*Development of Aerial Camera Stabilization and Its Effect on Photogrammetry and Photo Interpretation**

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ABSTRACT: *From the inception of aerial photography, the photographer searched for methods of holding his camera steady and vertical despite the vehicle's motions. Early attempts were generally based on the pendulous mass principle. As vehicle speeds increased, the motions became too severe for crude methods and the use of the gyroscope was introduced. Finally, it was recognized that center of gravity mounting was necessary, and improved gyroscope technology began to make possible the goal of complete isolation of the camera from the vehicle. This goal has been closely approached by the use of modern gyroscope and servo techniques.*

THE object of stabilization is two-fold. First and most important is the removal of the effects of aircraft motions, enabling the photographer to get laboratory resolution from his camera and film. The second object is to keep the camera so close to true vertical that subsequent rectification (except, possibly, for a small-scale change) is not necessary.

This paper shows to what extent these goals have been achieved. It also sketches the story of how this has come about and indicates what the future holds in store. It might be noted here that while perfection is theoretically the goal, the law of diminishing returns operates to force a more practical view. Thus, in steadiness, the attempt is to get less than 5 or 6 seconds of arc of motion in any exposure period for a 36 inch lens. This gives negligible resolution degradation. For verticality, 3 minutes of arc error is desired, this being the limit of accuracy of rectification. Both of these requirements have been met by present equipment. The conditions necessary for this will appear later.

Before plunging more deeply into the material, some of the reasons for stabilizing will be examined briefly. These may be classified as civil and military. In civil photography the advantages of stabilizing must be evaluated almost entirely on an economic basis. They may be briefly outlined as follows:

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(1) The automatic attainment of steadiness and of even a low degree of verticality eliminates the necessity for a skilled photographer to operate

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the camera, and reduces the load on the pilot.

(2) Improved steadiness makes practical the use of longer exposures. This has the advantage of extending the photographic day, or providing greater freedom in the choice of aperture and film.

(3) The greater imperviousness to aircraft motions makes possible photography in clear air turbulence, thus giving many more photographic days in the year.

(4) The enormously increased probability of good pictures reduces the number of necessary repeat flights.

(5) With sufficiently good verticality the necessity of rectification could be eliminated, and in some cases even ground control could be eliminated or simplified.

Before proceeding to survey the present state of the art, the history of the art will be described very briefly.

The first self-conscious attempts to stabilize an object in a moving vehicle occurred in the Age of Discovery. As ships ventured further from land the importance of accurate navigational instruments became apparent. The first instrument to receive this attention was the compass; this was suspended in gimbal rings to isolate it from the ship's motion. The first gimballed compass appeared in 1537.

The word "gimbal" is derived from the Latin "gemelus" meaning twin. From this came the Old French gemel, a term for a ring formed of two linked hoops used as betrothal or friendship rings in the 16th Century. The earliest mention of such a device occurs in the work of the 13th Century architect Wilars de Honecort. He described a handwarmer, a charcoal brazier supported in six gimbal rings to hold it top-side up. The six rings are apparently an erroneous attempt to eliminate gimbal lock. De Honecort added . . ."you may turn it about in any way and the cinders will never fall out. It is excellent for a bishop, for he may boldly assist at high mass, and as long as he holds it in his hands they will be kept warm. . . . "

