Project Report

ETS-63

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Ground-Based Electro-Optical Detection of Artificial Satellites in Daylight from Reflected Sunlight

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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GROUND-BASED ELECTRO-OPTICAL DETECTION OF ARTIFICIAL SATELLITES IN DAYLIGHT FROM REFLECTED SUNLIGHT

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Group 94

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ABSTRACT

The GEODSS system is currently designed to detect satellites electro-optically at night from reflected sunlight. Low altitude satellites are excluded from detection for most of the night because of the earth's shadow. If the GEODSS system could detect low altitude satellites in the daytime, it could then complement the mission of existing tracking radars which are generally located in different parts of the world. To perform this mission, an E-O sensor capable of handling the high background signals caused by bright daytime sky is required.

As a result of the study and experiments presented here, it was demonstrated that the ETS 31-inch f/5 telescope, when used with a readily-available silicon vidicon TV camera and a video processing system, can easily acquire and track low altitude satellites in full daylight with a limiting magnitude of $8^{m}.3$. In demonstrating this on 22 October 1981, a total of 20 satellite tracks on 18 different satellites was achieved in the daytime, and accurate precision positional data on 13 of the tracks were sent to the NORAD Space Defence Center. This demonstrated proof-of-concept for daylight GEODSS operations.

In connection with experiments in daylight space surveillance, an atmospheric phenomenon has been encountered which consists primarily of bright point images, apparently from windblown objects, moving through the field of view in clear daytime sky. The frequency of occurrence varied from one every few minutes to about 200 in the field at one time. They were not detected after sunset.

To investigate these objects or "angels" further, a parallax apparatus was constructed with two parallel TV cameras, which indicated that the altitude of the detected "angels" varied from a few hundred feet to 7000 feet. These "angels" are thought to be primarily seed transport vehicles and insects in the warmer months, and ice crystals in winter. Possibly the seed vehicles could also be present in winter.

These "angels" present no problem for satellite detection if an element set for a sought-after satellite is even approximately known. The "angels" simply would not track at the predicted angular velocities. They do present a problem if the orbital element set of a detected satellite is not known. In the latter case, a parallax technique, such as the one demonstrated here, would have to be employed to discriminate the nearer "angels" from satellites.

CONTENTS

I. INTRODUCTION

The GEODSS Experimental Test System (ETS), located on the White Sands Missile Range and operated by M.I.T. Lincoln Laboratory, has routinely detected artificial satellites electro-optically at night from reflected sunlight since the Fall of 1975. Satellites as faint as $18^{m}.5$ have been detected in clear, dark night skies. Most of the satellites detected have been at synchronous or near-synchronous ranges and are infrequently eclipsed by the Earth's shadow. The low-altitude satellites, which are eclipsed by the Earth's shadow for most of the night when they are in site coverage, have been detected only near dawn and dusk when they are out of the shadow.

Clearly, a useful additional mission for the GEODSS system would be the acquisition of low-altitude satellites in the daytime. The GEODSS system would then be able to complement the mission of existing tracking radars, which are generally located in other parts of the world. To perform this mission, an electro-optical sensor capable of handling the large background signals caused by the bright daylight sky is required.

Several questions come to mind immediately: 1. How bright are the low altitude satellites of interest in the daytime? 2. What detection sensitivity can an electro-optical sensor achieve in the daytime as a function of sky brightness, field-of-view (FOV), integration time, detector type, and signal processing technique? 3. How useful is this detection sensitivity in satisfying the daytime mission? 4. Can the existing ETS and GEODSS cameras provide the required detection sensitivity? 5. At what angular rates will the ETS or GEODSS telescope mounts have to be driven routinely for extensive tracking of low altitude satellites; and, can they do it?

In the Fall, 1980, Group 94 began a project called Daylight Satellite Acquisition and Tracking (DAYSAT) to answer these questions, and to demonstrate, if possible, GEODSS operations for satellites in daylight.

As a result of the study and experiments presented here, it was demonstrated that a readily available silicon vidicon TV camera system used on the ETS 31-inch f/5 telescope can easily acquire and track low-altitude satellites with a limiting magnitude of $8^{m}.3$. In demonstrating this on October 22, 1981, a total of 20 satellite tracks on 18 different satellites was achieved in full daylight, and precision positional data on 13 of the tracks were sent to the NORAD Space Defense Center. This demonstration proved the feasibility of conducting GEODSS operations in daylight.

II. SATELLITE CHARACTERISTICS

1. Orbital Characteristics.

The GEODSS system was designed primarily to track deep space satellites, i.e., by definition, those satellites whose mean motions are less than seven revolutions per day. These satellites include the synchronous and near-synchronous satellites, which are infrequently eclipsed by the Earth's shadow. In the current satellite catalog[1] maintained by the NORAD Space Defense Center, about 90% of the 4848 satellites listed have mean motions greater than seven, and most of these satellites are seldom visible during normal GEODSS operations. It is of interest, then, to make a survey of this class of satellites to find out what topocentric angular rates and ranges will be encountered when trying to detect them in the daytime.

