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AVIRIS scan drive design and performance

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ABSTRACT

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) images the ground with an instantaneous field of view (IFOV) of 1 mrad. The IFOV is scanned 30 deg from left to right to provide the cross-track dimension of the image, while the aircraft's motion provides the along-track dimension. The scanning frequency is 12 Hz, with a scan efficiency of 70%. The scan mirror has an effective diameter of 5.7 in., and its positional accuracy is a small fraction of a milliradian of the nominal position-time profile.

This paper describes the design and performance of the scan drive mechanism. Trade-offs among various approaches are discussed, and the reasons given for the selection of the cam drive. The salient features of the design are presented. The method of measuring performance is described, and the performance results are given.

1.   INTRODUCTION

The Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is an instrument which flies on NASA's U-2 and ER-2 aircraft and records the spectrum of sunlight reflected from the ground in the 0.4- to 2.5-μm region. This information has many potential uses, such as the identification of surface materials.

AVIRIS employs a mechanical scanner to view the ground. The overall instrument configuration is shown in Figure 1. The scanner provides a field of view (FOV) of 30

Figure 1. AVIRIS configuration.
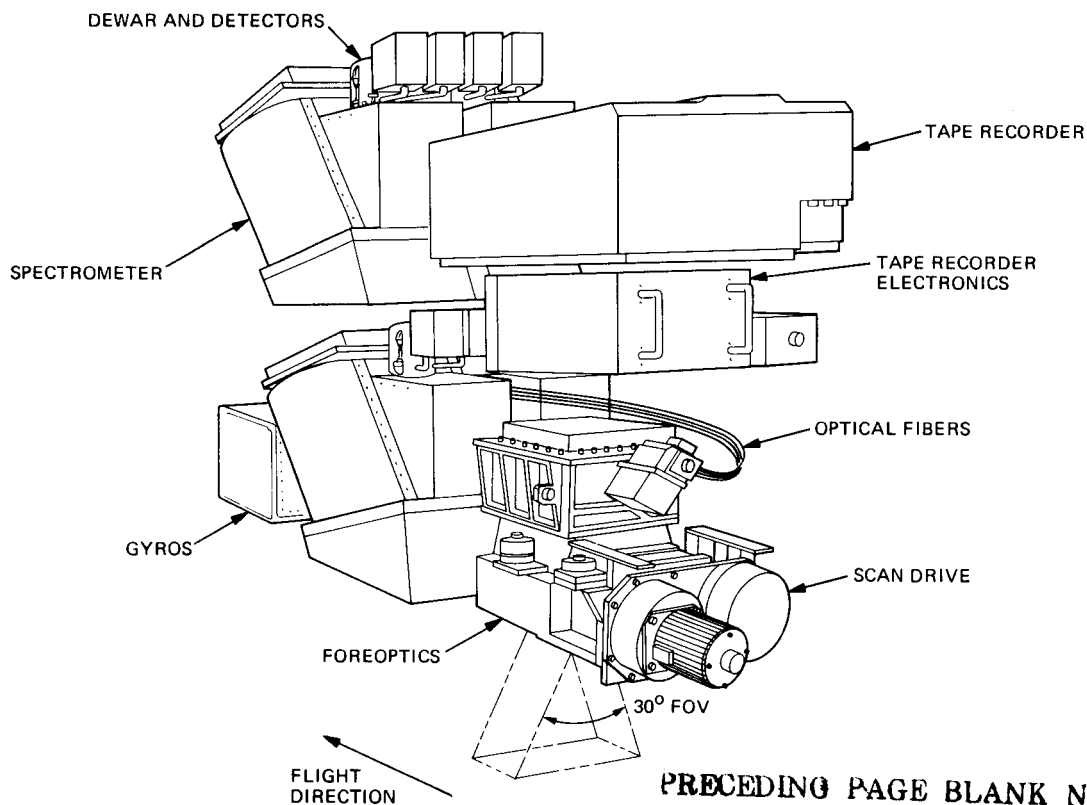
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deg. To achieve this, it must move only 15 deg, as the scan motion is effectively doubled by the mirror. A few degrees of overscan are provided to enable a compensation for roll motion of the aircraft. In Figure 2, a partial cross-section of the foreoptics, the scan mirror rotates ± 8.4 deg to move the instantaneous field of view (IFOV) ± 16.8 deg. This provides an instrument FOV of 33.6 deg. The scan profile, i.e., the motion of the scan mirror, is specified in Figure 3. It is the task of the scan drive to provide this motion.
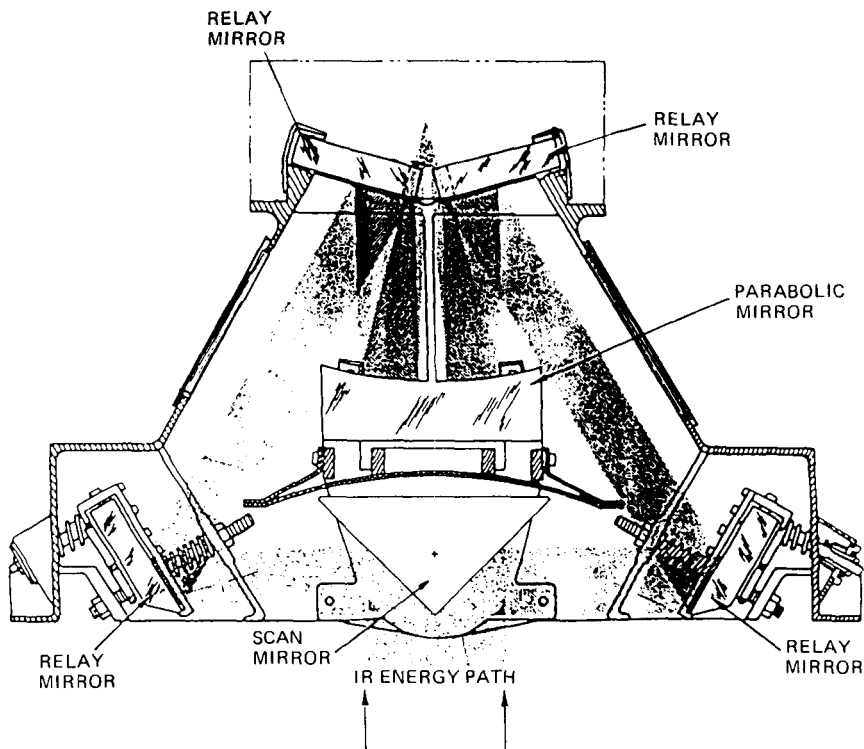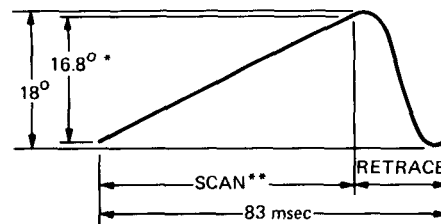

