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EVALUATION OF SKYLAB EARTH LASER BEACON IMAGERY

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Goddard Space Flight Center

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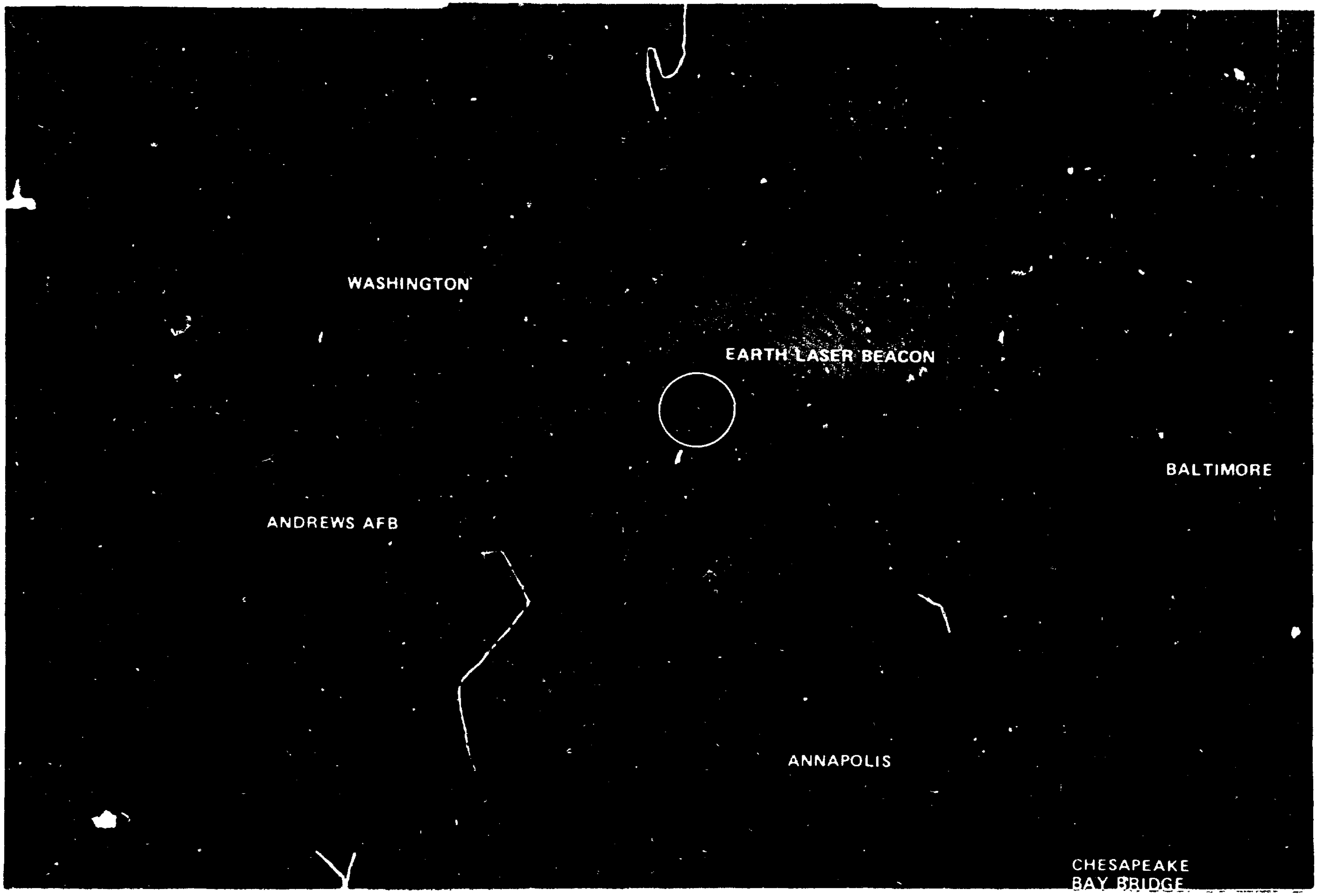
GREENBELT, MARYLAND 20771


WASHINGTON
EARTH LASER BEACON
BALTIMORE
ANDREWS AFB
ANNAPOLIS
CHESAPEAKE
BAY BRIDGE

FRONTISPIECE

EARTH LASER BEACON PHOTOGRAPH

3 DECEMBER 1974

The earth laser beacon is the bright green area at the center of the circle, near the vertex of the two green runways. The photograph should be viewed with the spiral bindings at the top so that the effects of obliquity are minimized. The Washington, DC and Capitol areas are then visible at the upper left of the page, as are the four bridges crossing the Potomac River from Arlington, Virginia. Andrews Air Force Base is at the left edge of the page. Baltimore, Maryland is at the right of the photograph, and the Chesapeake Bay Bridge is just visible at the bottom of the photograph, about two inches from the right edge. The two bridges crossing the inlet just to the left of the Bay Bridge are near Annapolis, Maryland and the U.S. Naval Academy. A great deal of the brilliancy of the earth laser beacon has been lost in the printing of the paper copy.

The laser power for this photograph was 3 watts; the wavelength was 5145 Å. The approximate area covered by the beacon on this occasion is 230 meters by 190 meters. The range to the spacecraft was 620 kilometers, and the spacecraft elevation was 44 degrees above the horizon. Spacecraft location was to the east, over the Atlantic Ocean.

Further discussion of this image, as well as an additional enlargement of the frame, is found in the third section of the report.

TABLE OF CONTENTS

1. INTRODUCTION and SUMMARY

During the Skylab 3 and 4 missions the Skylab spacecraft was illuminated by a low power argon ion and dye laser. The objectives of this earth laser beacon experiment were twofold: (1) to investigate the usefulness of low power lasers as terrestial "artificial stars" for visual navigation, spacecraft control, and aiming of manually directed scientific instruments; and, (2) to examine the utility of such lasers as spatial, spectral and photometric standards for earth sensing instruments.

The earth laser beacon was studied visually by the astronauts. In addition, they collected 35 mm hand-held color photographs of the beacon. Twelve photographs were obtained on Skylab 4 and two on Skylab 3. The laser power was varied from 0.95 watts to 3 watts, although on one occasion the power was raised to 10 watts and the mode of operation changed from continuous to pulsed. Laser wavelength ranged from 4800 Å to 6250 Å. Full angle divergence of the beacon was about 2 mrad.

The purposes of the present program were to analyze the imagery collected during the Skylab missions and to evaluate the utility of beacon lasers as terrestial "artificial stars" and instrument standards. Analyses of the imagery have revealed two unusual features of the earth laser beacon.

The beacon, even though of a low power ($\sim$ 1 watt), is considerably brighter than any other terrain feature. Simple computations indicate that the irradiance at the spacecraft from a one watt beacon should be an order of magnitude greater than a 10% Lambertian terrain reflector.[+] This brightness anomaly was observed on the imagery, with the brightest regions of the beacon image about five to ten times brighter than the surrounding terrain, and the darkest regions of the beacon about twice as bright as the surroundings. The beacon is readily visible on imagery at a distance in excess of 1500 km (900 miles). The power level for this particular image was but 0.95 watts. The only other recognizable features on the image are large scale geographic elements. The astronauts readily detected the beacon and described it as radiating "like a

[+] Cf. Appendix A.

neon light that's on in the daytime." With the aid of binoculars the astronauts were able to track a one watt beacon to a distance in excess of 2500 km (1600 miles).

The second unusual feature of the beacon was its large size. Since the beacon was a point source, the beacon was expected to cover an area of about one resolution element. Such an effect was approached only at extreme ranges (in excess of 800 km) at which the resolution began to approach the size of the beacon. The typical beacon extended over about 5 resolution areas with a characteristic dimension of about 200 m. The beacon always exhibited a bright central core which was about one resolution element in area and which contained about one-half of the total energy of the beacon. The shape of the beacon ranged from almost circular to elliptical, with eccentricities in excess of 2.

The observed size of the beacon was greater than expected. Consideration of the scales and symmetries of the problem indicates that the cause of the phenomenon is not instrumental but is due to an atmospheric effect. The possible causes include multiple, small-angle forward scattering, and scattering at very high altitudes ($\sim$ 80 km).

The observed beacon spreading has implications for remote sensing studies which require accurate measurement of atmospheric flare. It is well known that the degree of atmospheric flare is dependent upon terrain albedo. Measurements and models of atmospheric flare usually assume uniformity of flare over a region of terrain. If effects of target albedo on local flare conditions can extend over a scale of 200 meters, then flare variations due to target albedos can be important in studies of complex targets where such target brightness variations do occur.

Subsequent sections of this report discuss the experimental procedures, the imagery collected, data analyses and study conclusions.

2. DESCRIPTION OF EXPERIMENT

The earth laser beacon was located at the Goddard Optical Research Facility (GORF), approximately 20 km northeast of Washington, D.C. The beacon was a DC-operated argon ion laser designed for 100 watts, multiline, multi-transverse mode continuous output. Because of the multitransverse mode of operation, the output power was essentially uniform across the output beam. The argon ion was also utilized to pump a Coherent Radiation Model 490 jet stream dye laser to obtain the yellow/red wavelengths. Imagery was obtained at continuous power levels that ranged from 0.95 watts to 3 watts. On one orbit the argon laser was operated in a pulse mode at 10 watts. The space-craft was illuminated with only one wavelength at a time, and successful imagery was collected at 5145 Å, 5800 Å, 5900 Å, and 6250 Å. The shape of the laser output was either circular or elliptical-rectangular as depicted in Figure 2.1. The laser was linearly polarized, with the direction of polarization varying with aiming direction.

The Skylab satellite was tracked using a coelostat located in a 16-foot diameter dome perched atop a 25-foot high concrete block tower (Figure 2.2). Mirrors send the laser light up to the coelostat mount, which is driven by DC torque motors controlled by a Honeywell 516 General Purpose Computer. A guide telescope is mounted on the coelostat and boresighted to the laser beam (Figure 2.3). The satellite was always visible on the guide telescope when the satellite was illuminated by the earth laser beacon. A schematic of the earth laser beacon system is presented in Figure 2.4.

Typical beacon divergence was about 2 mrad (full angle). Since the range to the spacecraft was usually about 700 km, the beam diameter at the satellite was about 1.4 km. Pointing accuracy was ±0.1 mrad, or ±70 m at 700 km. The laser was always pointed directly at the spacecraft.

Figure 2.5 contains a diagram of the location of the laser at the Beltsville Airport on the U.S. Department of Agriculture Research Center. An oblique photograph of the experiment station and airfield is contained in Figure 2.6. The runways are old asphalt bounded by cleared grassy areas. Coniferous trees border the runways. The laser is situated a perpendicular distance of 370 m from the west end of the 8-26 runway, and about 800 m from

Fig. 2.1 Photographs of the output of the earth laser beacon. The wavelengths of the various beams are: 8 - 5800 Å; 12 - 5900 Å; 24 - 5145 Å; and, 35 - 4880 Å. Each small square corresponds to 0.5 minutes of arc.

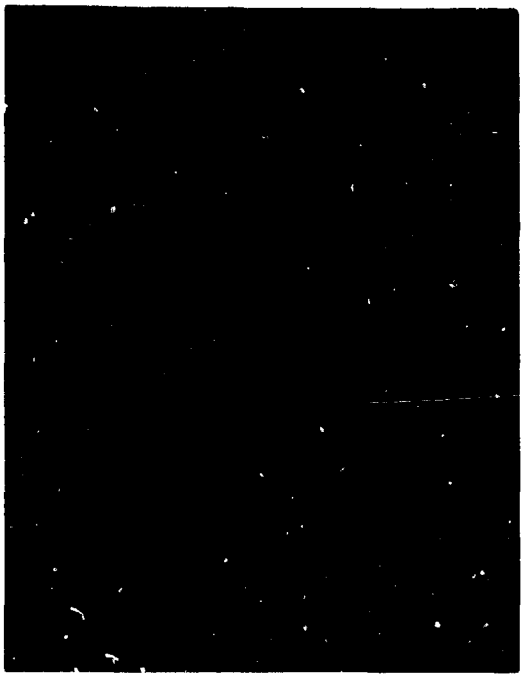
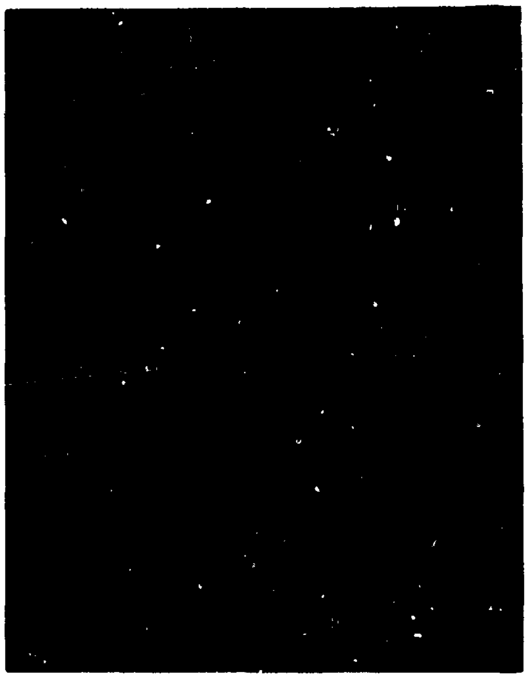
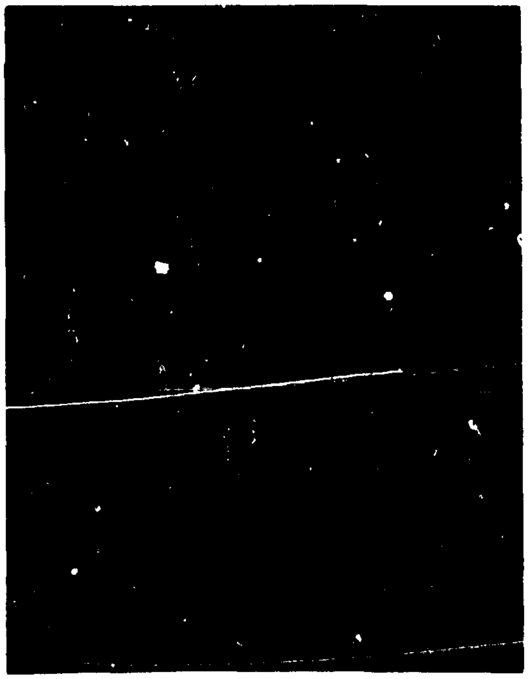
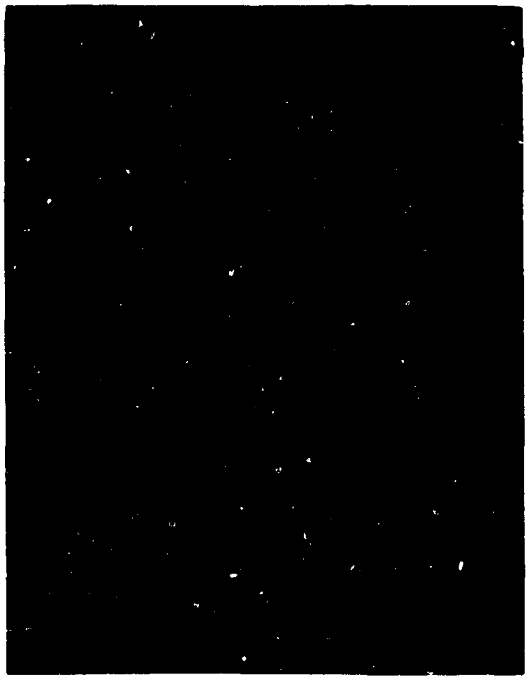
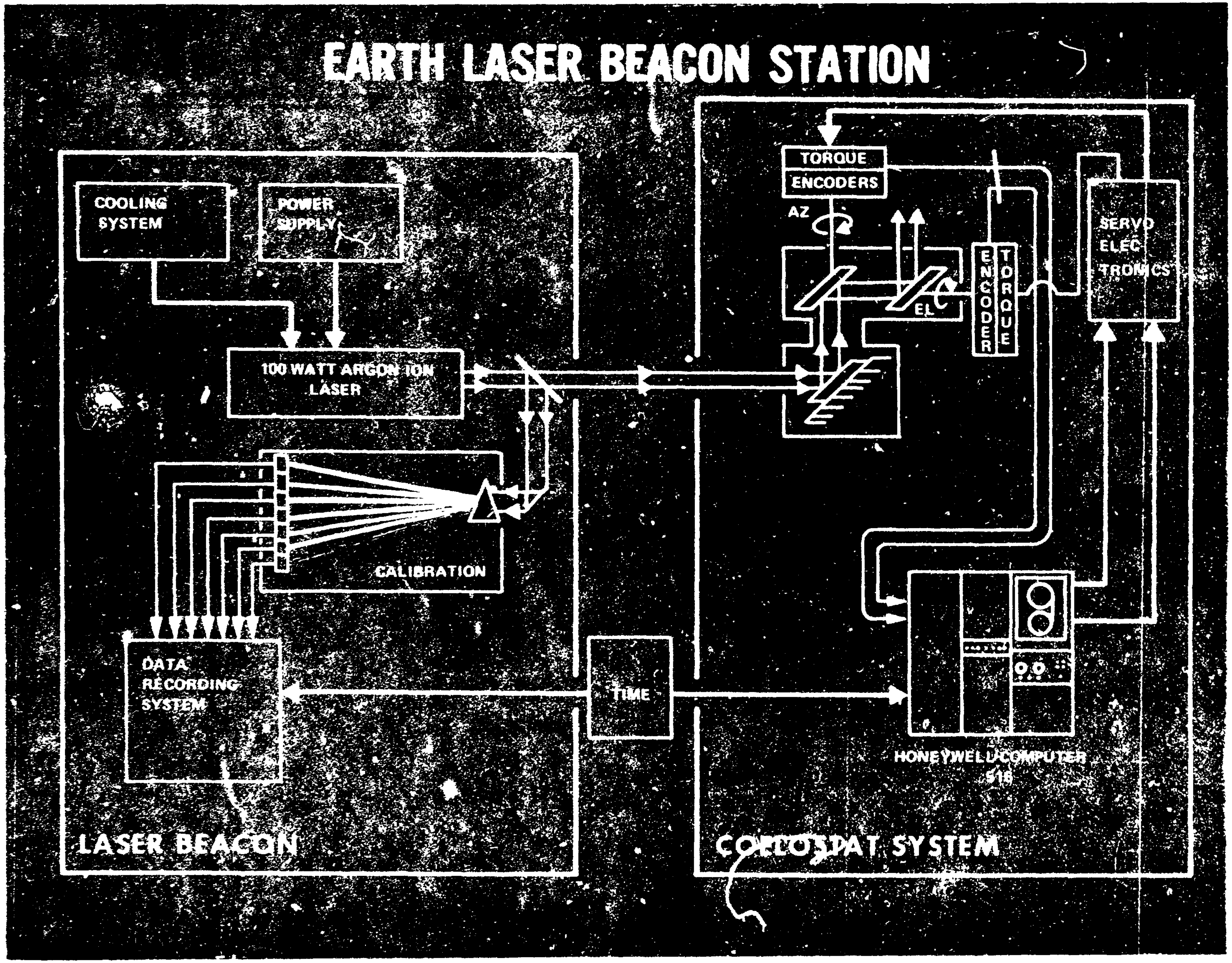





