RECOVERING PRECISE TILTS AND AZIMUTHS OF AERIAL MAPPING PHOTOGRAPHS*

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ABSTRACT

If precise tip, tilt, and azimuth of individual aerial mapping photographs could be recorded or recovered by airborne instrumentation alone with little or no reference to "Ground Control.," then the voluminous cost and time of photogrammetric mapping could be greatly reduced. In many mapping problems, it is often impossible or undesirable to occupy the ground. This paper deals with problems of airborne tilt recovery, and describes a few of the approaches investigated or under investigation at Reconnaissance Charting Branch, Wright Air Development Center. Finally, a description of an experimental airborne apparatus and technique for recovering precise tilts and azimuths of aerial photographs is offered by the author. This Celestial Tilt Indicator or Sun Camera was built and flight tested by the Reconnaissance Laboratory, Wright Air Development Center in conjunction with Corps of Engineers. Reference U.S. Patent 2,671,388.

THERE has been a long-standing need for a precise airborne tilt indicator for aircraft mapping cameras, or a device to sense the true vertical and maintain the mapping camera axis in a truly vertical position with each aerial exposure. Precise airborne tilt information, either recorded or zeroed in flight, is vital to accurate map compilation when it is impossible, undesirable, or too costly to occupy the ground area to accomplish adequate mapping control surveying. In many areas today where little or no ground control is available and map compilation processes demand the use of bridging techniques over considerable distances with precision, accurate tilt and azimuth information on each aerial photograph will strengthen significantly the accuracy of a bridge, and will allow control extensions over greater distances with increased accuracy.

In mapping with electronic positioning equipment (such as Shoran), where the space position of the photographic aircraft may be computed with a high degree of accuracy, accurate nadir point positions on synchronized data and camera recordings are mandatory to accurately identify the space position in relationship to the terrain detail. Utilizing Shoran for airborne mapping control then requires accurate camera tilt information for optimum results.

Considerable effort in the past has gone into instrumentation of the mapping aircraft in some manner to provide "control type" information for the map compilation process; for example, (1) The radio altimeter carry method for establishing vertical elevations, (2) The statoscope, (3) Horizon cameras, and (4) Gyro stabilized camers mounts, with vertical sensing elements. Various degrees of success have been achieved, but the results of most instrumentations have resulted in inaccurate results compared to ground plotting instrument accuracies, and there has been no reliable method of adequately checking or calibrating the instrumentation in most cases. As far as gyro stabilized camera platforms are concerned, their greatest benefit has been mostly from their steadying effect during exposure, and their eliminations of excessive tilts. They rely for their accuracy on a vertical sensing element which, in turn, is reliant to some extent on gravity. Results with camera gyro stabilized platforms to date have produced good "general orientation" tilt information and have enhanced map compilation considerably, especially when the proper flight procedure was followed to integrate long period accelerations on the aircraft to a near zero average. However, accuracies equal to or compatible with plotting instruments have not been achieved consistently with reliance. The tilt of individual aerial photographs, it is believed, must be achieved reliably to possibly 2 to 5 minutes of arc or less, to be utilized as an adequate substitute or supplement to sparse ground control.

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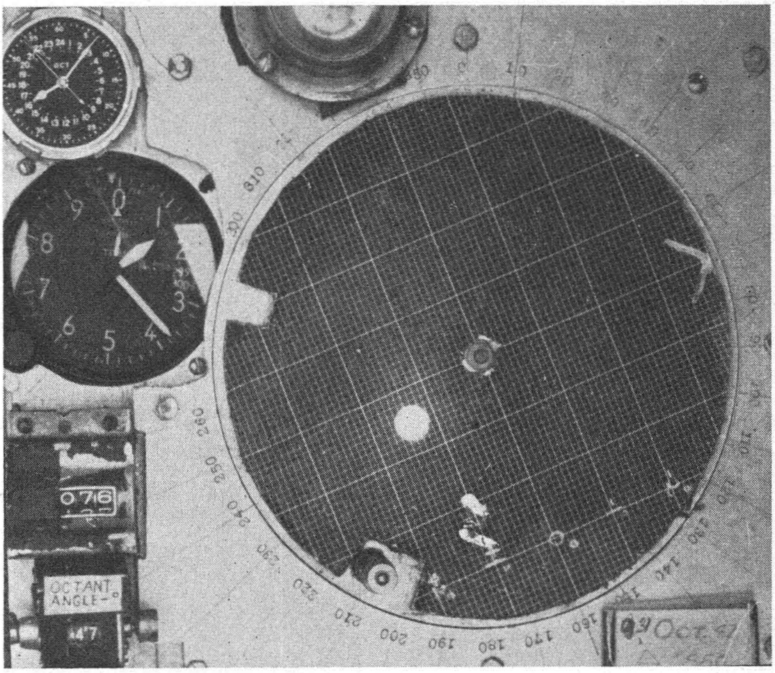

FIG. 1. Sample airborne tilt recording.