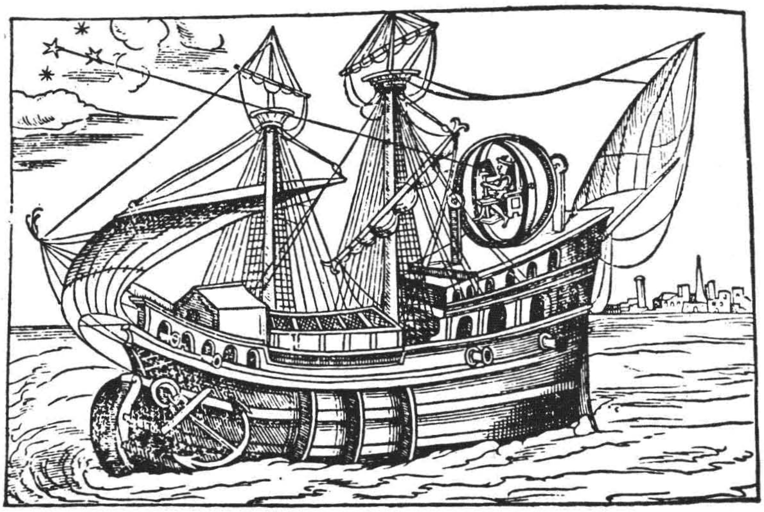

FIG. 1. Stabilized navigator of the 16th century.

In military photography the argument is even more forceful. There are two all important areas of usefulness.

(1) Guaranteeing a high degree of verticality is mandatory in mapping areas where no ground control is possible.

(2) Obtaining the highest probability of high resolution is essential. A mission is flown at great danger to personnel and equipment. It is not desirable to repeat a flight. It may not even be possible since the military picture may be in a state of flux. A mission *must* be fruitful.

After the use of the device on the compass it came to be used quite extensively for shipboard instrumentation. In the same century a suggestion was even made

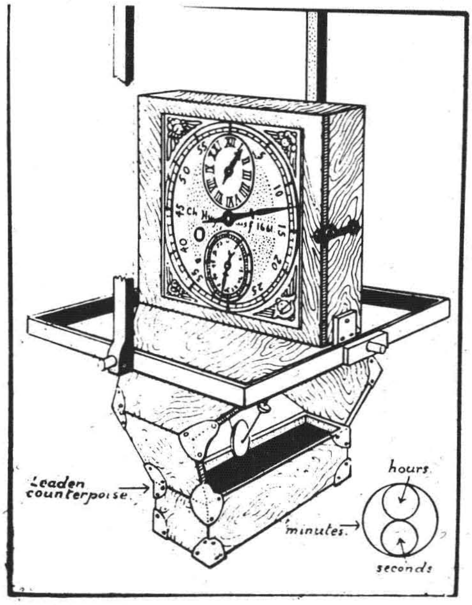

FIG. 2. Stabilized chronometer by Huygens.

to gimbal the navigating officer himself for taking Star Sights (Figure 1).

In 1659 Huygen's Marine Chronometer was gimballed and heavily weighted with lead so as to maintain verticality for the clock pendulum. Some success was obtained but time sufficiently accurate for Longitude measurements had to await Harrison's Chronometer using a torsional pendulum independent of vertical. It may be noted that almost all of the early attempts were based on the pendulous gimbal principle (Figure 2).

The gimbal was first applied to aerial photography in 1858. In this year, only 19 years after the invention of photography by Daguerre, a French balloonist, F. Tourachon, engaged in aerial photography, obtained a patent on a device to hold a camera in a vertical and steady position, by means of a pendulous gimbal suspension. One would think that a balloon would be steady enough for photography but there must be remembered the slow speed of the wet plates then in use. Figure 3 shows a view of Boston taken from a balloon in 1858. Messrs. King and Black exposed eight wet collodion plates and secured two good pictures, of which this is one.

The use of a pendulous suspension is undesirable because the unbalance necessary to get verticality causes the mount to respond to lateral accelerations. Some of the defects of this type of suspension can be alleviated by using a gyroscope. This instrument, however, was not at this time a practical device.

Gyroscopic principles had been known since early times and Newton formalized some of these motions, but the subject was still a learned discussion of an interesting toy. The word gyroscope was coined in 1852 by the French physicist Foucault. The etymological meaning is "rotation viewer" from the Greek, and was chosen on account of a method Foucault used to demonstrate the rotation of the earth. His apparatus is portrayed in Figure 4. Since this pre-dated electric motors, the wheel was demountable. It was put into the device in the center of the figure which geared it to a hand crank. It was brought up to speed and then put back into the gimbal structure. The microscope was used to examine the motion of a pointer attached to the gimbal.