Fig. 2.2 The earth laser beacon transmitter.

Fig. 2.3 The coelostat and guide telescope of the earth laser beacon.

Fig. 2.4 A pictorial diagram of the earth laser beacon system.


EARTH LASER BEACON STATION
COOLING SYSTEM
POWER SUPPLY
100 WATT ARGON ION LASER
CALIBRATION
DATA RECORDING SYSTEM
TIME
LASER BEACON
TORQUE
ENCODERS
AZ
EL
ENCODER
TORQUE
SERVO ELEC TRONICS
HONEYWELL COMPUTER 516
COELOSTAT SYSTEM

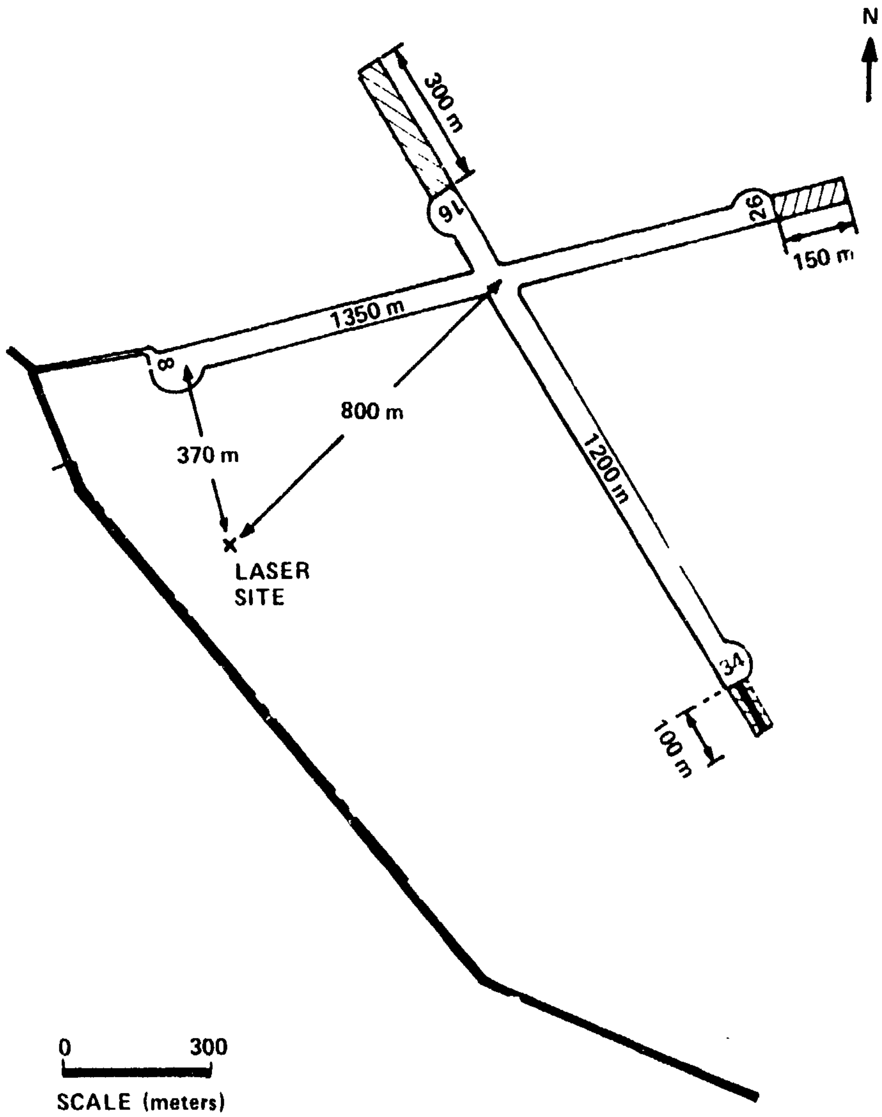


Figure 2.5 LOCATION OF THE EARTH LASER BEACON AT THE BELTSVILLE AIRPORT.

Fig. 2.6 Oblique photograph of the Goddard Optical Research Facility. The vertex of the runways at the Beltsville Airport is in the background.

NASA G-75-00383

the vertex of the two runways. The size of the building area at the experiment station is about 125 m by 50 m. The bare soil areas are about 125 m from the laser. The soils are reddish clay. The runways are about 1600 m long, including overrun areas. The width of the runway and boundary varies considerably, with typical size about 175 m.

Unfortunately the Skylab satellite did not pass directly over the experiment station. The typical elevation angle to the satellite was about 45°, with a slant range of 700 km. (Vertical Skylab altitude was 430 km.) Experimental data were obtained for slant ranges between 550 km and 2300 km, and corresponding elevation angles between 51° and 18°. Azimuthal directions to the satellite varied considerably.

Imagery of the earth laser beacon was taken from the Skylab satellite using a hand-held Nikon camera configured with a 300 mm lens. SO368 color film was used. This film is essentially Ektachrome MS2448 on a thinner base. Exposures were typically 1/500 sec or 1/250 sec at f4.5-f8. The satellite track necessitated oblique imagery, usually through the wardroom window. Image motion at 1/500 sec was about 15 m.

Unlike the S190A and S190B experiments, control step wedges for the film in the Nikon camera did not accompany the film in the spacecraft but were instead kept at Houston. Radiation dosage in the spacecraft was recorded, and film test strips which were subsequently subjected to radiation were processed to establish radiation effects. Thus density corrections for radiation dosage could be made for the original film step wedges. Radiation effects occur principally at higher film densities, and fortunately the majority of the densities studied were below the density range affected by radiation.

The original imagery and control wedges were copied by a contact printing process onto Ektachrome R5389 film (a neutral color balance, 1.0 gamma film). The 5389 copy imagery was used for data analysis. Comparisons were made between selected frames of the original and copy imagery, and these studies indicated almost no detectable difference in useful image properties between the original and duplicate imagery. Film densities on the original and duplicate imagery also agreed closely. Film gamma on the original imagery was about 2.0 at a density of 1.5, 1.5 at a density of 1.0, and 0.7 at a density of 0.5. The stated values of film gamma are representative of all three film layers.

Qualitative analyses of the copy imagery yielded a resolution estimate of about 20 lines/mm for the entire imaging system (camera, spacecraft window, atmosphere, films, and copy process). Twenty lines/mm at a slant range of 700 km corresponds to a resolution of 100 m. It should be emphasized that the 20 line/mm figure is an order of magnitude estimate only, and that this number should vary considerably with parameters such as target contrast.

3. DESCRIPTION OF IMAGERY

During Skylab 4 twelve photographs of the earth laser beacon were obtained on six dates between 1 December 1974 and 30 January 1975. Two photographs of the beacon were obtained on the Skylab 3 mission. Table 3.1 contains a listing of the Skylab 4 photographs, together with date, laser parameters, and qualitative image description. The beacon typically appears as a bright, highly colored spot (blue, green, orange), either circular, egg-shaped, or highly elliptical. The beacon is quite visible on the imagery, even at slant ranges at which only large scale terrain features are recognizable. On Frame 10 (29 January, 0.95 watts, 6250 Å) the beacon is visible at a range of 1500 km. The astronauts were able to track the beacon visually to a slant range in excess of 2300 km during the 30 January experiment.

Seven of the Skylab 3 and 4 frames are reproduced within this report, as either a full frame enlargement to 8 x 10 format, partial frame enlargement to 8 x 10 format, or both full and partial frame enlargements. The photographs so reproduced are frames 4,6,7,11 and 12 of the Skylab 4 imagery, and both Skylab 3 frames.

In viewing the imagery the reader should remember that the imagery is oblique, with typical tilt angle (complement of the elevation angle to spacecraft) of 45°. On such an image the scale is not constant. Along the principal line of the photograph (direction of tilt), the scale varies as the cosine squared of the tilt angle; in a direction perpendicular to the principal line the scale varies as the cosine of the tilt angle. A more detailed discussion of these effects can be found in Appendix B. The important point to remember, however, is that distances and angles between lines will be distorted by the geometry of the photograph.

TABLE 3.1

EARTH LASER BEACON PHOTOGRAPHS

Ref.#	Roll	Frame#	Date/Time (GMT)	Laser Parameters	Description
1	CX-20	SL4-196-7345	1 Dec/1441	10 watts, 5145Å 2 pulses/sec	Green dot. View from NYC to Washington. Some scattered clouds, but not over site.
2	CX-20	SL4-196-7346	1 Dec/1441	10 watts, 5145Å 2 pulses/sec	Green dot still visible. From farther north than #1. More haze.
3	CX-20	SL4-196-7347	1 Dec/1441	10 watts, 5145Å 2 pulses/sec	Cannot definitely identify beacon. View from very far north.
4	CX-20	SL4-196-7359	3 Dec/1430	3 watts, 5145Å	Bright green dot.
5	CX-20	SL4-196-7360	3 Dec/1430	3 watts, 5145Å	Bright green spot. More oblique haze than #4
6	CX-20	SL4-196-7367	4 Dec/1347	1 watt, 5145Å	Elongated green spot. Heavy haze south of Goddard. Sizeable atmospheric variations around target area.
7	CX-43	SL4-209-8209	27 Jan/1545	1.8 watts, 5900Å	Orange-red spot. Slightly elongated.
8	CX-43	SL4-209-8210	27 Jan/1545	1.8 watts, 5900Å	Spot appears smaller & rounder than #7. More haze than #7. From east looking west.
9	CX-44	SL4-206-7976	29 Jan/1419	0.95 watts, 6250Å	Very dull orange spot, almost in scattered clouds.
10	CX-44	SL4-206-7977	29 Jan/1419	0.95 watts, 6250Å	Spot appears brighter and redder than in #9.
11	CX-44	SL4-206-8000	30 Jan/1335	1 watt, 5800Å	Elongated orange spot. Very clear, no clouds.
12	CX-44	SL4-206-8001	30 Jan/1335	1 watt, 5800Å	Elongated orange spot which is less bright and more haze than #11.

There is a marked loss of vividness between the original transparencies and the paper prints of the report. The laser is brighter and more detectable on the transparencies. The astronauts made a similar comment relative to their visual observations during the Skylab experiment and the photographs they were shown during the experiment debriefings.

Photographs for the report have been selected to provide a representative sample of wavelength, power, and beacon shape and size. The two Skylab 3 photographs are included because they represent the largest beacons observed; because they increase the temporal data base for the phenomenon; and because of their similarity to Frames 11 and 12 of the Skylab 4 mission. Frames 4 and 6 portray data on successive days from almost the same spacecraft location, with only a change of atmospheric visibility and laser power. Frame 7 is the best example of beacon data in terms of exposure and resolution. Frames 11 and 12 are successive frames on the same orbit whose object space dimensions and orientation remain constant in spite of a 40% increase in range to spacecraft. Data analysis of the frames is contained in Section 4.

Figure 3.1   Full Frame Enlargement - Skylab 3, Frame B

4 September 1973

2.5 watts

5145 Å

This is the second of two frames obtained on the Skylab 3 pass. Slant range to the spacecraft is 745 km; the elevation angle is 36°. The beacon is 550 m long by 190 meters wide, and is the largest beacon observed during the experiment. Note the clouds to the east over the Chesapeake Bay, and the haze near Andrews AFB. Sensitometry was not available for this frame. We estimate, however, that the beacon is five times brighter than the surround in the green film band, and ten times brighter in the blue. The red layer is not exposed by the beacon. An enlargement of this frame is contained in Figure 3.2.