The distribution of mean motions (revolutions per day) of the 4312 satellites with mean motions of at least seven is presented in Table 1. The average mean motion of the population is 13.4 rev/day. Topocentric observers are interested in the apparent angular speeds and ranges which will be encountered. Calculation of these quantities from a sample of the low altitude satellite population yielded the following results for satellite passes at elevations greater than 30°:

1. Most apparent angular speeds are less than 0.5 deg/sec, but some extend to about 1.5 deg/sec.
2. The average range is about 1200 km, with some as far away as 9000 km.

These results provide an adequate appraisal of the near-Earth satellite detection problem for our current purpose.

TABLE 1

MEAN MOTION DISTRIBUTION OF LOW-ALTITUDE SATELLITES

Mean Motion (Rev/Day)	No. of Satellites
7-8	16
8-9	111
9-10	27
10-11	40
11-12	102
12-13	1047
13-14	1476
14-15	1205
15-16.5	288

The GEODSS mounts are specified to track satellites at rates up to four degrees per second. The only problem occurs near the pole, where the R.A. drive on an equatorial mount (such as the GEODSS and ETS mounts) may not be able to keep up with a fast satellite passing through the polar region. Depending on the satellite angular rate, a blind spot of a few degrees in diameter may have to be tolerated near the pole. In the case of an az-el mount, the singularity occurs near the zenith. The only effect is that the telescope would lose track for a few seconds while the satellite passed through the region of the singularity. The significance of this problem for daylight tracking of satellites will have to be investigated, and some data can come from the experiments reported here. If it turns out that the loss of track of a satellite for a few seconds is not acceptable, a mount configuration would have to be used which either had no singularity, or placed it out of the useable sky.

The ETS telescope mounts were not originally intended to track satellites faster than 200 arc sec/sec. However, modification of the servo loop parameters has enabled satellites moving as fast as 1.5 degrees per second to remain in track for short time periods and, while some mount vibration occurs, it does not preclude position measurement.

2. Solar Illumination-Expected Brightness.

To our knowledge, significant visible and near IR daytime brightness data on low altitude satellites have not been reported. Low altitude satellites have been detected frequently by the ETS during one or two hour time periods just after sunset or just before dawn when they are not eclipsed by the Earth's shadow. In the experience of one of the authors (E.W.R.), the brightnesses varied from about three to ten stellar magnitudes.

An estimate of the expected brightnesses can be made from the brightnesses of deep space satellites which have been routinely detected by the ETS. Assuming that synchronous and near-synchronous satellites observed by the ETS at night are similar in physical size and reflectivity to the low altitude satellites, brightness data taken from the ETS can be scaled to a typical near-Earth satellite range. For example, a satellite observed at 40,000 km would be $7^{m}.8$ brighter when observed at a range of 1000 km.

The brightnesses of synchronous and near-synchronous satellites has in general been found to vary with the sun-observer-satellite angle, or sun angle. For example, the sun angles of these satellites are smallest during the times of the solstices, and such satellites have been observed to be faintest at these times.[2] Satellite ephemerides indicated that sun angles for low altitude satellites during any time of the year in the daytime would vary from 0° (at the sun) to about 160°. At 160° the satellite and sun would both be low in the sky and approximately opposite to each other. But for most of the daytime, the sun angles would be substantially less than 160°. In these cases, only a fraction of the satellite will be illuminated that is facing the observer. Hence, brightness data taken on synchronous and near-synchronous satellites during the solistice periods when the sun angles are typically less than 160° may yield the most realistic predictions. The brightnesses of synchronous and near-synchronous satellites during solstice periods have been measured at the ETS (by E.W.R.) to be typically in the $13^{m}.0$-$16^{m}.0$ range, with some exceeding $18^{m}.0$. Then, low altitude satellites at a 1000 km range may be in the $5^{m}.2$-$8^{m}.2$ range, with some exceeding $10^{m}.2$. It appears that a detection sensitivity better than $8^{m}.0$ in the daytime is desired.

III. BRIGHTNESS OF THE DAYTIME SKY

The night sky brightness encountered in satellite detection at the ETS has varied from 16^m-22^m per square arc sec.[3] The brighter limit was encountered only a few degrees from a full moon when the sky was hazy. The brightness of clear blue sky has been reported to vary from 0.2 to 0.6 stilb.[4] A 0^m star per square degree outside the atmosphere produces a surface brightness of 0.84×10^{-6} stilb.[4] Then the day sky should vary from $4^m.3$ to $3^m.2$ per square arc sec.

A photographic exposure meter was used to monitor the brightness of the daytime sky, both at Lincoln Laboratory and at the ETS in New Mexico. The photographic units were converted to photometric units,[5] and then to visual magnitudes per square arc sec.[4] The results of several measurements indicated values ranging from $3^m.8$ to $5^m.4$ per square arc sec in the daytime, but not near the sun. Thus, a "bright" day sky of brightness $3^m.8$ per square arc second is 13.2 magnitudes (a factor of 1.9×10^5) brighter than a bright night sky of $17^m.0$ per square arc second.