The author has neen concerned with the airborne mapping problem since 1946, and especially with the problem of airborne mapping control. While this problem is sometimes acute in miltary wartime mapping problems, it is also of direct concern to commercial mapping organizations, especially mapping in virgin areas where it is difficult or too costly to perform ground control surveying adequate for the required map accuracy.

The approach to the airborne verticality problem presented here will be to record certain orientation information in flight with each photograph. This information will be utilized after the flight to recover the precise tilt and azimuth of each individual photograph, prior to map compilation. The instrumentation required to recover airborne tilt is considerably less, more easily designed, and does not require "an instantaneous local vertical" continuously while in flight. Such a vertical is not required in most cases (outside of general orientation) until the map compilation process, after the aircraft has returned to base. In the author's approach, it is also assumed that accurate tilt and azimuth recording is just as valuable information to the map maker as truly vertical photography (although the latter is certainly the most desirable). Displacements due to relief are inherent normally in all mapping photography and must be accounted for, while tilt displacements may be normally eliminated or ignored by the map maker in a precisely vertical aerial photograph.

This paper will report on development of an experimental "Sun Camera" or Celestial Tilt Indicator (Figure 1) of the Reconnaissance Charting Branch of Wright Air Development Center (Reference U.S. Patent 2,671, 388), and to present results of flight tests with experimental equipments. Acknowledgement is made to Engineer Research and Development Laboratories, Corps of Engineers, Ft. Belvoir, Virginia, to their Liaison Branch at Wright Air Development Center, and to the following individual engineers who assisted in the frabrication, testing, and design of the experimental equipment: Mr. Eldon D. Sewell, Mr. Lorenz, and Mr. George Whiting of the Corps of Engineers, Mr. James J. Deeg, Mr. Randall Gehrke, and Mr. James E. Henry of Wright Air Development Center, and Dr. C. Aschenbrenner of Boston University.

The general theory of the experimental

celestial tilt indicator is relatively simple. It is well known that the altitude of the sun can be accurately computed for a given position at a given time. This altitude is the vertical angle from a horizontal plane to center of the sun. The Celestial Tilt Indicator measures the altitude of the sun (octant angle reading ± the grid reading) from a plane which may or may not be horizontal. By knowing the approximate position of the aircraft (an error of one mile in position causes an error of 1′ in altitude) and by knowing the exact time of exposure the altitude of sun from the aircraft position can be determined. If the altitude of the sun as determined by the octant angle and the grid reading does not agree with the true altitude, the difference is the tilt of the camera towards or away from the sun at exposure.

CONSTRUCTION OF THE EXPERIMENTAL MODEL OF THE CELESTIAL TILT INDICATOR

The experimental model of the Celestial Tilt indicator was designed for use with the T-5 Mapping Camera. The equipment was designed for installation in either Type B-17G aircraft, or the Type F-13 aircraft. The plexiglass covering above the camera well in the Type B-17G aircraft may be lowered and pushed forward during aerial operation to obtain an unobstructed view of the sky and to avoid excessive refraction of the sun rays. In the F-13 installation, a camera window is installed directly above the vertical camera well.

The indicator itself consists of a light weight, tower shaped metal adapter which is attached to the four corners of the T-5 camera (see Figure 2). The adapter consists of the following major components:

a. Head Assembly.
b. Base Plate Assembly.
c. The Frame.
d. Recording Camera.

HEAD ASSEMBLY

The Head Assembly consists of:

a. A modified octant (vertical angle measuring device) which is used to measure the angle between the focal plane of the T-5 camera and the sun ray, and to reflect the sun rays onto a calibrated grid on the base plate assembly.

b. A transit Head, which may be set in increments of 10 degrees, and is used in turning the angle between the fiducial marks on the T-5 camera and the direction of the recorded tilt, so that any sun azimuth may be utilized in flight.

c. A lens of 53.25 inches focal length which is used to project the reflected sun rays onto the grid of the base plate assembly.

