CALIBRATION OF CAMERAS AND MULTIPLEX AEROPROJECTOR INSTRUMENTS

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AERIAL PHOTOGRAPHY HAS BEEN USED CONTINUOUSLY BY THE U. S. GEOLOGICAL SURVEY FOR SIXTEEN YEARS OR MORE AS AN AID TO THE CONSTRUCTION OF TOPOGRAPHIC MAPS. DURING A LARGE PART OF THIS PERIOD, IT HAS BEEN FELT THAT THE WORK OF THE TOPOGRAPHER WAS FACILITATED BY THE USE OF PHOTOGRAPHS AND INTEREST HAS OFTEN BEEN EXPRESSED AND SOME STUDY CARRIED ON IN PHOTOGRAMMETRY AS A BASIC MAPPING METHOD. DEVELOPMENTS ABROAD AND AT HOME, ESPECIALLY DURING THE PAST TEN YEARS, HAVE SHOWN VERY CLEARLY THAT THE GREATEST VALUE OF PHOTOGRAPHY TO THE MAP MAKER DOES NOT LAY IN ITS HELPFULNESS TO THE PLANE TABLE OPERATOR, WHICH IS VERY MATERIAL, BUT RATHER IN THE POSSIBILITY IT HAS FOR THE DEVELOPMENT OF NEW AND BETTER WAYS OF PRODUCING MAPS. THIS VALUE OF PHOTOGRAMMETRY AS AN ORIGINAL MAPPING METHOD IS NOW MORE GENERALLY RECOGNIZED BY PERSONS IN A POSITION TO JUDGE OF THE ADVANTAGE THAT WILL BE DERIVED FROM SUCH USE. IT IS BELIEVED THAT THIS INCREASED APPRECIATION OF THIS METHOD WILL BE SHARED ALSO BY MAP USERS OF THIS COUNTRY AS SOON AS TOPOGRAPHIC MAPS CONSTRUCTED BY PHOTOGRAMMETRICAL PROCESSES HAVE BEEN RELEASED FOR USE BY THE GENERAL PUBLIC. THE ADOPTION OF THESE NEW PROCESSES, WITH THE IMPROVEMENTS THAT MAY BE EXPECTED FROM TIME TO TIME, CARRY WITH THEM THE PROBLEM OF MAKING AND CALIBRATING MAPPING CAMERAS THAT WILL SUPPLY PHOTOGRAPHIC RECORDS OF A SUFFICIENT DEGREE OF ACCURACY. IT IS NECESSARY TO STUDY THE PROBLEM OF CAMERA CONSTRUCTION WITH THE VIEW OF INDICATING TO MANUFACTURERS THE QUALITY OF THE PHOTOGRAPHIC RECORD THAT MUST BE OBTAINED

STATEMENT OF IDEAL REQUIREMENT

PHOTOGRAMMETRY CAN ONLY ATTAIN ITS GREATEST USEFULNESS WHEN THE MATTER OF MAKING THE PHOTOGRAPHS IS APPROACHED WITH THE PURPOSE OF RECORDING AND PRESERVING THE TRUE ANGULAR INTER-RELATION OF DIRECTION LINES FROM THE CAMERA TO THE INFINITE NUMBER OF OBJECT POINTS THAT MAKE UP THE VIEW. THE EXACT PRESERVATION OF THIS BUNDLE OF DIRECTION LINES PRESENTS PROBLEMS THAT MUST BE SOLVED JOINTLY BY THE OPTICAL DESIGNER, THE MECHANICAL ENGINEER AND THE PHOTOGRAPHIC CHEMIST. THE POSSIBILITY OF ATTAINING GREAT ACCURACY IN THE MAPS TO BE DRAWN IN THE FUTURE IS DEPENDENT TO A GREATER DEGREE ON THE SUCCESSFUL APPLICATION OF PHOTOGRAMMETRY TO MAPPING PROBLEMS THAN ON ANY OTHER SOLUTION THAT OCCURS TO THE WRITER. HOWEVER, INCREASES IN ACCURACY OF MAPS SO CONSTRUCTED CANNOT BE OBTAINED WITHOUT CORRESPONDING INCREASES IN THE PRECISION WITH WHICH THE BUNDLE OF DIRECTION LINES IN THE VIEW CAN BE RECORDED AND LATER MEASURED IN THE LABORATORY. SO THE CAMERA BECOMES A SURVEYING INSTRUMENT IN FACT AND MUST BE SO REGARDED IF THE FULLEST ADVANTAGE IS TO BE TAKEN OF THE POSSIBILITY THAT PHOTOGRAPHY PRESENTS. IT IS NOT TOO MUCH TO EXPECT THAT AS A SURVEYING INSTRUMENT THE CAMERA BE EQUAL IN CONSTRUCTION AND ADJUSTMENT TO OTHER SURVEYING INSTRUMENTS AND YIELD RESULTS OF COMPARABLE PRECISION.

SINGLE LENS CAMERAS OF AMERICAN CONSTRUCTION, IN COMMON USE TODAY, WITH A VERY FEW EXCEPTIONS, CAN HARDLY BE CONSIDERED AS SURVEYING INSTRUMENTS. THERE IS NO REASON TO BELIEVE THAT THE REQUIREMENTS THAT MUST BE MET ARE BEYOND ACCOMPLISHMENT IF DIRECT EXPRESSION OF THE CHARACTERISTICS THAT A MAPPING CAMERA SHOULD HAVE CAN BE BROUGHT OUT BY DISCUSSION. IT IS BELIEVED THAT AN EXPLANATION OF THE NEED FOR CAREFULLY CONSTRUCTED CAMERAS WILL GO A LONG WAY TOWARD SECURING THE NECESSARY IMPROVEMENT IN DESIGN.

