THOMAS W. MILLER*
The Perkin-Elmer Corp.
Norwalk, Conn.

Testing an Image-Velocity Measuring Device

The device, which provides image motion compensation for aerial cameras, is tested by means of laboratory simulation.

(Abstract on page 848)

INTRODUCTION

THE EVALUATION of an image-velocity measuring device and the theory of its design requires the simulation of targets and motion and the employment of precise measuring techniques. The laboratory techniques used to gain confidence in the theory of the device are the subject of this article. Before describing the test methods, it is considered appropriate to describe briefly the device being tested.

In its final form, the device is intended to be a passive, airborne unit which will measure optically the angular rate of a reconnaissance aircraft as it travels over the ground. The output is to be a voltage linearly proportional to the angular rate (also termed V/H) and would be used to provide image motion compensation (IMC) for the camera and film.

A paper by Hufnagel, Hering, and Landsman presented at the October 8, 1964 meeting of the Optical Society of America described the device in detail. Figures 1 and 2 schematically illustrate its operation and Figure 3 is the sensor head itself. The electronics were in breadboard form. The sensor head was to be mounted on or near a camera, stabilized to the same degree as the camera, and aligned with ground track. The ground is imaged by the sensor head lens on a fixed grid consisting of many uniformly spaced lines which are perpendicular to the ground track.

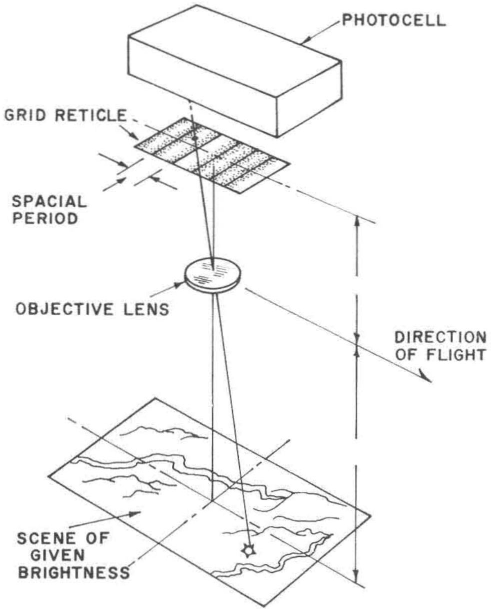

FIG. 1. V/H sensor operation.

Light transmitted by the grid is conducted to a light-sensitive detector (photodetector) via a lucite pipe. As the image moves across the grid, due to the relative motion of aircraft and ground, the light of the image is modulated by the grid at a frequency proportional to the motion. The photodetector converts this modulated image to an electrical signal which

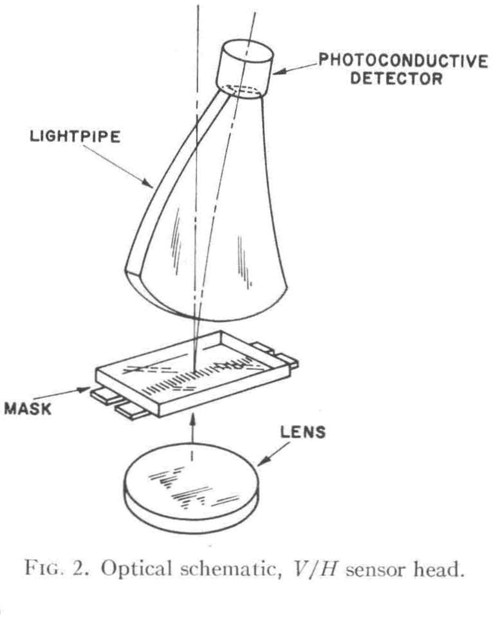

FIG. 2. Optical schematic, V/H sensor head.

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* Presented at the Annual Convention of the American Society of Photogrammetry, Washington, D. C., March 1965.