BASE PLATE ASSEMBLY (see figure 1)

The Base Plate Assembly consists of:

a. A calibrated grid, which is provided to receive the projected sun image, is used as a vernier for the octant angle. The combination of the octant angle and grid reading, as determined by the position of the sun image on the grid, is the total angle between the focal plane of the mapping camera and the sun from an assumed position at the instant of exposure. The sun image is approximately 32 minutes of arc in diameter; this diameter varies slightly throughout the year. The grid and lens system is designed to accommodate approximately 4 degrees of tilt, and is calibrated according to the focal length of the lens. The grid may be set at any horizontal angle, in increments of 10 degrees. During aerial operation, the grid azimuth and the transit angle are set on the same increment—10 degrees, 20 degrees, 30 degrees, etc. The grid azimuth and the transit azimuth are always turned clockwise through 360 degrees from the large fiducial mark of the matching T-5 print. The *O*-line of the grid is the *X* axis and the grid arrow line is the *Y* axis of the grid coordinate system. In aerial operation, after the camera crab or drift has been removed and the proper grid azimuth set on the transit head and grid, the *Y* axis of the grid is aligned by the photographer to the horizontal direction of the sun. This is accomplished by maintaining the sun image on or near the grid arrow line (*Y* axis) during flight. The *X* reading of the sun image recording is a combination of tilt 90 degrees to the sun azimuth (referred to as S_2 tilt in this report) and swing to the right or left of the sun azimuth (swing error). The S_2 tilt reading of the grid, however, has been reduced by the "sin" of the altitude of the sun, and the swing error reading on the grid has been reduced by the "cos" of the altitude of the sun. Swing error is defined as the angle between the sun azimuth and the grid

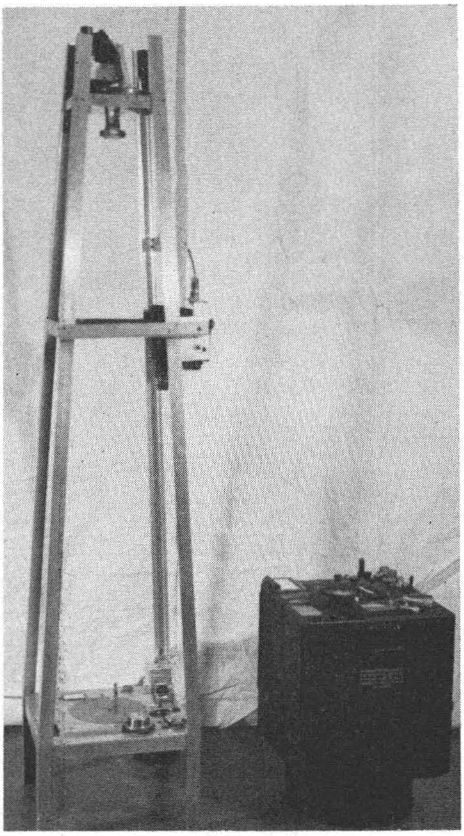

FIG. 2.—Celestial tilt indicator and T-5 mapping camera.

arrow at exposure.

b. A vibrated altimeter, modified Type C-13, is provided to indicate flying height and changes in altitude between exposure stations.

c. A Master Navigation Watch is used for recording the GCT time of exposure which is a necessary part of the tilt computation. This time recording is required to compute the altitude and azimuth of the sun at the time of exposure at the approximate photograph position.

d. An Exposure Counter is used to correlate the mapping and recording cameras. A delay relay (Type B-9) is introduced into the counter tripping circuit to eliminate counter movement during exposure.

e. An octant angle counter, which is manually set to correspond to the octant angle reading of the Head Assembly. This octant angle plus or minus the grid Y reading being the total angle between the focal plane of the mapping camera and the sun from an assumed position at the instant of exposure.

f. A sensitive transit level bubble, adjusted to the focal plane of the mapping camera, is photographed during ground calibration to confirm the level position of the focal plane at the instant of the ground calibration recording.

g. Such other items as a data card and electrical power receptacle are also provided.