THE ESSENTIAL PARTS OF AN AERIAL MAPPING CAMERA ARE THE LENS, THE SHUTTER, THE CAMERA CONE, THE FOCAL PLANE, THE FIDUCIAL MARKS AND THE FILTER, IF ONE IS USED. EACH OF THESE PARTS OF THE CAMERA WILL BE CONSIDERED BRIEFLY WITH THE INTENTION OF POINTING OUT THE NECESSITY FOR CERTAIN TYPES OF CONSTRUCTION TO MAKE POSSIBLE THE DESIRED PRECISION IN CALIBRATING THE CAMERA FOR USE.

THE LENS

THE LENS SHOULD BE WELL CORRECTED THROUGHOUT WITH SPECIAL ATTENTION TO CURVATURE OF FIELD AND DISTORTION OF THE IMAGE. DISTORTION HAS SUCH A DETRIMENTAL EFFECT ON THE USE OF PHOTOGRAPHS FOR THE PURPOSE WE HAVE IN MIND THAT EFFORTS

SHOULD BE MADE TOWARD ITS ENTIRE ELIMINATION INSOFAR AS THIS IS POSSIBLE. CURVATURE OF FIELD SHOULD BE MINIMIZED TO SECURE THE MAXIMUM SHARPNESS OF IMAGE WHICH IS ONLY POSSIBLE WHEN THE FIELD IS FLAT AND CAN BE BROUGHT INTO COINCIDENCE WITH THE FOCAL PLANE OF THE CAMERA. FOR THOSE CASES WHERE A MARKED CURVATURE EXISTS, A RECOMMENDATION SHOULD BE MADE BY THE TESTING LABORATORY AS TO THE PRINCIPAL DISTANCE TO USE SO THAT THE SETTING OF THE LENS IN THE CONE WILL BE SUCH THAT THE FOCAL PLANE WILL CUT THROUGH THE CURVED FIELD IN A POSITION THAT WILL GIVE THE MAXIMUM SHARPNESS OF IMAGE THROUGHOUT THE FIELD.

THE REQUIREMENTS AS TO FOCAL LENGTHS AND ANGULAR FIELD OF VIEW WILL VARY BECAUSE THEY MUST BE COORDINATED WITH THE MAPPING APPARATUS WITH WHICH THEY WILL BE USED. IT MAY BE SAID, HOWEVER, THAT A MARKED REDUCTION IN THE COST OF TOPOGRAPHIC MAPS CAN BE SECURED WHEN THE FIELD OF VIEW IS ENLARGED, SO IT IS IMPORTANT THAT THE EFFORT BE MADE TO GREATLY INCREASE THE FIELD WITHOUT DETRACTION FROM THE QUALITY OF THE IMAGE IN ANY DEGREE. MAPPING APPARATUS IS NOW AVAILABLE THAT REQUIRES A 90° FIELD OF VIEW IN THE CAMERA LENS IF THE UTMOST ECONOMY OF OPERATION IS TO BE SECURED. THE ADVANTAGES OF A WIDE ANGLE OF VIEW WILL BE APPRECIATED AFTER CONSIDERATION OF THE FOLLOWING TABULATION WHICH ASSUMES THE USE OF THE PHOTOGRAPHS IN THE MULTIPLEX AEROPROJECTOR:

RELATIVE EFFICIENCY OF NORMAL AND WIDE-ANGLE CAMERA FOR MULTIPLEX MAPPING
(SATISFACTORY COVERAGE ASSUMED FOR BOTH PLATES)

	7 x 9 INCH CAMERA	9 x 9 INCH CAMERA
HEIGHT ABOVE REFERENCE PLANE	18,700 FT.	18,700 FT.
EQUIVALENT FOCAL LENGTH	8.25 INCHES	6.00 INCHES
ANGULAR FIELD OF VIEW	69° 20'	93°
FORWARD OVERLAP	60%	60%
SIDE LAP	25%	25%
AIR BASE (NET GAIN FORWARD)	8,160 FT.	11,220 FT.
BASE ALTITUDE RATIO	1:2.29	1:1.67
NET GAIN LATERALLY	11,900 FT.	21,037 FT.
NEGATIVE SCALE	1:27,200	1:37,400
NET AREA PER PAIR (IDEAL CASE)	3.49 SQ.MI.	8.46 SQ.MI.
NUMBER OF STEREOSCOPIC MODELS PER 15' QUADRANGLE LATITUDE 35°	84	36
AREA PER MODEL (ACTUAL CASE)	2.92 SQ.MI.	6.8 SQ.MI.
PLOTTING SCALE ON MULTIPLEX	1:15,480	1:15,480
RECOMMENDED CONTOUR INTERVAL	50 FT.	30 FT.
ACCURACY OF DELINEATION OF CONTOURS	±25 FT.	±15 FT.
RELATIVE SENSITIVITY OF MEASUREMENT OF ELEVATION (0.1 MM. LINEAR PARALLAX)	11.91 FT.	9.08 FT.
ESTIMATED TIME PER MODEL ON MULTIPLEX	7 HOURS	10 HOURS
ESTIMATED TIME PER SQ. MI. ON MULTIPLEX	2.4 HOURS	1.47 HOURS