IV. SELECTION OF A SENSOR FOR DAYLIGHT DETECTION

1. The Current ETS and GEODSS Ebsicon Cameras.

If the ETS and GEODSS low light level sensors could be operated in daylight with adequate detection sensitivity, it would simplify the implementation of a daylight sensor for daytime GEODSS missions. These sensors employ ebsicons or I-ebsicons which use pre-scan gain to overcome readout and preamplifier noise.[6] An inherent problem in these cameras for daylight operation is that they can't be operated at a pre-scan gain below about a factor of 80[6] without producing a poorly focused image. This means that an ebsicon will saturate at a light intensity 80 times lower than it would if it could operate at unity gain. It also means that, for example, if the light intensity was 80 times higher than that allowed by the ebsicon saturation limit, the light intensity would have to be reduced by the same factor. By Poisson statistics in the photon-photoelectron conversion process in the first photocathode, the detection sensitivity would be brighter by $\sqrt{80}$ times, or $2^{m}.4$, than it would be if the ebsicon could operate at unity gain.

It was pointed out in Section II that a bright daytime sky is about 2×10^5 times brighter than a bright night sky, in which ebsicons on GEODSS and ETS telescopes operate in a near saturated condition. It is apparent that more than a factor of 80 in light attenuation will be required, and that an ebsicon with a minimum gain of 80 is already $2^{m}.4$ less sensitive than it would be at unity gain because of the lower saturation limit. A camera tube with unity pre-scan gain and a target with high charge-storage capacity, such as a silicon vidicon, should be considered instead.

In addition, two properties of the S-20 photocathode employed in the GEODSS and ETS ebsicons are not favorable to daylight operation. It has a quantum efficiency[7] centered in the blue region of the spectrum where clear daytime sky is brightest, and it may be damaged by daylight light levels. Consequently, the low light level GEODSS and ETS ebsicons will not be considered further for daylight operation.

2. Silicon Vidicon Cameras.

A TV-like camera for daylight operation should have the following characteristics:

1. High charge storage capacity
2. Reasonable signal current capacity
3. Not easily damaged by excessive light
4. Moderate resolution
5. Low lag
6. A broad spectral response which extends into the IR.

With the exception of number 3, all of these characteristics are desirable for nighttime imagers.

One photoconductive detector which possesses these properties is silicon. It is used as the photoconductor in silicon vidicon television cameras, and optical CCD imagers. Until CCD imagers are more fully developed, perhaps a silicon vidicon TV camera could be used for a daylight mission. Unlike the ebsicon, the silicon vidicon has a pre-scan gain of one.

Upon examining the availability of silicon vidicon cameras, it was found that only camera tubes with 16 mm diagonal targets were available. This camera would have a 0.23° diagonal FOV on the ETS telescope, which is small, but perhaps suitable to demonstrate satellite tracking.

a. Estimated Performance

A calculation can be made to predict what daytime detection sensitivity a silicon vidicon camera would have on the ETS 31-inch telescope and on a small 150 mm focal length test lens of the same f-number as the telescope. The prediction for the small lens can be tested by detecting a star of known brightness with it in the daytime, and measuring the resulting signal-to-noise ratio (SNR). This measurement can be scaled to test the 31-inch telescope prediction: the telescope should have a better detection sensitivity by a factor equal to the ratio of the area of its clear aperture to that of the lens. Polaris is a convenient star to use because it moves only about 1.5 degrees during the day, and it is bright enough ($2^{m}.04$)[8] to be found readily. Its B-V color index is $0^{m}.59$[8], which is slightly bluer than the sun at B-V = 0.62[4].

First the relative photon fluxes as function of λ from the sky and sunlight will be examined. The latter is assumed to be comparable to light reflected from satellites. Figure 1 illustrates this graphically.[9] Figure 2 shows the graphs in Fig. 1 with silicon[10] and S-20[7] quantum efficiencies plotted on them. The silicon response was taken from the published specifications of the RCA "Ultricon"[10] silicon vidicon camera tube. Its specifications indicated a broad spectral response and a high quantum efficiency. The advantage of the broad spectral response of silicon is evident.

