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Marking ERTS Images with A Small Mirror Reflector


FIG. 1. 22-inch mirror in position for satellite pass.

A slightly curved mirror only 22 inches in diameter was detected by the satellite more than 500 miles overhead.

THIS PAPER reports success in generating identifiable landmarks on imagery produced by the 917-km high Earth Resources Satellite (ERTS). Although the experiment was initiated as a backyard hobby project, further thought suggests that some variant of the procedure may have practical scientific use in

ABSTRACT: *A simple experiment demonstrates the feasibility of generating identifiable artificial landmarks on imagery provided by the Earth Resources Satellite, ERTS-1. The completely passive marking device is a small (56-cm diameter) mirror carefully positioned to reflect the sun's energy into the satellite's optical sensors at the time of an overpass. Calculations show that a somewhat larger, but still easily transportable, mirror system should be capable of marking the images with near 100-percent probability of success on cloud-free days. No orbital information is needed beyond that normally available to the general public through the government's EROS program. Possible applications of the technique include providing site identification and geodetic control in remote regions of the earth, and providing atmospheric transmission data coincident with other ERTS experiments.*

signaling, precise mapping, and atmospheric transmission measurements.

Figure 1 shows a 22-inch (56-cm) diameter vanity mirror carefully positioned to reflect the sun toward the satellite at the time of an overpass. Figure 2 is ERTS-1 imagery—Multi Spectral Scanner (MSS) Band 5—for the San Francisco Bay Area for 29 November, 1972. Two magnifications are used to show both the full frame (185-km square) and a detail where the characteristics of the satellite's imaging system provide a limiting resolution of about 80 m for high-contrast details on the earth's surface.

The spot generated by the solar reflection from the small mirror is clearly identifiable in the enlarged view in Figure 2(b). Even though the mirror is much smaller than an 80-m resolution element, the light energy returned in the direction of the satellite by the specular reflection is comparable to that re-