Gyroscopic instruments had to await technology capable of getting power to the wheel without coercing the suspension. In 1878 an electric motor was introduced and Foucault's experiment was successfully run by Hopkins. Subsequently a whole series of interesting applications appeared such as the early gyro compass

FIG. 3. Aerial view of Boston, 1858.

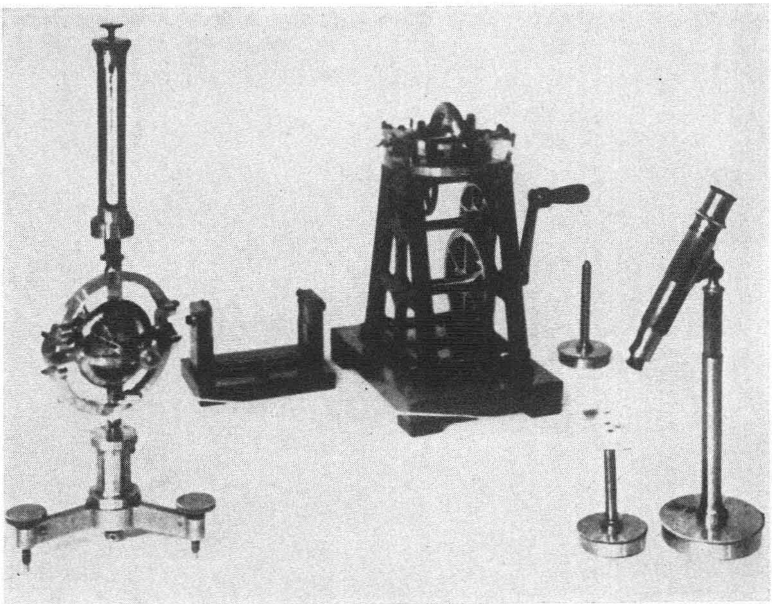

FIG. 4. Foucault's gyroscope, the first such instrument.

shown in Figure 5. This was one of the first instruments using an electric motor.

The first suggestion for the use of a gyroscope to stabilize an aerial camera was made by Stolze in the *British Journal of Photography* in 1881. The suggested device was to attach a gyroscope rigidly to a gimballed camera.

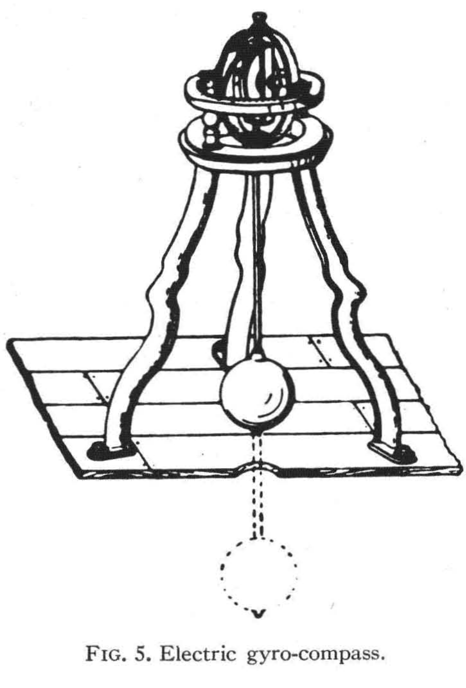

FIG. 5. Electric gyro-compass.

With the introduction of the airplane the problem of vibration had to be faced. In 1912 Gasser in Germany introduced the use of springs and a pneumatic cushion to the mounting of aerial cameras. With the airplane the other motions also became more severe, and a burst of activity was produced in the stabilization field.

Some of the first work was done in the United States. In 1915 A. Brock received a patent on a gyroscopically controlled camera mount with the gyroscope being rigidly attached to the gimballed camera. The wheel is in the center of Figure 6.

