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An easy to use, inexpensive, and rapid system for determination of tilt in an
aerial photograph has been developed at the Defense Mapping Agency Aerospace
Center. Image measurements are made with a calibrated template and tube magnifier.
Geodetic control points are then scaled from a large scale map source. Tilt
determination is then accomplished using Church's resection on a programmable
calculator, and allows for computation of surface feature lengths, widths, and
heights from a single image.

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TILT DETERMINATION OF
NON-VERTICAL PHOTOGRAPHY
USING A HANDHELD PROGRAMMABLE CALCULATOR

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Abstract

A system has been developed which allows the photo interpreter to determine the tilt of an aerial photograph. Input consists of image measurements made using a calibrated template and tube magnifier, and three geodetic control points scaled from large scale map source. Church's resection is used to compute the camera parameters on the Hewlett-Packard HP 41C program-mable calculator. Tilt determination allows computation of lengths, widths, and heights from a single image. These calculations follow naturally from the resection and are included in the system.

The system incorporates several desirable features. It is easy to learn and to use, and the resection converges within five minutes. The basic equipment is inexpensive and the calculator may be used for other applications.

1. INTRODUCTION:

A photo interpreter or photogrammetrist occasionally is presented non-vertical or oblique photography as his primary source for photogrammetric measurement. Poor flying conditions or inexperienced photographic technique frequently result in undesired nonverticality. Oblique photography may be chosen because a larger area of coverage can be achieved, and a look at the side of a feature to be analyzed permits a more reliable interpretation.

Whatever the source of tilt, the relatively simple measurements of vertical photography become extremely complicated and, without the assistance of a computer, prohibitively time-consuming.

A variety of disciplines rely upon on-the-site field measurements. For many, the level of sophistication does not warrant full-time use of a non-portable computing system. Recent developments in handheld programmable calculators make it possible to quickly resolve the tedious computations needed to determine the tilt of an aerial photograph. These instruments are precise and easy to use. Simple operating instructions and programmed prompts lead the operator through the procedure step-by-step with virtually no opportunity for blunders.

A computer program (Appendix B) was developed at the Defense Mapping Agency Aerospace Center (DMAAC) for the Hewlett Packard 41C calculator which determines the tilt of an aerial photograph using Church's Resection (Church, 1945). Horizontal and vertical ground measurements may then be computed for features on that photograph.

2. SOFTWARE:

Church's Resection was chosen because the math model, computation algorithm, and pre-tested data were readily available. Professor Earl Church developed the procedure and published it in 1945 in a Syracuse University technical paper. Virtually every theoretical photogrammetry student has cranked out the solution on a desk calculator or has programmed it in FORTRAN. The desk calculator procedure reputedly takes about six hours,

assuming no blunders. Present day students, after struggling through the first iteration, opt for the FORTRAN version (possibly an exercise designed to make students more receptive to the collinearity and coplanarity equations).

Professor Church's solution is iterative, and uses matrices and determinates to derive the exposure station coordinates and the swing and tilt of the aerial photograph (see American Society of Photogrammetry Manual of Photogrammetry, 1980). These values are defined in a rather unique coordinate system. He presents the solution in a "cookbook" form, and provides checks throughout to identify blunders.

Heights (Appendix A.II) and lengths (Appendix A.III) are computed by three digital rectification algorithms. One subroutine computes the direction cosines (Appendix A.I) of vectors from the principal point to the imaged nadir and to the base and top or the end points of the feature being measured. Image coordinates are then projected onto a horizontal plane passing through the nadir image. The vector passing from the principal point through the nadir is substituted for focal length in the conventional single image height and length equations (figures 1, 2, and 3).

The software design features repeated use of the direction cosine algorithm to reduce programming steps and conserve storage.