Figure 2. Foreoptics cross section.

* SCAN LINEARITY: 0.1 pixel
** SCAN EFFICIENCY: 70% min

Figure 3. Scan profile.

   The scan drive must also meet the following requirements: It must be "smooth," that is, it must not produce vibrations that excite resonances in the foreoptics or otherwise degrade its optical performance. It must have a lifetime of at least 300 hours of operation. It must be isolated from or be able to tolerate the aircraft environment, predominantly a 100-Hz vibration of 0.001-in. amplitude. Lastly, the scan drive has to be compatible with the aircraft and with the foreoptics.

2. IMPLEMENTATIONS CONSIDERED

   Several implementations of the scan drive were considered. The straightforward approach was to rotate a prism-shaped mirror whose cross-section is a regular polygon. Another approach was to attach a torque motor to the mirror shaft and direct-drive the mirror to produce the desired scan profile. A third implementation that was considered was to bump the mirror to reverse its direction and let it coast between impacts. The last approach considered was to drive a cam at a constant speed, with the scan mirror attached to the cam follower.

   The rotating, multi-faceted mirror approach was discarded early. The combination of the small FOV and required 70% scan efficiency would have resulted in a mirror 42 in. in diameter. Such a mirror would have been a significant task in itself and could not be accommodated in the U-2 aircraft because of its size.

   The use of a direct-drive torque motor was investigated at length. The early estimated torque requirements for the drive called for the motor to deliver 320 lb-in. of torque to the mirror and to accelerate the mirror (and motor rotor) at 14,000 rad/sec^2.*

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*It would be interesting to reassess this approach in the light of the final drive requirements, which are 55 lb-in. of torque and 4,200 rad/sec^2 acceleration. The scan rate, scan mirror travel, and scan mirror size were all reduced as the design proceeded, resulting in the relaxed performance requirements.

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Commercially available motors fell short of this performance. In addition, the motor power supply requirements were formidable. The development of such a motor and power supply were judged to be undesirable, and this approach was abandoned.

The next implementation considered was a "bump and coast" scan mirror like that used in the LANDSAT Thematic Mapper described in Reference 1. That design is a remarkable achievement that will surely find many applications. However, it is not suitable for this application because the scan time is necessarily equal to the retrace time. This would limit scan efficiency to less than 50%, which is too low for AVIRIS. The Thematic Mapper gathers data during both directions of scan mirror motion, and this bidirectional scanning results in a scan efficiency of over 90%. This approach was not considered for AVIRIS as it would have put a heavy burden on the computer facility used to process AVIRIS data.

The cam approach was adopted after eliminating these other implementations. It was always clear that a cam drive could generate the desired scan profile. However, this approach carried with it concerns about accuracy, vibrations, wear, and contamination from lubricants. For these reasons, it was initially considered to be the least attractive of the four approaches. However, as discussed below, the implementation of the cam approach to AVIRIS has been successful.

3. EVOLUTION OF SCAN DRIVE DESIGN

The basic concept is shown in Figure 4. If the cam is the proper shape, and if the follower is held in contact with the cam, the mirror will have the proper motion. The implementation of this simple concept is shown in Figures 5 and 6, and is obviously not so simple. One set of complications is the usual provisions for practical details: attachment points, bearing journals and housings, couplings, assembly/disassembly features, access ports, etc. However, there is another set of complications, which arises from the scan drive requirements. These are described below.
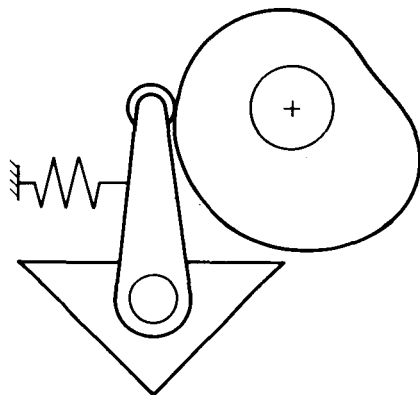

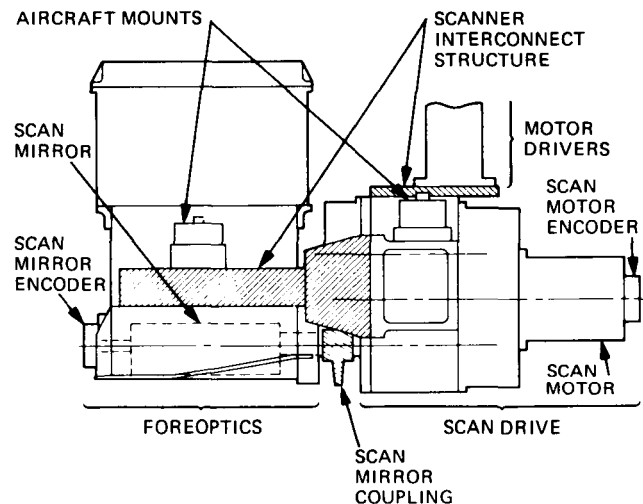Figure 4. Basic cam concept.

Figure 5. AVIRIS scanner.