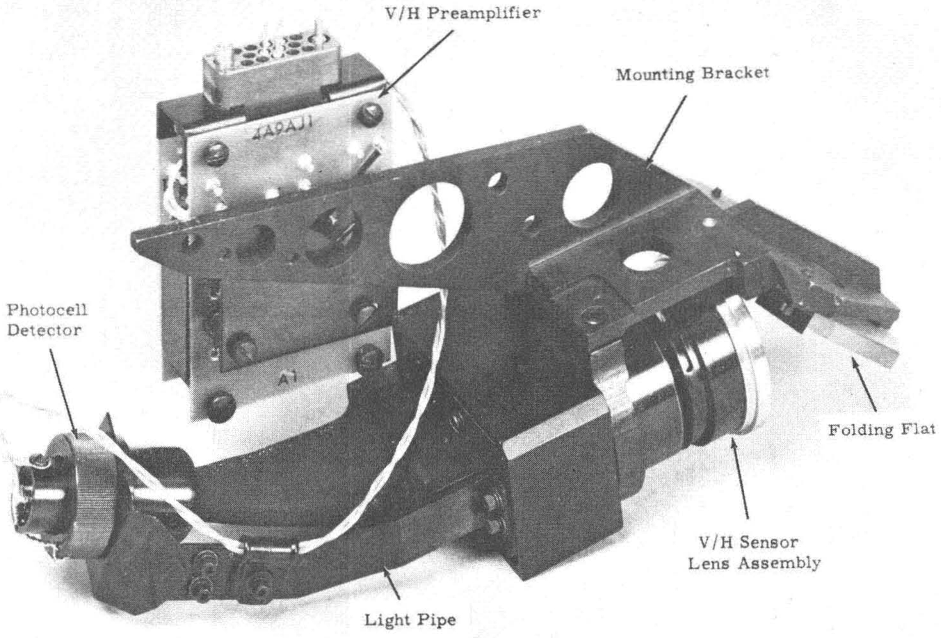

FIG. 3. V/H sensor head.

is electrically processed to produce a final output as a dc voltage.

LABORATORY SIMULATION

As flight testing is a long and costly process, it is more economical to simulate conditions in the laboratory. To this end, test methods and techniques were devised and are the chief subject of this article. Emphasis is placed on the opto-mechanical tests with minimum discussion of the electronics.

The geometric relationship between the ground motion and the frequency output of the sensor head is given by the formula:

$$F = fa\frac{V}{H} \tag{1}$$

where:

F = Output frequency in cycles per second, at infinity focus

f = Focal length of sensor lens in millimeters

a = Spatial frequency of grid in lines per millimeter

V = Ground track velocity of aircraft in feet per second.

H = Altitude in feet of aircraft above ground track

and

$H \gg f$.

The general test technique is described as follows. The sensor head was focused (at finite object distance) on a positive print of an aerial photograph. This print was mounted on a device which translated it linearly at right angles to the sensor head optical axis. The test consisted of illuminating the aerial photograph (or scene), moving it past the sensor head at a known velocity, and measuring the output frequency. The desired overall test accuracy was to be better than 1

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per cent in the V/H range of 20 to 50 milliradians per second.

As most readers are aware, the step between basic concept and successful implementation is a big one. Let me take you through each step of the way and bypass the blind alleys we followed on occasion.

LINEAR TRANSLATION

The choice of linear rather than rotary translation was a necessity, as the sensor was intended to work on a parallel-plane principle (i.e., the focal plane is parallel to the object plane). At finite object distances only linear translation satisfies this condition for extended fields. The field of view of the sensor is 30 degrees long in a direction parallel to the ground track and 1 degree wide.

The 30-degree length is intended to provide averaging of the small altitude variations created by terrain features (hills, valleys, cliffs) and is basic to the sensor design concept. Thus the longer the duration of stage travel the better the averaging and accuracy of V/H measurement. Continuous linear translation is possible with an endless belt scheme. However the problems of uniform velocity are more formidable than one would expect, inasmuch as we were looking for an absolute velocity accuracy of 0.1 per cent. We finally settled for a linear translation of finite travel which consisted of a carriage on rails (the carriage supporting the scene).