RECORDING CAMERA

A type A-4 35 mm. camera is used to record the sun image, grid, and base plate instruments, at the instant that the mapping camera exposure is made. A single frame solenoid tripper is a part of the recorder. See sample tilt recording photographs (Figure 1).

FRAME

The frame consists of four (4) 1-inch angle-dural legs which support the base plate, head assembly, and the recording camera. The height of the frame is approximately 65 inches; when mounted on the T-5 mapping camera, the over-all height is 85.75 inches.

TILT DETERMINATION AFTER FLIGHT (S_1 TILT COMPUTATIONS)

After the film has been processed, it is read with a magnifying glass or projector, and the data information tabulated. The approximate geographic position of the first photograph and the last photograph of each flight line is determined. This position should be accurate to within approximately one (1) mile. One nautical mile error will introduce an error of about one (1) minute of arc in the final tilt computation. A flight line of about 20 photographs may be computed at one time. If the flight line is longer, it is necessary to break the flight line into divisions of about 20 photographs, establishing the approximate position of every 20th photograph. The altitude and azimuth of the sun for the first and last photographs of the flight line is then computed, using the American Air Almanac and the Ageton Form H.O. 211. The accuracy of the Ageton solution is about 30 seconds of arc ($\frac{1}{2}$minute) which should meet present requirements. The sun altitude and azimuth of the remaining photographs of the flight line are then determined by interpolation. Atmospheric

TABLE 1

RESULTS OF TESTS WITH THE CELESTIAL TILT INDICATOR AS COMPARED WITH MULTIPLEX (S_1 TILT)

Exp. No.	Celestial Tilt Ind. (S_1)	Multiplex (with Ground control)	Difference
	Flight No. 2		
49	−53.5′	−55.5′	+2′
50	+15′	+11.5′	+3.5′
51	−14.5′	−17′	+2.5′
52	− 9′	−10′	+1′
53	−18′	−15′	−3′
	Flight No. 4		
32	+59′	+57′	+2′
33	−11′	−12′	+1′
34	+ 8.5′	−10′	−1.5′
35	+14.5′	+12.5′	+2′
36	− 8.5′	− 6′	−2.5′
37	+ 3′	0	+3′
38	+47′	+50′	−3′
39	+11′	+ 9′	+2′
40	+11.5′	+11′	+0.5′
41	+25.5′	+25′	+0.5′
42	−27.5′	−32′	+4.5′
125	+59′	+67′	−8′
126	+17.5′	+17′	+0.5′
127	−13.5′	−12′	−1.5′
128	− 8′	−10′	+2′
129	− 2.5′	0	−2.5′
130	+18′	+11.5′	+6.5′
131	+47.5′	+49′	−1.5′
132	+18.5′	+22′	−3.5′
133	+23′	+25′	−2′
134	+25.5′	+21′	+4.5′
135	+10.5′	+14′	−3.5′
136	+36′	+35′	+1′
137	−14′	−13′	−1′
138	+17.5′	+23′	−5.5′
139	− 9′	−12′	+3′
140	−26.5′	−25′	−1.5′
141	+22.5′	+21′	+1.5′
142	−19.5′	−15′	−4.5′
143	−11′	−10′	−1′

Multiplex work by George Whiting, Corps of Engineers. Average (Approx. 2.5′).

refraction corrections for flying height for the sun angle should be made from the tables in H.O. 211, or from the tables in the American Air Almanac. As a matter of convenience, the refraction correction is added to the computed sun altitude.

The next step in the computation is the ground calibration of the octant angle. The ground calibration exposures taken immediately before take-off and after landing, with the mapping camera focal plane in the level position, are utilized in computing the sun altitude and azimuth using the air base geographic position. A comparison between this computed altitude of the sun and the octant angle plus or minus grid reading indicates the octant angle calibration. This calibration angle is made for all grid azimuth angles utilized in the flight, and the calibration is then applied to the octant angle. This corrected octant angle plus or minus the grid Y reading indicates the angle between the sun and the focal plane of the mapping camera at each exposure. A comparison between this angle and the computed sun altitude indicates the tilt in the direction of the sun. This tilt in this report will be known as S_1 tilt. A plus S_1 tilt indicates that the nadir point on the print is located toward the sun.

The tilt 90 degrees to the direction of the sun will be referred to in this report as S_2. A plus S_2 tilt indicates that the nadir point on the print is located to the right of the sun azimuth.