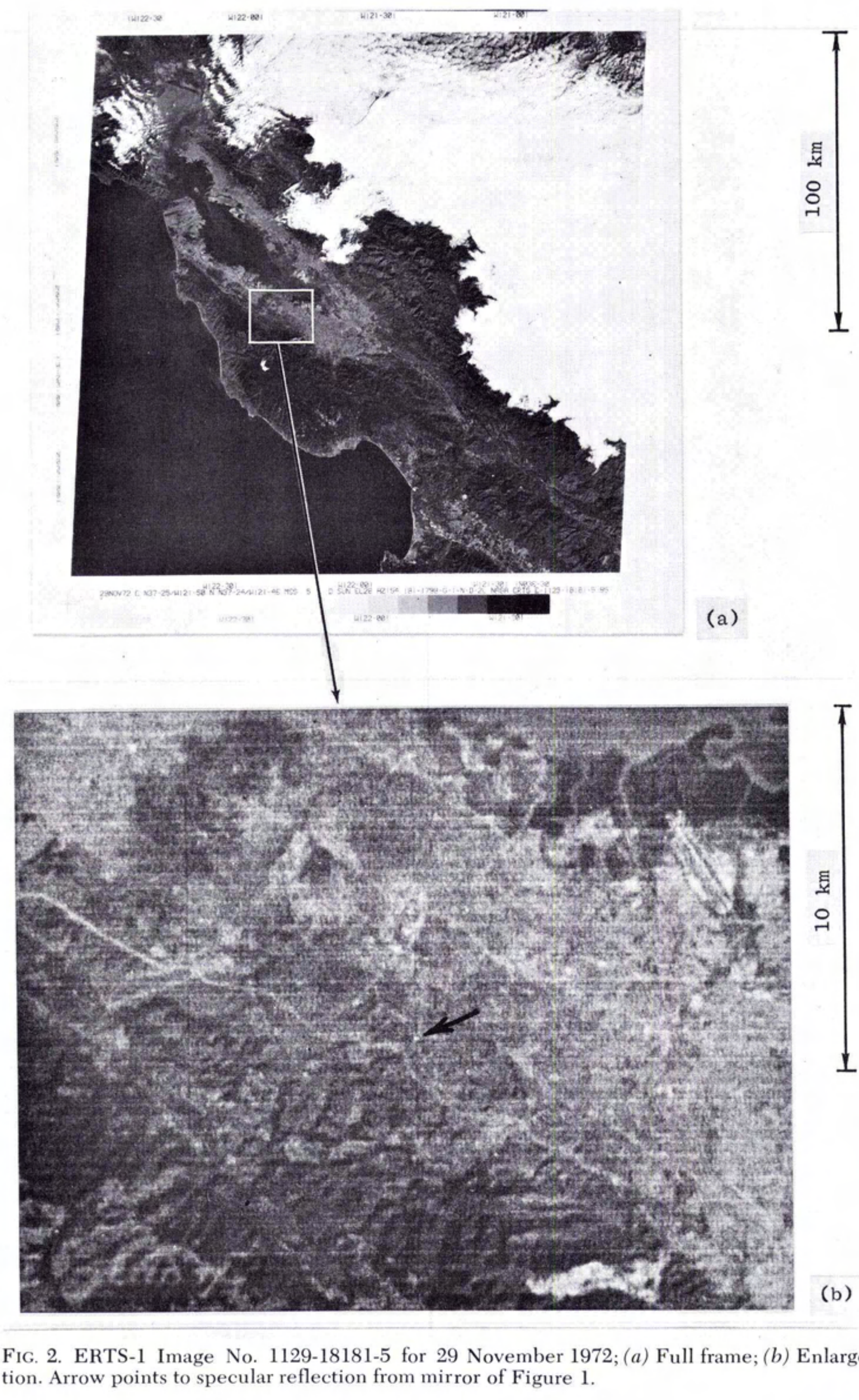

FIG. 2. ERTS-1 Image No. 1129-18181-5 for 29 November 1972; *(a)* Full frame; *(b)* Enlarged section. Arrow points to specular reflection from mirror of Figure 1.

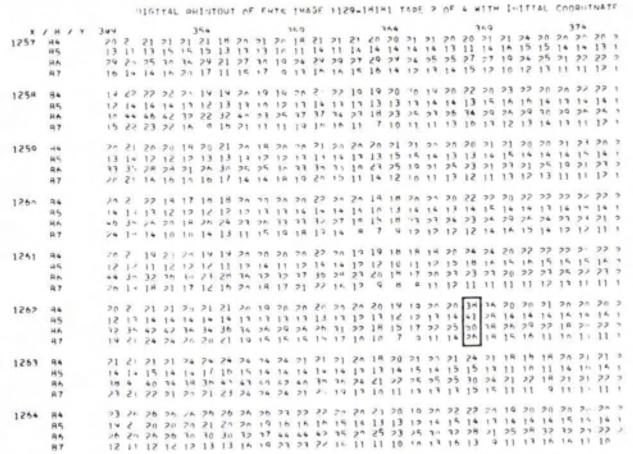

FIG. 3. Computer printout of section of digital tape record for 29 November, 1972. The mirror return is marked on scan line 1262.

sulting from a white diffuse target—for example, snow or sand—filling the entire resolution element of slightly one acre (0.45 hectare) in area.

The spot was initially located in the image with the aid of a superimposed local map. Responses were obtained in all four MSS bands; the spot shows up more convincingly, however, in a carefully registered color-composite image. To dispel doubts that a photographic flaw might have generated the spot on the image transparencies, a computer-compatible digital tape of the source data as telemetered from the satellite was obtained from NASA. Figure 3 shows a printout of sensor responses in all four spectral bands for a small region approximately centered on the mirror site. Each vertical group of four two-digit numbers corresponds to one picture element, or *pixel*, nominally 79 m high by 57 m wide. The pixel groups are arrayed in rows and columns corresponding to scan lines and sample numbers within the image. The four spectral bands are listed for each pixel from top to bottom as green, red, near-IR, and IR. The response scales are linear for all four bands and have a full-scale count of 127 for the first three bands and a full-scale count of 63 for the IR band. Analog plots of the data for the scan line containing the target are given in Figure 4. The response from the pixel containing the mirror is higher