The stellar magnitude of a satellite or star that this camera could detect with a SNR = 6 in the daytime with a $5^{m}.0$ per (arc sec)^2 sky brightness for both the ETS telescope and test lens may be predicted as follows:

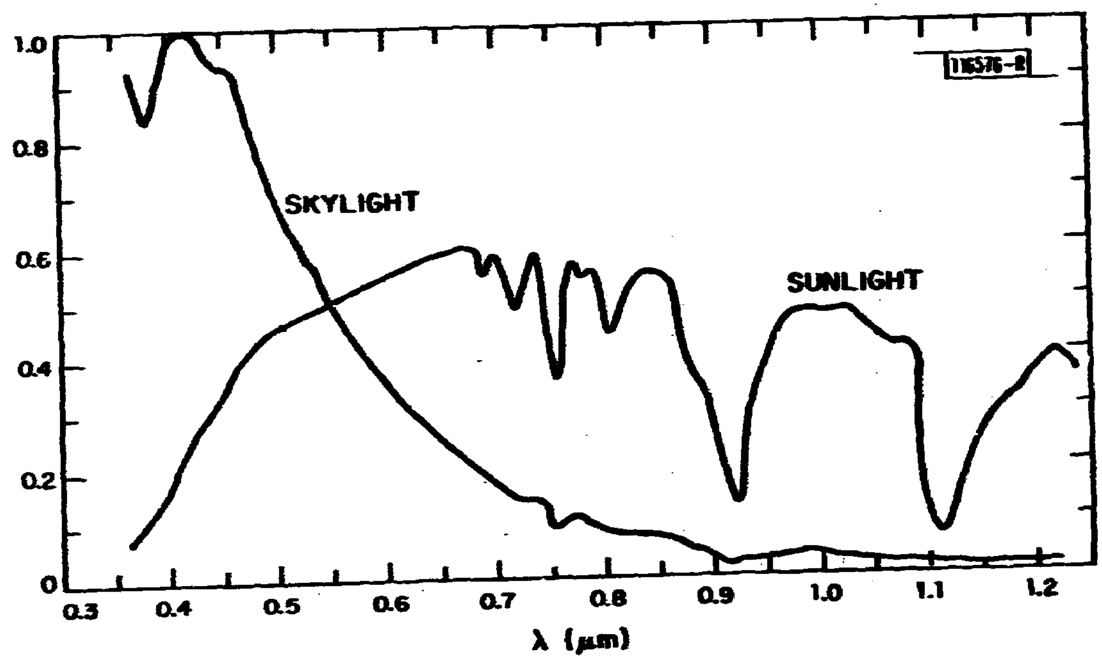

Fig. 1. Relative photon flux from sky background and sunlight through two air masses[9].

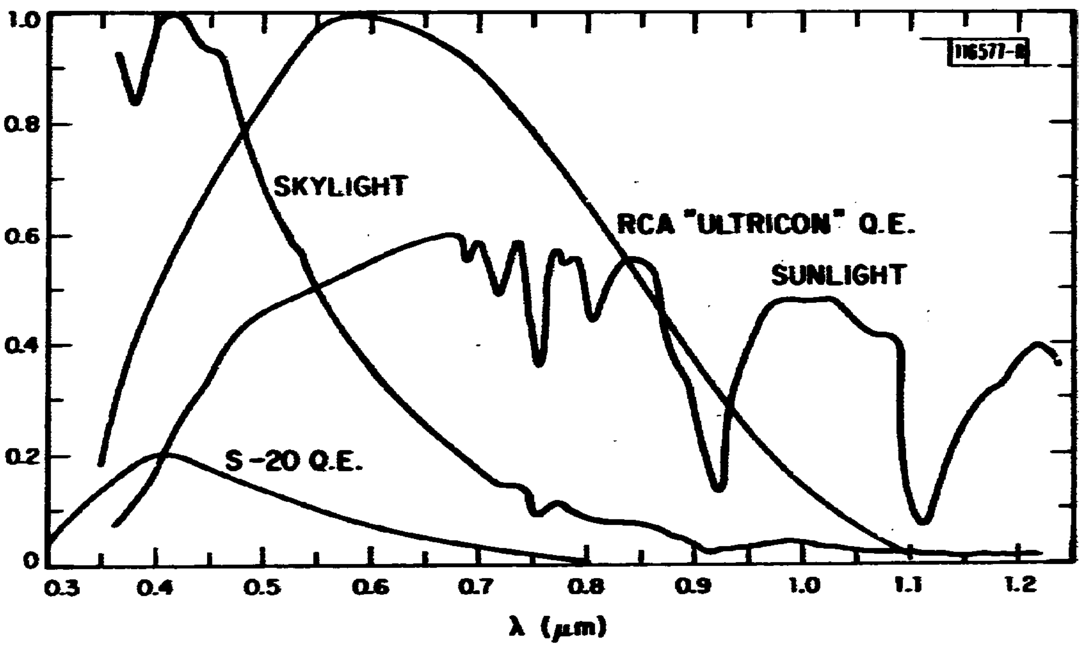

Fig. 2. The graphs of Fig. 1 with S-20 and RCA "Ultricon" quantum efficiencies inserted.

From Poisson statistics,

Let $S = 6\sqrt{B + N^2}$, where

S = Signal Photoelectrons per integration period, all of which are assumed to fall in one pixel.

B = Sky background photoelectrons per pixel per integration period.

N = Camera self noise equivalent "photoelectrons" per pixel per integration period.

As pointed out earlier, unlike the ebsicon, the silicon vidicon has only a unity gain prior to scan; each photon absorbed produces at most one electron-hole pair.

