*Verticality in Photogrammetry**

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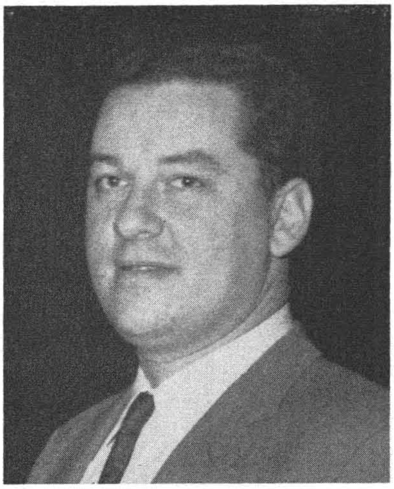
ABSTRACT: *Recent military developments have produced a resurgence of interest in the production of truly vertical pictures. Verticality of the photography can be used to relieve the ground control requirements of the survey. The extent to which this is so for various types of operations is described, as well as the effect of the residual error in verticality. The capability of present day systems for obtaining vertical photography is discussed.*

The use of modern electronic aids in conjunction with vertical photography permits an even greater reduction in ground control. A description of the verticality requirements of mapping systems using electronic aids is given.

The possible civil uses of these developments are described and a forecast of future systems made.

BEFORE the Civil War, the elite of the United States Army were the Topographic Engineers. The top men of their classes at West Point competed for assignments as topographic engineers. Both Generals McClellan and Lee were former topographic engineers. This attitude was due to the all-importance of good maps in a war of maneuver.

Today, in the rapidly changing and shifting military picture, the most outlandish spots become daily of key importance. Once more the importance of mapping and reconnaissance is coming to the fore. This importance has been often challenged by the view that in the event of war, nuclear weapons would enable us to completely smash the enemy's potential in a short time with bombing of a very low order of accuracy.



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It was General Loper who pointed out at the 19th Annual Meeting of the American Society of Photogrammetry that this was a dangerous notion. The enemy also has nuclear weapons. It becomes of utmost importance to avoid a miss on a military target, since a single omission may lead to a disastrous counterattack. By no means a negligible factor is the waste of these enormously costly weapons at a time when they would be very difficult to replace. So, in spite of their large radius of destruction, the enormous stakes behoove us to be extremely accurate and to build up a sizeable margin of safety in our bombing. The first prerequisite for this is the compilation of good military maps and their constant revision.

One of the first missions after the initial retaliation must be the reconnaissance and mapping mission.

* Delivered at the Society's Semi-Annual Convention, St. Louis, Mo. Oct. 4, 1957.

The military mission differs in many important respects from the civilian. Perhaps the most important difference is the complete inaccessibility of the enemy territory which must be mapped. This leads to a mapping situation in which we have extremely sparse and questionable ground-control. The military man must search for a substitute. The essential purpose of ground-control is to supply a means for restoring the six unknown elements of exterior orientation. Any instrument or system which can supply the missing data in full or in part can substitute for ground-control. Recent years have seen the development of a number of interesting techniques which can perform this function.

The six elements of exterior orientation are the x and y coordinates of the camera, the altitude, the crab angle and the tip and tilt of the camera. Horizontal-control may be achieved by means of a variety of aids from inertial or astral navigators to various radio and radar aids to navigation. Most of these will serve to locate the aircraft only approximately, but Shoran can be used over distances up to 250 to 300 miles to give geodetic accuracy to horizontal-control.

Vertical-control can be established by barometric or radio or radar means. One of the best instruments for the purpose is a narrow beam radar of high accuracy called the Airborne Profile Recorder. Altitude errors over terrain can be kept below 10 feet with this instrument. Figure 1 indicates that in order to attain meaningful accuracy, the beam should be directed in a known way toward the ground. Displacement of the beam results in a change in indicated altitude. With the narrow beams now available, it is desirable to mount the *APR* Antenna in a stabilized mount of good vertical accuracy, especially in areas of rugged terrain. To date, much experimental work has been done by using the type A-28 Mount with very good results.

