX; up is positive, down is negative.

R: Distance on film optical center to any point under consideration

($R = \sqrt{X^2 + Z^2}$).

RADD: Radial correction to R to correct for lens distortion; program steps 21 + 1 through 22 is the lens distortion correction sequence.

AZ: Horizontal orientation of camera principle axis if no resection analysis is to be used; input, size ± XXX.XXXXX; THIS INPUT CARD IS OMITTED IF RESECTION ANALYSIS IS USED; AZ(1) indicates azimuth of left camera, AZ(2) indicates azimuth of right camera.

VANG: Vertical orientation of camera principle axis if no resection analysis is to be used; input, size ± XX.XXXXX; THIS INPUT CARD IS OMITTED IF RESECTION ANALYSIS IS USED; VANG(1) indicates angle on left camera, VANG(2) indicates angle on right camera. Elevation angle is plus, depression angle is minus.

XO, YO, ZO: Coordinate location of a desired object point in the grid system assigned by the input spatial location XC, YC, and ZC of the left camera.

All other variables in the program are intermediate values in the solution of the spatial triangulation (steps 68 through 28).

II FORTRAN Source Program

```
*1208

      DIMENSION X(2,100),Z(2,100),F(2)
      DIMENSION VANG(10),AZCO(2,10),AZ(10)
      DIMENSION VERCO(2,10),ICAM(2),SINVA(2),COSVA(2),TANV(2)
      DIMENSION SECV(2),HANG(2,100),SFX(2),SFZ(2)
```

```
 1   READ  11, IYR, MON, IDAY, INIT, INIO, J, K, ICAM(1), ICAM(2), D,
         ROTB, XC, YC, ZC
11   FORMAT(3I3, 1X, I7, 1X, 2I3, I4, 2I2, F7. 1, F10. 5, F9. 0, F8. 0, F6. 0)
     PUNCH  12, IYR, MON, IDAY, INIT, INIO
12   FORMAT (10X, 5HDATE  I3, 1H/I3, 1H/I3, 5X, 5HTIME  I7, 5X, 6HPHOTO  I3)
     READ  13,XLC, ZLC, XRC, ZRC, SFX(1), SFZ(1), SFX(2), SFZ(2)
13   FORMAT(4F8. 3, 4X, 4F9. 6)
     E=0. 0174533
     ROTB=E*ROTB
     I=J+K
     DO  21M=1, I
     READ  14, X(1, M), Z(1, M), AZCO(1, M), VERCO(1, M),
    1X(2, M), Z(2, M), AZCO(2, M), VERCO(2, M)
14   FORMAT(2F8. 3, F10. 5, F9. 5, 2F8. 3, F10. 5, F9. 5)
     X (1,M)=XLC-X(1, M)
     X(2,M)=XRC-X(2, M)
     Z(1,M)=Z(1, M)-ZLC
     Z(2, M)=Z(2, M)-ZRC
21   CONTINUE
     DO  22  L=1, 2
     DO  23  M=1, I
     R=SQRTF(X(L, M)**2+Z(L, M)**2)
     COS=X(L, M)/R
     SIN=Z(L, M)/R
     ICAN=ICAM(L)
     GO  TO  (40, 41, 42, 1, 43), ICAN
40   IF  (R-36. 5)44, 44, 45
41   IF  (R-36. 5)46, 46, 47
42   IF  (R-31. 5)48, 48, 49
43   IF  (R-34. 0)50, 50, 51
44   RADD=0. 0000135*R**2+0. 000356*R
     GO  TO  55
45   RADD=-. 000214*R**2+0. 016644*R-0. 291