COMPARING THE FIGURES GIVEN ABOVE, IT WILL BE SEEN THAT THERE ARE LESS THAN ONE-HALF AS MANY PLATES OF THE WIDE-ANGLE TYPE TO HORIZONTALIZE AS IN THE CASE OF THE NORMAL TYPE OF PHOTOGRAPH, AND, ASSUMING THE SAME NUMBER OF HORIZONTAL AND VERTICAL CONTROL POINTS FOR THE AREA IN EACH CASE, THERE WILL BE A GREATER NUMBER OF POINTS PER MODEL FOR THE WIDE ANGLE PHOTOGRAPHS WITH A GREATER INCREASE IN STRENGTH OF THE WORK. THE BASE ALTITUDE RATIO IS MUCH IN FAVOR OF THE WIDE-ANGLE TYPE OF PHOTOGRAPH RESULTING IN A GREATER ACCURACY IN MEASUREMENT OF VERTICAL DISTANCES, THE GAIN BEING ABOUT 30% BASED ON COMPUTATIONS FOR LINEAR PARALLAX. THE LARGE AREA PER MODEL WILL PERMIT GREATER SEPARATION OF CONTROL, OR PASS, POINTS WHICH MAKES FOR MORE ACCURATE CORRESPONDENCE SETTINGS. THERE WILL BE FEWER EDGES AT WHICH AN ACCURATE JUNCTION OF MODELS MUST BE SECURED, LESS PHOTOGRAPHIC FLYING, THE POSSIBILITY OF REDUCING THE AMOUNT OF CONTROL AND FINALLY AS A RESULT OF THE FAVORABLE FACTORS THAT HAVE BEEN MENTIONED, A REDUCTION IN COST OF MULTIPLEX OPERATIONS.

THE CALIBRATION OF A CAMERA IS ADVERSELY AFFECTED BY FAILURE OF THE MANUFACTURER TO PERFECTLY CENTER THE VARIOUS ELEMENTS OF THE LENS. FAILURE TO DO THIS RESULTS IN AMBIGUITY IN THE DETERMINATION OF THE PRINCIPAL POINT OF THE CAMERA AS

THE LENS TAKES ON THE PROPERTIES OF A WEAK PRISM AND ROTATES THE AXIS ON THE EMERGENT SIDE OF THE LENS OUT OF THE PROLONGATION OF THE EXTERIOR AXIS. THE ERRORS CAUSED BY THIS BEHAVIOR CAN BE COMPENSATED TO SOME EXTENT IN STEREOSCOPIC MAPPING INSTRUMENTS, SUCH AS THE MULTIPLEX, BY INCLINATIONS OF THE PROJECTORS EQUAL TO THE PRISM EFFECT OF THE LENS, BUT MAKES IT IMPOSSIBLE TO CALIBRATE THE CAMERAS BY DIRECT METHODS WITHOUT THE DEVELOPMENT OF SPECIAL TESTING APPARATUS. CARE MUST BE TAKEN IN MOUNTING THE LENS ELEMENTS AND CELLS TO MAKE THE AXES COINCIDENT AND NORMAL TO THE FLANGE SURFACE OF THE SHUTTER IN WHICH THEY ARE ASSEMBLED. THE SHUTTER SHOULD BE HELD IN POSITION BY BRINGING THE FLANGE OF THE SHUTTER AGAINST THE PROPER MACHINED SURFACE OF THE CAMERA CONE AND THEN CLAMPING AND DOWELING IT IN POSITION. THIS WILL ASSURE RETURN OF THE LENS TO POSITION WITHOUT DISTURBING THE CALIBRATION SHOULD IT BECOME NECESSARY TO DISMOUNT THE SHUTTER FOR REPAIRS. THE PRACTICE OF HOLDING THE LENS ELEMENTS AND SHUTTER IN POSITION BY MEANS OF SCREW THREADS SHOULD BE ABANDONED FOR MAPPING CAMERAS AS IT NECESSITATES A RECALIBRATION OF THE CAMERA EVERY TIME THE LENS ASSEMBLY IS DISTURBED.

The Shutter

THE SHUTTER SHOULD BE OF A TYPE THAT WILL EXPOSE THE ENTIRE PLATE ALMOST SIMULTANEOUSLY. SHUTTERS THAT OPERATE ON THE PRINCIPLE OF FOCAL PLANE SHUTTERS EXPOSE ONE SIDE OF THE PLATE BEFORE THE OTHER AND THEREFORE DISTORT IMAGES WHEN PHOTOGRAPHS ARE MADE FROM MOVING AIRCRAFT. THERE IS PROBABLY NO SERIOUS OBJECTION TO THE USE OF FOCAL PLANE SHUTTERS IN TERRESTRIAL MAPPING CAMERAS, BUT CERTAINLY THEY HAVE NO PLACE IN AERIAL CAMERAS THAT WILL BE USED IN MAKING PHOTOGRAPHS FOR TOPOGRAPHIC MAPPING.

ATTENTION IS DRAWN TO THE NEED FOR GREAT RIGIDITY IN THE SHUTTERS AND A DESIGN THAT WILL PERMIT THEM TO BE TAKEN APART FOR OVERHAULING AND THEN REASSEMBLED WITHOUT DISTURBING THE CONSTANTS OF THE LENS OR OF THE CAMERA. PARTICULAR ATTENTION IS CALLED TO THE PROBLEM OF DESIGNING SATISFACTORY SHUTTERS FOR THE WIDE ANGLE LENSES THAT ARE COMING ON THE MARKET.