Crab of the pictures can be reduced to quite low values by orienting the camera in azimuth. Absolute orientation can be achieved if the aircraft is provided with a good directional reference to which the camera can be slaved. Inertial navigators and other modern aircraft reference systems can provide this accuracy. Excellent drift metering is now available by optical scanning or with Doppler Radar.

The tip and tilt of the camera can be controlled by means of proper camera mounting. This last will be treated in greater detail in the latter part of this paper.

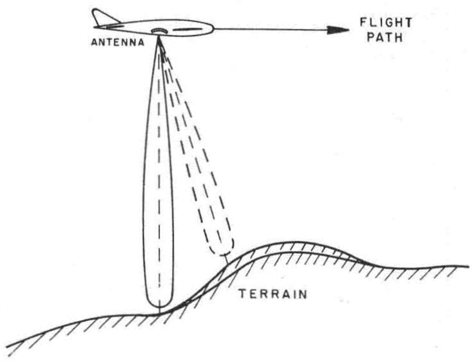

FIG. 1

Before proceeding to the main theme of this paper, a few words about an extremely important side issue will be of interest. Map accuracy is unquestionably influenced by resolution. In the case of military photography this is especially true since no one will provide clearly identifiable control points. What ground-control exists will be sparse and every bit of it must be used. To make accurate identification possible it is essential that maximum resolution be provided. This resolution must be attainable under military flying conditions which are far from ideal.

Resolution is destroyed by motion of the camera during exposure. This motion is often reduced by a reduction in the exposure time. This has several important drawbacks:

1) Resolution is a function of exposure (see Figure 2). Reduction of exposure limits photography to ideal lighting conditions and reduces resolution in shadow areas.

2) The shorter exposure time restricts use to fast films and these do not yield the best resolution. The other alternative is to reduce the camera motions.

The camera motions may be divided into three classes: (a) Vibration caused by the aircraft and by mechanisms in the camera and mount. (b) Roll, pitch and yaw motions of the aircraft and, (c) Forward motion of the aircraft.

At the 1957 meeting of the Society of Photographic Scientists and Engineers Squadron Leader Herold recently pre-

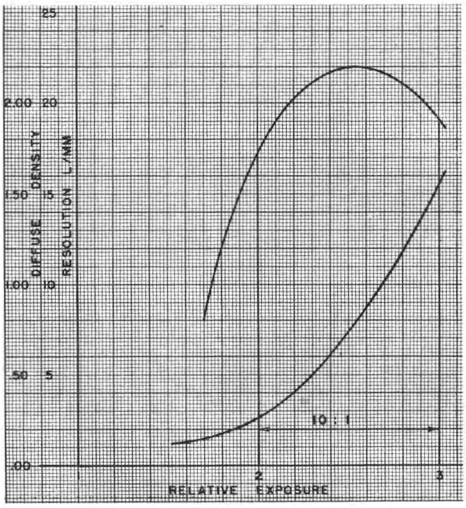

FIG. 2. Resolution vs. exposure. From Technical Note 37, Ordwes Lab. "Photographic Resolving Power at Low Contrast: Three Aerial Emulsions," by K. Roustis, Wesleyan University. Target contrast 0.14, Super XX film.

sented an excellent paper on the extent to which the first class (a) is troublesome. The author believes this paper will be published in the Journal of that Society. The second class of motions has been ably treated by Mr. Ernest Pallme in a paper entitled "Camera Mounting for Photogrammetric Purposes" in Vol. 22 No. 5 of PHOTOGRAMMETRIC ENGINEERING. As a result of recent work in camera mounting, it is felt that the effects of these first two classes may be essentially removed. The forward motion of the aircraft—the third class—is generally removed by swinging the camera or moving the film in such a manner as to compensate for the image motion.

If image motion compensation is to be of maximum effectiveness in modern fast airplanes and with a variety of scales, it must be executed with good accuracy. One aspect of this problem is of interest namely that the accuracy is a function of the angular difference between the direction of *IMC* and the ground track. This is due to the fact that the cross axis image motion will be uncompensated. The size of the *IMC* error is given in Figure 3. The image motion is usually measured in a scanner or in a drift sight. If these instruments are not vertically stabilized, the measurement of drift angle will be made in the plane of the aircraft instead of in a horizontal plane. For eight degree motions of the aircraft, the resulting error in measurement of drift angle is in excess of a degree. Reference to Figure 3 shows that the resulting *IMC* error is about 1.7 per cent. This is rather large for high speed operations; the conclusion is that we must vertically stabilize the scanner, drift sight or viewfinder that is used to determine drift angle and *IMC* speeds.