In 1922 a patent was granted to Cooke for a gyroscopic mount. In this device we see the first attention given to balance. To avoid the gyroscopic precession caused by unbalance, it was necessary to take the film off the gimbals through the bellows arrangment in Figure 7.

Figure 8 illustrates the first Servo approach. S. Fairchild received a patent in 1923 for an arrangment which used a gyro for reference only. Some means of data take off was provided, and a system of levers and motors used to keep the camera slaved to the gyro. The gyroscope used in this mount is illustrated in Figure 9.

This scheme failed of success only be-

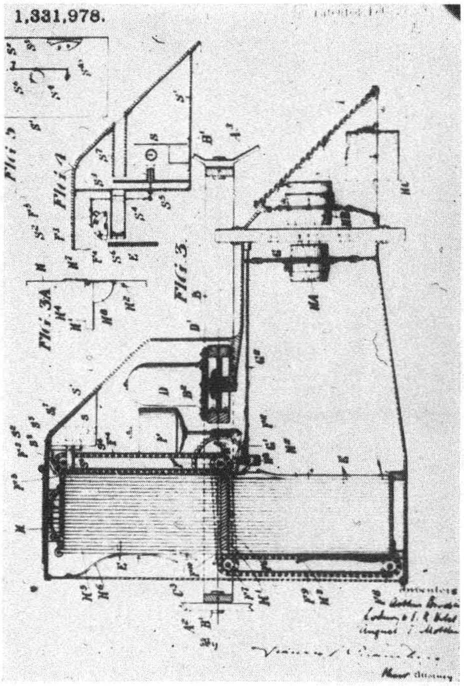

FIG. 6. Gyroscopically stabilized camera mount vintage 1915.

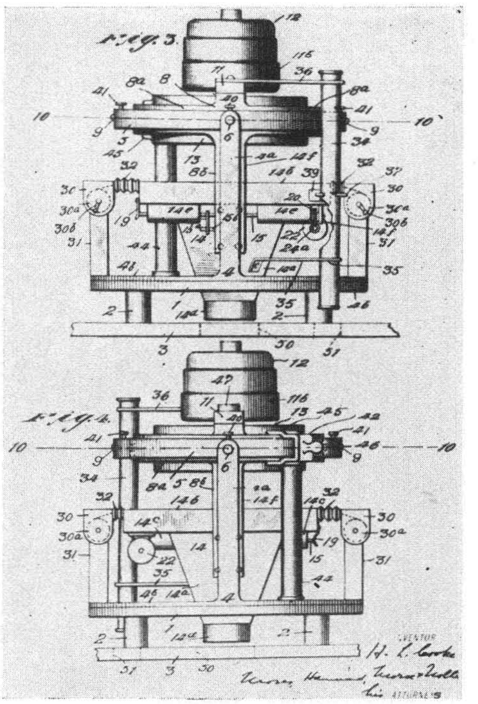

FIG. 7. Gyroscopically stabilized camera mount with balance control in 1922.

cause at that time there were no gyros of sufficient accuracy and no servo devices which would ensure low enough reaction torques on the gyro. A typical vertical gyro of that period is shown in Figure 10.* On account of these difficulties the stabilized mount disappeared from view and no further developments occurred until the start of World War II.

Early in that war the principal problems were those of vibration. A series of sponge rubber mounts were developed by Robinson and manufactured by Aeroflex

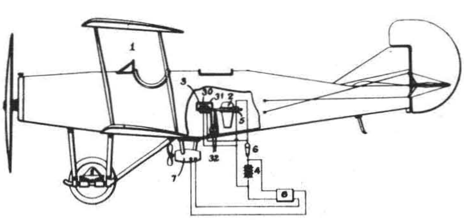

FIG. 8. Camera mount servo controlled to gyroscopic reference in 1923.