3. HARDWARE:

The HP 41C programmable calculator (Hewlett-Packard, 1979) was chosen because it had memory expandable to the requirements of the solution and because of the authors' familiarity with the programming language. (Choice of this calculator does not constitute endorsement by DMAAC of Hewlett Packard or the HP 41C calculator.) The HP 41C features continuous memory, LED display, and magnetic card reader. With memory modules, the calculator is expandable to more than 300 registers (250 with card reader attached). It is battery operated with very low power consumption, and accessories include rechargeable batteries. The system is suitable for office or field applications.

4. PROCEDURE:

Computing heights or lengths with this system consists of measuring map coordinates, measuring image coordinates, and operating the calculator program. The system concept was developed to increase accuracies with a minimum of operator training and a minimum of opportunity for operator error.

Map derived control is scaled from large scale map source such as United States Geological Survey (USGS) 1:24000 scale topographic maps. The user reads the Northing and Easting from the Universal Transverse Mercator (UTM) grid with, for example, the Metric Coordinate Reader (CR-2) (USGS, 1973), manufactured by USGS. The Geological Survey reports that 15 meter accuracies are expected with their 1:24000 maps.

A 1-centimeter grid aligned to the fiducials of the photo is fixed in place. To measure photo coordinates, the user counts the grid lines to determine centimeter values. Using a Bausch & Lomb calibrated tube magnifier, he reads x and y coordinates to a least count of 0.1 millimeter. (Choice of the Bausch & Lomb calibrated tube magnifier does not constitute endorsement by DMAAC of Bausch & Lomb or its products.) Paper stretch of the photo, image quality, and other factors will contribute to error; however, 0.2 millimeter accuracies are expected as a worst case.

To operate the calculator program, the user first runs the routines for Church's Resection (Appendix B, Line 01). Algorithms for length or height determination are then applied.

Church's Resection requires as input: 1) UTM Easting, Northing and height of three widely spaced, non-collinear photoidentifiable control points; 2) the x and y image coordinates of the control; 3) focal length of the camera; and 4) approximate UTM coordinates of the exposure station. These values are input into the calculator's storage registers. The user then starts the program to compute corrections to exposure station coordinates. With reasonable approximations (less than 1000 meters away from the true values), the solution converges after three or four iterations. Corrections to the revised coordinates of the exposure station will be less than one meter.

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The operator then executes the command to compute tilt - the angle nOp , imaged nadir, principal point, and imaged principal point; swing - the angle in the photo plane measured clockwise about the optical axis from the + y-axis to the imaged nadir; and azimuth of the principal plane - the UTM azimuth of the direction of tilt. These values are automatically stored for use in the following algorithms.

A subroutine called Direction Cosines (DC) (Appendix B, Line 413) computes the vector algebra common to the height and length determinations. The user must input into the storage registers the x, y of the feature of interest and focal length of the camera. That is, the base and top of a vertical feature or the end points of a horizontal feature.

The final step is to command the calculator to execute the height (Appendix B, Line 471) or the length (Appendix B, Line 491) subroutine.

The software was designed for practical photo interpretation applications and will give results comparable to those obtained with conventional vertical photography. Obviously, the geometry is strongest with a 152.43 cm focal length camera and control widely spaced to form a strong three-sided pyramid.

Distance measurements are considered to be small, such as the length of a bridge, the edge of a building, or a plot boundary. As with conventional vertical photography, no compensation is made for displacement due to elevation differences.

5. CONCLUSION:

The use of tilted aerial photography until now has been largely limited to qualitative applications. A photogrammetrist can use slightly tilted photography on a stereo plotter or the photo interpreter can send it to the photo lab for rectification. However, these procedures require elaborate optical equipment, are time consuming, and require highly skilled technicians.

The tools and procedures for the digital rectification described in this paper open new opportunities for the use of tilted photography. The components are inexpensive, reliable, and virtually maintenance free. The system is easily learned and can be used in either the office or field. Furthermore, a photo interpreter with access to a powerful programmable calculator will develop his own algorithms to make his time more productive.