The moving carriage design followed good mechanical engineering and model shop practices. A synchronous motor drove a capstan wheel through a series of belts and pulleys. A fine wire, wrapped about the capstan and an idler provided linear translation. The moving stage rode on two parallel bars and was clamped to the wire. The entire system was essentially open-loop from a servo viewpoint, and depended on the accuracy of the power-line frequency for uniform velocity. By reversing the travel of the stage, we could make use of its motion in each direction for the tests. The discontinuity at reversal was overcome electrically by an external memory circuit.

Specifically, we wanted to know:

(a) How accurately does the V/H device work?
(b) Over what types of terrain features will it work?
(c) How low/high must the scene contract be for specific accuracy?
(d) Over what ambient light levels will it work?
(e) How repeatable is it?
(f) What happens over cloud cover?
(g) What are the effects of pointing in pitch, roll and azimuth?
(h) What is instrumentation error?

Many of these questions are interrelated so that the choice of test method involved a compromise which would yield an optimum test condition.

ABSTRACT: *A laboratory method and technique for testing an image-velocity measuring device yielded accurate and useful results. The device being tested was a passive, airborne unit which detects the angular ground rate* (V/H) *of the aircraft and provided a voltage proportional to* V/H *for use in IMC. A moving target, consisting of various aerial photographs, was used to simulate ground rates. Scaling for finite object distances and scene contrast were important considerations. Simulated light levels over the range of 50 to 700 foot-lamberts were used. Test results approaching instrumentation accuracy of ± 0.3 per cent were obtained.*

GEOMETRIC CONSIDERATIONS

The most straightforward approach was to tackle the geometrical relationship expressed in Equation 1. Each of the quantities can be measured separately and its accuracy established. One addition to this equation is necessary for working at finite object distances: a change in the image distance. For finite object distances the change in f and the value of H can be related by simple thin lens formulae. Making the appropriate substitutions for f and H in Equation 1 we get

$$F_1 = \frac{faV}{k} \tag{2}$$

and

$$u = \frac{f(f+k)}{k} \tag{3}$$

where

u = finite object distance, in millimeters (equivalent to H)
k = increase in focal distance, f, for finite object distances, in millimeters
F_1 = frequency for finite object distance (u) in cycles per second
a, V and f are as defined earlier, with V in millimeters per second

By this technique, we could make k a precisely known shim to shift the focal plane from infinity focus and also set the computed object distance u. Needless to say, we did not have a thin lens in practice and were faced with having to establish the nodal planes of the lens if we were to mechanically position the object distance u. A simpler, more precise technique, which was used successfully, was to back-project the grid and adjust the object distance to get a known, computed angular field at the object plane. This proved simple to do because: (1) the grid was made with the lens and matched with it (including radial orientation); and (2) the grid was accurately calibrated and the back-projected image (at the object plane) can be measured with a scale to an accuracy of 0.25 per cent. Thus the geometry and adjustment of the sensor head was accurate to the combined, independent accuracy of the measurement of f (typically ± 0.1 per cent), k (typically ± 0.17 per cent), and u (as ± 0.25 per cent). This leaves only the stage velocity to measure (typically ± 0.14 per cent). The measurement of these values was straightforward using routine optical inspection methods of good quality control.

The stage velocity was measured by interrupting a photocell with a series of accurate, uniformly-spaced holes in a plate attached to the stage, measuring the interruption period with an electronic counter, and taking an average of each of ten interruption periods during one pass of the stage. (Over any single period the stage rate was known to be better than 0.1 per cent). The stage rate divided by the object distance was the V/H rate of the test. (It is interesting to note that later tests found us testing the stage motion with the V/H sensor rather than the other way around.) The usage of Equation 2 and careful alignment should permit the prediction of F_1 and confirmation by test.