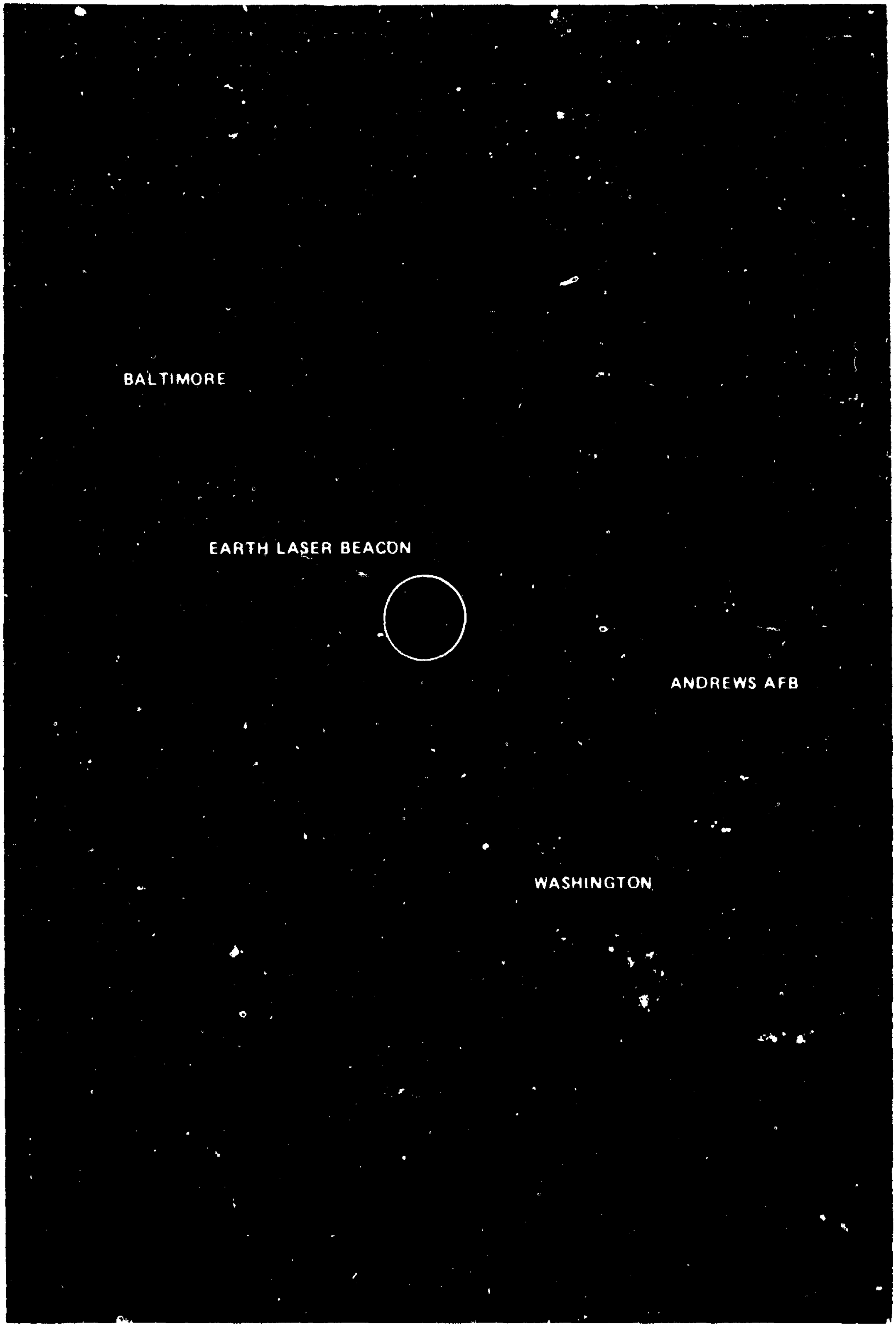

BALTIMORE
EARTH LASER BEACON
ANDREWS AFB
WASHINGTON

Figure 3.2   Partial Frame Enlargement - Skylab 3, Frame B

4 September 1973

2.5 watts

5145 Å

The figure is a 2.5x enlargement of a portion of Figure 3.1. Total enlargement from the original is about 17x. The beacon appears as a long, thin pencil, very similar in appearance to the beacons of Frames 6,11 and 12 of the Skylab 4 mission. Microdensitometry of the blue and green film layers indicates that the beam center is close to the center of the pencil. The visual impression that the laser is brightest at one end is caused by the red layer of the film, which is not sensitized by the beacon. Maximum brightness in the red layer is at the upper end of the beacon.

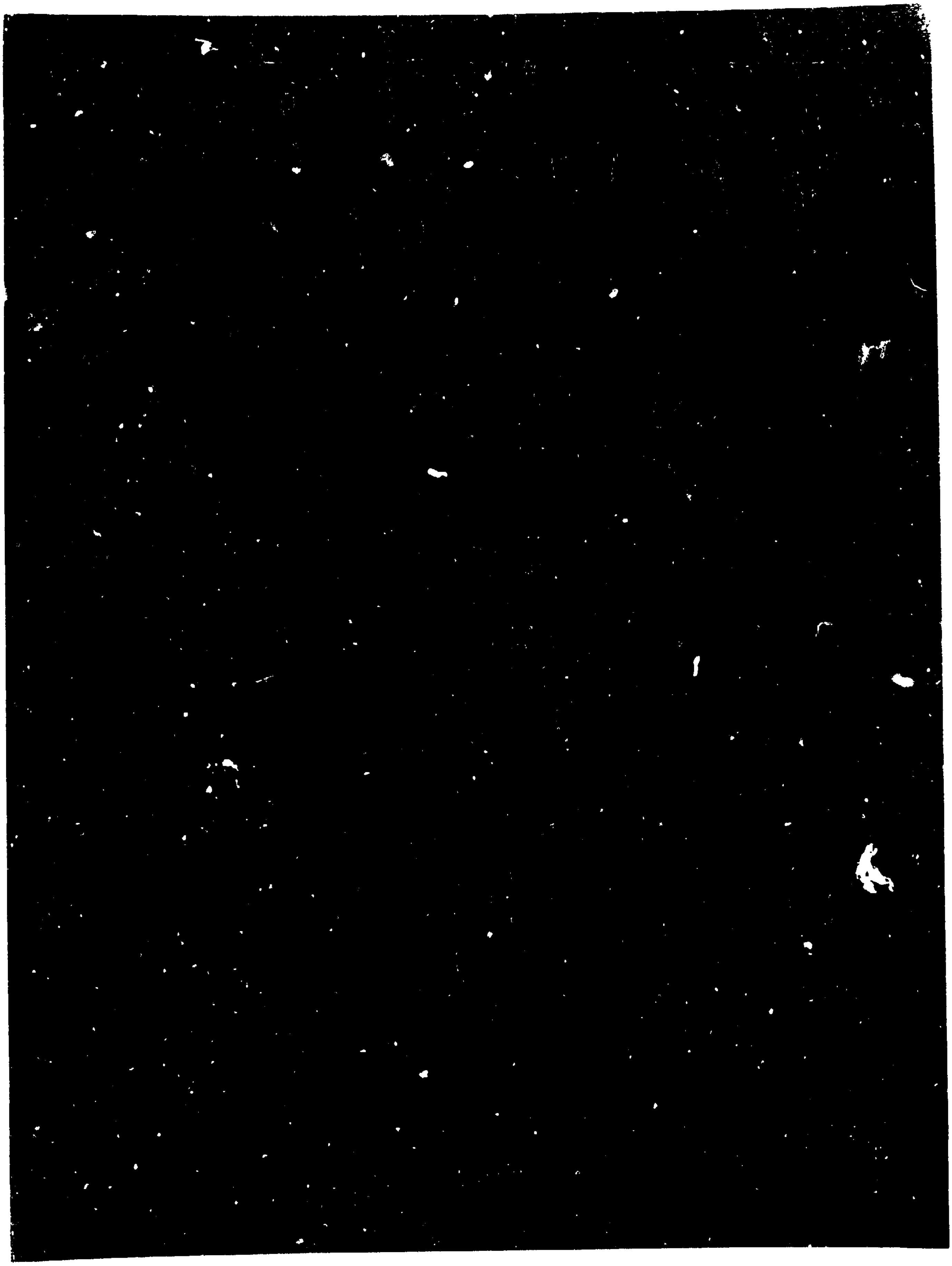


Figure 3.3 Partial Frame Enlargement - Skylab 3, Frame A
4 September 1973
2.5 watts
5145 Å

The figure is a 17x enlargement of the frame just preceding Frame B of Figures 3.1 and 3.2. Range to spacecraft is 755 km; elevation angle is 35°. The beacon is more diffuse than Frame A, being 500 m by 200 m in size. Microdensitometry was not performed on this frame. Note that the long axis of the beacon coincides almost exactly with that of Frame A.

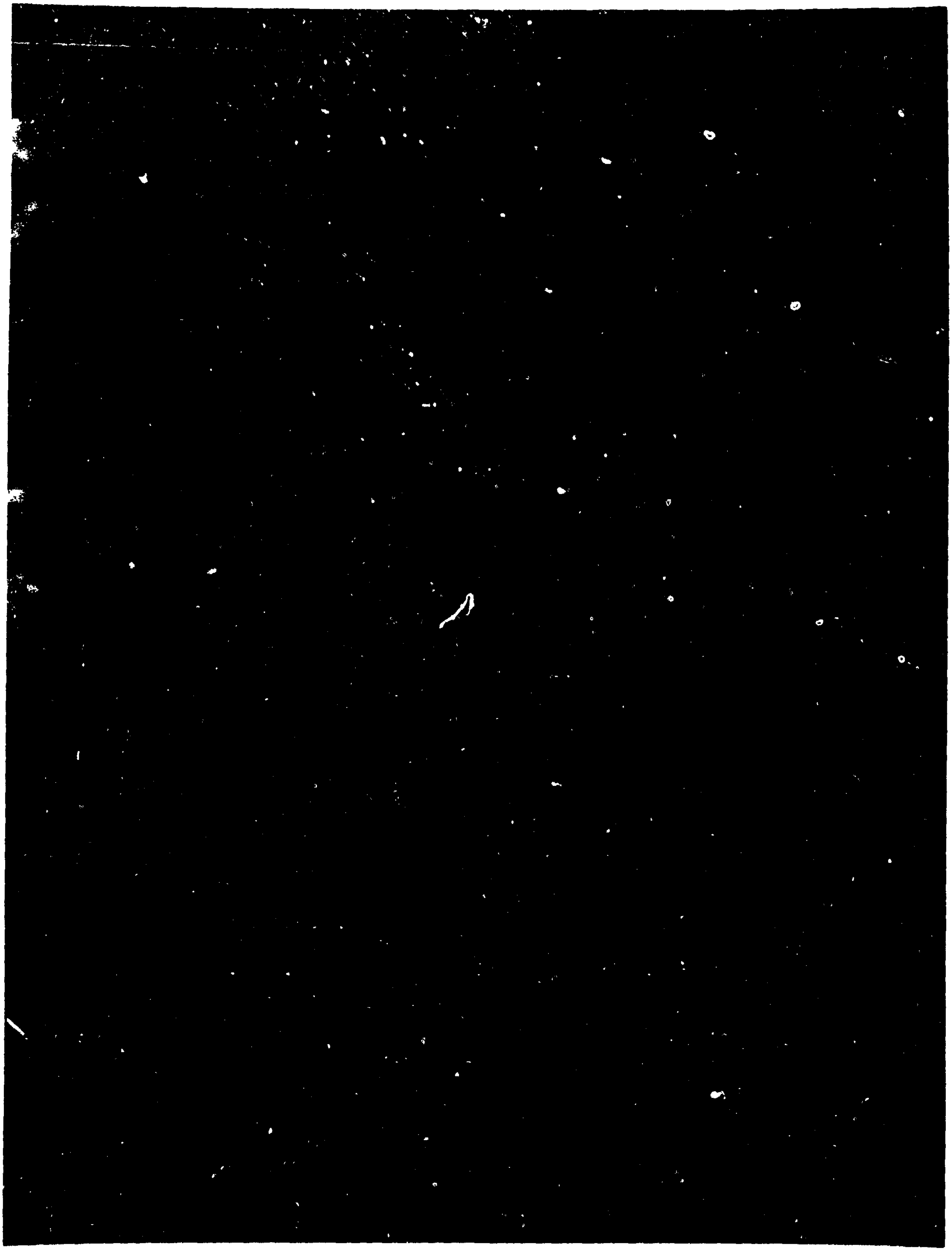


Figure 3.4 Partial Frame Enlargement - Frame 4

3 December 1974

3 Watts

5145 Å

The figure is a 3 x enlargement of the Frontispiece. Total enlargement from the original is 20 x. The beacon consists of a white central area together with a green outer ring. This is one of the beacon frames which was overexposed. A properly exposed beacon would be blue-green.

The distortion of the angle between the runways because of obliquity is evident. The coniferous trees bordering the runway are visible as is the soil area between the laser and the runway vertex.

The beacon covers an area 230 m x 190 m, with the dimensions on the original film 115μ x 95μ. The size is equivalent to 3.4 resolution areas. The white inner circle is about 35μ in diameter.

Figure 3.5 Full Frame Enlargement - Frame 6

4 December 1974
1 watt
5145 Å

This photograph was taken from almost the same point in space as Frame 4 of the Frontispiece. The range to the spacecraft is 630km, and the elevation angle is 43°. The laser power has been decreased to 1 watt from the 3 watt level of Frame 4. Atmospheric haze is much more prominent in this figure. Compare, for example, the visibility of the Capitol area and the bridges across the Potomac River on this figure and the Frontispiece. The beacon is now elongated, with dimensions 360m by 160m. The direction of elongation is very close to the direction to the spacecraft. The enlargement is 6.8x.

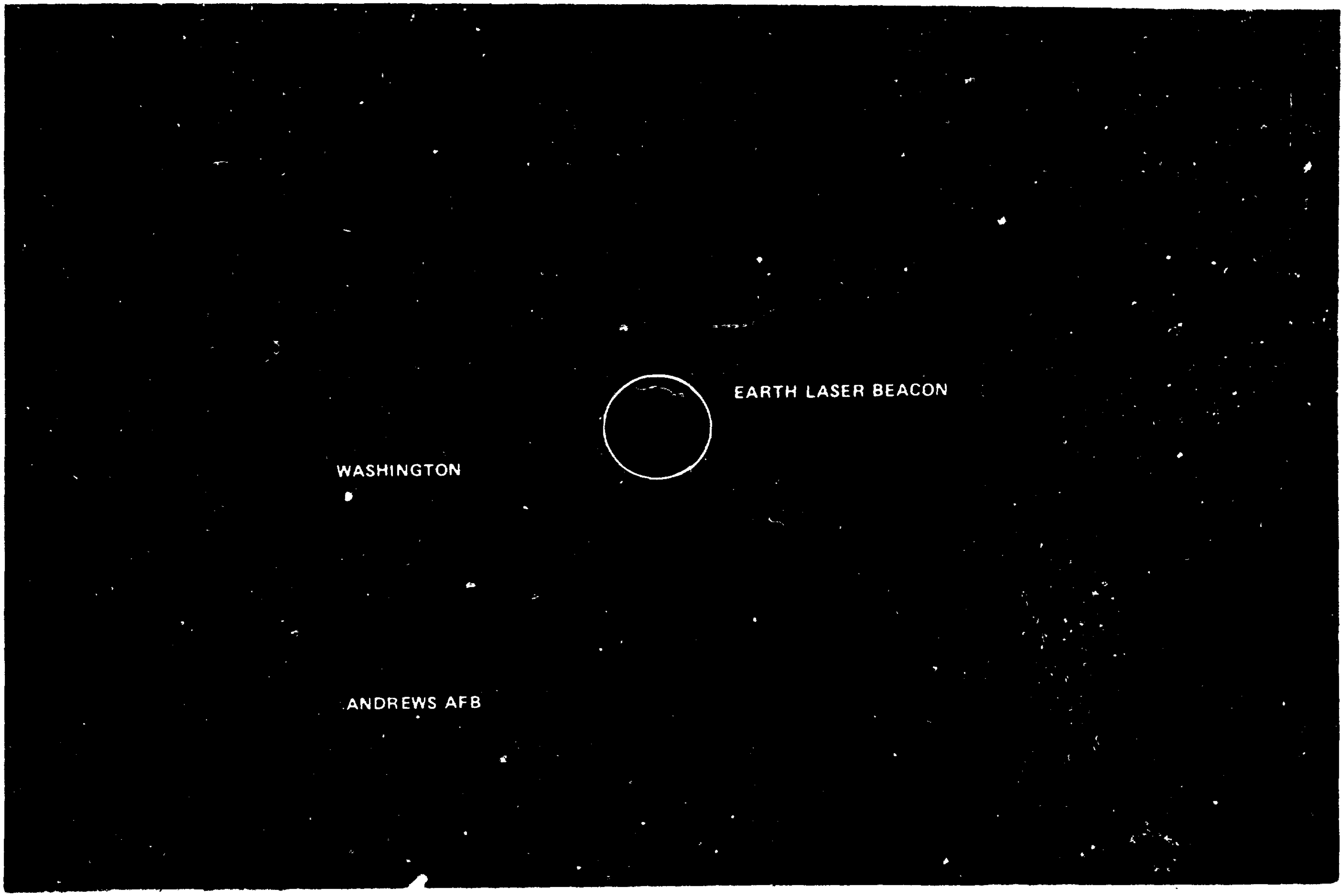

EARTH LASER BEACON
WASHINGTON
ANDREWS AFB

Figure 3.6 Full Frame Enlargement - Frame 7

27 January 1975

1.8 Watts

5900 Å

The spacecraft is at a range of 640 km, with an elevation angle of 42°. The size of the beacon is almost egg shaped, with dimensions 280 m by 160 m. The direction of the elongation is almost orthogonal to the direction of the spacecraft. The enlargement from the original is 6.8x. The beacon covers an area 360 m x 160 m, equivalent to 4.1 resolution areas. Dimensions on the original film are 175μ x 75μ.