The spring that holds the follower arm against the cam must be quite strong because of the high accelerations during retrace. This spring has to be compressed once each scan, and a considerable torque on the camshaft is required to do this. It turns out that this torque is the driver in sizing the motor. This is not a problem during operation, since the torque can easily be supplied by the momentum of a flywheel on the camshaft. Rather, it is during start-up that the motor must supply the torque. But start-up is a firm requirement and so the spring had to be eliminated to avoid the high torque requirement for the motor. The solution is the conjugate cam, which is the first addition to the simple basic concept. Conjugate cams provide the same follower motion, one from the "clockwise" side of the follower and the other from the "counterclockwise" side. This is shown in Figure 7. One cam provides the force to rotate the follower in one direction and its conjugate provides the force to rotate it in the other direction. This is the same idea as the "Desmodromic Drive" used to operate the valves of an internal combustion engine. Now the motor torque requirement is reduced to overcoming bearing drag and windage losses, plus a little for accelerating the whole machine up to speed in a reasonable time (a few seconds). Except for the bearing and windage losses, which are small, the system conserves mechanical energy. This makes analysis of the machine relatively easy.

OSCILLATING
COUNTERWEIGHT

FLYWHEEL

ROTATING
COUNTERWEIGHT

SECTION B-B

CAMSHAFT
BALANCE
WEIGHT

TIRE

SCAN
MOTOR
COUPLING

SCAN
MIRROR
COUPLING

SECTION A-A

FOLLOWER ARM
(4 EACH)

OSCILLATING
COUNTERWEIGHT
SHAFT

ROTATING
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CAM
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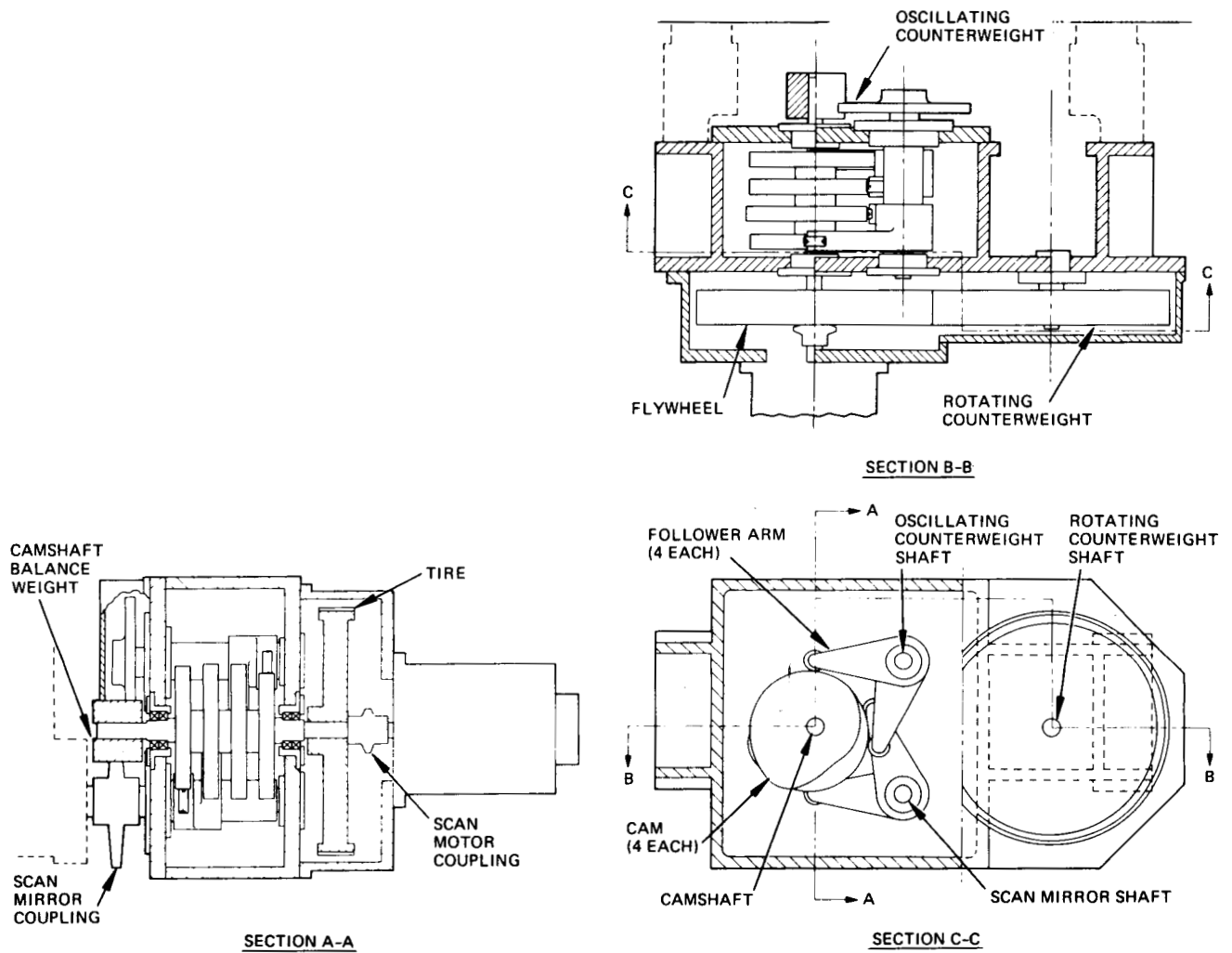
CAMSHAFT