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REFERENCE

American Society of Photogrammetry (1980), "Manual of Photogrammetry Fourth Edition", American Society of Photogrammetry, Page 62, 105 Virginia Ave., Falls Church, VA 22046.

Church, Earl (1945), "Revised Geometry of Aerial Photography", Syracuse University Bulletin 15, Syracuse, New York.

Hewlett-Packard (1979), "Owner's Handbook and Programming Guide HP-41C", Hewlett-Packard Company, 1000 N.E. Circle Blvd., Corvallis, OR 97330

United States Department of the Interior Geological Survey (1973), "Metric Coordinate Reader CR-1", United States Department of the Interior Geological Survey, 1340 Old Chain Bridge Road, McLean, VA 22101

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APPENDIX A

Math Model

I. Direction Cosines:

Image coordinates of nadir x_n , y_n and z_n

$$x_n = \overline{pn} \cos (90 - s) \quad (1)$$

$$y_n = \overline{pn} \sin (90 - s) \quad (2)$$

$$z_n = -f \quad (3)$$

where $\overline{pn} = f \tan t$,

s is swing,

f is focal length,

t is tilt, and

$\overline{pn}$ is the vector from the imaged principal point to the imaged nadir.

Computation of direction cosines l , m , and n .

$$l_i = x_i/d_i, \quad m_i = y_i/d_i, \quad n_i = z_i/d_i \quad (4)$$

$$\text{where } d_i = \sqrt{x_i^2 + y_i^2 + z_i^2} \quad (5)$$

Angles between vectors are computed using the cosine law:

$$\angle v_1ov_2 = \cos^{-1} (l_1 l_2 + m_1 m_2 + n_1 n_2) \quad (6)$$

where $\angle v_1ov_2$ is the angle at the principal point o between two vectors.

The value $\overline{on}$ is used in computing both heights and distances.

$$\overline{on} = f/\cos t \quad (7)$$

Refer to Figures 1, 2, and 3 for graphic representation of variables.

II. Height Determination:

b' and t' are points where vectors from the principal point to the base and top of the object being measured would intersect a horizontal plane passing through the imaged nadir.

$$\overline{nb'} = \overline{on} \tan \angle nob \quad (8)$$

$$\overline{nt'} = \overline{on} \tan \angle not \quad (9)$$

d_i' is the rectified image displacement.

$$d_i' = \overline{nt'} - \overline{nb'} \quad (10)$$

r' is the rectified radial distance from the imaged nadir to the rectified image of the base of the object.

$$r' = \overline{nb'} \quad (11)$$

H is the height of the exposure station above the object.

$$H = Z_o - H_F \quad (12)$$

where Z_o is the height of the exposure station above the datum (computed in Church's resection), and

H_F is the elevation of the object above the datum.

Substituting the values into the conventional height determination equation

$$\text{height} = d_i' H / r' \quad (13)$$

III. Length determination:

The equation for the length of an object on a conventional vertical aerial photograph is

$$L = l(Z_0 - H) / f \quad (14)$$

where L is the length of the object l is the imaged length of the object and the other parameters are as defined before.

Using the horizontal plane passing through the imaged nadir we can substitute the rectified image values:

$$L = l' (Z_0 - H) / \overline{on} \quad (15)$$

where l' is the rectified image length.

l' is the vector subtraction of the vectors $\overline{oe_1'}$ and $\overline{oe_2'}$, where e_1' and e_2' are the rectified image points of the ends of the object being measured.