The Camera Cone

PROVISION MUST BE MADE FOR MAINTAINING A FIXED RELATIONSHIP BETWEEN THE LENS AND THE FOCAL PLANE. TO ACCOMPLISH THIS IT IS ADVISABLE THAT THE LENS, THE CONE AND THE FOCAL PLANE BE ASSEMBLED AS A UNIT. IF THE CONE IS DESIGNED FOR GREAT RIGIDITY AND CAST FROM MATERIAL OF A LOW COEFFICIENT OF EXPANSION WITH THE FOCAL PLANE AND SHUTTER SEAT MACHINED TRULY PARALLEL TO EACH OTHER, THE MOST IMPORTANT REQUIREMENTS FOR MAINTAINING A CONSTANT PRINCIPAL DISTANCE FOR THE CAMERA WILL HAVE BEEN MET. THE DESIGN LEADS TO DIFFICULTY IN ADJUSTING A LENS TO A GIVEN PRINCIPAL DISTANCE UNLESS A HEAVY RING IS INSERTED BETWEEN THE SHUTTER FLANGE AND ITS SEAT IN THE CAMERA CONE. WITH THIS RING IN PLACE, IT IS POSSIBLE TO MAKE SLIGHT CHANGES IN THE PRINCIPAL DISTANCE BY MACHINING THE RING TO THE REQUIRED THICKNESS.

CONSIDERATION SHOULD BE GIVEN TO THE POSSIBILITY OF CONTROLLING THE TEMPERATURE OF THE CAMERA CONE, THE LENS AND THE OPERATING MECHANISM WHEN WORKING AT HIGH ALTITUDES WHERE LOW TEMPERATURES MAY NORMALLY BE EXPECTED. THIS PRECAUTION WILL DO MUCH TO PREVENT CHANGES IN THE CONE THAT MIGHT ALTER THE PRINCIPAL DISTANCE OF THE CAMERA AND CHANGES IN THE LENS ITSELF THAT WOULD DISTORT THE IMAGE AND FOCAL LENGTH, AND WILL ELIMINATE MANY OF THE MECHANICAL FAILURES THAT OCCUR WHEN OPERATING AT VERY LOW TEMPERATURES. TEMPERATURE CONTROL WILL BECOME INCREASINGLY IMPORTANT AS FLIGHT ALTITUDES ARE INCREASED IN THE FUTURE. IN THE CASE OF FILM CAMERAS, HUMIDITY CONTROL SHOULD BE STUDIED TO AVOID CHANGES IN THE FILM BASE DUE TO EXCESSIVE DRYNESS OF THE ATMOSPHERE AT HIGH ALTITUDES.

The Fiducial Marks and the Principal Point

ALL MEASUREMENTS MADE ON PHOTOGRAPHS INTENDED FOR MAPPING USE MUST BE REFERRED TO SOME FIXED LINE AS AN ORIGIN. THE LINE COMMONLY ACCEPTED FOR THIS PURPOSE IS THE NORMAL DROPPED FROM THE REAR NODAL POINT OF THE CAMERA LENS TO THE FOCAL PLANE OF THE CAMERA, THE POINT SO INDICATED BEING THE "PRINCIPAL POINT." THE DISTANCE FROM THE REAR NODAL POINT TO THE FOCAL PLANE OF THE CAMERA IS THE "PRINCIPAL DISTANCE." THE PRINCIPAL POINT MUST BE INDICATED ON ALL PHOTOGRAPHS MADE WITH A MAPPING CAMERA AND THE METHOD COMMONLY USED TO ACCOMPLISH THIS, IN CAMERAS WITHOUT A GLASS FOCAL PLANE PLATE, IS BY INSERTING FOUR FIDUCIAL MARKS IN THE FIELD OF VIEW IN SUCH POSITIONS THAT LINES DRAWN BETWEEN OPPOSITE MARKS WILL

INDICATE THE POSITION OF THE PRINCIPAL POINT BY THEIR INTERSECTION.

THE EXACT LOCATION OF THE POINT CAN BE DETERMINED IN SEVERAL WAYS BUT IN ANY EVENT, THE TESTS SHOULD BE MADE AFTER THE LENS, THE FILTER AND THE FIDUCIAL MARKS HAVE BEEN MOUNTED IN THE CONE. IT IS EVIDENT THAT THIS METHOD OF LOCATING THE PRINCIPAL POINT WILL NECESSITATE A TYPE OF FIDUCIAL MARK THAT CAN BE ADJUSTED TO THE DESIRED POSITION AFTER THE PRINCIPAL POINT TEST HAS BEEN MADE AND THEN FASTENED RIGIDLY WHEN ITS POSITION IS VERIFIED. THE MARKS MUST BE ADJUSTABLE SO THAT THEY CAN BE MOVED TO THE DESIRED POSITIONS AND THEN DOWELED TO PREVENT FURTHER MOVEMENT.

FIDUCIAL MARKS MAY BE EITHER OF A MECHANICAL OR OPTICAL TYPE, THE MOST SATISFACTORY DESIGN IN ANY CASE BEING DEPENDENT TO A GREAT DEGREE ON THE MAPPING APPARATUS WITH WHICH THE PHOTOGRAPHS WILL BE USED. WHEN THE MECHANICAL TYPE IS ADOPTED, ATTENTION SHOULD BE GIVEN TO THE SURFACES THAT WILL CAST THEIR SHADOW ON THE FOCAL PLANE IN ORDER THAT THEY WILL SHOW CLEAR CUT DEFINITE LINES ON THE PHOTOGRAPHS. THE OPTICAL TYPE OF MARK CAN BE DESIGNED TO PROJECT A MINUTE DOT ONTO THE FILM OR PLATE SURFACE, WHICH WILL PROVE MOST SATISFACTORY WHEN USED WITH MAPPING INSTRUMENTS THAT HAVE OBSERVING SYSTEMS OF CONSIDERABLE MAGNIFICATION.