We now have camera, Airborne Profile Recorder, *IMC* scanner and a variety of viewfinders, radars, infra-red cameras which must be vertically stabilized in the moving aircraft. This problem will be examined in greater detail. There are numerous methods for establishing the vertical on an aircraft. A tabulation of each of these together with a brief discussion may be helpful in clarifying both the difficulty and usefulness of the various methods.

A. PHOTOGRAMMETRIC METHODS

These photogrammetric methods are all ways of performing a resection of space. Required are a minimum of three well-spaced points whose ground coordinates (x, y, z) are accurately known. There are a great variety of such methods, most of which are undoubtedly well known to the Members of this society. Perhaps the most accurate and most appropriate, now that computing machines are so widely available, are the analytical methods. One of these has been described by Dr. Hellmut Schmid in a number of papers in PHOTOGRAMMETRIC ENGINEERING. By using ex-

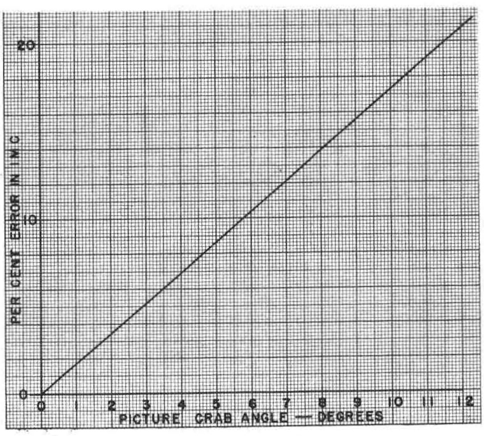

FIG. 3. Image motion compensation error vs picture crab.

tremely flat plate glass for photography and every possible precaution to attain first order results, Dr. Schmid has been able to reduce errors of orientation to a small fraction of a minute of arc. The amount of labor and the cost of equipment are very great, however, and errors would of course multiply as ground control became uncertain or poorly identified.

B. Ground Camera Method

The elements of this method are presented in Figure 4. If a camera is located on the ground and its orientation is known, a picture is taken with it at the same time that the aircraft camera is exposed. The angle θ is obtained from measurement of the aircraft coordinates on the ground camera picture. The angle α is similarly obtained from the aerial negative. The orientation is the difference of these angles. The disadvantages of this method are obvious. It requires a ground camera and a radio link or careful timing to attain simultaneity. Of course, the enemy will not permit such an installation. However, the method is certainly of value for tests and may also be useful as an alternative to accurately surveyed ground control points. In a mapping flight which cantilevers into uncontrolled territory, the initial orientation might be obtained more cheaply by this method than by surveying.

C. Horizon Photography

This method calls for exposing pictures which include at least two widely-spaced points on the horizon. These pictures must have a known angular relation to the vertical camera. It is a method which has been used for years by the military. It suffers from several basic disadvantages.

a) The great distance to the horizon makes penetration to the horizon difficult except in unusually clear air. For an altitude of 40,000 feet the sea horizon lies 230 nautical miles away.

b) Over land areas the horizon may be displaced due to relief.

c) The large effect of atmospheric refraction at these angles can introduce errors due to varying density conditions along the ray path. If the horizon is visible in two places, of course the two rays to the horizon (corrected for dip and refraction) establish a horizontal plane. The perpendicular to this plane is the desired vertical.

D. Ground Reflection Method

This method is based upon the principle of the Auto-Collimator. A light is carried on the aircraft. When the plane passes over a body of water, the light is reflected back to the plane only by the vertical ray (see Figure 5). If the camera is then exposed, a normal photograph will be obtained with a bright spot where the reflected light is imaged. The spot defines the nadir. This method is subject to several disadvantages, the chief of which is the limitation to areas containing many sizeable undisturbed bodies of water. Appreciable errors can be produced by tides, wind or other influences tending to produce changes of head across the surface.