$$l' = \overline{oe_2'} - \overline{oe_1'} \quad (16)$$

$$= \overline{oe_1'}^2 + \overline{oe_2'}^2 - 2 \overline{oe_1'} \overline{oe_2'} \cos \angle e_2' oe_1' \quad (17)$$

$$\overline{oe_1'} = \overline{on} / \sin \angle noe_1 \quad \text{and} \quad (18)$$

$$\overline{oe_2'} = \overline{on} / \sin \angle noe_2 \quad (19)$$

APPENDIX B

Program Listing

01	LBL ^T Y	41	XEQ 14	81	LBL 15
	CF 00		27.02601		CLX
	.00201		STO 56		LBL 50
	STO 56		-1		RCL IND 56
	48.05001		STO 57		X / 2
	STO 57		XEQ 04		+
	XEQ 15		26.03801		ISG 56
	-.00099		STO 57		GTO 50
	STO 59		.00801		SQRT
10	39.04101	50	STO 56	90	1/X
	STO 57		XEQ 13		1 E5
	XEQ 03		27.03501		X < > Y
	9.01701		STO 57		*
	STO 57		XEQ 06		STO IND 57
	XEQ 06		XEQ 12		LAST X
	XEQ 09		27.02901		3
	LBL 58		STO 57		ST- 56
	18		54.05001		RDN
	STO 56		STO 58		LBL 51
20	36	60	42.04401	100	STO IND 56
	STO 57		STO 56		ISG 56
	.00201		52		GTO 51
	STO 58		STO 59		.003
	STO 59		55		ST+ 56
	XEQ 08		STO 60		ISG 57
	.00201		43		GTO 15
	STO 56		STO 61		RTN
	48.05001		XEQ 07		LBL 02
	STO 57		BEEP		RCL 39
30	XEQ 15	70	View 44	110	RCL 51
	FS? 00		PSE		-
	GTO 10		View 43		100000
	-.00099		PSE		*
	STO 59		View 42		STO 51
	51.05301		STOP		RCL 40
	STO 57		XEQ 11		RCL 52
	XEQ 03		GTO 58		-
	XEQ 02		SF 00		100,000
	42.04701		GTO 58		*
40	STO 56	80	STOP	120	STO 52

121	RCL 41	161	RCL IND 57	201	ISG 56
	RCL 53		RCL IND 58		X < > Y
	-		*		LAST X
	100000		STO IND 56		R
	*		RCL 57		*
	STO 53		3		STO IND 56
	RTN		,		RDN
	LBL 03		9		ST- IND 56
	0		MOD		LAST X
130	STO IND 57	170	STO 57	210	ENTER /
	.003		ISG 58		ISG 56
	ST + 59		RCL IND 57		RTN
	LBL 52		RCL IND 58		RTN
	RCL 59		*		LBL 06
	3		STO IND 56		RCL 01
	+		ISG 58		RCL 03
	9		ISG 56		RCL 00
	MOD		GTO 53		RCL 04
	STO 58		RCL 56		XEQ 05
140	RCL IND 59	180	35	220	RCL 02
	RCL IND 58		X > Y?		RCL 03
	*		GTO 04		RCL 00
	STO IND 57		RTN		RCL 05
	ISG 59		LBL 14		XEQ 05
	GTO 52		RCL 48		RCL 02
	ISG 57		ENTER /		RCL 04
	GTO 03		ENTER /		RCL 01
	CLX		RCL 39		RCL 05
	STO 42		RCL 49		XEQ 05
150	STO 44	190	XEQ 54	230	RCL 01
	STO 46		RCL 40		RCL 06
	RTN		RCL 50		RCL 00
	LBL 04		XEQ 54		RCL 07
	.003		RCL 41		XEQ 05
	STO + 56		RCL 48		RCL 02
	1		LBL 54		RCL 06
	STO + 57		ST- IND 56		RCL 08
	42.04801		RDN		RCL 00
	STO 58		*		XEQ 05
160	LBL 53	200	ST+ IND 56	240	RCL 07