GREAT CARE IS REQUIRED IN PLACING THE FIDUCIAL MARKS AS IT IS ESSENTIAL THAT THE AXIAL LINES THEY DEFINE INTERSECT IN THE PRINCIPAL POINT OF THE CAMERA. THE ACCURACY REQUIRED WILL VARY WITH THE MAPPING APPARATUS THAT IS USED BUT IN ANY EVENT, THE ALLOWABLE TOLERANCE MUST BE SMALL. AN INFINITELY DISTANT OBJECT IN A DIRECTION NORMAL TO THE FOCAL PLANE OF THE CAMERA WILL HAVE ITS IMAGE AT THE PRINCIPAL POINT WITH A PERFECTLY CENTERED LENS, AND RECENT TESTS INDICATE THAT THIS POINT CAN BE DETERMINED BY BENCH METHODS WITH AN ACCURACY OF $\pm$ 0.025 MILLIMETER OR BETTER. HOWEVER, THE POINT SO DETERMINED IS NOT COINCIDENT WITH THE FOOT OF THE PERPENDICULAR TO THE FOCAL PLANE UNLESS THE LENS IS PERFECTLY CENTERED AND ANY FAILURE OF THE AXIS TO COINCIDE WITH THE NORMAL TO THE FOCAL PLANE WILL HAVE THE EFFECT OF SWINGING THE INNER CONE OF RAYS THROUGH A SMALL ANGLE WITH RESPECT TO THE EXTERIOR CONE. THIS IS DETRIMENTAL TO THE CALIBRATION OF CAMERAS FROM WHICH PRECISE RESULTS ARE DESIRED UNLESS SPECIAL APPARATUS IS DESIGNED FOR THESE TESTS. THE LABORATORY METHOD OF DETERMINING THE PRINCIPAL POINT IS MORE DIRECT AND PROBABLY CAN BE MADE MORE ACCURATELY THAN IS POSSIBLE BY METHODS DEPENDING ON COMPARATOR MEASUREMENTS OF PLATES EXPOSED ON OBJECTS IN THE HORIZON WHOSE ANGULAR SEPARATION IS KNOWN, PROVIDED THE LENS MANUFACTURERS CAN SUPPLY PERFECTLY CENTERED LENSES FOR MAPPING PURPOSES OR SPECIAL APPARATUS CAN BE DEVISED FOR MAKING THE TEST.

CAMERAS WITH GLASS FOCAL PLANE PLATES CAN HAVE THE PRINCIPAL POINT DETERMINED AS BEFORE AND THEN ETCHED DIRECTLY ON THE GLASS SURFACE, THUS ELIMINATING THE NEED FOR FIDUCIAL MARKS. CAMERAS OF THIS TYPE CANNOT BE UTILIZED FOR TOPOGRAPHIC WORK UNLESS A SPECIAL LENS IS COMPUTED FOR USE WITH THE GLASS PLATE OR THE PHOTOGRAPHS ARE USED WITH APPARATUS IN WHICH A COMPENSATING REFRACTION CAN BE INTRODUCED. NATURALLY, THE GLASS PLATE CONTRACTS THE NORMAL IMAGE BY REFRACTION SO IT IS NECESSARY TO CALCULATE AND ASSEMBLE A LENS WITH A DEGREE OF DISTORTION THAT WILL COMPENSATE FOR THE EFFECT OF THE PLATE. THE BEST PRACTICE WILL BE TO AVOID THE USE OF SUCH PLATES IN CAMERAS TO BE USED FOR STEREOSCOPIC MAPPING.

THE AXIAL LINES INDICATED BY THE FIDUCIAL MARKS SHOULD INTERSECT AT 90° OR SOME OTHER STRONG ANGLE. HOWEVER, THE 90° INTERSECTION IS MOST SATISFACTORY AS IT PERMITS USE OF THE PHOTOGRAPHS IN ANY COMPARATOR MEASURING DEVICE. THE TOLERANCE THAT CAN BE PERMITTED FOR THE ANGLE OF INTERSECTION IN SUCH CASES SHOULD BE OF THE ORDER OF 90° $\pm$ 30" WHERE CONSIDERABLE MAGNIFICATION WILL BE USED, ALTHOUGH GREATER TOLERANCE CAN BE PERMITTED WHEN THE NEGATIVES ARE USED WITHOUT MAGNIFICATION OR ENLARGEMENT. GRADUAL IMPROVEMENT IN INSTRUMENTS UTILIZING PHOTOGRAPHS MUST BE EXPECTED IN THE FUTURE AND WITH THESE CHANGES A DECREASE IN THIS TOLERANCE MAY BE EXPECTED.

THE PRINCIPAL DISTANCE

THE PRINCIPAL DISTANCE MAY BE FOUND BY SEVERAL METHODS INVOLVING COMPUTATION FROM COMPARATOR MEASUREMENTS OF PLATES THAT HAVE BEEN MADE OF TEST OBJECTS INCLUDING KNOWN ANGLES OF SEPARATION OR IT CAN BE DETERMINED FROM MEASUREMENTS MADE ON AN OPTICAL BENCH. THE STRENGTH OF THE METHOD OF DETERMINING THIS DISTANCE BY COMPUTATION DEPENDS GREATLY ON THE FACT THAT TWO OF THE TEST POINTS ARE PURPOSELY SELECTED IN THE OUTER ZONES OF THE FIELD AND THE RESULT THEREFORE INCLUDES THE EFFECT OF ANY DISTORTION THAT MAY EXIST. VALUES THAT ARE CONSISTENT TO 0.01

MILLIMETER ARE TO BE EXPECTED BY THIS METHOD.

The Light Filter

Light filters are utilized frequently to reduce the effect of haze. Filters intended for use with mapping cameras should be constructed from optical flat glass to eliminate any refraction effects that might be detrimental to the accuracy of the maps. All calibration tests of the camera should be made with the filter fixed in the position in which it will be used. The method of mounting the filter should be such that it will always have the same relation to the lens that existed during the calibration test. With perfectly flat glass filters, it will be possible to change filters on a camera without disturbing the calibration but this is not true otherwise.