E. Astronometric Methods

Observations on celestial bodies can be

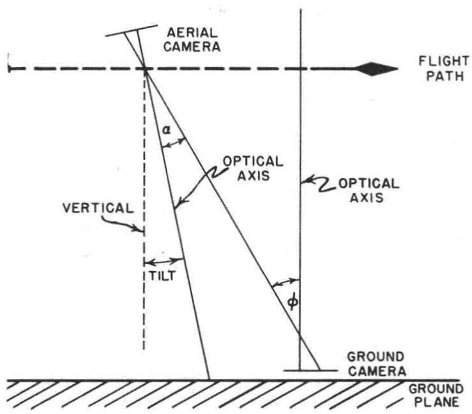

FIG. 4. Ground camera method.

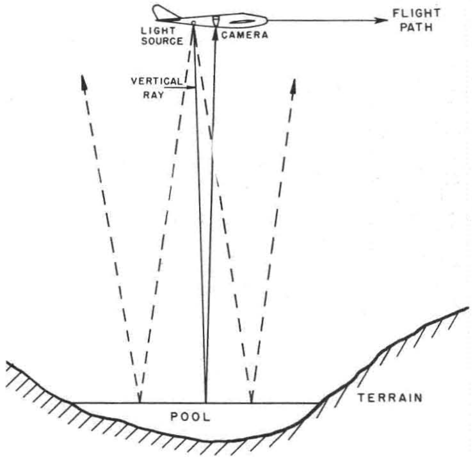

FIG. 5. Ground reflection method.

used to orient and to locate bodies on the earth's surface. The various problems can be described as follows:

a) Observation of the altitude and azimuth angles of a single body at a known time can establish location. Observation of altitude presumes a knowledge of vertical; observation of azimuth, a knowledge of True North.

b) Observation of the altitudes of two bodies at a known time can establish location. Once more a knowledge of vertical is presumed. These two are the classical problems of the mariner and surveyor.

c) Known position and time combined with observation of two bodies can establish orientation in vertical and azimuth.

d) Known position and time combined with observation of a single body can only define a vertical plane. In order to define the vertical, the direction of True North must be known.

Now the error in establishing vertical is affected by the error in Geographic Position only to the extent of one minute of arc for every nautical mile of error. It is rare that a mapping photo would be indeterminate to that extent. Of course, photography is usually a daytime affair so that case d) is the one that would be presented and the body would be the sun. One disadvantage of the method is that a vertical plane only would be defined. However, case c) may be useful for test of other methods if the photography is performed at night.

F. Introspective Methods

This name was chosen because these methods are all essentially self-contained. The position of vertical is determined by measurements which have no reference to the world outside the aircraft. These methods can be divided into two basic extremes with a number of intermediary methods. The extremes are the pendulous methods and the inertial methods.

a) pendulous methods

Of course, *the* method of establishing a vertical on the ground is the pendulum, spirit level or similar device. This is the basic reference aboard today's aircraft as well. However, the pendulum suffers from a very basic flaw, it indicates the direction of the resultant acceleration to which the support is subjected. If gravity were the only such acceleration the pendulum would be accurate. But aboard the aircraft there are always other accelerations. There is no way in which the effect of gravity can be separated out except by distinguishing between the relatively constant and the variable components. Since one so often hears that some particular aircraft is so stable that the pictures taken in it will be very close to vertical, it might be worthwhile to examine the errors resulting from some typical flight conditions. This may be done by tabulating the flying conditions which result in some arbitary level of error. In Table I this is done for errors of 3 minutes of arc. A few words of explanation may be in order on each of these items.

Table 1

Item	
1. Gusts, turbulence	.00087 g.
2. Longitudinal acceleration	1 knot/min.
3. Rate of turn at 600 knots	0.143°/min.
4. Coriolis at lat. 45°	150 knots
5. Rhumb line at lat. 45° course 45°	500 knots

1. If the aircraft suffers horizontal accelerations due to gusts or turbulence amounting to less than 1/1,000 the acceleration of gravity, a 3 minute error results.