Expressions for S and B are given as follows:

$S = \psi_S a q_S t$, and

$B = \psi_B \alpha^2 a q_B t$, where

ψ_S = signal photon flux in photons/m^2(sec)

a = clear aperture of telescope in m^2

q_S = average quantum efficiency of detector to sunlight

q_B = average quantum efficiency of detector to skylight

t = integration time in seconds

ψ_B = sky background photon flux in photons/m^2 sec.(arc sec)^2

α^2 = pixel angular area in (arc sec)^2

Then, ψ_S which produces a SNR = 6 as a function of the above quantities may be written as:

$$\psi_S = \frac{6\sqrt{\psi_B \alpha^2 a q_B t + N^2}}{a q_S t}$$

For now, the sky background noise is assumed to be much larger than self noise. Then

$$\psi_S \cong 6\sqrt{\frac{\psi_B q_B \alpha^2}{a q_S^2 t}}$$

ψ_B: It has been computed[11] that a 0^m solar type star, outside the atmosphere, will produce a flux density of 5×10^{10} photons/m^2. sec. over the bandwidth 300 to 920 nm. For a sky background of $5^m_.0$ per (arc sec)^2, $\psi_B = 5 \times 10^8$ photons/m^2. sec. (arc sec)^2.

q_S and q_B: The average quantum efficiencies of the RCA "Ultricon" camera tube[10] to sunlight and skylight were approximately computed as follows: Figure 2 shows graphs of the "Ultricon" quantum efficiency and relative photon flux from sunlight through two air masses and skylight as functions of λ. For the region 350 nm $\leq \lambda \leq$ 1050 nm, we construct 15 equally spaced intervals 50 nm wide, starting at λ = 350 nm. Then from Fig. 2,

$$q_S = \frac{\sum_{i=1}^{15} \begin{pmatrix}\text{"Ultricon"} \\ \text{quantum efficiency}\end{pmatrix}_{\lambda_i} \begin{pmatrix}\text{relative photon flux} \\ \text{for sunlight}\end{pmatrix}_{\lambda_i}}{\sum_{i=1}^{15} \begin{pmatrix}\text{relative photon flux} \\ \text{for sunlight}\end{pmatrix}_{\lambda_i}} = 0.64$$

Repeating the calculation for q_B with "sunlight" replaced with "skylight" yielded the same value: $q_B = 0.64$. Inspection of Fig. 2 indicates that the results for q_S and q_B are reasonable.

t: 1/30 sec for the standard TV frame time

a, α^2: The clear aperture and pixel area, respectively, are presented in Table 2 for the ETS 31-inch telescope and the 150 mm (focal length) test lens.

Before a calculation of detection sensitivity can be made, saturation limits for the TV camera must be determined. There are two possible limiting factors to the number of photoelectrons the camera can process: the finite charge storage capacity of the target and the read beam current limit. (The dynamic range of the video amplifier chain is assumed to be adequate.) Table 3 presents the relevant data for the camera tube, and the results of the saturation limit calculations for target capacity and beam current. Table 3 indicates that the camera tube is beam current limited, and that an attenuation of $\frac{1.6 \times 10^{11}}{6.2 \times 10^{11}} = 0.26$ would be required in the optical path. For this calculation of detection sensitivity, a neutral density filter will be used for the required attenuation. Since a red filter should improve detection sensitivity, the calculation should be pessimistic.

Calculations were made for both 2.5 and 5.0 arc sec seeing disks, which affect the detection sensitivity for the 31-inch system, but not for the 150 mm test lens. The pixel size with this lens is limited by the camera to be no smaller than 35 arc sec in diameter at low backgrounds, and larger at high backgrounds. The results of the calculations are as follows: The RCA "Ultricon" silicon vidicon camera when mounted on the ETS 31-inch

TABLE 2

OPTICAL SYSTEM DATA

Lens	150 mm f/3 Kinoptic	31-Inch f/5 ETS Telescope
Focal Length (mm)	150	3934
Horizontal FOV (deg) with SiV Camera Tube	4.9	0.18
f	8	5
Optical Efficiency	0.90	0.58
Clear Aperture (M^2)	2.5×10^{-4}	0.20
Pixel Area (arc sec)^2 for 2.5 arc sec diameter seeing disk:	4.9×10^3	6.3
Pixel Area (arc sec)^2 for 5.0 arc sec diameter seeing disk:	4.9×10^3	27

TABLE 3

SILICON DIODE ARRAY TV CAMERA PROPERTIES

Camera Model:	RCA Model E1056/A
Tube Type:	RCA 4532 A/U, specially selected for few blemishes
Maximum Target Current:	750 mA [10]
Target Voltage:	8 V [10]
Target Capacity:	4500 Pf/cm^2 [12]
Target Dimension:	16 mm, diagonal [10]
FWHM* of Point Image, High Pedestal:	0.2 μ sec.
Computed Maximum Number of Charges due to Target Capacity:	2.8×10^{11}
Computed Maximum Number of Charges due to Beam Current Limit of 750 mA:	1.6×10^{11}
Computed Number of Charges due to $5^{m}.0$ per (arc sec)^2 Sky Brightness for ETS Telescope:	6.2×10^{11}