Having disposed of the geometric aspects, let us consider some other interesting parameters.

TERRAIN SIMULATION

As there is an infinite variety of terrains and there was no restriction to the selection of test targets, we let availability dictate our choice of aerial photos. Though such photos did not give us a 3D model, they did give us light modulation variations. Our search was restricted by the requirements that the photos be of continuous ground cover, be sufficient for the stage length, and have a scale which would give us some semblance of altitude. Since the sensor lens was nominally two inches in focal length, the combination of a 30-degree field of view and stage travel limited us to object distances on the order of 650 millimeters (25.6 inches) which made the photo problem awkward. However, as aerial cameras are our business, we were able to obtain some aerial scenes satisfactory for our needs.

The effective altitude at which the sensor *sees* the scene can be computed from the knowledge of the altitude and focal length at which the original was taken. For a contact print the geometric relationship is

$$h = \frac{f_2}{f_1} \times \frac{u}{v} \times H$$

where

h = apparent altitude, in feet, as seen by the sensor
f_2 = focal length of sensor lens, in millimeters
f_1 = focal length of lens which took original photo, in millimeters
H = altitude at which original photo was taken, in feet
u = finite object distance when testing sensor, in millimeters
$v = f_2 u/(u - f_2)$.

By controlling the contrast in the prints, we arrived at some objective, high-, medium-, and low-contrast scenes. The scenes (or targets) as actually assembled consisted of two pieces in order to increase the total scene length. This was done as follows: two enlargements were carefully made of each scene, one a mirror image of the other. They were joined at this mirror fold line and mounted. To minimize cross correlation of right- and left-hand scenes, the joining line (and entire scene) was tilted 3° about the vertical to the scene. Making the prints was an art rather than a science as it was necessary to control enlargement, exposure and contrast. Perseverance and repeated printings yielded the necessary prints. The final print was judged by eye for contrast and exposure while the correct enlargement was proven by the ability to join left and right prints. Figure 4 is a re-