2. If the aircraft speeds up or slows down by as much as 1 knot for each minute of time, a 3 minute error in the pendulum results.

3. If the aircraft turns, the pendulum will be thrown outward by centrifugal acceleration. A turn at a rate of 1/7 degree per minute at 600 knots would produce an error of 3 minutes of arc. This turn is about half the rate at which the earth turns.

4. This item, the Coriolis force, has a fancy scientific name, but is actually a rather simple effect. If a pilot flies from point A to another at B, he would attempt to follow the great circle route. This is shown in the following Figure 6. If he remains stationary at A as the earth moves, he follows the path A to A' If he flies toward B on a great circle route, he would follow the path A to B'. Now the centrifugal force resulting from the greater curvature of this path over the path AA' is called Coriolis. This varies with latitude and speed and gives an error of 3 minutes of arc at Latitude 45 degrees and a speed of 150 knots.

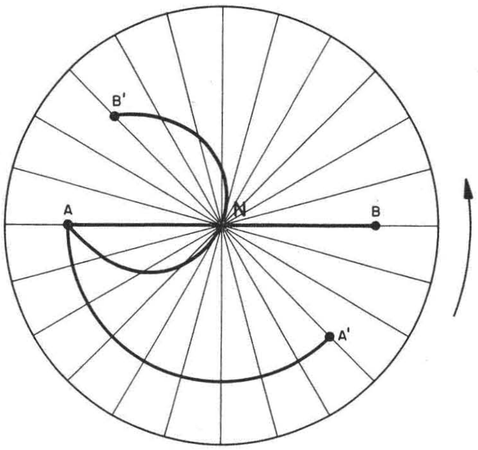

FIG. 6. Coriolis acceleration.

5. Actually the pilot seldom flies great circle courses. He breaks up the flight into small portions of constant course flying. Such a path is not even a straight line on the earth's surface. If he follows a constant bearing at latitude 45 degrees with course angle 45 degrees, a speed of 500 knots will produce a 3 minute error from this source alone. It becomes evident from all this, that a simple pendulum is of little value in establishing an accurate vertical. It may be improved, however, by the addition of a gyroscope.

A Vertical Gyro consists of a gyroscopic wheel upon which is mounted a pendulum. If the wheel is not vertical, the pendulum produces a signal which is used to exert a torque on the wheel tending to bring it to vertical. This torque is very small and the gyro comes very slowly to vertical. If an acceleration causes the pendulum to deflect, the gyro will very slowly move away from vertical. When the acceleration ceases and the pendulum returns to vertical, the gyro has only moved away a very small amount, and it now tends to reduce even this error. The effect is, therefore, to reduce the swings to which the pendulum is subject, the Vertical Gyro acts as a filter on the pendulum. But the long term errors are not removed, since the gyro will then have time to align itself with the pendulum.

There exist various improvements on this simple system, but in no case can the errors be reduced below about $\frac{1}{4}$ degree. The other disadvantage of such systems is that the flight must be at least nominally straight and level since only the variable effects are reduced.

b) INERTIAL METHODS

In recent times a new system for obtaining the vertical has been designed which eliminates the disadvantages of the pendulous systems. This system measures the aircraft accelerations and computes the effect of these motions on the vertical. The system is theoretically correct and suffers only from errors arising from instrumental imperfections. These methods are unquestionably the method of the future and can be used to give a system, with presently available components, giving an error of less than 3 minutes of arc in spite of maneuvers and other disturbances.

Of this list of methods, the only ones of real value for a military mission are the so-called introspective methods. A concluding glance at some of the uses to which a vertical reference can be put will clarify the levels of accuracy required and the necessity for vertical mounts for military work. Since some of the most costly portions of civil work lie in the ground survey and in orientation of the pictures, it can be seen that any aid on these portions of the process would be of great value.