241	RCL 02	281	ISG 57	321	ST+ 56
	RCL 01		GTO 57		ST+ 57
	RCL 08		RCL IND 60		ISG 59
	XEQ 05		ST/IND 56		GTO 08
	RCL 06		.003		.003
	RCL 04		ST+ 57		ST+ 59
	RCL 03		8.003		3
	RCL 07		FS? 00		ST- 57
	XEQ 05		ST- 57		ISG 58
250	RCL 05	290	3	330	GTO 08
	RCL 06		ST+ 58		RTN
	RCL 03		6		LBL 09
	RCL 08		FS? 00		RCL 09
	XEQ 05		ST+ 58		RCL 08
	RCL 05		ISG 56		*
	RCL 07		GTO 56		RCL 12
	RCL 04		RCL IND 61		RCL 05
	RCL 08		CHS		*
	LBL 05		STO IND 61		-
260	*	300	RCL IND 59	340	RCL 15
	STO IND 57		CHS		RCL 02
	RDN		STO IND 59		*
	*		FC? 00		+
	ST- IND 57		RTN		STO 54
	ISG 57		1		RTN
	RTN		ST+ 58		LBL 10
	RTN		ST+ 59		-1.00901
	LBL 07		9.01703		STO 57
	RCL IND 59		STO 57		18.02601
270	CHS	310	.003	350	STO 56
	STO IND 59		ST+ 56		XEQ 13
	LBL 56		ISG 61		9.01703
	0		GTO 07		STO 57
	STO IND 56		RTN		27.01703
	LBL 57		LBL 08		STO 58
	DSE 58		RCL IND 56		.00201
	RCL IND 57		RCL IND 57		STO 56
	RCL IND 58		-		21
	*		STO IND 59		STO 59
280	ST+ IND 56	320	1	360	54

361	STO 60	401	RCL 07	442	STO 56
	1.00703		/		3.00901
	STO 61		ATAN		STO 57
	XEQ 07		X<O?		12.01301
	GTO 16		+		STO 55
	LBL 11		STO 40		LBL 18
	RCL 44		RCL 00		CLX
	ST+ 36		RCL 03		STO IND 55
	RCL 43		/		LBL 17
370	ST+ 37	410	ATAN	451	RCL IND 56
	RCL 42		STO 41		RCL IND 57
	ST+ 38		STOP		*
	RTN		LBL T DC		ST+ IND 55
	LBL 12		RCL 14		ISG 57
	RCL 27		RCL 40		ISG 56
	RCL 08		TAN		GTO 17
	*		*		ACOS
	RCL 28		STO 15		STO IND 55
	RCL 07		RCL 40		.00201
380	*	420	CHS	461	STO 56
	-		90		ISG 55
	RCL 29		+		GTO 18
	RCL 06		STO 16		RCL 14
	*		COS		CHS
	+		*		RCL 39
	STO 55		STO 00		COS
	RTN		RCL 15		/
	LBL 13		RCL 16		STO 17
	ISG 57		SIN		STOP
390	RCL IND 57	431	*	472	LBL T H
	STO IND 56		STO 01		RCL 13
	ISG 56		RCL 14		TAN
	GTO 13		STO 02		*
	RTN		STO 05		STO 13
	LBL 16		STO 08		RCL 17
	RCL 06		0.00201		RCL 12
	ACOS		STO 56		TAN
	STO 39		48.05001		*
	360		STO 57		STO 12
400	RCL 08		XEQ 15		RCL 13
		441	.00201	482	-

```

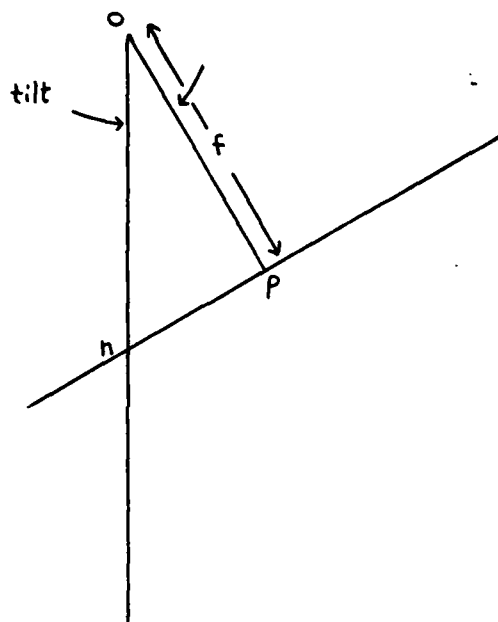
483 STO 11
    RCL 38
    RCL 28
    -
    *
    RCL 12
    /
490 STOP
    LBL 1 L
    RCL 17
    RCL 12
    SIN
    /
    STO 12
    RCL 17
    RCL 13
    SIN
500 /
    STO 13
    3.00501
    STO 56
    6.00901
    STO 57
    CLX
    STO 18
    LBL 19
    RCL IND 56
510 RCL IND 57
    *
    STO 18
    ISG 57
    ISG 56
    GTO 19
    RCL 12
    RCL 13
    *
    RCL 18