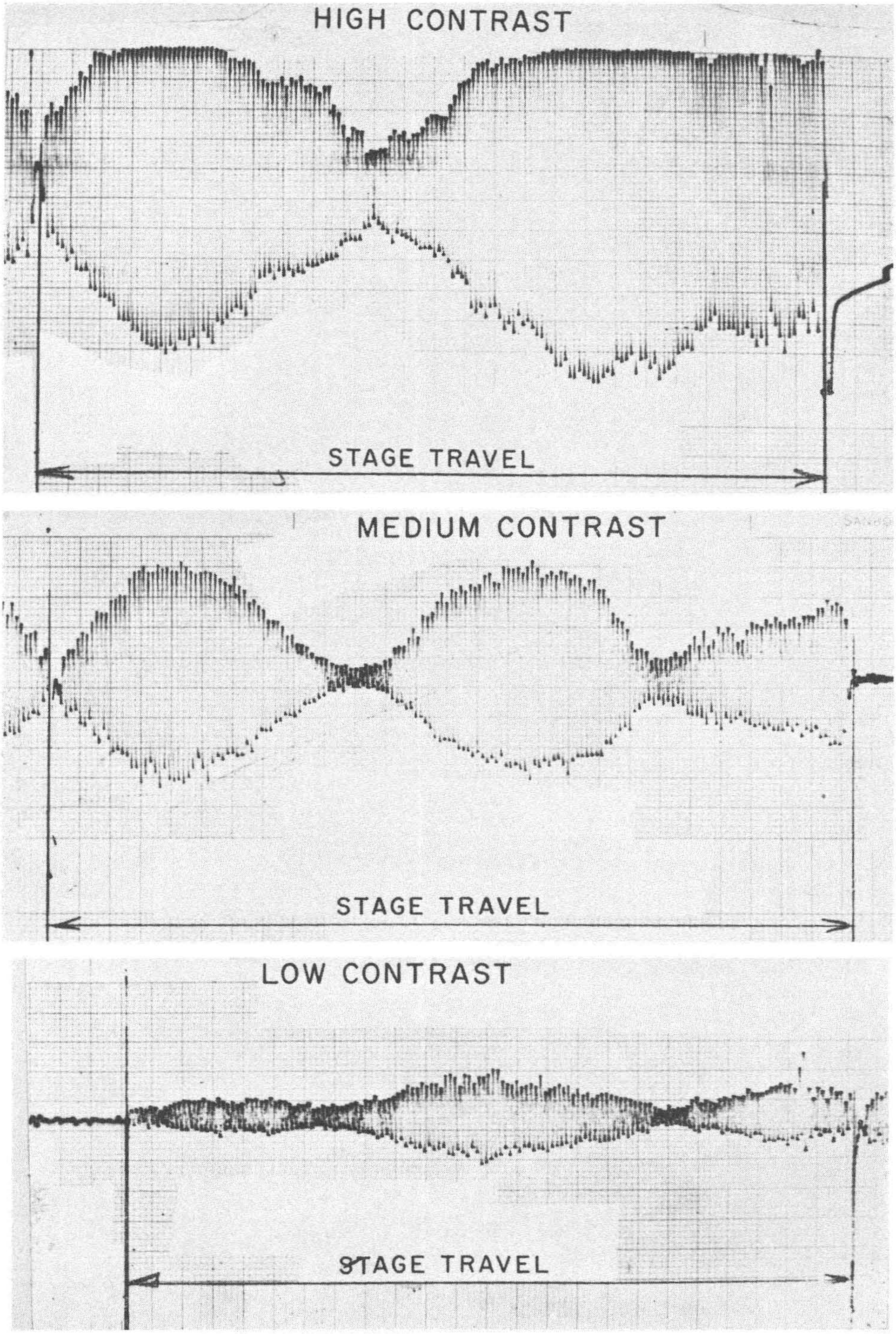

FIG. 4. Sensor output at various contrasts.

cording of the photodetector output for high-, medium-, and low-contrast sections of a scene for the same illumination level. The V/H information is contained in the frequency of the output. The scene was illuminated by two halide type, high-intensity lamps, specifically Sylvania DXN lamps.

Early in our usage of these lamps we discovered that they must be powered from a well filtered and regulated (±0.01 per cent) DC source because AC power gave us a detectable light flicker (to say nothing of the various transients on a power line in a busy laboratory). As frequency was our chief information, the usage of a dc source was a necessity. Most of our test work was run at a 700 foot-lambert level which gave a comfortable illumination level without creating too much heat and provided an adequate electrical signal-to-noise ratio (approximately 50:1 S/N). The absolute value of the light level was not critical because the sensitivity of the detector was fairly uniform over a large brightness range. The spectral quality of the light and the spectral response of the photodetector were compatible. Computations showed that as long as the modulation level was greater than the equivalent narrowband noise of the electronics and dc level was unimportant. Thus, scene contrast was more important to performance than actual brightness.

CONTRAST AND BRIGHTNESS

The worst test condition was a high V/H rate at low light level with a low-contrast scene. The high V/H rate reduced the averaging time which is fixed by the electronic time constant and the field of view. The low light level placed the sensor photodetector at its lowest sensitivity region (plus increasing its time constant, which increases with lower light levels), while the low-contrast scene gave us low modulation levels. The results of a typical "worst condition" test were:

Scene	Low contrast
Brightness	100 foot-lamberts
V/H Rate	44.27 mrad/sec.
Sensor Measured Rate	44.67 mrad/sec.
Error	+0.4 mrad/sec.

For scenes with more contrast, the typical error was ±0.2 mrad/sec.

For the low-contrast scene used (and admittedly "low contrast" is a subjective term) we found that a light level of 20 to 40 foot-lamberts was the lowest brightness at which we could still obtain an accurate output—that is, no worse than ±0.5 milliradian per second. The lowest detectable scene modulation was about 0.04 per cent. Thus, two things were at work to set a lower limit of performance:

(1) the decreased photodetector sensitivity and increased response time at low light levels; and
(2) the system noise with respect to scene modulation.