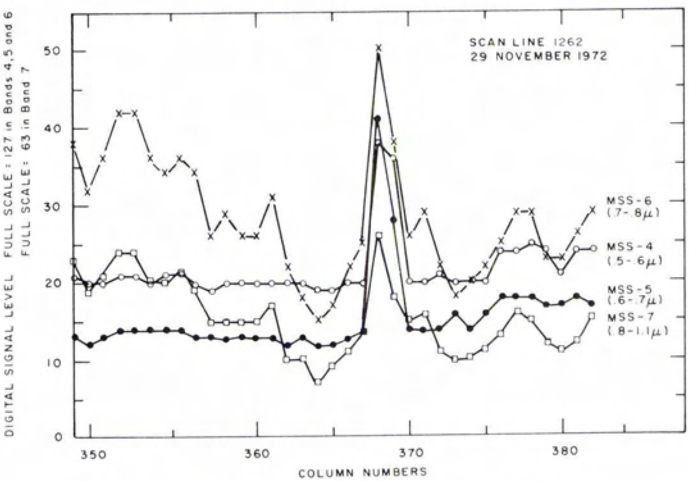

FIG. 4. Analog plot of digital values for four MSS bands along scan line containing mirror return.

than for any other single cell within the field and exhibits a contrast of greater than 2:1 with the average surrounding area in all four spectral bands.

It is a tribute to the optical performance of the MSS sensor system that the point response appears to be limited vertically to a single element. The partial response in the element adjacent horizontally to the right presumably results from digital sampling of the sensor analog waveform just before and slightly after its peak; that is, the true peak response probably was slightly higher than that indicated by the numerical printout.

From six attempts in 1972-73 identifiable returns were found on four occasions: 29 November, 4 January, 4 April, and 10 May. Geographic coordinates for the target site are: 37.390°N, 122.147°W.

Experimental Procedure

Certain concessions in favor of economy and convenience determined the choice of the size and curvature for the mirror to be used. An initial calculation revealed that with perfect pointing accuracy, a 16-in (40.6-cm) diameter plane mirror should provide a saturation signal at the satellite for all four spectral bands. (The quantitative analysis is in a later section.)

With a plane mirror, however, the beam divergence after reflection would be 0.5°—the angular width of the sun as viewed from earth—and this would correspond to a beam diameter at satellite altitude of only 8.5 km. Even if the cumulative pointing errors could be held to something less than the 0.5° beamwidth—a challenging but not insurmountable task for an amateur project—the precise satellite orbital position cannot be predicted closer than perhaps 10 to 20 km with data normally available to the general public.

Consequently, as a compromise, the mirror was made slightly convex (by bowing against a thin washer placed behind its center) to achieve an approximately 1° beam, as determined by observing the light pattern reflected onto a distant wall. To partially compensate for the resulting 4:1 reduction in flux density at satellite altitude, the mirror diameter was increased to 22 inches—a somewhat arbitrary size limitation set primarily by factors of convenience and cost. The uncertainty in satellite location gave only about a 50-percent probability of obtaining a *hit* on any given try, but this fact was accepted in return for keeping the signal strength clearly above the average background whenever a hit was achieved.

The stable platform for the mirror was a 55-gallon oil drum filled with water. North was determined by sightings on Polaris, with due correction for its slight polar offset. A simple aluminum frame for holding the mirror was made to pivot around a pin affixed to the center of the oil drum. The frame also provided an adjustment for the elevation angle.

To find the direction in which the normal to the mirror should point, azimuthal angles were marked off around the rim of the drum and elevation angles were set with a carpenter's square and spirit level. An attempt was made to make all measurements accurate within ± 0.1 degree. Time for check-in purposes was obtained when required from radio station WWV. The satellite track, the planned beam intercept point, and time were predicted from the averages of measurements made from ERTS-1 images made on three previous passes over the same area. The sun direction at intercept time was derived from tables in the *Nautical Almanac*, and the bisector of the angle between sun and satellite directions was computed with an HP35 hand calculator.

With all angles pre-calculated, the only tasks required on the morning of a satellite overpass are to set the mirror and frame on the oil drum and to adjust azimuth and elevation angles. Nature does the rest. No one needs to be on site at intercept time except perhaps to check on local cloud conditions. At the instant the satellite scanner is imaging the mirror site (about 10:18 Pacific Standard Time for our experiments), the satellite will be somewhere within the 17-km diameter reflected sunbeam.