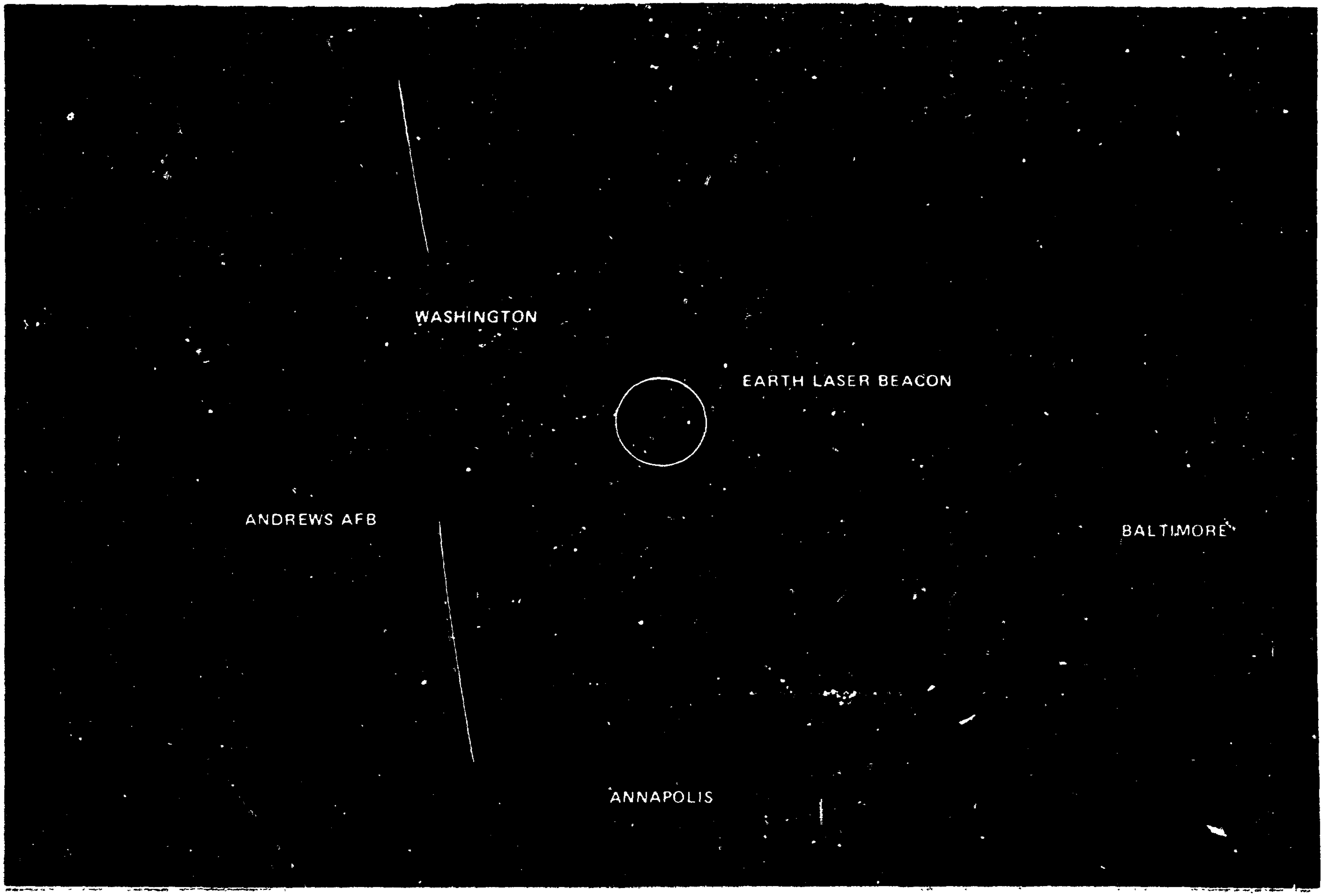

WASHINGTON
EARTH LASER BEACON
ANDREWS AFB
BALTIMORE
ANNAPOLIS

Figure 3.7 Partial Frame Enlargement - Frame 7

27 January 1975

1.8 Watts

5900 Å

Tctal enlargement from the original is 20 x. The enlargement from Figure 3.6 is 3 x.

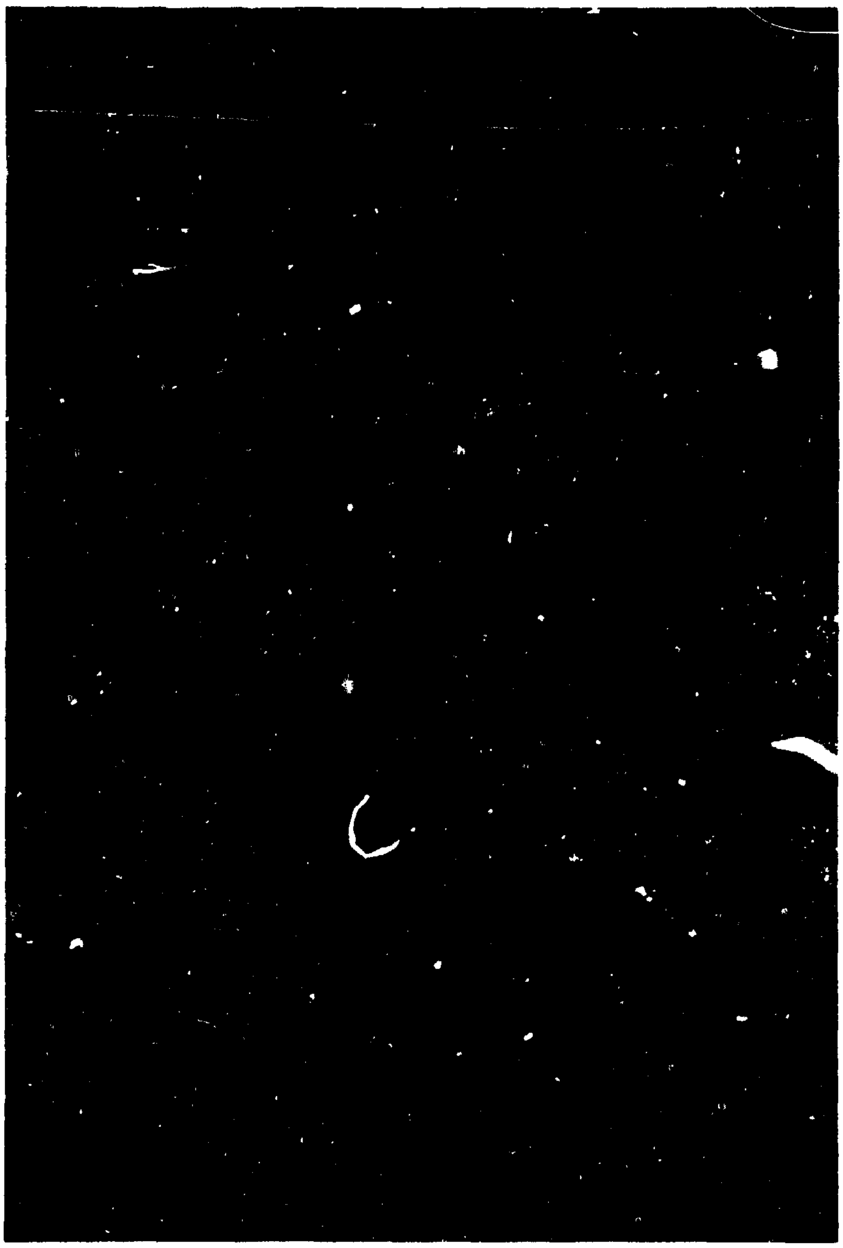


Figure 3.8 Full Frame Enlargement - Frame 11

30 January 1975
1 watt
5800 Å

Frame 11 contains the largest beacon observed on Skylab 4. The spacecraft here is closer than on any other frame - with range 550 km and elevation 51°. The spacecraft is to the north of the Beltsville Airport. The image is best observed with the spiral binding held to the left. The long axis of the beacon is at an acute angle to the direction to the spacecraft. The orange-red spot appears 370 m x 170 m in the red film layer, and 290 m x 140 m in the green film layer. The beacon is a brighter orange-red on the original imagery.

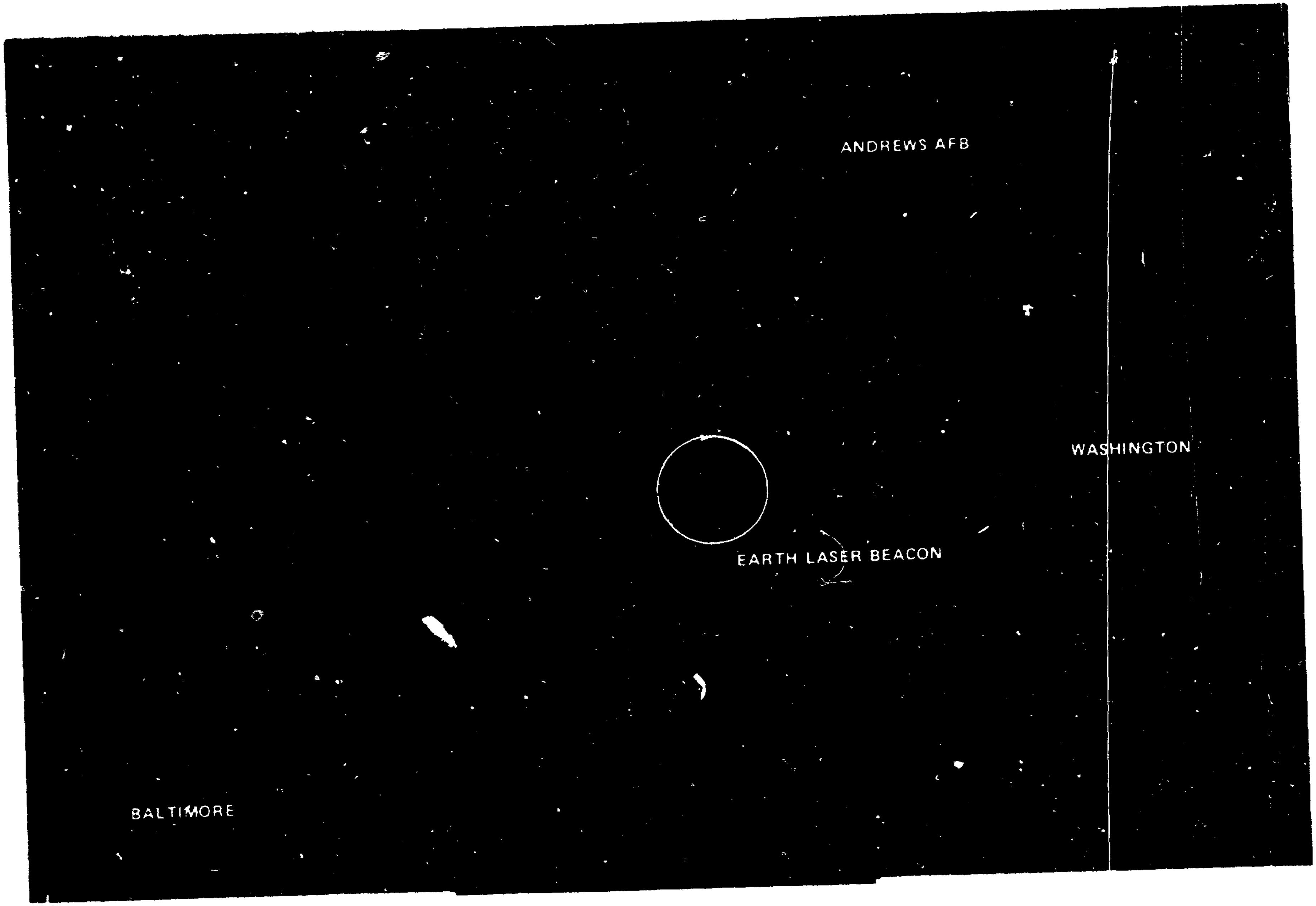

ANDREWS AFB
WASHINGTON
EARTH LASER BEACON
BALTIMORE

Figure 3.9 Partial Frame Enlargement - Frame 11

30 January 1975

1 watt

5800 Å

The beacon is enlarged 3 x from Figure 3.8, and 20 x from the original. The orange-red tone of the beacon is not as vivid as the original, but is more representative than the tone of Figure 3.8.