SCAN MIRROR SHAFT
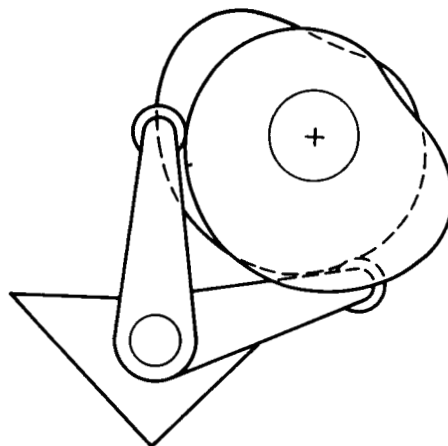
SECTION C-C

Figure 6. Scan drive details.

Figure 7. Conjugate cams.

Since the mirror velocity is constant during the scan, there is no requirement for acceleration--the mirror and scan drive are simply coasting. During scan the mirror is moved slowly forward; during retrace it is moved rapidly backward. The faster speed means it has more rotational energy. This energy comes from the cam, which must slow down in giving up its energy. As the mirror again changes direction and moves slowly forward for the next scan, it returns this energy to the cam, returning it to its original speed, which is the proper speed for scanning. The rotational energy of

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it would occupy if the scan were perfectly linear. Since a pixel is a milliradian, a
tenth of a pixel is a tenth of a milliradian. Accounting for the optical doubling
produced by the scan mirror, this converts to 0.05 mrad on mirror position. Since the
range of mirror positions is 16.8 deg, this is about one part in 6,000. Again, if the
follower arm is 3 in. long, $\pm$ 0.05 mrad converts to $\pm$ 0.00015-in. tolerance on the
position of the follower. This $\pm$ 0.00015 in. is the total error budget, and includes
follower and camshaft bearing runout, two cam profiles (the cam and conjugant cam), and
dynamics due to flexing during operation. It is clear from these numbers that the
0.1-pixel tolerance was a formidable challenge; for the cumulative error, it was
considered a goal rather than a firm specification.

A precision encoder was used to measure the performance of the scan drive. The
precision encoder was not attached to the end of the scan mirror because the shaft
connecting the mirror to the encoder and the encoder disk are a spring-mass system whose
motion would be different from the mirror's. Rather, the scan mirror was removed and the
encoder was attached to the scan drive with a test inertia and shaft. Care was taken to
match the shaft stiffness and test inertia to the scan mirror shaft stiffness and scan
mirror inertia. This assured that the motion of the encoder disk in the test setup
matched the motion of the mirror in the flight configuration.