Quantitative Analysis

Input data for determining the required size for a marker mirror are:

- Spectral power density of sunlight
- Sensitivity of the satellite-borne scanner
- Attenuation due to a round trip through the atmosphere
- Beam divergence required to obtain reliable intercept

Table 1 lists published values for the first three of these parameters for the four spectral regions of interest.

An absolute minimum for the last parameter, the beam divergence, appeared to be 0.5°—the value resulting from the use of a plane mirror. Any smaller value would require not only an expensive converging mirror but also precision too great to be achieved with simple tools. A more practical lower limit to beam divergence is set by the lack of

TABLE 1. PHYSICAL DATA REQUIRED TO CALCULATE EXPECTED SIGNAL FROM MIRROR TARGET

ERTS Band Nomenclature	λ (μ)	Solar Power Density at Top of Atmosphere (1) (W/m^2)	ERTS-1 Sensor Sensitivity. Radiance for Full-Scale Response (2) (W/m^2 steradian)	Atmospheric Transmission Factor* (3)
MSS-4 (Visible Green)	0.5-0.6	193	24.8	0.342
MSS-5 (Visible Red)	0.6-0.7	163	20.0	0.442
MSS-6 (Near I. R.)	0.7-0.8	128	17.6	0.520
MSS-7 (1 μ I. R.)	0.8-1.1	248	46.0	0.613

*Incident path at 26.5° elevation; reflected path at 87.2° elevation.

Sources: (1) McGraw-Hill (1965) Handbook of Geophysics, New York, New York, p. 16-4; (2) NASA Document No. 715D4249, ERTS-1 Data Users' Handbook, p. A-10; (3) Elterman, L. (1964) "Atmospheric Attenuation Model," AFCRL Environmental Research Paper No. 46.

precise orbital position information for the satellite, particularly the cross-track, near east-west direction.

According to data published by NASA before launch, the cross-track position of the orbit for successive passes over the same area was expected to drift slowly westward at a maximum rate of about 4.7 km per week. In the normal course of events, this drift would then slow down, reverse, and increase eastward until corrective action was taken by ground command. The stated intent was to control the cross-track drift so as not to exceed 37 km during the life of the mission.

Careful measurements made of landmarks in imagery of the San Francisco area for the first few ERTS cycles revealed a total cross-track spread of 14 km. No clear trend was evident, however, and there was no way of knowing whether an orbital correction was imminent.

At the time, the turn-around period for obtaining imagery from the EROS data center in Sioux Falls, South Dakota, via the general public access route was typically eight weeks. This was long enough that reliable prediction over the period appeared hopeless; consequently, a probabilistic approach was taken for the initial experiments and a compromise 1° conical beam was chosen.

The results of signal strength calculations based on the foregoing assumptions are compared with the return levels actually measured and are shown in Table 2. The experimental return in all four bands is actually slightly higher than predicted. Two possible explanations for this fortuitous circumstance are: the satellite happened to traverse a *hot spot* in the mirror beam (with the crude bowing scheme used, the pattern was far from uniform), or the atmospheric attenuation may have been somewhat less than that given by Elterman's Standard Atmosphere model.

MIRROR SIZE FOR FUTURE EXPERIMENTS

The observed performance of the ERTS-1 system during its first year of operation provides a basis for planning future experiments. Possible applications of the technique would include provision both for site identification and geodetic control in remote regions of the earth and for atmospheric transmission data coincident with other ERTS experiments. If operation with the minimum possible mirror size is critically important, an obvious step would be to attempt to obtain directly from the NASA control center completely current information on both the orbital drift and any planned corrections. The difficulty of obtaining this information, however, has not been explored. On the other hand, there is unmistakable challenge and occasionally there may be practical incentive in working independently. A review of the performance of the ERTS system actually observed over its first year of operation shows that the orbital control is sufficient to promise a relatively high probability of success by working with a mirror only modestly larger than the one reported here.

If the prelaunch orbit control promises are actually kept, then one should always be able to intercept the satellite track with a properly pointed beam 37 km wide at orbital altitude with a 2.3°-beam divergence in the cross-track direction.