```

```

520 *
    2
    *
    CHS
    RCL 12
    X / 2
    +
    RCL 13
    X / 2
    +
530 SQRT
    STO 19
    RCL 38
    STO 19
    RCL 27
    RCL 28
    -
    *
    RCL 17
    /
540 STOP
    END

```



$$\overline{np} = f \tan \angle t$$

Low oblique photo viewed
in the plane nop

Figure 1

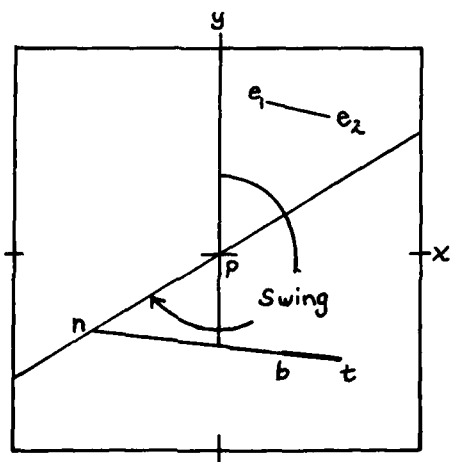
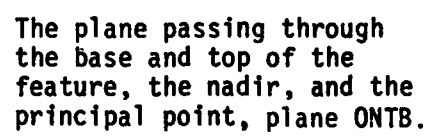
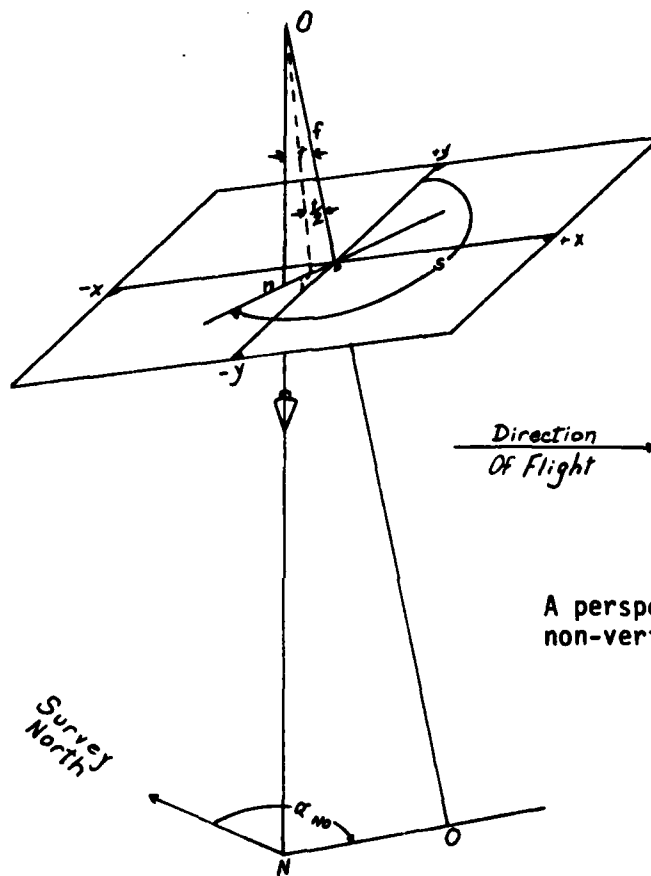


Photo plane of tilted aerial
photograph showing swing,
imaged nadir, and imaged
vertical feature.