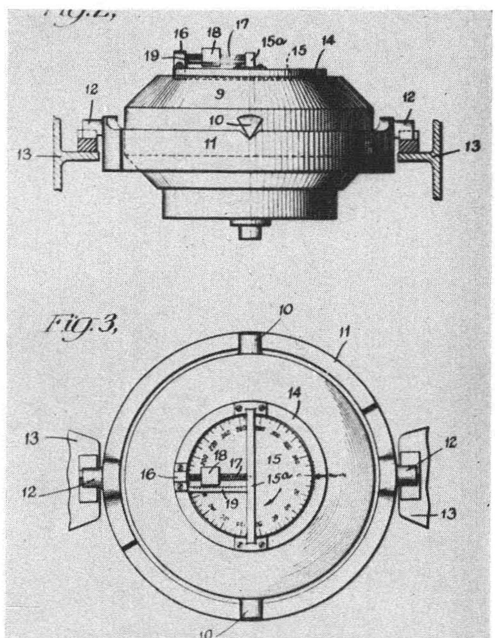

FIG. 9. Gyroscope from the mount in Figure 8.

* Compare this crude device to a modern vertical gyro manufactured by Aeroflex Laboratories specifically for aerial camera stabilization; see—Figure 11.

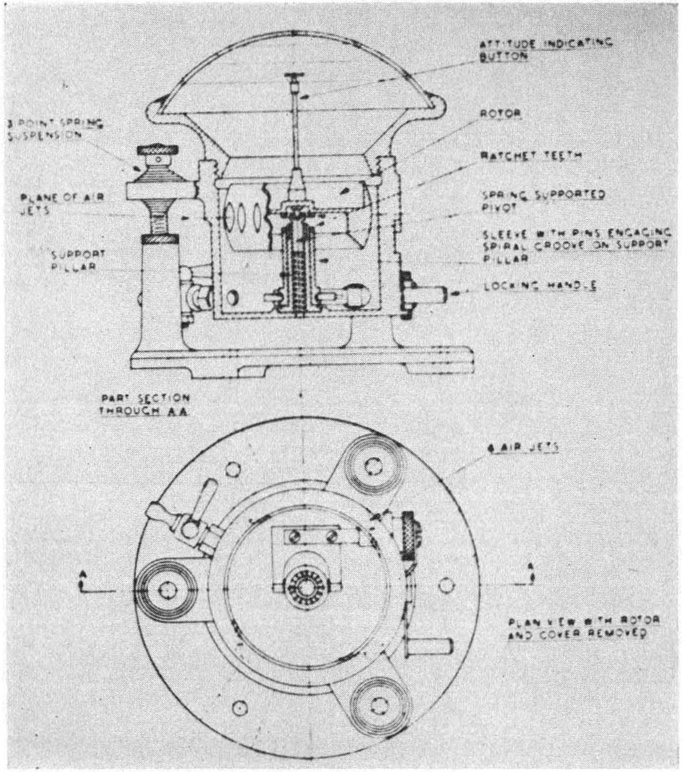

FIG. 10. Typical vertical gyro of the early twenties.