The Multiplex Aeroprojector Calibration

The calibration of the Multiplex Aeroprojector should properly be considered in a separate paper but considering the fact that information on this subject is meager and the matter is closely related to the calibration of mapping cameras that is being carried on, at this time it seems advisable to discuss the most important aspects of the subject briefly.

The successful operation of the Multiplex depends on its ability to reproduce exactly in the laboratory the cone of rays below the mapping camera at the instant of exposure of the original negative. The process calls for the reduction of each negative to a small size diapositive and then reprojection of this plate as one step in the mapping operation. The characteristics of the aerial camera and the reducing camera used in making the diapositive plates are constant so it is apparent that all projectors must have the same principal distance to satisfy the requirement for similarity of the conical systems. Any variation of this distance will introduce irregularities in the conical projections and consequently inaccuracies in the maps. It is likewise important that the black dot on the fixed glass plate in the focal plane of each projector be coincident with the principal point of the projector, otherwise, errors will be introduced in the model.

Tests of U. S. Geological Survey standard and wide-angle Multiplex Aeroprojectors show clearly that rather serious variations in the principal distances exist in the projectors when they are received from the factory. This is a matter that could easily be corrected by the manufacturer and which would immediately be reflected by a simplification of the work of adjusting the diapositives, and in increased accuracy of results, particularly, in mountainous country. This is so important that it should be mentioned in all specifications covering orders for new equipment.

Measurements of the principal distance in the projector might be described most exactly in this case as the "equivalent principal distance," as proper allowance must be made for the glass plate in the projectors. Tests should be made of newly received equipment to determine the "equivalent principal distance" of each projector and necessary alterations be made to bring all to a common value. When this has been done, the centering of the glass plate should be tested and any necessary correction secured by adjustment of the plate itself.

A variation in the focal length of the mapping camera from that for which the Multiplex reducing printer is properly adjusted will disturb the similarity of the original and reproduced cone of light rays. Small variations can be compensated for by utilizing a vertical scale for height measurement somewhat different from the horizontal scale. It is better and much more convenient, however, to reset the Multiplex reducing camera to give a proper reduction, particularly, if the area to be mapped is large. A measurement of the focal lengths of the reducing camera projection lens will be found invaluable in this case.

Conclusion

Recent experience with the calibration of mapping cameras intended for stereoscopic mapping and in test work with the Multiplex Aeroprojector, has lead the writer to certain conclusions which he believes warrants the careful consideration of the Society.

1. The calibration of cameras intended for use in stereoscopic mapping projects is rather unusual in this country and calls for the design of special

EQUIPMENT BEFORE THEY CAN BE MADE PROPERLY IN THE LABORATORY. THIS MATTER IS ALREADY RECEIVING THE ATTENTION OF THE NATIONAL BUREAU OF STANDARDS AND IT IS HOPED THAT THE NECESSARY EQUIPMENT WILL BE AVAILABLE FOR USE BEFORE ANY LARGE NUMBER OF MAPPING CAMERAS ARE PRESENTED FOR TEST.

THE ADJUSTMENT OF THE FIDUCIAL MARKS IN THE CAMERA AFTER THE DETERMINATION OF THE PRINCIPAL POINT HAS BEEN MADE IS PROBABLY OUTSIDE OF THE WORK THAT THE NATIONAL BUREAU OF STANDARDS IS IN A POSITION TO PERFORM. FOR THIS REASON, IT WOULD BE WELL FOR THE U. S. GEOLOGICAL SURVEY, AS A BUREAU INTERESTED IN TOPOGRAPHIC MAPPING, TO EQUIP ITSELF TO SET THE FIDUCIAL MARKS AND THEN MAKE A FINAL CHECK OF THE ACCURACY WITH WHICH THIS HAS BEEN ACCOMPLISHED. PROVISION SHOULD ALSO BE MADE FOR LOCATING THE PRINCIPAL POINT BY COMPARATOR MEASUREMENTS ON TEST PLATES INSTEAD OF THE BENCH METHOD.

2. A STUDY OF THE PROBLEMS OF THE DESIGN AND CALIBRATION OF CAMERAS INTENDED FOR USE WITH PHOTOGRAMMETRICAL APPARATUS LEADS ONE TO BELIEVE THAT ALL PHOTOGRAPHS OF EXTENSIVE AREAS SHOULD BE MADE WITH CAMERAS OF THE GENERAL TYPE DESCRIBED IN THIS PAPER REGARDLESS OF THE IMMEDIATE USE FOR WHICH THEY ARE OBTAINED. THIS WILL MAKE THE NEGATIVES AVAILABLE FOR TOPOGRAPHIC MAPPING WITHOUT INCREASING THE COST OF THE PHOTOGRAPHS TO THE PURCHASER. IT IS REALIZED THAT SOME COMMON MEETING GROUND MUST BE FOUND THAT WILL MAKE POSSIBLE THE USE OF SPECIAL CAMERAS AND SPECIFIED FOCAL LENGTHS BY BUREAUS NOT INTERESTED IN TOPOGRAPHIC MAPPING, BUT A PROPER SPIRIT OF COOPERATION SHOULD BRIDGE THIS DIFFICULTY. MORE SERIOUS OBSTACLES TO OVERCOME WILL BE THE ELIMINATION OF SHRINKAGE EFFECTS THAT MAY BE EXPECTED IN FILM DURING SEVERAL YEARS STORAGE AND THE DIFFICULTY OF ESTABLISHING GROUND CONTROL ON PHOTOGRAPHS THAT NO LONGER CORRECTLY REPRESENT THE APPEARANCE OF THE GROUND DUE TO SEASONAL CHANGES IN VEGETATION.