* Full Width at Half Maximum Amplitude, Measured on Optical Bench.

telescope should have a detection sensitivity of $9^{m}.2$ or $8^{m}.5$, for the atmospheric seeing disks of 2.5 and 5.0 arc sec, respectively. When the camera is used with the 150 mm test lens, the detection sensitivity is predicted to be $2^{m}.0$. The 150 mm lens, when set to f/8, should result in about the same sky background photoelectron count per pixel as the ETS 31-inch f/5 telescope, when attenuation due to the central blockage and measured transmission loss is accounted for.

So far, any self noise in the camera has been assumed to be much less than the background noise. Neglecting possible self noise degradation and contrast improvement expected with red filters, the detection sensitivity of the silicon vidicon camera when used on the ETS 31-inch telescope is predicted to be better than $8^{m}.0$ in the daytime. The detection sensitivity of the camera when used with the 150 mm lens should be $\sim 2^{m}.0$ in the daytime.

At this point, it appeared to be worthwhile to set up an experiment to detect Polaris ($2^{m}.04$) in the daytime with the 150 mm test lens. Any constrast improvement provided by the use of red or near IR filters could be measured at the same time.

V. MEASURED LIMITING MAGNITUDE IN DAYLIGHT USING CALIBRATED STARS

1. Video Signal Processing Considerations.

In November, 1980, a Cohu 2820b silicon vidicon camera with an RCA 4532A camera tube was borrowed for testing. This tube is an earlier version of the RCA 4532A/U, with slightly less quantum efficiency.

Initial operation of the test camera soon indicated that shading and fixed pattern noise had to be reduced for operation in daylight. This was not surprising, since it has been reported that the silicon vidicon does possess substantial fixed pattern noise.[13] Also, shading, or the curved video pedestal produced by variations in sensitivity over the format, would be most pronouced at the high signal levels produced from operation in daylight.

The signal processing technique illustrated in Fig. 3 reduced both of these effects substantially: The video signal was taken directly from the video pre-amp in the camera and passed through a high pass filter to reduce signal variations slow in time with respect to signals from point images. A reference frame of blank sky, taken at the prevailing sky brightness, was stored in a digital image processor, which was either a Quantex Model DS-20 or DS-30. This reference frame was then subtracted from the processed live video, which was already corrected for shading, to produce a video display with substantially less fixed pattern noise and shading effect. The video signal processing circuitry built into the camera for normal TV use, such as AGC, was not used.

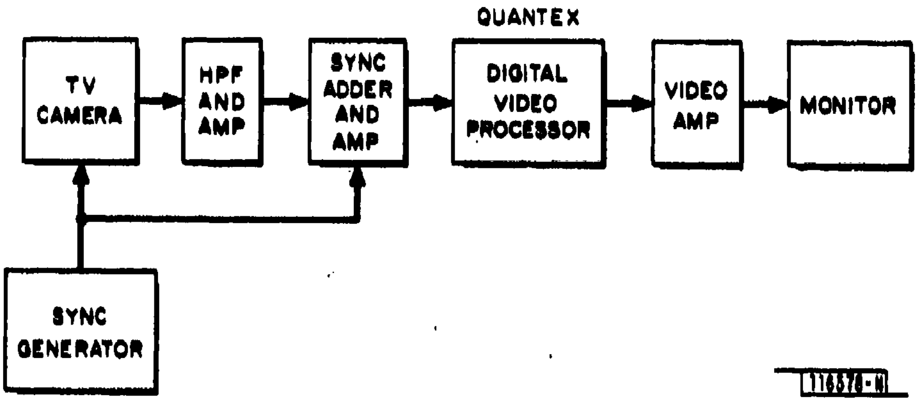

Fig. 3. The video signal processing system for daylight operations.

2. Daylight Detection of Polaris from Lincoln Laboratory

On December 31, 1980, the star Polaris was detected in full daylight with a Cohu 2820B camera and a 150 mm test lens pointing through the North window of Room L-024 of Lincoln Laboratory. With the signal processing technique just described now implemented, the resulting SNR was about 6. The result was obtained with a near-IR Kodak Wratten No. 87 filter[14] in the light path with the aperture set to f/3.5. The filter blocks light of wavelength shorter than 770 nm.

At this point, an RCA E-1065A Silicon Vidicon Camera with the 4532A/U "Ultricon" camera tube was acquired. On January 28, 1981, the new camera was used to detect Polaris in daylight with the same lens, filter, and signal processing technique. The SNR produced by Polaris was, again, about 6, but with the aperture now set to f/8 (versus the earlier f/3.5).