The encoder generates 11,250 pulses in one revolution. The time between pulses is
recorded by the GSE computer. The error in scanner look direction is obtained by the
following analysis. The number of pulses in the linear scan is

$$16.8 \text{ deg} \times \frac{11,250 \text{ pulses}}{360 \text{ deg}} = 525 \text{ pulses}$$

$$1 \text{ pulse} = \frac{2,000\pi \text{ mrad}}{11,250 \text{ pulses}} = 0.5585 \text{ mrad}$$

Let t_i be the time between pulse i and pulse i-1. Then the mirror position error at
the time of pulse k is

$$e_k = \left(\begin{array}{l}\text{actual position of pulse k}\\ \text{at the time pulse k occurs}\end{array}\right) - \left(\begin{array}{l}\text{ideal position of pulse k}\\ \text{at the time pulse k occurs}\end{array}\right)$$

$$= (k - \bar{\omega} \sum_1^k t_i) \times 0.5585$$

$$= (k - \frac{525}{\sum_1^{525} t_i} \times \sum_1^k t_i) \times 0.5585 \text{ mrad} \tag{1}$$

Equation (1) gives the mirror position referenced to the beginning of the scan, in
milliradians. The pixel-to-pixel error within a scan line is determined by

$$e_k' = e_k - e_{k-1} \tag{2}$$

The optical look direction errors are double the mirror position errors calculated by
Equations (1) and (2). They are given in Table 1 for a variety of operating conditions.
In the table, column headings Q1, Q2, Q3, and Q4 refer to the 1st, 2nd, 3rd, and 4th
quarters of the scan line, respectively. The values in the table are the maximum errors
observed in each quarter of the scan profile.

Several observations can be made from Table 1. Over the expected temperature range of
0 deg C to 10 deg C, the maximum error from the start of the scan is about 0.26 mrad, or
0.26 pixel. (The start of the scan is controlled to within 0.05 pixel of nominal by a
signal from an onboard gyro. The nominal condition is defined as having the center pixel
of the scan at nadir.) The error can be positive or negative, resulting in a mismatch of
up to 0.52 pixel from one scan line to the next, but within a scan line, no pixel
deviates by more than 0.26 pixel from the position it would have if the scan profile were
perfectly linear. This is well within the required performance envelope. The 0.52-pixel
mismatch is along the start of scan edge (left-hand edge) of the picture only. The mis-
match decreases to a maximum of about 0.28 pixel at the right-hand edge of the picture.
This improvement in performance as the scan line proceeds is due to damping out of dis-
turbances produced by the torques on the mirror (and follower) during retrace. These
torques may be thought of as a one-two punch, one clockwise and one counterclockwise.

The next observation is that the pixel-to-pixel error is, at worst, 0.06 pixel, which is also within the required performance envelope. There were approximately 50 hours of operation on the scan drive at the last scan profile measured. It has been observed, however, that there is a gradual degradation in performance with time. The reasons for the degradation appear to be settling of joints and/or deformation of inadequately hard materials. These measurements will be repeated after the first season of operation and compared with the results shown in Table 1. Table 2 summarizes the results of Table 1 and compares them with the scan dynamics requirements as they were finally defined.

5. CONCLUSION

Both performance requirements for the AVIRIS scanner have been met. The pixel-to-pixel linearity within a scan line was measured to be 0.06 mrad or better; the goal was 0.1 mrad. The second goal was that the position of any given pixel within a scan line not deviate by more than 0.5 mrad from the position it would have if the scan were perfectly linear; the measured performance was 0.26 mrad or better. The result of this performance is excellent image geometry in the raw flight data. Figure 8 is an AVIRIS image of Rogers Dry Lake at Edwards Air Force Base, California. The only computer processing that was done was a simple stretch to enhance the contrast. Note the map-like quality of the image and the lack of obvious distortions. This image is in the 1.026-μm spectral band.