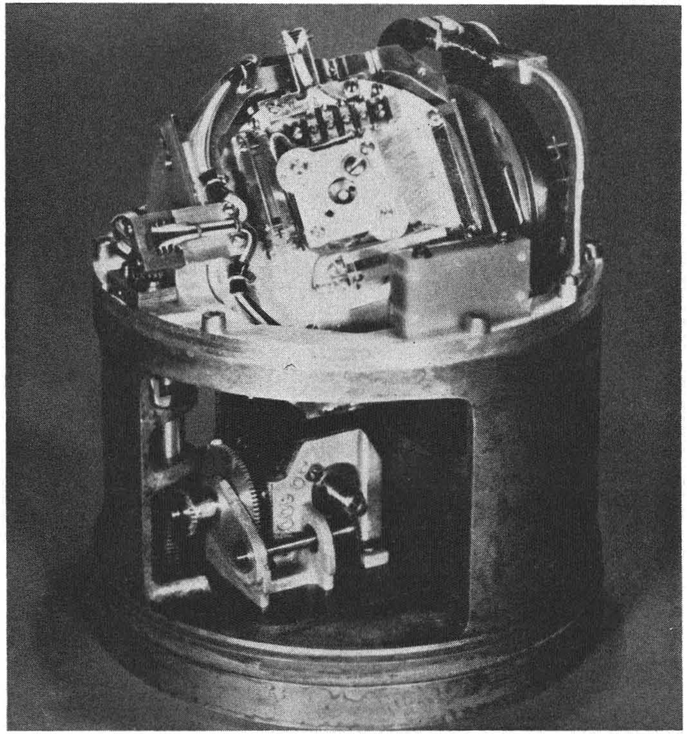

FIG. 11. Modern vertical gyro by Aeroflex Laboratories Incorporated.

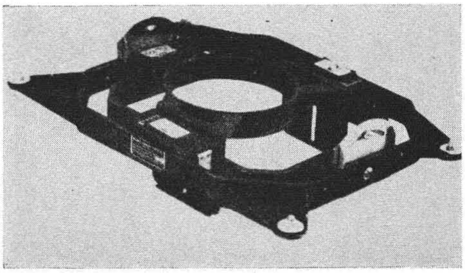

FIG. 12. Vibration isolated mount of World War II.

Laboratories. Typical of these mounts are the A-17 illustrated in Figure 12 and the A-8, A-27, A-17 and the NR-1, 2 for the Navy. Depicted in Figure 13 are a couple of typical installations.

Among the first to feel the necessity for improvement were the British. In late 1941 the British completed development of a gyroscopically stabilized mount. This was probably the best of its type and was a reapplication of the original ideas in the field. A gyroscope was rigidly attached to a balanced gimbal suspension carrying the camera. Great care was taken to balance it accurately. The greatest disadvantage of this type of mount is the enormous size of the gyroscope required. This not only makes manufacture of a sufficiently accurate gyro difficult, but actually constitutes a physical danger to the ship. This mount also incorporated provision for rotating the mount to compensate for forward motion of the aircraft.

When work was undertaken in the United States it was early realized that the principle of primary importance for steadiness is the accurate location of the center of gravity at the intersection of the axes of rotation. The early work was done by the Harvard Optical Research Lab. which mounted 2 K-40 cameras on a $\frac{1}{8}$ inch steel ball, located at the common center of gravity. The results indicated excellent elimination of the influence of vibration, but no important improvement of the long period motions of the aircraft.

After the war much of the work done by the Germans came to light. This work culminated in the Steinheil mount which was perhaps 75 per cent complete when the war's end stopped work. The men and the mount were brought to the United States where the work was completed and the mount became a prototype for the Air Force A-28 mount. The principle of this was the use of gyros as reference units only. A servo system using an optical data pick off was used to slave the mount to the gyros. The mount is shown in Figure 14.

This mount was redesigned to use American components and to take a series of American cameras. The resulting mount is the A-28 production mount (Figure 15) manufactured by Aeroflex Laboratories.

The accuracy of verticality is perhaps $\frac{1}{2}$ to 1 degree. The isolation from long period motions is excellent but from vibrations is not very satisfactory. It depends upon excellent low frequency isola-