It was primarily this measurement which led to the prediction that the silicon vidicon TV camera, when used on the ETS 31-inch telescope, possessed a useable detection sensitivity for daylight satellite tracking. Scaling the result from the test lens aperture to that of the ETS 31-inch telescope, each with the Kodak 87 filter in place, results in satisfactory detection sensitivity predictions of $9^{m}.7$ for a 2.5 arc sec seeing disk, and $8^{m}.9$ for a 5.0 arc sec seeing disk with a field of view of 0.23° (diagonal).

At the aperture of f/8 and with the Kodak Wratten No. 87 filter in the light path, the camera was operating just below the saturation when the best SNR was produced from the image of Polaris. The only requirement for the camera operator to perform when the sky brightness changed was to store a new reference frame of blank sky in the signal processing apparatus for background subtraction.

The detections of Polaris resulting in a SNR $\cong$ 6 with the test lens were on very clear days. Frequently, the SNR produced from the image of Polaris was on the order of three on days which were slightly hazy. Such slight haze was practically invisible to the unaided eye.

A number of experiments were conducted to investigate contrast enhancement with red and near IR filters on several occasions. These are discussed in Appendix I.

3. The ETS Results

During the period of 6-12 February 1981, the silicon vidicon camera system was taken to the GEODSS Field Site in New Mexico to be tested on the ETS 31-inch telescope. Figure 4 is a photograph of the silicon vidicon camera on the ETS telescope. The detection sensitivity was measured to be $8^{m}.3$ by detection of faint stars in a daylight sky brightness of $5^{m}.2$ per square arc sec. The Kodak Wratten 87 filter was used, and the video pedestal voltages were similar to those measured when the test lens was used instead.

Table 4 shows the results of all calculations, extrapolations, and measurements of detection sensitivity for comparison. The daylight atmospheric seeing disks were typically 5.0 arc sec and larger. Occasionally, in calm early mornings and near dusk, the seeing disk was 2-3 arc sec, but these were for relatively short times.

Table 5 is a record of the star[15] detections made on the 31-inch telescope on this trip, and on a second trip in October, 1981, as indicated.

The detection sensitivity results displayed in Tables 4 and 5 are corrected for no intervening atmospheric extinction, which was assumed to be $0^{m}.25$ per air mass, a typical value measured at night.[3]

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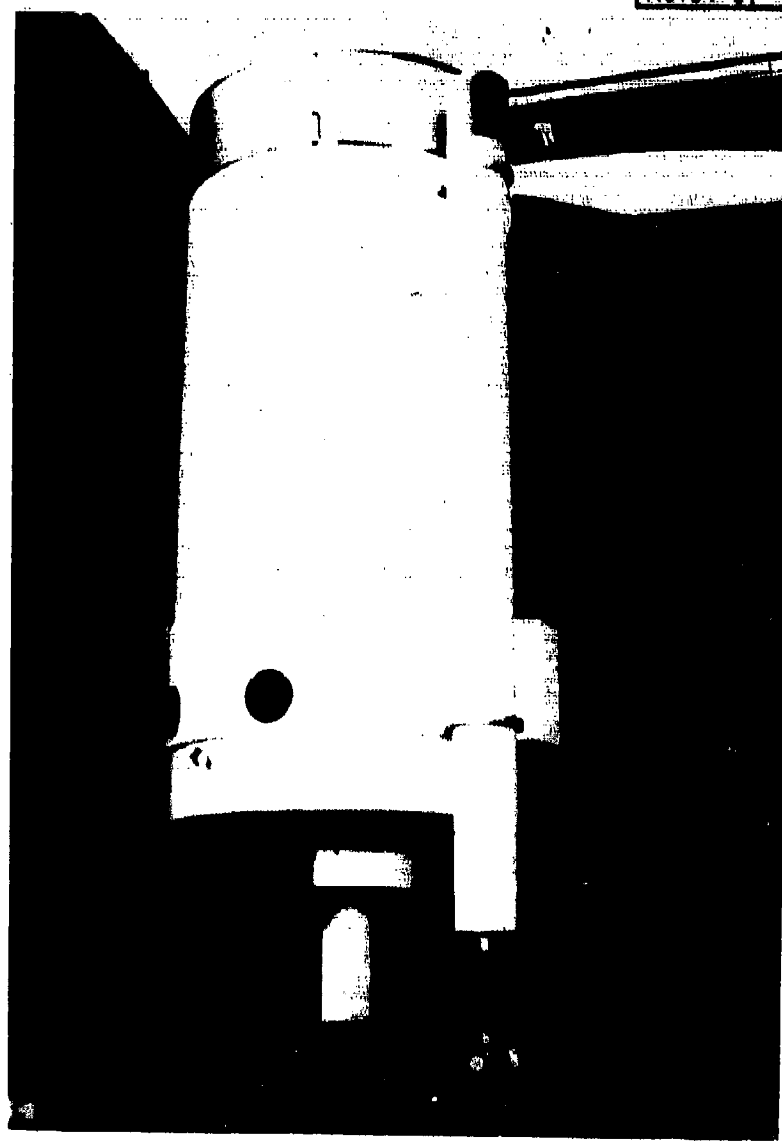


Fig. 4. The ETS 31-inch f/5 telescope with the RCA "Ultricon" silicon vidicon television camera.