Table 1. Scan Profile Error

Date	Temp	Cumulative Error From Scan Start (mrad)				Pixel-to-Pixel Error (mrad)			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
9/08/86	RT[1]	0.329	0.183	0.105	0.102	0.045	0.029	0.014	0.019
9/08/86	RT	0.217	0.135	0.116	0.091	0.039	0.031	0.019	0.021
9/10/86	RT	0.161	0.063	0.063	0.079	0.033	0.023	0.021	0.016
9/10/86	0 deg C	0.202	0.159	0.155	0.141	0.063	0.049	0.035	0.019
9/10/86	0 deg C	0.115	0.094	0.128	0.115	0.039	0.025	0.025	0.014
9/11/86	30 deg C	0.181	0.120	0.090	0.097	0.040	0.039	0.024	0.016
9/11/86	0 deg C	0.258	0.257	0.197	0.132	0.063	0.058	0.034	0.021
9/11/86	30 deg C	0.109	0.064	0.087	0.091	0.029	0.016	0.021	0.011
9/11/86	30 deg C	0.165	0.075	0.069	0.072	0.036	0.031	0.016	0.016
9/17/86	RT	0.316	0.192	0.090	0.082	0.047	0.026	0.024	0.021
9/17/86	10 deg C	0.130	0.111	0.075	0.095	0.043	0.028	0.018	0.018
9/17/86	10 deg C	0.154	0.109	0.110	0.102	0.038	0.022	0.018	0.013
9/17/86	10 deg C	0.161	0.094	0.073	0.091	0.038	0.032	0.018	0.017
9/18/86	5 deg C	0.180	0.146	0.126	0.142	0.035	0.020	0.020	0.020
9/18/86	5 deg C	0.146	0.140	0.096	0.106	0.030	0.020	0.015	0.015
9/18/86	5 deg C	0.174	0.137	0.085	0.073	0.035	0.025	0.020	0.015
9/18/86	15 deg C	0.173	0.134	0.103	0.098	0.045	0.030	0.020	0.015
9/18/86	15 deg C	0.202	0.173	0.114	0.102	0.040	0.035	0.015	0.015
9/18/86	15 deg C	0.227	0.139	0.119	0.119	0.045	0.025	0.015	0.015
9/19/86	RT	0.459	0.260	0.139	0.115	0.056	0.041	0.021	0.016
9/19/86	RT[2]	0.600	0.436	0.252	0.191	0.072	0.048	0.018	0.018
9/19/86	RT[2]	0.556	0.399	0.271	0.154	0.058	0.052	0.033	0.027
9/19/86	RT[2]	0.565	0.399	0.246	0.232	0.064	0.054	0.021	0.024

[1]Room temperature.
[2]Without rotating counterweight.

everything on the camshaft during scan must be much greater than the rotational energy of everything on the mirror shaft (mirror and cam follower) or else the camshaft will slow down significantly during retrace, thereby reducing scan efficiency. The cam design assumes a constant-speed cam in order to avoid the challenge of predicting exactly how much slowdown occurs during retrace. Hence, the next addition to the simple concept is a flywheel on the camshaft.

The requirement for vibration-free operation has not yet been addressed. If the angular momentum of the system, which includes everything on the camshaft plus everything on the mirror shaft, is plotted over the scan-retrace cycle, it is not constant. This can be understood by considering the following. Since the system is conservative (nearly), $\frac{1}{2}I_1\omega_1^2 + \frac{1}{2}I_2\omega_2^2$ is constant. Here I_1 and I_2 are the inertias of everything on the mirror shaft and camshaft, respectively; ω_1 and ω_2 are the rotational speeds of the mirror shaft and camshaft, respectively. For the angular momentum to be constant, $I_1\omega_1 + I_2\omega_2$ must be constant. The only ways to satisfy both of these equations are for $I_1 = I_2 = 0$, or for $\omega_1 = \omega_2 = 0$, or for $I_1 = I_2$ and $\omega_1 = -\omega_2$. None of these is the case for the scan drive, and hence the angular momentum varies during the cycle. The rate of change of momentum requires a torque to produce it; the housing must exert a torque on the system consisting of the two shafts. In turn, the housing exerts a reaction torque on the structure that holds it: the foreoptics. This is just what needs to be avoided. The solution is to add two more elements. One is an oscillating counter-weight with a follower arm and the same inertia as the scan mirror. The oscillating counterweight is driven by two more cams on the camshaft so that its motion is equal and opposite to the motion of the scan mirror and its follower. The other is a rotating counterweight. Its inertia matches the inertia of everything on the camshaft, and its motion is equal and opposite to the camshaft motion. This is a brute-force approach that satisfies one of the conditions for constant angular momentum, namely, for each I and ω, there is an equal I and an equal and opposite ω.