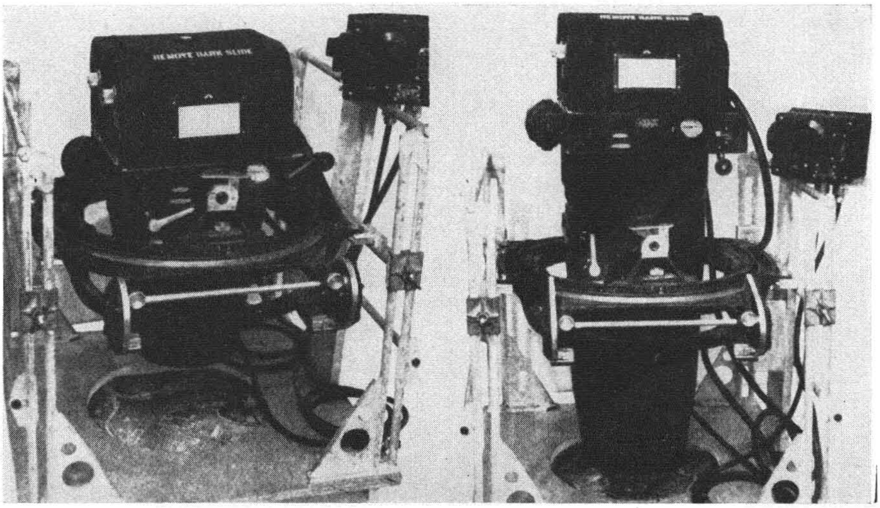

FIG. 13. Two typical installations of vibration mounts, World War II.

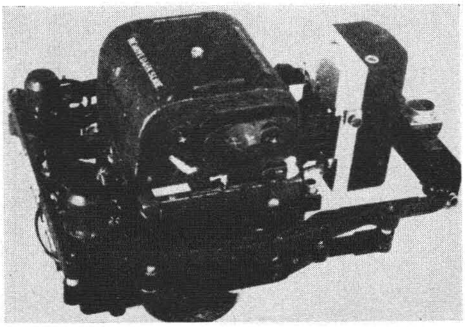

FIG. 14. Air force prototype A-28 (Steinheil) mount.

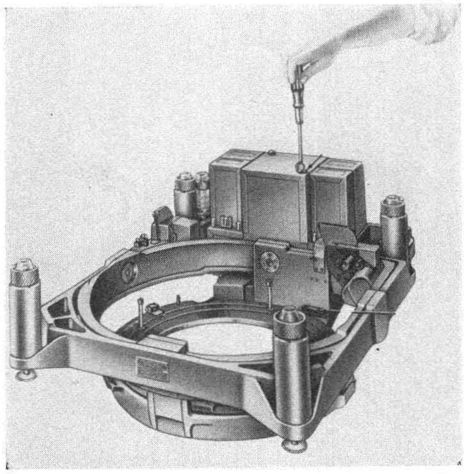

FIG. 15. Production A-28 mount.

tors for this purpose. Really satisfactory isolation from fast disturbances cannot be obtained with geared servos since the motor and gearing constitute a restraint on the gimbal. Where a skilled operator is available without too high a cost, it is better to eliminate the servo and to return to the idea of a balance point mount. Such a mount was designed for the Geological Survey by Aeroflex Laboratories and is depicted in Figure 16. This mounts two T-11 cameras on a small Hooke's joint of extremely low friction. The photographer keeps the mount level and the *cg* suspension keeps resolution high.

If automatic operation is required the same or better results may be obtained by the use of torquers to slave the mount to a vertical gyro. Such a mount is shown in Figure 17. The design has progressed to the point of making the camera essentially independent of aircraft motions. The mount was designed for night operations with exposures of 0.1 second. Motion during this exposure is kept to less than 6 seconds of arc in any exposure period giving essentially laboratory resolution for the K-36 camera. The verticality is only slightly different from that obtained with the A-28.