METHODS OF OBTAINING S_2 TILTS AND RESULTS OF AERIAL TESTS WITH THE TILT INDICATOR

In order to obtain S_2 tilts (the tilt 90 degrees to the S_1 tilt), the following method is outlined. In this, "Control Tie Strips" are flown with the Tilt Indicator at a time when the Sun azimuth has changed by at least 40 degrees. These "Control Tie Strips" are spaced according to the amount of "Tilt Control" required, and are flown at right angles to the mapping flight lines, with at least 80 per cent overlap. The S_2 tilt of the mapping photograph at each intersection point is then obtained by use of the Multiplex. In this method, the S_1 tilt of the mapping diapositive and the S_1 tilt of the "Control Tie Strip" diapositive are set into the projectors of the Multiplex with the level after the relative swing has been established. With these adjustments locked in position, the parallax is then removed with the remaining Multiplex adjustments. The S_2 tilt of the mapping diapositive may then be obtained by direct measurement with the level. Using the computed sun azimuth, the true azimuth of the large fiducial axis of the mapping diapositive may then be established.

Once the tilts and azimuths of the diapositives at the intersection points have

TABLE 2

TEST RESULTS OF THE CONTROL TIE STRIP METHOD (S_2 TILT OF MAPPING)

Morning Flight (Tie Strip)	Afternoon Flight (Mapping)	S_2 Tilt (Control Tie Strip Method)	S_2 Tilt (Multiplex with Ground control)	Difference
Exp. No.	*Exp. No.*			
78 (pair)	50	−18.5′	−23′	+4.5′
80 (pair)	50	−21′	−23′	+2′
80 (pair)	51	+43.5′	+45′	−1.5′
80 (repeat)	51	+44′	+45′	−1′
80 (repeat)	51	+46′	+45′	+1′
82 (pair)	51	+43′	+45′	−2′
82 (repeat)	51	+41′	+45′	−4′
82 (pair)	52	+ 1° 29′	+ 1° 27.5′	+1.5′
84 (pair)	52	+ 1° 27′	+ 1° 27.5′	−0.5′
44 (pair)	51	+36′	+45′	−9′
44 (pair)	53	− 2° 31′	− 2° 37.5′	+6.5′
45 (pair)	49	+13′	+13′	0
45 (pair)	52	+ 1° 29′	+ 1° 27.5′	+1.5′
47 (pair)	50	−24′	−23′	−1′

Multiplex work by George Whiting, Corps of Engineers.

been obtained, the intervening diapositives may be bridged and a true model obtained in the Multiplex. Bridging between intersection points may be accomplished with the use of the Multiplex or by analytical solutions.

THE TESTS

In the test shown by Tables 1 and 2 the the S_1 tilt obtained from the Tilt Indicator was set in each diapositive of a pair with the level, after the Swing orientation had been made. The sun had changed azimuth by approximately 95 degrees in this test.

With the S_1 tilt of each diapositive "Set" in the projectors, the parallax was removed with the other adjustments, and the S_2 tilt of the Mapping diapositive read from the level.

CONCLUSIONS

The tilt of an aerial photograph in the direction of the sun (S_1 Tilt) can be obtained with the original experimental model of the Celestial Tilt Indicator to within approximately 3.5 minutes of arc. The tilt obtained with the "Control Tie Strip" method, 90 degrees to the sun (S_2 Tilt), is accurate to within approximately 4 minutes of arc. Both S_1 and S_2 Tilt or resultant tilts of mapping photographs can be obtained at "Tie Strip" intersection points, if the Tie Strip photographic flight is made at a time when the sun azimuth has changed by at least 40 degrees from the mapping flight. Azimuths of aerial photographs have been obtained with the experimental Tilt Indicator accurate to within 10 minutes of arc. Greater accuracies are believed possible.

The research and development information on this experimental investigation has been presented as a subject of possible interest to the society.

SEMI-ANNUAL MEETING

While attending the Semi-Annual Convention, Sept. 7–8–9–10 at Los Angeles, be sure to take advantage of the many tours arranged, Disneyland, TV Shows, fashion shows, China Town, Olvera Street, Catalina Island and the Huntington Library-museum. Bring the family. Fun for all during and after the convention. Make it a real vacation. SEE YOU IN LOS ANGELES.