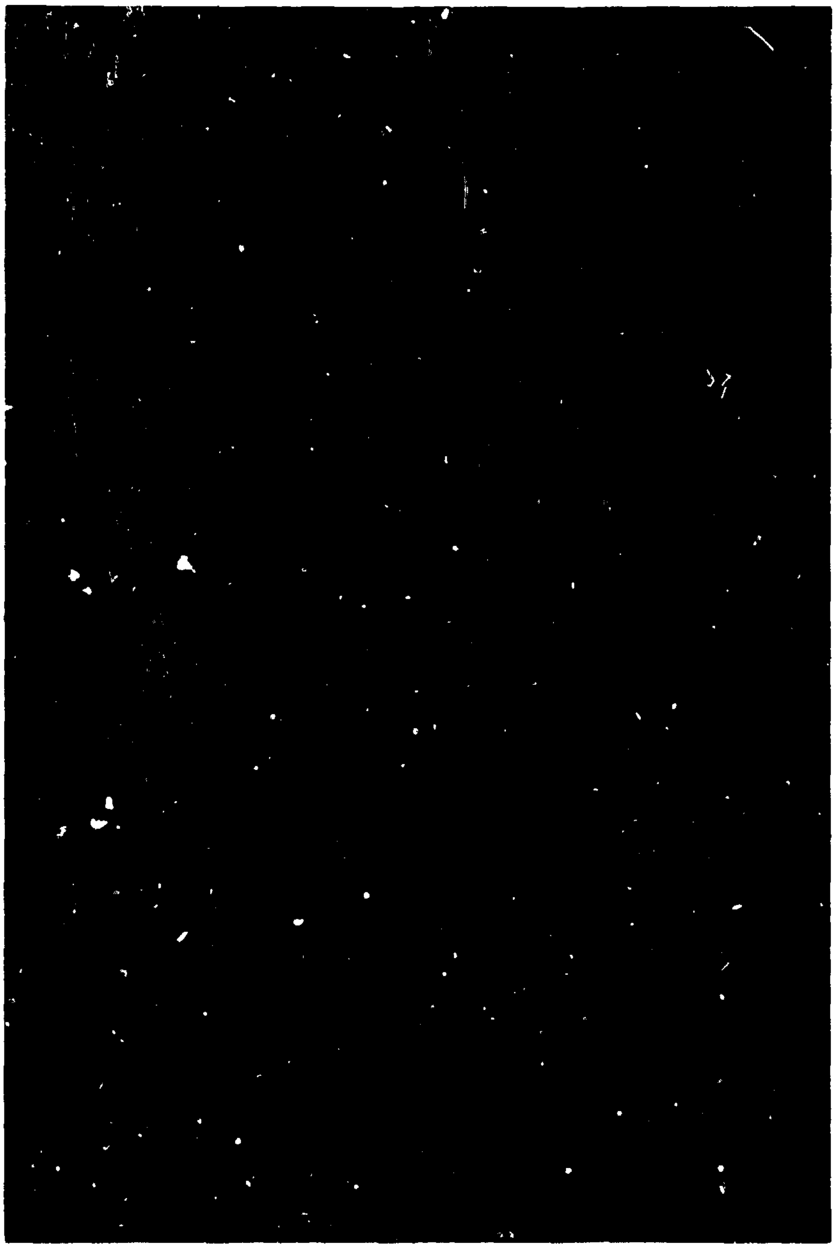
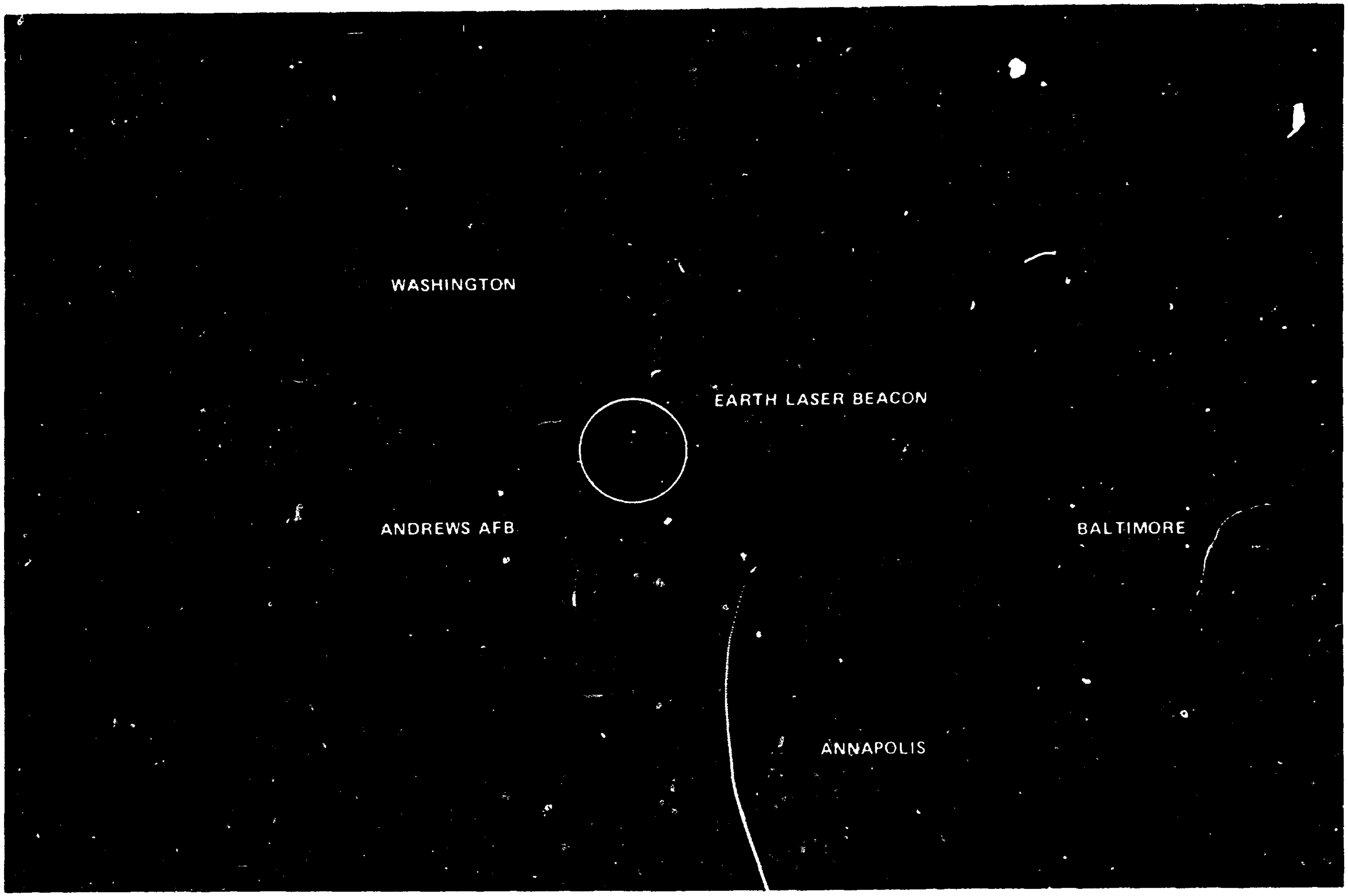


Figure 3.10 Full Frame Enlargement - Frame 12

30 January 1975
1 watt
5800 Å

Frame 12 was taken immediately after Frame 11 (Figures 3.8 and 3.9) The range to the spacecraft has increased by 40%, to 780km, with elevation angle now 34°. The beacon remains an orange-red ellipse. The major axis of the ellipse is now almost orthogonal to the direction to the spacecraft, and is aligned closely with the major axis of the beacon of Frame 11. The size of the beacon is 330m by 190m in the red layer, and 310m x 140m in the green layer. These dimensions correspond well to the beacon dimensions of Frame 11. Frames 11 and 12 are one of the three sets of sequential imagery which were analyzed.


WASHINGTON
EARTH LASER BEACON
ANDREWS AFB
BALTIMORE
ANNAPOLIS

4. DATA ANALYSIS

The spatial extent of the beacon and the radiance distribution within the beam were defined by photometric analysis of the beacon imagery. The procedure involved the generation of enlargement separations of appropriate film layers, densitometry of the Beltsville Airport area on the enlargement separations, and removal of exposure effects caused by atmospheric flare and underlying terrain.[1-3]

A Nikon copy camera was used to make 20x enlargement separations of the red and green layers of the imagery. Wratten 90 series filters were used for the separation process. The enlargement camera configuration (camera, light table) had previously been checked for format uniformity and degree of flare.[1] To minimize flare effects, the film step wedge was copied with the enlargement camera and processed with the separations. Any extraneous flare introduced by the enlargement camera was thus incorporated into the D-log E curve and removed in the subsequent data reduction. Separations were also made at an enlargement of 400x, however only the 20x enlargement set was used for the final data reduction.

The 20x enlargements were studied on a color analyzer, essentially a device which displays densities in a color encoded form on a color monitor. All areas of a scene within a specified density range are encoded in a single color by such a device. The color analyzer thus simplifies the densitometric analyses of complex scenes by presenting the density patterns in a visual format.

Figure 4.1, for example, depicts the energy distribution for the red layer of Frame 12. The ordering of colors in terms of increasing exposure or energy is: yellow, light blue, green, orange, pink, violet, red and dark blue. This ordering is true for all figures in the report, although all colors do not appear in each example.

The exposure data of Figure 4.1 must be corrected for the exposure contributions due to atmospheric flare and terrain elements within the beacon image. Because the resolution of the imagery was only 100m, it was not possible to use analyses of scene shadow areas to measure the atmospheric flare.[1,2] The exposure of large bodies of water was therefore utilized as an estimate of the atmospheric flare. Such an estimate is quite good in the red spectral band where the reflectance of clear water is about 1% or less.[4] The error increases in the green band due to the increased reflectance of water in the green and the greater proportion of surface-reflected skylight radiance.

The exposure caused by atmospheric flare on Skylab imagery is quite high (of the order of a 10% reflector) and hence the estimate of flare from exposures of bodies of water should be satisfactory.[5] In fact, the largest error in the measurement is probably caused by the necessity of using bodies of water about 20km distant from the beacon. Atmospheric variations may be expected to occur over this scale of distance.

Ideally, successive frames of imagery with the beacon on and off would permit an accurate definition of the extent of the beacon and its radiance distribution by a subtractive image process. Unfortunately such imagery was not available. Study of the Goddard Optical Research Facility on film layers not sensitized by the beacon indicates that the Facility covers an area of one resolution element (the actual facility dimensions are 50m x 125m), with total exposure about 1.2 times that of the surrounding terrain. Definition of the beacon extent was therefore based on patterns of unusually high radiance. Estimate of background terrain exposure was based on the largest exposure value found on the periphery of the beacon.

Figure 4.1 is discussed as an example of the analyses conducted. The beacon boundary is defined to be the outside of the orange ring. The largest background terrain exposure is that of the green encoding, which has an exposure of 20 units [after subtraction of the measured atmospheric flare of 15 units of exposure]. The corrected exposure values of the four beacon regions - orange, pink, violet and red - are thus 10, 30, 75 and 235 exposure units, respectively.

The central spot is 13 times brighter than the background terrain, and the outermost region of the beacon has a radiance almost equal to that of the background. The beacon size is 130μ x 75μ on the original film, or 330m x 190m after scaling. About 70% of the total energy in the beacon is within the central resolution element area.

The energy distribution of the beacon of Figure 4.1 is characteristic of all the beacons studied. In general, about 50% of the total energy of the beacon is within the central resolution area; the central portion of the beacon is about 5-10 times brighter than the background terrain; and, the outermost region of the beacon has energy about equal to that of the background.

The brightness difference between the central portion of the beacon and the background terrain can be compared with the brightness difference expected - although some care must be taken. The beam power pattern is not uniform, and atmospheric turbulence fluctuations will change the portion of the beam power pattern illuminating the spacecraft. The scale of the turbulence effects is of order 0.1 mrad, and an angular change of this magnitude can modify the beam power significantly (cf. Fig. 2.1).

Nevertheless, the direct beam power is in reasonable agreement with the calculation that a 1 watt beacon should be about thirty times brighter than a 10% terrain reflector. The central region of the beacon is 13 times brighter than the background. Some of the laser energy has also sensitized the green film layer, where the central region is three times brighter than the background. The sensitivity of the green film layer to 5800 Å illumination is less than the average sensitivity of the green film layer.*

* It is interesting to note that the total beacon exposure in the green is 0.28 times the total beacon exposure in the red. The green band of the film is 0.33 times less sensitive to 5800 Å illumination than the red band, in good correspondence with the measured value of 0.28.

Figure 4.1 (Upper Frame) Color Encoding

Frame 12-Red Band

1 watt

5800 Å

780 km range

The original photograph is contained in Figure 3.10. The colors in order of increasing energy are yellow, light blue, green, orange, pink, violet and dark blue. The colors from yellow to red may be traced sequentially from the outside of the beacon to the center of the beacon.

Atmospheric flare exposure is 15 units. The exposure values after removal of atmospheric flare exposure are tabulated below. The beacon is defined to extend from the red through the orange areas. The exposure of the green encoding, 20 units, is utilized as the background exposure in the area of the beacon. The exposure due to the laser from the red to orange areas is therefore 235, 75, 30 and 10 units.

The central resolution area contains about 70% of the total energy in the beacon. The central portion of the beacon is about 10 times brighter than the surround, and the outer regions are of the same brightness as the surround. The beacon size is 130μ x 75μ on the original, and 330 m x 190 m in object space. The beacon extends over 4 resolution areas and has an eccentricity of 1.7.

Exposures (Atmospheric Flare Removed)

Yellow	5
Light Blue	10
Green	20
Orange	30
Pink	50
Violet	95
Red	255

Figure 4.2 (Lower Frame) Color Encoding

Frame 12-Green Band

1 watt

5800 Å

780 km range

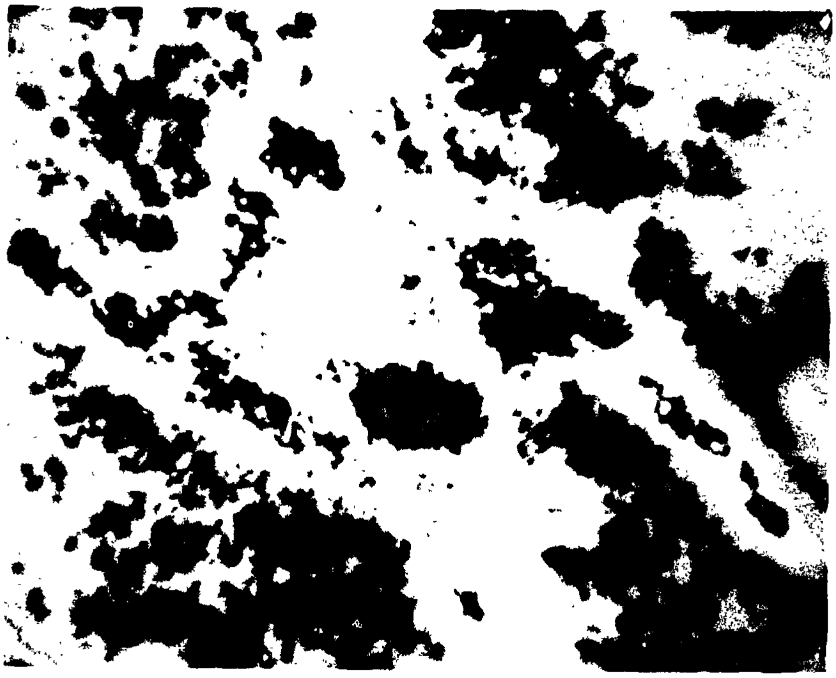
Atmospheric exposure is 18 units. The exposure values after removal of atmospheric effects are tabulated below. Background exposure in the area of the beacon is taken to be the orange level (16 units). The beacon consists of two regions - violet and pink, with corrected exposures of 46 and 13 units.

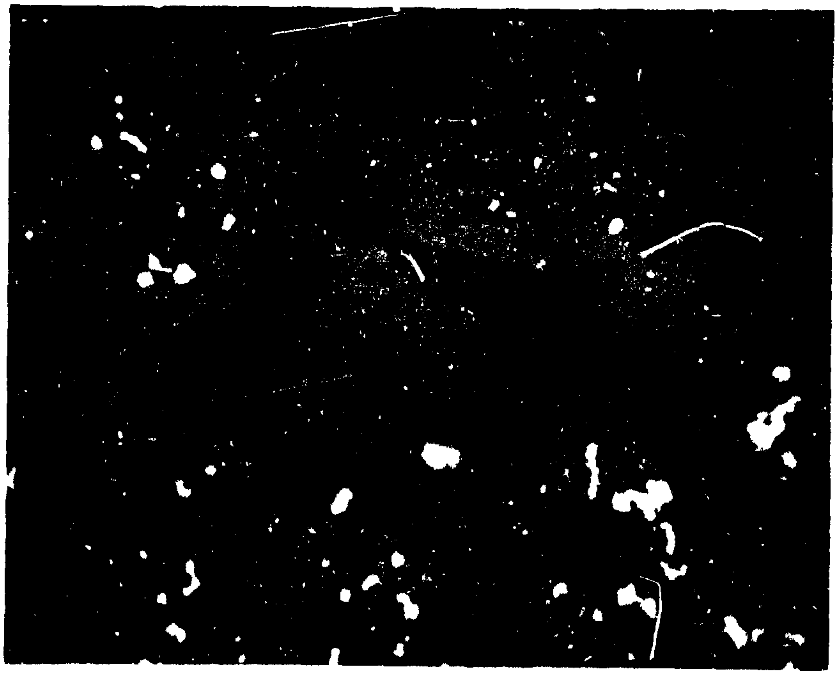
Approximately 50% of the beacon energy is the central resolution area. The central portion of the beacon is about 3 times brighter than the surround. (The green film layer is 33% less sensitive to 5800 Å illumination than the red film layer; in addition, the reflectance of the surround is higher in the green than in the red).