Figure 2





A perspective view of a non-vertical photograph

Figure 4

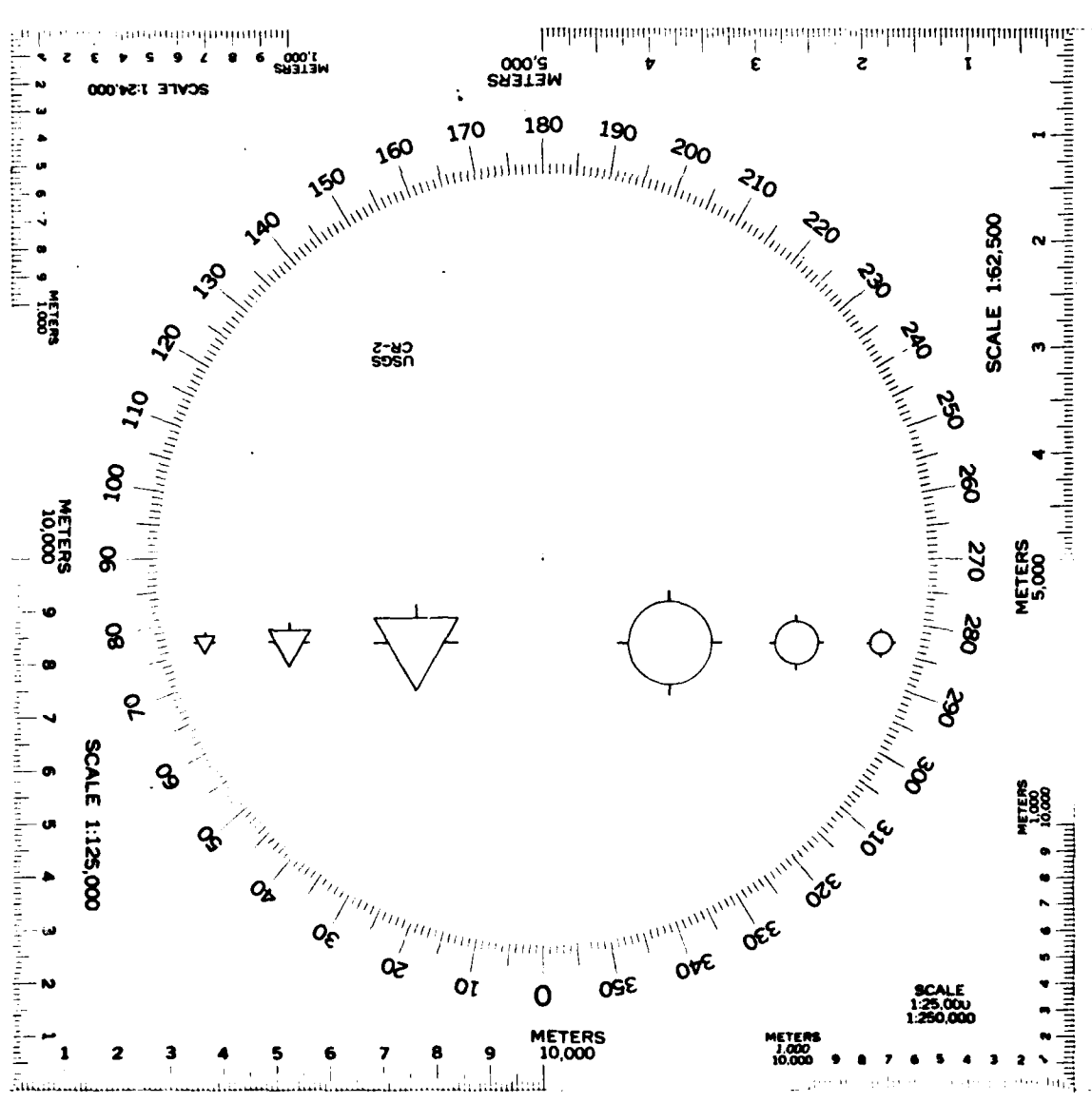


FIGURE 5. The CR-2 Metric Coordinate Reader

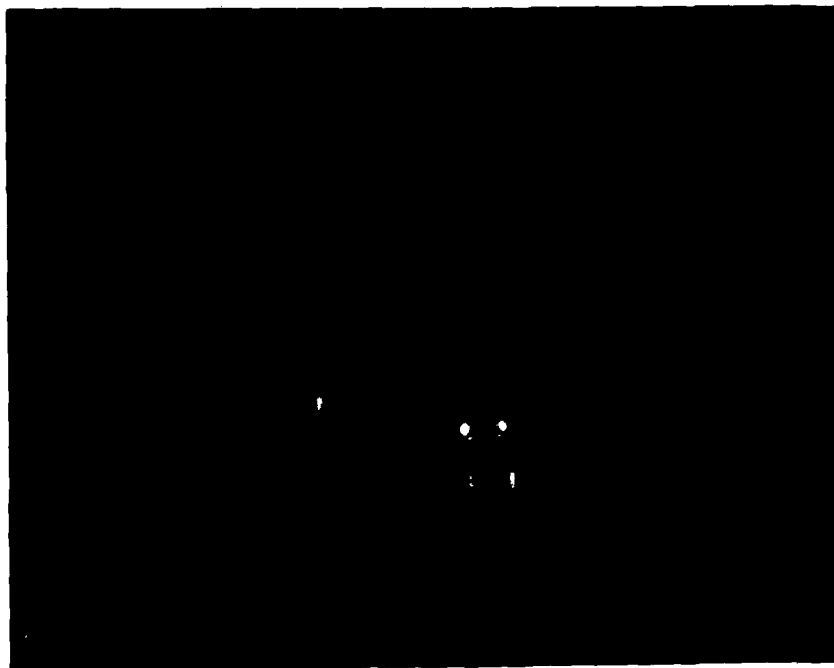


FIGURE 6. Bausch & Lomb Tube Magnifier



FIGURE 7. Measuring Photo Coordinates

Biographical Sketch

Roberta L. Braundel is a Cartographer (Photogrammetry) in the Techniques Office of the Air Target Materials/Nav-Plan Charting Division of the Aerospace Cartography Department at the Defense Mapping Agency Aerospace Center. She received her bachelors degree in Data Information Systems from Tarkio College and is currently working on her masters degree in Computer Science at the University of Missouri/Rolla. She is currently assisting in the development of various automated techniques associated with map and chart production as well as in the development of automated methods of chart production scheduling and control. Mrs. Braundel is a member of the American Congress on Surveying and Mapping and serves as Secretary of the St. Louis Section - ACSM.

Philip K. Alderman received his bachelors degree in mathematics in 1967 from Southern State College in Arkansas. He received his masters degree in Civil Engineering (Photogrammetry) in 1971 from the University of Illinois. His mapping career includes experience as a cartographer, analog and analytical Stereo Plotters, Aerial Photo-Inspector, instructor at the DMAIAGS Cartographic School and project engineer in the DMAIAGS Bolivia Project. He is currently assigned to the Techniques Office of the Air Target Materials/Nav-Plan Charting Division of the Aerospace Cartography Department at the Defense Mapping Agency Aerospace Center. Mr. Alderman is a member of the American Society of Photogrammetry and the American Congress on Surveying and Mapping.

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