55   F(L)=178. 251
     GO  TO  60
46   RADD=0. 0000105*R**2+0. 000356*R
     GO  TO  56
47   RADD=-0. 000180*R**2+0. 013990*R-0. 244
56   F(L)=179. 430
     GO  TO  60
48   RADD=0. 0000141*R**2+0. 000254*R
     GO  TO  57
49   RADD=-0. 000175*R**2+0. 011929*R-0. 180
57   F(L)=180. 676
     GO  TO  60
```

```
50   RADD=0.0000155*R**2+0.000147*R
     GO TO 58
51   RADD=-0.000188*R**2+0.014304*R-0.246
58   F(L)=178.371
60   X(L, M)=(R-RADD)*COS/SFX(L)
23   Z(L, M)=(R-RADD)*SIN/SFZ(L)
22   CONTINUE
     IF (J)62, 61, 62
61   READ 15, AZ(1), AZ(2), VANG(1), VANG(2)
15   FORMAT (2F10.5, 2F9.5)
     AZ(1)=AZ(1)*E
     AZ(2)=AZ(2)*E
     VANG(1)=VANG(1)*E
     VANG(2)=VANG(2)*E
     GO TO 68
62   DO 24 L=1, 2
     SUMV=0.0
     SUMH=0.0
     NO=0
     DO 25 M=1, J
     IF (AZCO(L, M))63, 67, 63
63   AZCO(L, M)=E*AZCO(L, M)
     VERCO(L, M)=E*VERCO(L, M)
     C=SINF(VERCO(L, M))*SQRTF(X(L, M)**2+Z(L, M)**2+F(L)**2)
     PART 1=C*F(L)
     PART 2=F(L)**2+Z(L, M)**2
     PART 3=C**2-Z(L, M)**2
     IF (Z(L, M))64, 64, 65
64   OP=PART 1+SQRTF(PART 1**2-PART 2*PART 3)
     GO TO 66
65   OP=PART 1-SQRTF(PART 1**2-PART 2*PART 3)
66   AD=SQRTF(PART 2**2-OP**2)
     VANGT=ATANF(OP/AD)
     SUMV=SUMV+VANGT
     ZPRIM=Z(L, M)+F(L)*SINF(VANGT)/COSF(VANGT)
     HANGT=ATANF(X(L, M)/(F(L)/COSF(VANGT)-ZPRIM*SINF(VANGT)))
     SUMH=SUMH+AZCO(L, M)-HANGT
     GO TO 25
67   NO=NO+1
25   CONTINUE
     S=J-NO
     VANG(L)=SUMV/S
     AZ(L)=SUMH/S
24   CONTINUE
68   ANG=AZ(2)-3.1415927
     IF(ANG) 71, 71, 70
```

```
70   AZ(2)=AZ(2)-3.1415927
71   BNG=3.1415927-AZ(1)
     IF(BNG)  72, 72, 73
72   AZ(1)=6.2831854-AZ(1)
     GO  TO  74
73   AZ(1)=BNG
74   DO 26 L=1, 2
     SINVA(L)=SINF(VANG(L))
     COSVA(L)=COSF(VANG(L))
     TANV(L)=SINVA(L)/COSVA(L)
26   SECV(L)=1./COSVA(L)
     N=J+1
     DO 28  M=N, I
     DO 27  L=1, 2
     Z(L, M)=Z(L, M)+F(L)*TANV(L)
     HANG(L, M)=ATANF(X(L, M)/(F(L)*SECV(L)-Z(L, M)*SINVA(L)))
27   CONTINUE
     BETA1=AZ(1)-HANG(1, M)
     BETA2=AZ(2)+HANG(2, M)
     DELTA=3.1415927-BETA1-BETA2
     S1=D*SINF(BETA2)/SINF(DELTA)
     TANV1=Z(1, M)*COSVA(1)*COSF(HANG(1, M))/(F(1)*SECV(1)-Z(1, M)*
        SINVA(1))
     XP=S1*COSF(BETA1)
     YP=S1*SINF(BETA1)
     ZP=S1*TANV1+2.059*S1**2*10.**(-8)
     XO=XP*COSF(ROTB)-YP*SINF(ROTB)+XC
     YO=XP*SINF(ROTB)+YP*COSF(ROTB)+YC
     ZO=ZP+ZC
     PUNCH  16, M, XO, YO, ZO
16   FORMAT  (3X, I4, 12X, F10.1, 5X, F10.2, 5X, F10.3)
28   CONTINUE
     GO  TO  1
     END
```