The size of the beacon is 120μ x 55μ, or 310 m x 140 m. The beacon extends over 3 resolution areas, and has an eccentricity of 2.2.

Exposures (Atmospheric Flare Removed)

Green	8
Orange	16
Pink	29
Violet	62





Figures 4.2 to 4.7 contain additional displays of the beacon densitometry. Table 4.1 contains a summary of key beacon parameters: namely, date, range, power, wavelength, size, and radiance distribution. The two SL-3 frames, as well as the eight SL-4 frames which were analyzed in detail, are included in the table.

Frames 4 to 6 form a set of data taken on successive days. The spacecraft was in practically the same location for frames 4 and 6. No significant change in beacon size occurs between frames 4 and 5, although the beacon of frame 6 is about 25% larger than those of the previous day. Examination of frames 4 and 6 (Frontispiece and Fig. 3.5) shows that much more haze is prevalent on Frame 6.

The beacon in frame 6 **is** also elliptical as are the beacons in frames 7,11,12 and the two SL-3 frames.

Frames 7 and 8 are successive frames on the same pass, as are frames 11 and 12 and the two SL-3 frames. Ellipticity occurs on the first photograph of all three sets, and is retained on the second frame of two of the three passes. Ellipticity does not occur on frame 8, although here the range has increased to the point where the shape can be lost due to resolution size.

The ellipses are oriented randomly with respect to camera format and external geometry (such as direction to spacecraft, or local terrain). The ellipses, however, remain fixed relative to a ground coordinate system between frames 11 and 12, and between the two SL-3 frames. The eccentricities range from 1.7 to 3.2.

The two SL-3 frames contain the largest beacons observed, with the major dimension approximately 500m. One of the SL-3 beacons (frame B) is strikingly similar in shape to frames 11 and 12. Significant atmospheric variations near the GORF are visible on both SL-3 frames. Range to spacecraft was about 750km for both SL-3 frames. Densitometry of frame B indicates that the brightest portion of the beam is in the center of the ellipse.

TABLE 4.1 SUMMARY OF BEACON PARAMETERS

DATE	WAVE LENGTH	POWER	FRAME	RANGE (Km)	IMAGE SIZE (μ)	OBJECT SIZE (M)	e[1]	RESOLUTION AREAS[2]	BRIGHTNESS[3]	CENTRAL ENERGY[4]
4 Sept. 1973	5145 Å	2.5w	SL-3A	755	200 x 80	500 x 200	2.5	6.2	-	See Note 5
			SL-3B	745	225 x 70	550 x 190	3.2	6.5	5x (GN)	
3 Dec. 1973	5145 Å	3w	4 GN	620	115 x 95	230 x 190	1.2	4.4	-	-
			5 GN	710	105 x 95	230 x 230	1.1	4.4	3x	50%
4 Dec. 1973	5145 Å	1w	6 GN	630	175 x 75	360 x 160	2.3	5.3	5x	60%
27 Jan. 1974	5900 Å	1.8w	7 GN	640	135 x 75	280 x 160	1.8	4.1	3x	40%
			8 GN	830	70 x 70	190 x 190	1.0	2.0	-	-
29 Jan. 1974	6250 Å	0.95w	10 RED	1500	70 x 55	350 x 270	1.3	1.5	-	-
30 Jan. 1974	5800 Å	1w	11 RED	550	200 x 90	370 x 170	2.2	7.2	10x	35%
			11 GN	550	160 x 75	290 x 140	2.1	4.7	2.5x	35%
			12 RED	780	130 x 75	330 x 190	1.7	3.9	10x	70%
			12 GN	780	120 x 55	310 x 140	2.2	3.0	3x	50%

1. Eccentricity of image.
2. Number of resolution areas over which the beacon extends.
3. Relative brightness between the brightest area of the beacon and the beacon surround.
4. Percent of total beacon energy contained within an area of one resolution element at the center of the beacon.
5. The size of the SL-3 beacons was established by visual measurement of the imagery.

Figure 4.3 (Upper Frame) Color Encoding

Frame 11-Red Band

1 watt

5800 Å

550 km range

The original imagery of Frame 11 is reproduced in Figures 3.8 and 3.9. Frame 11 was obtained on the same orbit as Frame 12, but at much closer range (550 km vs 780 km). Atmospheric flare exposure is 10 units. Much of the background is not encoded because of the dynamic range of the encoding device. The color encoding is tabulated below.

The beacon extends through the light blue region. Background exposure is that of the yellow level. The beacon energy from violet to light blue is 95, 50, 30, 15 and 10 units. The central resolution area contains 35% of the beacon energy. The central portion of the beacon is 10 times brighter than the background. The beacon size is 200μ x 90μ , or 370 m x 170 m. The beacon extends over 7.2 resolution areas, and has eccentricity 2.2.

The total area of this beacon (in object space) is within 5% of that of Frame 12 (Figure 4.1), and the central portion of the beam has a brightness relative to the background almost identical to that of Frame 12.

Exposures (Atmospheric Flare Removed)

Yellow	10
Light Blue	20
Green	25
Orange	40
Pink	60
Violet	105

Figure 4.4 (Lower Frame) Color Encoding

Frame 11-Green Band

1 watt

5800 Å

550 km range

Atmospheric exposure is 10 units. The beacon extends over the pink, orange and green areas. Background exposure is that of the blue region, 11 units. Beacon exposures from pink to green are 26, 13 and 5 units.

Approximately 35% of the beacon energy is in the central resolution area. The central part of the beacon is 2.5 times brighter than the surround. The beacon size is 160μ x 75μ, or 290 m x 140 m. The beacon extends over 4.7 resolution areas, with eccentricity 2.1.

The total area of the beacon is within 5% of that of Frame 12, Figure 4.2. The brightness of the central region relative to the background is almost identical to that of Frame 12. The eccentricity also corresponds to that of Frame 12.

Exposures (Atmospheric Flare Removed)

Yellow	7
Light Blue	11
Green	16
Orange	24
Pink	37

Figure 4.5 (Upper Frame) Color Encoding

Frame 4-Green Band

3 watts

5145 Å

620 km range

Copies of Frame 4 are contained in the Frontispiece and Figure 3.4. Unfortunately, the frame is overexposed in the center of the beam, and accurate sensitometry is not possible. The background is not encoded, because of the lack of dynamic range of the encoding device. Definition of the beacon extent is difficult on this figure. From study of Figure 3.4, the beacon most probably extends through the light blue area. The size of the beacon is then 115μ x 95μ , or 230 m by 190 m. The beacon extends over 4.4 resolution areas, with an eccentricity of about 1.2.

Sensitometry was possible on the next frame of this orbit, Frame 5 (range 710 km). The results are included for comparison with Figure 4.6 below. About 50% of the total energy was in the central resolution area, with the brightest area of the beacon 3 times the background. The beacon size was 105μ x 95μ , or 250 m x 230 m. The beacon extends over 4.4 resolution areas, with an eccentricity of 1.1.

Figure 4.6 (Lower Frame) Color Encoding

Frame 6-Green Band

1 watt

5145 Å

630 km range

The original photograph is reproduced in Figure 3.5. Atmospheric exposure is 10 units. Background exposure is that of the light blue area, 13 units. The beacon exposures, after correction for background, from pink through green are 69, 23 and 8 units.

The central resolution area contains about 60% of the total energy. The brightest region of the beacon is 5 times brighter than the background. The beacon size is 175μ x 75μ or 360 m x 160 m. The beacon extends over 5.3 resolution areas, and has an eccentricity of 2.3. This beacon is about 30% larger than the beacon of Frame 4. Frames 4 and 6 were taken from nearly the same spacecraft location. The power of Frame 6 was decreased to 1 watt, and atmospheric haze was much more prevalent on the orbit for Frame 6.

Exposures (Atmospheric Flare Removed)

Yellow	8
Light Blue	13
Green	21
Orange	36
Pink	82

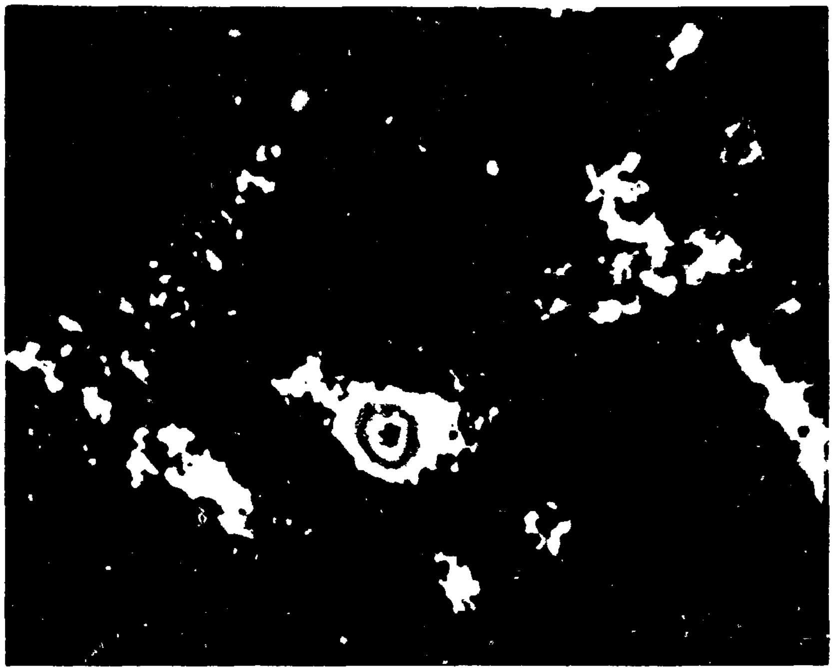


Figure 4.7

Color Encoding
Frame 7-Red Band
1 watt
5900 Å
640 km range

The original photograph is contained in Figures 3.6 and 3.7. The background is not encoded. The orientation of this frame is identical to that of Figure 3.7-i.e., the runway vertex is directly above and to the right of the wide end of the beacon. The background exposure is 3.5 units. Atmospheric exposure is 4.0 units. The exposures of the beacon from pink to yeallow after removal of background are 11, 8.5, 6, 4 and 2.5.

Forty percent of the energy is in the central resolution element, and the brightest region of the beacon is 3 times brighter than the background. The size of the beacon is 135μ x 75μ , or 280 m x 160 m. The beacon extends over 4.1 resolution areas, and has an eccentricity of about 1.8.

The green layer is not exposed by the 5900 Å wavelength. Study of the laser site in this band reveals an exposure between 10 and 20% larger than the background surround of the site.

Exposures (Atmospheric Exposure Removed)

Yellow	6.0
Light Blue	7.5
Green	9.5
Orange	12.0
Pink	14.5

5. DISCUSSION OF RESULTS

The principal features of the beacon imagery observed above are as follows. The typical beacon extends over 4.5 resolution areas with an average dimension on the film of 110μ. About one-half of the beacon energy is contained within the central resolution area of the beacon. Six of the fourteen beacon images are elliptical; the average eccentricity of the ellipses is about two. The ellipses are oriented randomly with respect to internal camera parameters, but remain fixed relative to a ground coordinate system on frames of the same orbit. The ellipses are oriented randomly relative to a ground coordinate system on different dates. The film plane dimensions of the beacon decrease on successive frames as range to the spacecraft increases; however, the object space dimensions of the beacon remain uniform as the scale change with range is accounted for. Some correlation between beacon size and atmospheric clarity appears to exist.

We have been unable to explain these observations on the basis of instrumental effects within the camera or film. The beacon phenomena would therefore appear to lie within the atmosphere, possibly in some form of a multiple scattering effect.

Some of the beacon size is undoubtedly due to a blooming or emulsion scattering effect. However, under equivalent laser power and exposure parameters an upper bound for film effects will be the difference between the smallest beacon image observed and the point spread of the system. This smallest dimension is of order 60μ, only slightly larger than the resolution spot size of 50μ.

Film effects due to overexposure or emulsion scattering should also exhibit circular symmetry, in contrast to the large number of beacon examples which are strongly elliptical. One might associate the image anisotropy with emulsion scattering related to polarization (since the beacon was linearly polarized). However, the direction of polarization changes with aiming due to mirror rotation within the coelostat. The ellipses would therefore have to rotate on successive frames of imagery, in direct contrast to the effect observed on frames 11 and 12 and the Skylab 3 imagery in which the ellipses remain fixed relative to a ground coordinate system.

Since all of the beacon images occur within a 1.5mm radius of the center of the format, lens aberrations are considered an unlikely cause of the beacon size. In this region of the format the performance of the lens should be excellent. Lens aberrations and other camera effects should also exhibit symmetry with respect to internal camera geometry. Such symmetry was not observed, as witnessed in the random orientation of elliptical images, the fact that both elliptical and circular images were observed, and the constancy of beacon object space parameters between frames of the same orbit.

The final argument against the possibility of instrumental effects is visual observation of the phenomenon by the astronauts. On Skylab 3 Astronauts Bean and Lousma confirmed the beacon size and shape manifested in the Skylab 3 imagery. They described the beacon as both a neon tube lying in the plane of the earth and as a searchlight coming up through the atmosphere. Strangely, the photographs were taken by Scientist-Astronaut Garriott who did not verify the beacon size and shape, but described the beacon as only a dot.

In this respect the conditions and capabilities of the individual observers must be taken into account. The resolving capability of the eye is between 0.3 mrad and 1.0 mrad, depending upon the contrast of the object, the physical state of the observer, etc. At the Skylab 3 range of 750km the resolvable object size should therefore be between 200m and 700m. The size of the Skylab 3 beacons were of order 500m by 200m. The discrepancy between the three observers is thus not unreasonable.

The typical dimensions of the Skylab 4 beacons were about 250m by 150m, much closer to the resolving limit of the eye. The Skylab 4 astronauts did not confirm an elongation of the beacon, but described the beacon as having size--similar to a christmas tree bulb at a distance of several hundred yards. The transcripts of the Skylab 3 and 4 Experiment Debriefings are contained in Appendix C.

We therefore conclude that the growth of the beacon is due to an atmospheric effect. The present experimental data are insufficient to specify the atmospheric phenomenon involved. One possibility would be multiple scattering within the atmosphere; a second possibility would be scattering from objects such as noctilucent clouds at heights in the range of 80 km.

The origin of the beacon spreading cannot be due to atmospheric fluctuations. The angular scales of fluctuation phenomena are less than 0.1 mrad, and the time scales are less than 200 cycles per second. The time scale is of too long a period to affect imagery at 1/500 second, and the angular broadening of the beacon (10 mrad⁺) is two orders of magnitude larger than 0.1 mrad⁺.

We may examine the range of parameters required for multiple forward scattering to cause the beacon growth. The broadening of a beam through an optical thickness τ and physical thickness χ is approximately[6] of a

$$0.4\chi\sqrt{\tau} \tag{5-1}$$

A broadening of about 150m would thus occur for $\tau \sim 0.1$ and $\chi \sim 1$ km.

Some estimate of the particle sizes giving rise to the scattering may be obtained. If we assume that the 10 mrad beam spread is an upper bound for the size of the forward diffraction peak, then

$$10\ \text{mrad} \leq 0.6\lambda/r \tag{5-2}$$

where r is particle radius.[7] Eq. (5-2) yields $r \geq 30\mu$. It has been shown that if $2\pi r/\lambda > 30$, 40% of the scatter remains within the diffraction cone.[7] Here $2\pi r/\lambda > 360$, and loss of scattered energy to non-forward directions is small. Particles with $r \geq 30\mu$ would be consistent with ice crystals in thin cirrus clouds in the troposphere.

⁺A spread of 200m at a slant range of 15km (10km vertical height).