The requirement for scan linearity calls for a constant camshaft speed during the scan. Two ways of achieving this were considered: to measure the mirror position during scan and apply more or less torque to the camshaft as required, or to put a large inertia on the camshaft and rely on it to maintain constant speed. Both options appeared suitable, but the latter was chosen primarily because the early design work and breadboard hardware were made that way and functioned well. The selected approach requires only a low-resolution mirror encoder and a slow servo. In fact, the servo purposely ignores speed variations within one revolution--its only task is to maintain the correct number of revolutions per second. It is the task of the flywheel to maintain constant speed within one revolution.

This completes the description of the unusual features of the scan drive. A synopsis of the scan drive design follows.

The mirror shaft has a pair of follower arms which are driven by conjugate cams. The camshaft has a second pair of conjugate cams, which drive an oscillating counterweight with a motion equal and opposite to the scan mirror motion. The camshaft is motor-driven at constant speed and includes a flywheel. A rotating counterweight is driven with a motion equal and opposite to the camshaft motion. The rotating counterweight is a wheel equal in diameter to the flywheel on the camshaft. The flywheel drives the rotating counterweight by a friction drive: the outside diameter of each wheel is a 1/8-in.-thick rubber (polyurethane) tire. The camshaft is driven by a three-phase induction motor. All four shafts of the scan drive (camshaft, mirror follower shaft, oscillating counterweight shaft, and rotating counterweight shaft) are mounted in Barden Precision Ball Bearings (duplex pairs). The lubrication is Braycote 600 grease. The couplings attaching the motor to the camshaft and the output shaft (scan drive) to the scan mirror shaft (foreoptics) are metal bellows couplings with zero backlash. The motor and the scan mirror have optical encoders to permit control of the instrument by the electronics. The scan drive is attached (bolted and pinned) to the foreoptics and supports the scan drive electronics. This entire assembly is the scanner. The scanner attaches to the aircraft via four elastomeric mounts to isolate the scanner from the aircraft vibrations.

4. PERFORMANCE MEASUREMENT

The most critical scan profile performance specification was 0.1-pixel linearity over the full scan (see Figure 3). This means that the center-to-center spacing between adjacent pixels should not vary by more than 0.1 pixel. A tenth of a pixel is a very desirable tolerance. If it could be met, the instrument would provide an excellent image in the geometric sense, and computer data processing requirements would be minimized. The second specification was that the cumulative error in pixel position over an entire scan not exceed 0.5 pixel, i.e., no pixel should be more than 0.5 pixel from the position

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Table 2. Scan Dynamics Requirements

Description	Required Performance	Measured Performance
Scan rate	12 scans/sec	12 scans/sec
Cumulative pixel position error over scan (pixel size = 1.0 mrad)	0.5 mrad	0.26 mrad
Maximum pixel-to-pixel position error	0.1 mrad	0.06 mrad
Angular motion of scan drive housing due to vibration	0.1 mrad	0.01 mrad

Figure 8. AVIRIS image of Rogers Dry Lake.

Additional improvements might yet be made in a scanner of this type by the use of materials with a higher stiffness-to-weight ratio, such as beryllium or metal matrix composites. With these materials and careful attention to detail, it is estimated that the scan profile errors achieved with this design could be reduced by nearly half or the scan efficiency increased to as much as 80% or 85%.

6. REFERENCE

1. John Charles Starkus, "Large Mirror Assembly of the New Thematic Mapper Developed for LANDSAT 4 Earth Resources Satellite," in Infrared Technology IX, Irving J. Spiro and Richard A. Mollicone, editors, Proc. SPIE 430, 85-91 (1983).

7. ACKNOWLEDGMENT