SENSOR PERFORMANCE

The tests gave us some interesting insight on sensor performance. After many test runs, we observed a pattern of sensor error with the instantaneous stage position. Investigation showed that during its travel the stage was slow to start, reached its calibrated value at mid-motion and decreased near the end of its travel. To reduce the instrumentation errors, the output was read at the same stage position for each traverse of the stage. In this manner the random error due to stage motion was essentially eliminated. The accuracy with which the object distance was set contributed a bias which showed in the error spread of many readings. Repetition taught us the experimental techniques of how much (or little) care was needed in aligning the sensor head to the stage. Reasonable care was sufficient to set the object distance by the back-projection method. Proof of this lay in variations of error polarity. Once the skills had been acquired, the error spread in output was randomly plus and minus for ten readings or more.

The accuracy with which the input (V/H rate) was known was the rms error of each of the errors of the independent parameters (f, a, k, u and stage rate). This was ±0.16 per cent, or 0.030 to 0.08 milliradian per second over the range of V/H rates used.

Repeatability of the tests was excellent. The basic instruments used were an electronic counter (good to ±0.05 per cent) and a digital voltmeter (good to ±0.05 per cent). For a range of 20 to 50 milliradians per second, from low to high contrast, and 100 to 700 foot-lamberts the maximum error in the sensor, including instrumentation errors, was ±0.5 milliradian per second.

No attempt to simulate cloud cover was made either synthetically or within the scene photograph itself. Intermittent cloud cover constitutes a lack of contrast and thus a "no-signal" condition. Any protection against this will have to be solved in the electronics.

The question of the effect of local variation in terrain altitude was not tested because of the problems of implementation. However, reasoning told us that if these altitude variations are less than one per cent of the mean altitude, the error in sensed V/H, due to this cause alone, must also be less than one per cent. Further, terrain fluctuations are essentially averaged due to the 30-degree field (as described earlier) and to filtering techniques possible in the electronics.

One or two experiments were made on the effect of pitch, roll and azimuth positions (static not dynamic). The magnitude of pitch, roll and azimuth angles used was limited. Pitch was essentially limited by the amount of defocusing that could be tolerated. Assuming a permissible focal plane variation of ±0.5 millimter at the finite focus used, the pitch angle on the test stage could not exceed ±0.5 degree. At infinity focus, the pitch angle could be greater than this as shown by design calculations, and the system should remain within a ±0.5 milliradian per second error. Roll presented no problem except for the physical problem of holding the sensor with respect to the stage and compensating for the increased object distance. Roll angles up to 15 degrees were tested. At infinity focus, the effect of roll position should be only a cosine variation. Azimuth angles were the easiest to arrange and tests up to ±7 degrees azimuth showed sensor output reduction by the cosine of the angle also.

SUMMARY

What has been presented herein is a description of the parameter tested, the nature of the test arrangement, and identification of the chief parameters contributing to test accuracy of the sensor head.

The chief parameters were velocity (provided by a moving stage), object distance, focal length, and grid spacing. The overall instrumentation accuracy was ±0.16 per cent. Consideration was given to scene contrast, average brightness level and V/H rates. Brightness levels ranged from 50 to 700 footlamberts over a V/H of 20 to 50 milliradians per second. Accuracy of the system being tested approached the instrumentation accuracy. The effects of pitch, roll, and azimuth pointing on performance were briefly investigated.

ERRATA

Page 639, July 1965: the caption for the photograph should read as indicated below.

FIG. 1. Mrs. Clarice L. Norton receiving the Sherman Mills Fairchild Photogrammetric Award from Mr. John Carter representing the Fairchild Camera and Instrument Corp. The purpose of the award is to stimulate the development of the art of aerial photogrammetry.