A second possibility for the beam spread would be single scatter from high altitude phenomena such as noctilucent clouds. At an 80km vertical height characteristic of such clouds (112km slant height), the beacon size would be of order 250m. A single small angle scatter event would be sufficient to create the beacon image. The far field pattern of the beacon, as modified by atmospheric propagation, would then determine the beacon image shape. In this regard it may be significant to note that beacons with elliptical patterns always evidence elliptical image shapes; beacons with circular patterns manifest both circular and elliptical images.

Both of the above phenomena are but hypotheses requiring a great deal of additonal investigation. Relatively little is known about noctilucent phenomena, including the very existence of such clouds at lower latitudes. The optical thickness reported would also seem too small to generate the degree of scatter required. In the case of multiple scattering one would expect a circular symmetry to the broadening. Hence a suitable explanation must be found for the origin of the ellipticity of the beacon. Perhaps anisotropy of the scattering particles can supply such an explanation.

6. CONCLUSIONS AND RECOMMENDATIONS

We have observed above that the most unique characteristic of the earth laser beacon is its unusual size. The typical beacon extends over approximately 4.5 resolution areas, and has a characteristic dimension of 200m. An analysis of the scales and symmetries of the experiment indicate that the cause of the beacon size is atmospheric, although a specific phenomenon cannot be identified on the basis of currently available data.

The fact that the beacon extends over such a large area enhances its potential as an artificial "terrestrial star" for visual navigation and aiming purposes. The enlarged beacon is more visible than a point beacon. In fact, we would recommend that future experiments consider increasing the beam divergence for the target acquisition phase of the experiment, with a subsequent decrease of beam divergence once the astronauts have sighted the beacon. The increased initial beam spread would permit easier location of the beacon; the decreased final beam spread would result in more accurate aiming and tracking once the beam has been acquired.

It is also our contention that the increased beacon size has little effect on the utility of the beacon as a photometric standard. Identical propagation effects would modify terrain radiance. Hence, the center of the beacon could serve as a photometric standard.+ In this respect, the use of several beacons would permit automatic calibration of sensing instruments as described below.

A photometric standard is desirable because exposure at the spacecraft E, due to terrain reflectance, R, is

$$E = \alpha R + \beta \tag{6-1}$$

+ Atmospheric fluctuations can cause the power at the spacecraft to vary, if the far field pattern is not uniform (Figure 2.1). Increased uniformity over the beam pattern should therefore be developed.

where α is dependent upon atmospheric transmittance and sensor parameters, and β is proportional to atmospheric flare and sensor parameters. Eq. (6-1) holds for a given spectral band. The principal data analysis problem concerns the fact that the values of α and β are not known. The use of multiple earth laser beacons should permit determination of α and β.

The earth laser beacon would seem to have maximum utility as a photometric standard if its output radiance toward the spacecraft were automatically modified in direct proportion to changing total irradiance at the laser site. The modification could be accomplished quite simply using a cosine collector and photodetector. The system would be remarkably similar to those utilized in underwater relative irradiance meters.

The laser radiance would then be equivalent to that of a Lambertian reflector of some reflectance, R_s. The resultant exposure at the spacecraft would be

$$E_s = \alpha R_s + \beta \qquad (6\text{-}2)$$

A set of earth laser beacons with relative power levels, f_i , would allow determination of β and α through the set of equations

$$E_{si} = \alpha(f_i R_s) + \beta \qquad (6\text{-}3)$$

Such a configuration would permit automatic calibration and status monitoring of electronic sensors, since the pixel(s) corresponding to the brightest regions of the beacons could be directly integrated into the recording/processing scheme.

Because remote sensing detectors have limited dynamic ranges, a photometric standard should ideally be of the same brightness as the targets being studied. Maintaining a brightness for the beacon which is near the brightness level of the targets under analysis could make the beacon difficult to detect and position within the image. The problem can be resolved if one of the laser lines can be made much brighter than surrounding terrain, while the other two lines remain at a lower brightness range. Many earth resource experiments do not require all channels of information. For example, water resource studies using color imagery do not require detailed red layer information (an exception would be sediment transport studies). Hence the red laser line could be used for detection and positioning by increasing its brightness. Similar comments can be made about vegetation studies, mineral resource studies, etc.

We recommend that additional experiments be conducted to determine the specific cause of the beacon spreading. Such experiments could contribute to our current understanding of atmospheric propagation phenomena, and would enhance the utility of the beacon as a navigational aid and instrument standard. Both the ERTS/LANDSAT systems and high altitude aircraft flights should be considered as data collection sources for additional experiments. In defining additional experiments we note that it would be highly desirable to know the altitude(s) at which the beacon phenomena occur, and the relationship of the spreading to meteorological parameters such as wind direction, temperature, humidity and even time of year.

We would recommend that additional experiments include vertical imagery as well as oblique imagery. The relationship, if any, to the degree of obliquity should be established.

The resolution of the data collection system should be improved, perhaps to a level equivalent to that of the S190B Earth Terrain Camera. Successive imagery with the laser on and off should be a prime experimental consideration. Night imagery would serve a useful purpose.

The earth laser beacon is clearly a unique and exciting development of the space program. The beacon appears useful as both a navigational aid and a sensor photometric standard. In addition, the beacon has led us to question our current understanding of atmospheric propagation phenomena. Additional effort in this area of basic research could lead to new concepts and devices in atmospheric probing. We greatly appreciate the opportunity to have participated in this interesting program.

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APPENDIX A

RELATIVE LASER POWER

The calculation of the relative power between the laser and a Lambertian terrain reflector is straightforward. The resulting values of the relative power are sufficiently unusual that we reproduce the calculation here.

The laser energy striking a detector of area Δ is

$$\frac{4P_L\Delta}{\pi R^2\theta^2} \qquad \text{(A-1)}$$

where P_L = laser power,
R = range to spacecraft, and
θ = full angle beam divergence.

The energy reflected into the detector area from a resolution element of Lambertian terrain is

$$H_o\frac{Aa}{\pi}\cos\phi\ \cos\psi\ \frac{\Delta}{R^2} \qquad \text{(A-2)}$$

where H_o = solar irradiance over the detector bandwidth,
A = terrain area corresponding to a resolution element,
a = terrain reflectance,
ϕ = reflection angle, and
ψ = solar zenith angle.

The relative power, p, between the laser and the terrain element is therefore

$$p = \frac{4P_L}{aH_oA\theta^2\cos\phi\ \cos\psi}. \qquad \text{(A-3)}$$

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The relative brightness is directly proportional to the laser power, and is inversely proportional to terrain brightness, laser divergence and resolution area of the camera.

Letting P_L = 1 watt,

$a = 0.1$,

$A = \pi r^2 = \pi\ (50\ m)^2$.

$\Theta = 2.5 \times 10^{-3}$,

$\phi = 45°$,

$\psi = 75°$, and

$H_o = 0.14$ watts $m^{-1} Å^{-1} \times (1000\ Å) = 140$ watts m^{-1};

as typical conditions for the present experiment, we have p = 31.8 ≈30. A one-watt, 2.5 mrad divergence beam is thus 30 times brighter than a terrain element 100 meters in size.

The fact that the imagery was taken early in the morning (solar zenith angle of 75°, elevation angle of 15°) contributes a factor of 3.9 to p. Viewing the terrain at 45° adds an additional factor of 1.4. The value of p for zenith sun and a vertical view of the terrain is p = 5.8. The value of p for the S190B Earth Terrain Camera would be p = 146 [zenith sun, vertical view, 20 m resolution].

APPENDIX B

IMAGE RECTIFICATION

The scale within an oblique photograph is not constant, but varies with format position. The scale in a direction orthogonal to the principal line is

$$S_{\perp} = S_v \frac{\cos(t+\phi)}{\cos \phi} \tag{B-1}$$

where S_v is vertical scale, t is the tilt angle of the principal axis of the camera measured from the nadir direction, and ϕ is the angle between the film principal point, lens nodal point and format position measured along the principal line. The vertical scale is f/H, where f is the camera focal length and H is the altitude.

In the direction of the principal line the scale, S_p, is as

$$S_p = S_v \frac{\cos^2(t+\phi)}{\cos^2 \phi} \tag{B-2}$$

For the Nikon camera and 300 mm lens, the angle ϕ is very small ($\phi \leq 2^o$). In addition, t is large for the present experiment ($\sim 45^o$). The above expressions thus simplify to

$$\begin{aligned} S_{\perp} &\cong S_v \cos t \\ S_p &\cong S_v \cos^2 t. \end{aligned} \tag{B-3}$$

The scale along any line at an angle ψ relative to the principal line is

$$S = S_v f \sqrt{f^2 \cos^2 \psi + \sin^2 \psi}, \tag{B-4}$$

where $f = \cos(t+\phi)/\cos \phi$. Eq. (B-4) can be derived simply as follows.

Let the y axis be along the principal line, and the x axis be orthogonal to the principal line. Let upper case letters correspond to the object space, and lower case to the image space. Let L be the object space length of a line at angle ψ with respect to the principal line, and w the image space length. Then

$$L^2 = dX^2 + dY^2 = L^2(\sin^2\psi + \cos^2\psi). \qquad \text{(B-5)}$$

By definition,

$$w^2 = x^2 + y^2,$$
$$x = S_v f X, \text{ and}$$
$$y = S_v f^2 Y. \qquad \text{(B-6)}$$

Thus,

$$w^2 = S_v{}^2 f^2 X^2 + S_v{}^2 f^4 Y^2. \qquad \text{(B-7)}$$

Letting $w = SL$, we have

$$S^2 = S_v{}^2 f^2 [\sin^2\psi + f^2\cos^2\psi] \text{Q.E.D.} \qquad \text{(B-8)}$$

Eq. (B-4) permits simple rectification of imagery, provided tances along two orthogonal directions are known. In this case, if ψ_1 is the angle relative to the principal line of a line from a reference point to object 1, and if ψ_2 is corresponding angle of the line from the reference point to object 2, then $\psi_1 + \psi_2 = \pi/2$ by construction. The scales along the directions to objects 1 and 2 are

$$S_1{}^2 = S_v{}^2 f^2 [f^2\cos^2\psi_1 + \sin^2\psi_1]$$
$$S_2{}^2 = S_v{}^2 f^2 [f^2\sin^2\psi_1 + \cos^2\psi_1]. \qquad \text{(B-9)}$$

The parameter f is given by the solution to

$$S_v^2 f^4 + S_v^2 f^2 - (S_1^2 + S_2^2) = 0, \qquad \text{(B-10)}$$

and ψ_1 by

$$\cos^2\psi_1 = \frac{S_1^2 - f^2 S_v^2}{(f^2-1) f^2 S_v^2} \qquad \text{(B-11)}$$

For the earth laser beacon imagery, the distance from the vertex of the runways at the Beltsville Airport to a portion of Andrews AFB, and the distance from the runway vertex to a settlement west of the Beltsville Airport were used to establish camera tilt and location of principal line. These two directions are orthogonal in object space.

APPENDIX C

ASTRONAUT DEBRIEFINGS

This appendix contains the transcript of the debriefings of the astronauts subsequent to the Skylab 3 and 4 missions. It should be pointed out that the unusual results of the Skylab 3 mission suggested that the laser had been misaimed. The possibility that the spacecraft was not illuminated directly was therefore considered. In this instance, the astronauts would have observed only scattered illumination from the beam propagating through the atmosphere.

Densitometry of the second of the Skylab 3 frames suggests that the beam was properly aimed for this frame. In this frame the brightest region of the beacon is close to the center of the beacon image. The distribution of beacon radiance is very similar to the patterns observed on many of the frames of Skylab 4, when the laser did illuminate the spacecraft directly. Densitometry has not been performed on the first Skylab 3 image, although the similarity between the shape of this beacon and that of frame 4, Skylab 4, should be noted.

SKYLAB 1/3
COROLLARY
EXPERIMENTS DEBRIEFING

PREPARED BY

ORBITAL ASSEMBLY PROJECT OFFICE

SKYLAB PROGRAM OFFICE

National Aeronautics and Space Administration

LYNDON B. JOHNSON SPACE CENTER

Houston, Texas

OCTOBER 16, 1973

T053, SKYLAB-EARTH LASER BEACON EXPERIMENT

QUERY The next one was the laser beam.

QUERY Here are some of the pictures we took of the laser beam.

BEAN The laser was the only thing that I saw during the mission that had a neon-light look to it. Everything else on the ground was not dull, but flat and not radiating. This actually radiated like a neon light that's on in the daytime outside. It has a brilliance to it.

GARRIOTT Are these 300-millimeter photographs?

QUERY Yes. There was some confusion about that, but I believe all the photos were 300-millimeter Nikons.

QUERY At first we thought you'd taken some Hasselblad, but I don't believe you did.

QUERY The second set of photos that we blew up we found on the filmstrip, but they didn't come out; they were underexposed. If I looked at the records correctly, they were approximately an f/4.5 and the others were approximately a f/8. They were also blurry so there might have been some movement, although the shutter speed was 1/500 of a second.

GARRIOTT If we had set the light meter right for the terrain it should have shown up overexposed. Right?

QUERY Hopefully, although the effect that we get by seeing the line rather than the spot means that we probably are aimed slightly off axis. What you're actually seeing is forward scatter of the beams that comes through the atmosphere. It is the same effect you would get if you looked down the end of a pencil and tilted it slightly off your line of sight. If you then projected that back into the plane you would essentially see a line. That's what you are seeing there.

QUERY We're aimed slightly off axis. You're not exactly centered in our beam at this time.

QUERY We see a little bit of the side of the beam as it comes through the atmosphere.

BEAN You're saying that there's enough scattering in the atmosphere that you can see the path of the beam.

QUERY Yes. This is what you see.

BEAN That is probably why we saw those bright points on the beam we reported, because it was somehow intercepting clouds that you couldn't see and things like that.

GARRIOTT Is that why you see a line?

QUERY Yes.

QUERY We suspected the forward scatter as the source of the line. When you reported multiple spots on the second sighting that was something we wanted to go into a little further.

GARRIOTT If scattering in the atmosphere is the correct explanation than you must be pointed about 45 degrees away, not just a couple of degrees away.

GARRIOTT Most of the scatter would probably occur within the first kilometer or two. It has to be pretty low altitude scattering for us to see it by eye.

QUERY We would not have predicted seeing scatter before you reported it.

GARRIOTT If you were mispointed what would be the maximum error, a few degrees?

QUERY No, probably less than 30 or 40 arc minutes.

GARRIOTT I see; 1 degree would be the upper limit.

QUERY Yes.

QUERY I would have suspected we were off about a degree, but possibly we were off more.

QUERY Concerning the relative ease of sighting and its use as a beacon, did you have any trouble picking it up? Did you locate the beacon by picking up landmarks, or was it just there when you looked out?

GARRIOTT We knew pretty well where Goddard was. The first time I could see it and these two fellows weren't looking. It looked like a bright dot. I guess these are the pictures because I could see it. Then I got the camera out and took some photographs.

QUERY It should appear as a very bright dot when you are within the beam. It's approximately a mile in diameter. If you're within that mile diameter, there should be a spot.

GARRIOTT That's the way it looked, and I'm a little puzzled by the photograph.

QUERY The only thing we could surmise is that by the time you got the camera around, it slipped off the track. We found out later, after the second sighting, that we had an encoder problem in the elevation axis. It could have been that as you were coming up in elevation the encoder wasn't coming up with the shaft.

GARRIOTT The second day, all three of us were looking and Al and Jack saw it, but I never could see it.

LOUSMA The time that I remember seeing it you were looking out. We were going by pretty fast and it was a little cloudy at the time. I really didn't know where to look but I saw something that looked different than the rest of the little puffy clouds. It had that shape. I think that's what drew my eye to it without my really knowing where to look.

QUERY Did it appear to scintillate like stars scintillate? Was it a fairly constant, nonscintillating source?

BEAN It didn't seem to scintillate, but it had beads along it, or bright points. It didn't appear as a nice line like that. It was straight, yet three or four places along it were bright.

QUERY Do you mean a single beam with bright spots along it rather than multiple beams?