3. THE NEED FOR SETTING THE EQUIVALENT PRINCIPAL DISTANCE OF ALL MULTIPLEX PROJECTORS TO BE USED ON THE SAME BAR TO SOME COMMON VALUE HAS BEEN MENTIONED BUT THE REQUIREMENT MUST GO MUCH FURTHER THAN THIS FOR ANY ORGANIZATION THAT MAY EXPECT TO UTILIZE A CONSIDERABLE NUMBER OF THESE INSTRUMENTS IN THE FUTURE. THE FAILURE TO HAVE A COMMON EQUIVALENT PRINCIPAL DISTANCE PREVENTS THE INTERCHANGE OF PROJECTORS FROM ONE BAR TO ANOTHER. IT IS BELIEVED THAT THIS RESTRICTION ON THE FREEDOM OF USE OF THESE INSTRUMENTS SHOULD BE REMOVED. THE GEOLOGICAL SURVEY IS USING FOR ITS FIRST STANDARD TYPE PROJECTORS AN EQUIVALENT PRINCIPAL DISTANCE OF 45.79 MILLIMETERS, ALTHOUGH A VALUE OF 46.00 MILLIMETERS IS PREFERABLE AND THE CHANGE WILL BE MADE LATER. IT WILL GREATLY SIMPLIFY OPERATIONS FOR THIS BUREAU IF ALL OTHER PROJECTORS OF THIS TYPE THAT MAY BE PURCHASED IN THE FUTURE ARE SECURED ON ORDERS SPECIFYING THE VALUE OF 46.00 MILLIMETERS. THE WIDE ANGLE PROJECTORS OF THE SAME BUREAU HAVE NOT YET BEEN ADJUSTED TO A COMMON PRINCIPAL DISTANCE BUT IT IS EXPECTED THAT 22.00 MILLIMETERS WILL BE ACCEPTED FOR THIS INTERVAL.

MANUFACTURERS OF THE MULTIPLEX AEROPROJECTOR, OR SIMILAR APPARATUS, MIGHT READILY INCREASE THE USEFULNESS OF SUCH EQUIPMENT AND THE ACCURACY OF ITS OPERATION BY MAKING THE EQUIVALENT PRINCIPAL DISTANCE EXACTLY 46.00 MILLIMETERS FOR THE STANDARD AND EXACTLY 22.00 MILLIMETERS FOR THE WIDE ANGLE INSTRUMENTS DURING THE ASSEMBLY OF THE EQUIPMENT. ACCURACY OF RESULTS AND A GREATER EASE OF OPERATION WILL BE SECURED BY THESE REFINEMENTS.

4. THE PRACTICE OF THE GOVERNMENT IN CONTRACTING FOR ITS AERIAL PHOTOGRAPHS MAY BE ACCOMPANIED BY SEVERAL DISADVANTAGES WHERE THE CONTRACTS CALL FOR PHOTOGRAPHS TO BE USED FOR STEREOSCOPIC MAPPING. THE DISADVANTAGE TO THE CONTRACTORS WILL BE THE REQUIREMENT FOR NEW CAMERA EQUIPMENT TO MATCH PROPERLY THE CHARACTERISTICS OF THE VARIOUS TYPES OF STEREOSCOPIC MAPPING APPARATUS THAT MAY BE IN USE. THE GOVERNMENT ITSELF WILL BE COMPELLED TO CALIBRATE ALL CAMERAS BOTH BEFORE AND AFTER USE TO BE ASSURED THAT ERRORS THAT MIGHT BE INTRODUCED IN THE MAP BY THE CAMERA ITSELF ARE ELIMINATED. ONE WAY IN WHICH THIS DIFFICULTY MIGHT BE AVOIDED WOULD BE FOR THE GOVERNMENT TO PROVIDE THE CAMERAS TO BE USED BY THE CONTRACTORS PROTECTING ITSELF AGAINST DAMAGE TO THE EQUIPMENT BY A SUITABLE BOND.

5. CONSIDERATION OF THE USE OF AERIAL PHOTOGRAPHS AND THE SPECIFICATIONS FOR MAPPING CAMERAS HAVE LEAD TO SOME STUDY OF THE POSSIBLE ADVANTAGES OF PHOTOGRAPHS OF CIRCULAR SHAPE INSTEAD OF THE USUAL SQUARE OR RECTANGULAR SHAPES THAT ARE IN COMMON USE. IT SEEMS TRUE THAT THE CIRCULAR PHOTOGRAPH IS MORE EFFICIENT THAN EITHER OF THE OTHER SHAPES BECAUSE IT PERMITS REDUCTION OF THE SIDELAP AND THE FORWARD LAP WITHOUT ENDANGERING SATISFACTORY COVERAGE AND IT APPROXIMATELY DOUBLES THE STEREOSCOPIC AREA, THUS MAKING POSSIBLE BETTER CORRESPONDENCE SETTINGS OF THE

MODELS AND BETTER USE OF CONTROL THAT MAY BE AVAILABLE. IT IS RECOMMENDED THAT FURTHER STUDY BE GIVEN THE MATTER WITH THE VIEW OF DEFINITELY DETERMINING WHAT APPEARS TO BE MARKED ADVANTAGES.