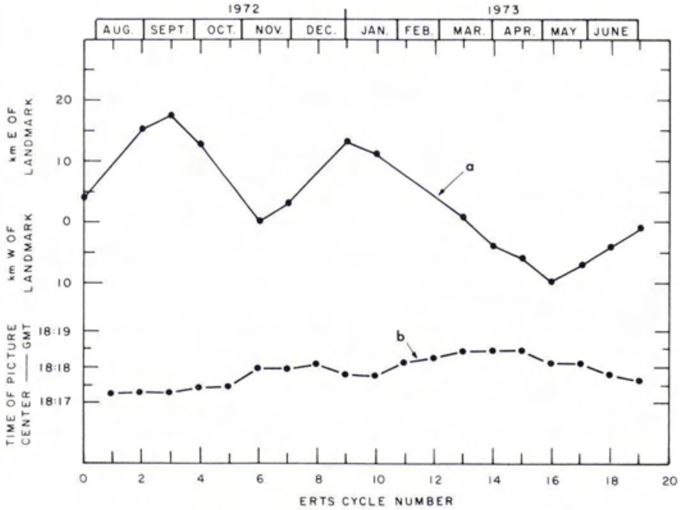

FIG. 5. Drift of ERTS-1 nadir points relative to fixed landmark San Francisco Bay area. Curve *a*—cross-track drift. Curve *b*—time drift.

Figure 5, Curve *a*, shows the cross-track drift in subsatellite point locations for the San Francisco Bay Area image through most of the first year of operation. The curve was derived from careful measurements on known landmarks and from data given in the image annotation blocks. The absolute latitude-longitude information given there was found usually to be in error by a few km; however, the difference between quoted coordinates for picture center and nadir points was assumed to provide a valid measure of satellite attitude error. Consequently, to locate the subsatellite point (nadir point) in the image, appropriate offset values were measured from the physical center of the frame. The drift of these points relative to an easily identifiable landmark (Calavaras Reservoir) is plotted in Figure 5, and the total variation is seen to be actually well within the promised 37 km. Thus, the experience of the first year's operation indicates that a cross-track beamwidth of 2.3° should be adequate to ensure that the track always will be intercepted.

For the in-track direction, the beam spread

TABLE 2. COMPARISON OF PREDICTED AND OBSERVED SIGNAL LEVELS

	Percent of Full Scale			
	MSS-4	*MSS-5*	*MSS-6*	*MSS-7*
Predicted mirror signal (input conditions per Table I, 22 inch mirror, 100% efficiency, 1° conical beam, perfect aim)	11.0%	14.8%	15.6%	13.6%
Observed mirror signal (response above background as measured from digital tape)	14.2	22.0	20.4	23.8
Average background signal level in vicinity of target as measured from digital tape	15.6	10.3	19.0	17.2

can be less because cross-track scanning is continuous for the multispectral scanner, and a knowledge of the precise intercept time is not as important as it would be for a shuttered camera such as the Return Beam Vidicon. To calculate the mirror pointing angles, the assumption was made that the center of the reflected beam should intercept the satellite track at a 90° angle. This assumption implied a hope that the combined effect of satellite attitude error and any nonperpendicularity of the scan swath to the spacecraft axis would average less than the in-track beamwidth. The aforementioned measurements on the imagery indicate that the overall attitude fluctuations never exceeded ± 0.25° throughout the year, and the successful contact verifies that a 90° intercept angle is indeed the proper objective.

The only remaining requirement is that the intercept time not be so far from nominal that the calculated sun angle will not be correct. Curve *b* of Figure 5 plots the picture center time from the Bay Area image for the first year as taken from the frame identification numbers. The total time spread is shown to be just over one minute, and the variation with time is relatively gradual. During a one minute period, the apparent sun motion would move the reflected beam only 0.25° in cross-track direction and appreciably less in the in-track direction. Thus, the 1° beamwidth of the original experiment or perhaps even the 0.5° beam afforded by a noncurved mirror should be adequate to ensure reliable intercept in the in-track or near north-south direction.

A reasonable design for a second-generation marker would appear to be a 2-ft × 6-ft (.61 × 1.8-m) mirror, bowed in the long direction to give a 2.3° beam. This should permit a high probability of intercept and provide a signal level over three times that reported here.

ACKNOWLEDGEMENTS

Although the experiment was a spare-time, privately funded project, Stanford Research Institute's assistance in providing computer time and reproduction facilities for preparation of this report is gratefully acknowledged.

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