BEAN That's right. It was as a necklace might appear.

QUERY Okay.

QUERY We plan on SL-4 to attempt to run some experiments with the VTS system using the beacons as a visual ground-tracking source. Do you see any problems in that?

BEAN It should be easy to do.

GARRIOTT That will be very bright, won't it?

QUERY The brightness increases as the square of the magnification. When you zoom into 22 it will be roughly 500 times brighter than what it is.

QUERY On T002, we hope to use it as a visual star on the ground or on the horizon. We also were going to provide other colors, probably very bright red.

QUERY One of the things we're planning to do on SL-4 is use the sextant to look at the laser and also to get a sight on a star. There is some doubt in our minds that this can be accomplished. They will have only a short period of time to find the laser. They will be going fast and will be needing some time to sight the star at the same time. Do you think that will be possible?

GARRIOTT Yes, I think it is possible. If he gets all set up, finds his star before he gets there and knows where the horizon is, he's ready to be looking for the laser beam. Then he should be able to do it.

QUERY Will you be able to do half of them in the daytime?

GARRIOTT   Yes, if you have the right geometry so he can see it from the window without having to be over the sill.

SKYLAB 1/4
EARTH RESOURCES
EXPERIMENTS DEBRIEFING

PREPARED BY
ORBITAL ASSEMBLY PROJECT OFFICE
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National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas

MARCH 5, 1974

QUERY Okay, if we're going to shift now to T053, the Goddard laser beacon experiment.

POGUE That was a neat experiment.

CARR Very interesting.

GIBSON Yes; it was.

CARR I'll never understand how you take a quarter of a watt of power and make it visible for 800 or a 1000 miles.

GIBSON What size was the laser?

QUERY Approximately an inch across.

GIBSON Do you know how large it was when it got out to 1000 miles?

QUERY It was approximately 2000 feet across at the spacecraft.

GIBSON It was that much?

POGUE When you moved the beam, we didn't lose it.

QUERY Yes; we could steer it back and forth, and at times we steered it off you. The SL-2 crew saw forward scatter of the beam. It looked like a typical searchlight coming up through the atmosphere. We photographed that effect on the last mission.

QUERY But for some reason we could not get that effect on your mission. The atmosphere is a weird thing to work with. It does things one day, and doesn't do them the next, so we just couldn't duplicate it. We had a fairly unique situation the day that they saw forward scatter.

POGUE How did you verify forward scatter and the fact that they kept it in sight while you were steering off?

QUERY We hadn't planned it; it was an accident. It did not appear as a point on the photograph that they took. Appears as a baseball bat with the large end towards you. At that period, evidently, we were pointed off the spacecraft 3 or 4 degrees; we haven't figured that out yet. Rather than

QUERY (CONT'D) seeing a very bright point, you saw almost a neon tube in the plane of the Earth, of course. They couldn't see much depth.

POGUE We never saw that!

QUERY We tried to simulate that. We tried to steer off you a known amount to, see if you could see that forward scatter. The moment we steered it off you 1 degree, you would see no forward scatter effect at all. These were at higher power levels than we had observed the effect on SL-2. So it's just a unique case of atmospheric conditions on the day that happened to occur, although it did occur twice on SL-2.

POGUE Did you know whether or not there were inversions?

QUERY We think that is possibly some of the cause, because the one day, when they saw the neon tube effect, it appeared as a very long line with brightening of the line two or three places along so that it was essentially passing through very thin cloud areas and brightening up at that point. We see that at night when we are working with thin clouds. As the beam passes through them, it immediately gets very bright in that location and then dims down as it goes on through.

CARR That must have been atmospheric effect. With us you were working in the winter when the air is considerably more stable with lower humidity.

GIBSON We never did it at night though, did we?

QUERY We never steered off a known amount at night. We were going to try that if we had gotten a second night. We did have one night pass. Why were you not able to see the beam on a couple of the pass?

CARR The first couple of weeks we were up there, we were learning how to spot things on the ground and how to recognize things; I think that's all that was. We probably weren't looking in the right place.

QUERY Orientation?

CARR You could see large bodies like large continents, but when it came to finding the Potomac River the first couple of times, you really had to work. You gained expertise after you had been up there for a while.

GIBSON It never really appeared to come right out of Goddard. Where I would put Goddard on the map and where I saw that coming from were not the same.

QUERY It was located approximately 4 miles from Goddard.

CARR He's talking about 40 or 50 miles.

POGUE When I finally saw it, I remembered significantly shifting my visual line of sight.

CARR On certain days where the lighting was right, Andrews jumped right out at you. You could see Andrews and run up the runway.

QUERY Yes; it was due north of Andrews. SL-2 used that as their guide.

CARR Andrew's wasn't available to us as a guide early in the mission because the lighting wasn't right to see it. The hook or knee in the Potomac River was what I used.

QUERY Did you have a different concept of its appearance from the way it actually appeared? Did you expect to see the searchlight effect or did it appear different?

GIBSON I thought I would be able to see the searchlight effect when it moved off, but I never did.

CARR I had no preconception at all; I didn't know what to expect. When it was a plain bright light, I accepted that. The brightness with respective background marginal, no; particularly with the green. The green jumps right out at you. If you're going to use a laser, you should start

CARR (CONT'D) with green for acquisition, and after acquisition, you shift to a white or a yellow for range.

QUERY You could follow it longer on the yellow, but acquire it better in the green?

CARR Right. That 1-watt light was 1600 miles.

GIBSON We never had them side by side for comparison. I agree that the yellow seemed to hang in there much longer than anything else. That may have been atmospheric conditions.

QUERY We had two passes where we left it on for quite a distance.

CARR We had 1600 miles once and then you hit us with a 1-watt beam and then dropped it back to 1/4, which we watched to approximately 800 miles. Another day we watched a green to 1200. That's why I conclude that you could see yellow or white farther than green. We saw the yellow/white 1600 miles and the green, 1200 mile. I could not confuse green with random flashes from the ground. Because we saw many random flashes, reflections of the Sun on object on the ground, green is the best color.

POGUE What we are telling you is accurate for the conditions of the flight. Remember at those long ranges we were getting significant radius scattering. That's why we could see the orange and yellow longer.

GIBSON These were also with binoculars.

POGUE One of them, I saw way out.

GIBSON Wasn't that a figure like 1600 or 1200?

CARR That was with binoculars. Bill lost it at 800 or nearly 1000.

POGUE It was well beyond 800, because I had to watch it. I couldn't look at a watch or anything because I had to keep my eye on it.

CARR Going for the SIA to report that you could see it might cause you to lose it.

QUERY What if you had the situation where you were coming over the horizon and you were going to acquire it on the horizon rather than pick it up and lose it on it? In other words, a higher approach?

GIBSON It could be significantly higher unless you knew exactly where to look. You could see it if you were pointed right at it with the binoculars.

QUERY Was it significantly bright on that one night pass?

POGUE Very bright. That was a 1/4 watt, if I remember.

QUERY Was the appearance of the beacon itself a very definite point source rather than an extended, blurred object?

CARR It wasn't a blur but I wouldn't call it a point source either. It had dimension; it wasn't a point.

GIBSON If you took a very small Christmas tree bulb and held it off at a couple of hundred yards and you were barely able to see it, to me, that's a point, and that's what I saw. I didn't see any width across it.

QUERY Did the beam seem ~~sinuate~~ scintillate?

GIBSON No it was steady.

POGUE We did get dropin and dropout but I think that was due to intervening cloud layers that we'd pass over.

QUERY Possibly.

QUERY The one time we used the flashing beacon, did that aid acquisition in any way? Do you think flashing over a steady state might be an aid?

CARR I think so.

GIBSON What's the flash frequency? I don't recall seeing that.

QUERY It'll run you about 2 pps or something like that, 50 percent duty cycle.

GIBSON What were you limited to in terms of total power? Could you have gone up to 10 watts?

QUERY Oh, yes; we could have gone to a 100.

GIBSON If we had gotten very far out I wish you would have done that.

QUERY On one of those passes where you did go quite a ways out, I tried to raise the power to about 3 watts to see if you could reacquire without binoculars, and I think there was a case of time in there. You probably looked away just as I hit the power.

POGUE We always had that middleman.

GIBSON We had an awful lot of middlemen in there, and for real-time work, that was not the way to go. We had quite a bit of power available; we just never used it. We were trying to pin down the minimal amount of power to determine the typical power level that you'd want to use for manual acquisition, in case you were going to put together

GIBSON (CONT'D) — an operation station. We had the capability for much more power.

POGUE — Why didn't you jazz it up at first until you acquire, and then drop it down?

QUERY — The first time you did acquire, I think we were running 10 watts at that time. You know the eyes are a very bad photometer in relative brightness between 10 watts and 3 watts or 10 watts and 1 watt.

CARR — They all look the same, as far as I can see, even the 1/4-watt one, as long as I could see, didn't look any dimmer than the 1 watt. You just lost it quicker.

QUERY — Did acquistion of the beam become easier once you became accustomed to its appearance?

CARR — Yes.

QUERY — Did you find you had to locate the beacon by finding geographical features?

POGUE — You had to be looking in the right area. But a couple of times when we were having trouble, I used the geographical features. I think that was one of those low-power passes, and I use that question-mark-shaped river. I specifically

POGUE (CONT'D) remember that I was having trouble that day and I did use it. But, mainly, if you just looked at the Potomac area and you could locate the beam.

GIBSON If you're in the general location, your eyes can just scan and you'll pick it up.

QUERY That's the sort of feeling we wanted to get.

CARR We're not being consistent saying that, because by looking in the general area and scanning at the beginning of the mission, we were not finding it. It wasn't until we had a geographical location that we could really find it.

POGUE That's how I picked up that one yellow one.

GIBSON If you can let your eyes just wander around inside a 5-degree area you have time to pick it up.

QUERY We had hoped to do some VTS on the beacon, but didn't get to it. In your experience with VTS, do you think something like that would be readily easy to track or acquire? It would have been a lot brighter, of course, with your VTS system.

CARR I don't think so. I don't think the VTS was any better than the binoculars, really. But I think it could be done.

QUERY With the zoom effect on your VTS, the beacon would have appeared brighter. When you're out to 22-1/2 power, it would appear 400 times brighter.

POGUE But I'm afraid that you would have acquired it using the low magnification. So I don't think that would have helped you actually acquire it, but there is magnification capability even in a low-power zoom. We were picking up other things so I don't know why we couldn't have picked that up.

QUERY Okay. Were the binoculars standard 750's or were they in some way unique?

CARR I think they were 10-power binoculars. They were typical of some of the equipment we had. Much better equipment is available to be used, but we took the "dime store" variety.

POGUE We should have all had our own pair of binoculars. I'm farsighted and Jerry's nearsighted, and every time each of us used the binoculars, we'd have to refocus them.

QUERY Would the beacon be useful if you were attempting to point an instrument in an area where there's no significant geographic features to identify?

POGUE I think that would be very useful.

CARR It seems to me that you'd really have to widen the beam and use lots of power.

QUERY Widening the beam will not help.

POGUE You mean they would have the ability to track you as you came over?

QUERY Yes, they would have the ability to track you. We had no trouble tracking; in fact, we saw you during the day.

GIBSON How far out could you follow us?

QUERY That depended on the Sun angle, the pass, and the time of day. We'd follow you, essentially, to the horizon.

CARR I'm reluctant to say that the laser beam would be handy for us to sight on the ground because we just said that it was very important to locate it by using the geographical cues. You're now asking if we could locate it without geographical cues. I think we've already shown that we probably could not unless we have something like a 4- or 5- degree field of view, which would give us something like a 95-percent probability of having the laser in the field of view.

GIBSON Or if the ground called up a horizon location for a given moment and the crewman had some angle relative to the flight path, he could locate the laser from an orbiting spacecraft. If the laser beam were high powered, flashing, and green, it might be visible.

CARR Based on our method, that is, looking out the window at the general area with a naked eyeball or a pair of binoculars, the answer is no.

POGUE If you had a beacon aimed at the spacecraft which was continually on so that it was visible at 50 degrees forward track and the spacecraft had some specified times to watch for it, I think that system could be used to an advantage. This would be true particularly in searching for something like the Rio Grande Reservoir in Colorado where the surface is white on white; the mountains are snow covered and the lakes are snow covered.

GIBSON I guess you have to be careful how you word that question. Assuming it's better than zero, it's a question of whether you then are going to narrow it down for us and tell us the general location, say, 5 or 10 degrees. Of course, the more defined that location, the higher the probability we'll see it.

POGUE	I could see tremendous potential for this system in the ground truth sighting, for instance, and where you are trying to pick up a specific area of vegetation. Beacons could be positioned, sighted, the ground notified of the sighting, and then the beam turned off to avoid polluting the tracking data.
CARR	Yes. If that sort of thing were available where you had optics to look through and gimbals to set and a time along the track to work, it should work well.
GIBSON	What would be the future applications?
QUERY	Our thinking was that the beacon would, when you were doing fairly high resolutions in spectrometry, similar to those you did with the S191, give you the capability to locate precisely a very unique area for the agricultural investigations in the Earth resources program.
POGUE	Yes, an example of that would be the insect infestation in Oregon that they wanted us to photograph? How portable is that equipment?
QUERY	It's very portable, unlike the piece of equipment we have been using.
POGUE	The tracking equipment, too?

QUERY Yes. We already have three mobile laser sytems in the field.

POGUE I was flying the airplane while Jerry was tracking some sites around Phoenix. I couldn't see how he was going to distinguish some of those fields.

QUERY The laser beacon would also be a very good source of calibrated energy at the target area. Some of the S191 people were interested in the possibility of calibrating the Earth's atmosphere with it. They've had to use the onboard spectrometer for determining atmospheric activity, but that involved a great deal of guesswork.

CARR Used with a VTS type of system with reasonably good optics and a good tracking system at both ends, it would seem to be very feasible.

QUERY The other application would be to build an auto track to beacon on the ground. You can lockup on the horizon, for instance, and just let the instrument track it independent of the spacecraft's movement.

POGUE The windows in the sensors are such that the beacon could be located between two sensors in a spectrum wit no problems as far as data gathering is concerned.

QUERY The various colors that we put up were put up with a dial laser, which was continuously tunable over a huge range. In the case where we were going to operate with ERTS, were planning to put a very narrow spectral line midway between two of the channels in the multispectral scanner. This would also provide a method of spatial calibration, to see if the detectors were lying in the right plane. Some of the applications we were attempting to at least evaluate on this mission were equipment calibrations.

CARR You could certainly improve your data with something like that. Being able to calibrate on a target would be terrific.

POGUE And if you had a pure laser signal, you could sample that at the spacecraft for atmospheric continuation. You could calibrate your atmosphere at the same time and take that out of the data that you were getting from the true sites.

QUERY We were going to attempt to evaluate that application. When you see green in the beacon itself, we're actually putting out about seven different spectral lines at that time.

GIBSON Is that right?

QUERY Yes. Well, I shouldn't say that. In one case we were emitting a single green line at 5145 But the laser has the capability of putting out a blue-green line which is made up of seven different spectral lines.

GIBSON Did you actually use polychromatics?

QUERY I think toward the end, the last couple of times, we had scheduled a polychromatic pass but, we did not have time to get it in. We would like to have done that with the spectrometer. It would have been a nice way to get some calibration data on the spectrometer's operation, because you could have measured the spectral band width. It's a very good calibration on the spectrometer because the lines are very narrow, 1/100 of an angstrom. We monitor the power in each line, we know the energy density of the spacecraft quite accurately, and we know the divergence. We measure the energy distribution in the beam in the ground.

QUERY I think that completes our agenda for today unless somebody has an item that we overlooked. Tomorrow morning we're scheduled to start the CSM systems; then tomorrow afternoon we'll start plowing through the workshop systems.

CARR Were you able to make any adjustments on this APCS?