THE INTERPRETATION OF LENS TESTS AND CAMERA CALIBRATIONS*

BY

IRVINE C. GARDNER

I. INTRODUCTION

AIRPLANE MAPPING REQUIREMENTS ACCOUNT FOR MORE THAN HALF OF ALL THE TESTS MADE ON PHOTOGRAPHIC OBJECTIVES AT THE NATIONAL BUREAU OF STANDARDS. AS METHODS OF MAPPING BECOME MORE PRECISE AND, PARTICULARLY, AS THE STEREOSCOPIC METHOD OF PLOTTING CONTOURS BECOMES THE MORE USUAL METHOD OF TREATING A SERIES OF PHOTOGRAPHS, THE TESTING OF THE LENSES BECOMES MORE IMPORTANT AND GREATER PRECISION IS REQUIRED. THIS TENDENCY IS MADE VERY EVIDENT BY THE CHARACTER OF THE TESTS THAT ARE NOW BEING REQUESTED AND BY THE INCREASED INTEREST IN SPECIFICATIONS FOR LENSES AND CAMERAS. IN VIEW OF THIS IT HAS SEEMED ADVISABLE TO PRESENT A DETAILED DESCRIPTION OF THE LENS TESTS** REGULARLY CONDUCTED BY THE NATIONAL BUREAU OF STANDARDS AND TO DISCUSS, IN DETAIL, THE INTERPRETATION OF THE TESTS, THEIR SIGNIFICANCE, AND THEIR AVAILABILITY FOR DIFFERENT PURPOSES. A PRELIMINARY DISCUSSION OF CERTAIN ELEMENTARY OPTICAL PRINCIPLES IS INCLUDED BECAUSE THEIR USE IS NECESSARY IN AN ADEQUATE PRESENTATION.

II. METRICAL CHARACTERISTICS OF ABERRATION-FREE IMAGERY

1. OBJECT AT AN INFINITE DISTANCE

THE METRICAL CHARACTERISTICS OF AN IMAGE FORMED BY AN IDEAL LENS, ENTIRELY FREE FROM DISTORTION, ARE COMPLETELY DETERMINED BY THE EQUIVALENT FOCAL LENGTH AND THE LOCATION OF THE TWO NODAL POINTS. THESE METRICAL RELATIONS, FOR AN INFINITELY DISTANT OBJECT POINT, ARE ILLUSTRATED BY FIGURE 1, WHERE THE NODAL POINTS ARE INDICATED AT N AND N' AND THE FOCAL LENGTH HAS THE VALUE F. POINTS I, A, AND B ARE ASSUMED TO BE INFINITELY DISTANT. POINT I IS ON THE AXIS AND POINTS A AND B ARE LOCATED BY A AND B, THEIR ANGULAR DISTANCES FROM THE AXIS. THE IMAGES, FORMED IN THE FOCAL PLANE, ARE AT I', A', AND B' AND, AS INDICATED ON THE DIAGRAM, POINTS A' AND B' ARE DISTANT F TAN A AND F TAN B FROM THE AXIS.

THE NODAL POINTS OF A CAMERA LENS ARE THE POINTS OF UNIT ANGULAR MAGNIFICATION. A RAY, MAKING THE ANGLE A WITH THE AXIS AT N, THEREFORE, LEAVES THE FINAL SURFACE MAKING AN EQUAL ANGLE WITH THE AXIS AT N'. THESE RAYS, BEFORE AND AFTER PASSING THROUGH THE LENS, ARE INDICATED BY THE SOLID LINES IN THE DRAWING. SINCE, HOWEVER, THE OBJECT POINTS ARE INFINITELY DISTANT, THE DOTTED LINES DRAWN THROUGH N', PARALLEL TO THE FULL LINES, ALSO PASS THROUGH A AND B. HENCE, WHEN THE OBJECT IS INFINITELY DISTANT, WE HAVE A SPECIAL SIMPLIFIED TYPE OF IMAGERY IN WHICH THE POINT N NEED NOT ENTER THE CALCULATION AT ALL. WHEN A CAMERA IS USED IN AN AIRPLANE, THE SURFACE TO BE PHOTOGRAPHED IS AT A VERY LARGE BUT NEVERTHELESS FINITE DISTANCE FROM THE LENS. THE CONDITIONS OF FIGURE 1, HOWEVER, CAN BE UTILIZED. ASSUMING THAT THE OBJECT IS AT AN INFINITE DISTANCE IS EQUIVALENT TO ASSUMING THAT THE OBJECT IS SO FAR AWAY THAT A SHARP IMAGE IS OBTAINED IN THE FOCAL PLANE I' A' B'; AND THAT THE ANGLE BETWEEN LINES DRAWN FROM N AND N' TO A GIVEN OBJECT POINT IS NEGLIGIBLE. IF IT BE ASSUMED THAT THE PLANE OF THE FILM CAN FAIL TO COINCIDE WITH THE PLANE OF BEST FOCUS BY 0.05 MM WITHOUT HARMFUL RESULTS, IT CAN BE SHOWN THAT AN OBJECT DISTANT D FROM A LENS OF FOCAL LENGTH F WILL BE SATISFACTORILY IMAGED IN THE FOCAL PLANE, AND CAN THEREFORE BE ASSUMED TO BE INFINITELY DISTANT IF

$$D/F \geq F/0.05. \qquad (1$$

WHEN F EQUALS 150 MM (6 INCHES), D MUST EQUAL OR EXCEED 450 METERS (1500 FT.) TO

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** FOR A DESCRIPTION OF THE PRECISION LENS TESTING CAMERA, AN APPARATUS SPECIALLY DESIGNED FOR THE TESTING OF AIRPLANE CAMERA LENSES AND AIRPLANE CAMERAS, SEE RESEARCH PAPER RP984 IN THE APRIL, 1937 ISSUE OF THE NATIONAL BUREAU OF STANDARDS JOURNAL OF RESEARCH. SEPARATE REPRINTS WILL BE PURCHASABLE FROM THE SUPERINTENDENT OF DOCUMENTS, WASHINGTON, D. C. FOR FIVE CENTS (STAMPS NOT ACCEPTABLE).