The first use of vertical pictures is in the production of mosaics. By taking vertical pictures one very tedious portion of the work is removed. In Figure 7 is shown a stapled mosaic made of contact prints from photography in a fixed mount. The extreme buckling is largely caused by tilt. In Figure 8 we have a similar mosaic made up of photographs taken in the Type A-28 vertical mount. The residual buckling is largely due to scale error which could be eliminated by using an Airborne Profile Recorder and printing to scale.

The accuracy of slotted templet assemblies could be improved with photography having tilts of less than 5 minutes. For multiplex work, tilts of less than 3 minutes of arc would be of great usefulness in setting up where ground control is sparse.

For civil purposes one of the most promising uses seem to be in locating the nadir point of shoran controlled photography. At an altitude of 10,000 feet a 3 minute error would produce a displacement of the nadir of only 8.7 feet on the ground.

When inertial systems become more widely used, a further advantage can be made available to the photogrammetrist.

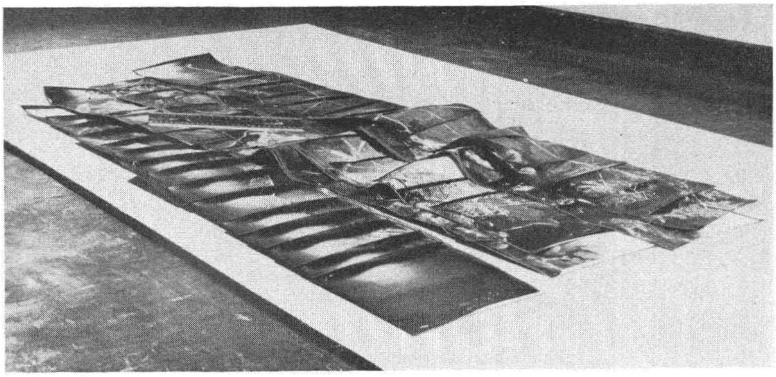

FIG. 7. Uncontrolled mosaic of stapled photography made in a fixed mount. Note buckling and gap in foreground.

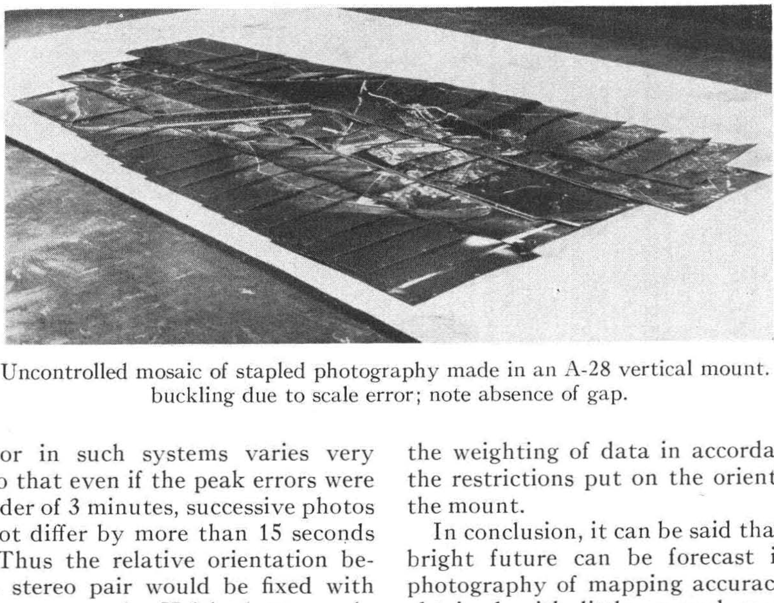

FIG. 8. Uncontrolled mosaic of stapled photography made in an A-28 vertical mount. Residual buckling due to scale error; note absence of gap.

The error in such systems varies very slowly so that even if the peak errors were of the order of 3 minutes, successive photos would not differ by more than 15 seconds of arc. Thus the relative orientation between a stereo pair would be fixed with sufficient accuracy for Kelsh plotter work, and of great value even for first order plotters. In addition, in analytical work a cantilever extension could be improved by the weighting of data in accordance with the restrictions put on the orientation by the mount.

In conclusion, it can be said that a really bright future can be forecast in which photography of mapping accuracy can be obtained with little ground control and with greatly simplified instrumentation for compilation.