Pictured in Figure 18 is a mount recently designed to give extreme precision in verticality coupled with the high level of steadiness. This utilizes torquer servos and rate gyros to keep the mount motions

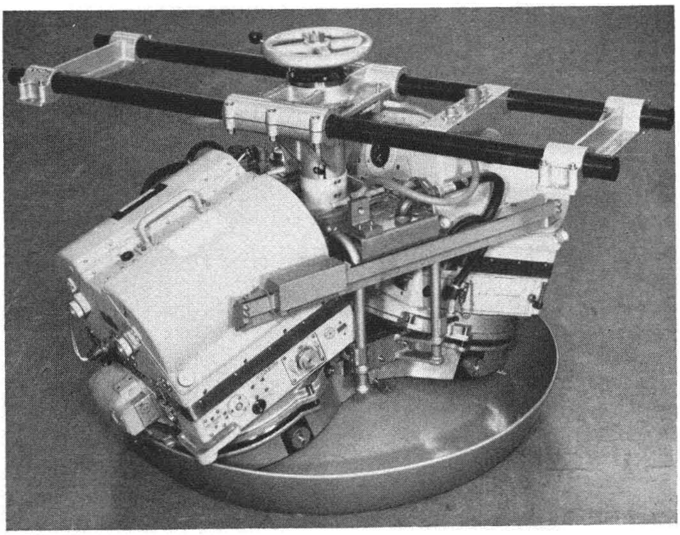

FIG. 16. Balance point mount for two T-11 cameras.

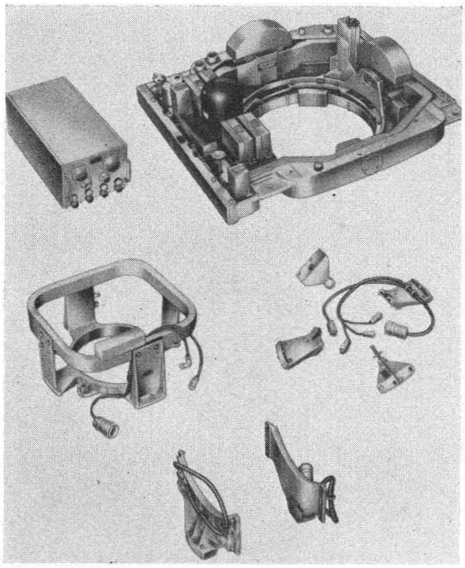

FIG. 17. Torquer driven mount with vertical gyro reference.

down. Verticality is principally a function of obtaining a good reference, which is present in the Aircraft for which this mount was designed. The verticality error of this mount is less than 3 minutes of arc but the size of the equipment for the vertical reference is enormous.

Future work in this field must and will be directed toward reducing the size, complexity and cost of the accurate vertical reference and of the mounts in general. Several development programs are now in progress toward that end. The author feels that the problem of steadiness has been adequately solved, and the program is now directed toward simplification and increasing reliability. A high accuracy vertical reference really suitable for photographic work has not yet been perfected however. Most of the long term development must be directed toward this end. The advantage of eliminating rectification and simplifying ground control are apparent.

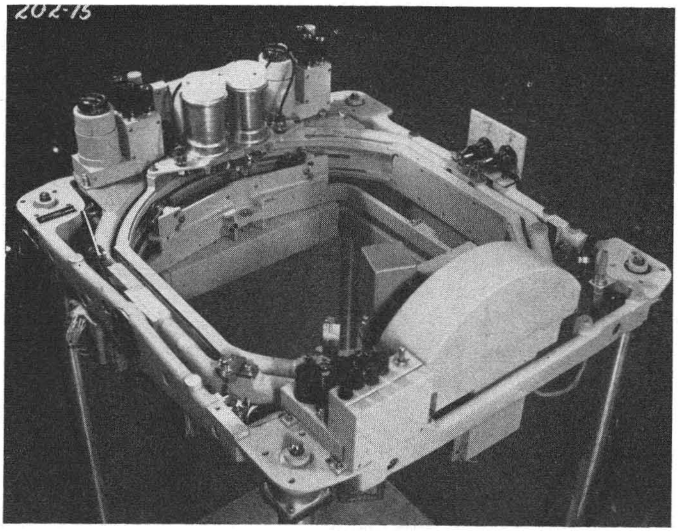

FIG. 18. Torquer driven mount with external high accuracy reference.