TABLE 4

PREDICTED AND MEASURED DETECTION SENSITIVITY FOR SNR = 6

Detection Sensitivity for SNR = 6 at a Sky Brightness of $5^{m}.0/(\text{arc sec})^2$:

Seeing Disk Diameter (arc sec)	2.5	5.0
Computed for 150 mm Lens* with no Spectral Filter:	$2^{m}.0$	$2^{m}.0$
Measured from Detection of Polaris with 150 mm Lens* and Kodak Wratten No. 87 Filter:	$2^{m}.4$	$2^{m}.4$
Computed for ETS Telescope: (no Spectral Filter)	$9^{m}.2$	$8^{m}.5$
Predicted for ETS Telescope from SNR Measurements with 150 mm Lens:	$9^{m}.7$	$8^{m}.9$
Measured for ETS 31-Inch Telescope and Kodak Wratten No. 87 Filter:	—	$8^{m}.3$

*A seeing disk smaller than 35 arc sec will not affect the 150 mm lens result.

TABLE 5

FAINT STAR DETECTIONS IN DAYLIGHT MADE WITH THE SILICON VIDICON TV CAMERA SYSTEM AND ETS 31-INCH f/5 TELESCOPE ON THE DATES INDICATED

DATE	STAR[15]	V	B-V	el (deg)	SKY BRIGHTNESS $M_v/(\text{arc sec})^2$	SNR	DET SENS SNR=6
1	15058	7.51	0.77	63.1	5.2	9	8.3
1	15179	8.90	0.69	51.8	5.2	low	
1	19506	8.60	0.63	62.4	5.2	low	
1	15675	8.31	0.77	57.6	5.2	∿ 4	
2	15058	7.51	0.77	54.0	4.2	9	8.3
3	8572	6.38	0.66	87.1	5.3	22	8.1
3	7668	7.69	0.81	57.1	5.3	9	8.4

DATES: 1. 12 February 1981
2. 20 October 1981
3. 22 October 1981

FOV (deg): 0.18 x 0.14
Seeing Disk: 5 arc sec
Filter: Kodak Wratten #87

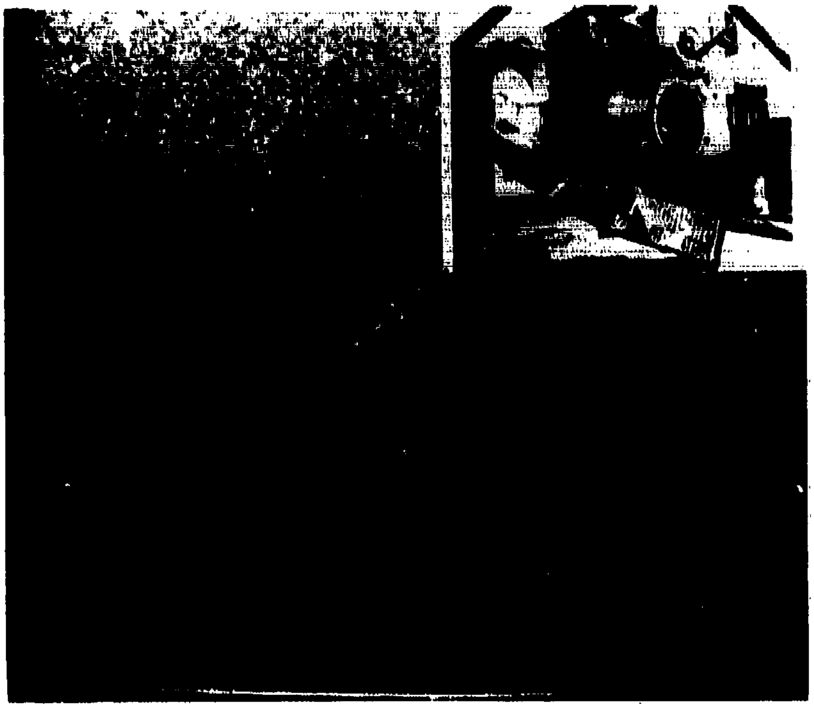
VI. THE DAYLIGHT ACQUISITION OF SATELLITES

On the first of our trips to test the daylight camera on the ETS telescope, which was during the period 6-12 February 1981, two satellites were detected in daylight; the Explorer 38 payload (3307), and the Soviet Meteor 1-30 satellite (11848). Explorer 38 was tracked on four different occasions, and varied in brightness from $5^{m}.5$ to $7^{m}.0$, at ranges from 6000 - 9000 km. One successful track extended to within 21° from the Sun. Figure 5 shows the satellite in track. The Meteor satellite was detected just before setting, and its brightness was about $6^{m}.0$ at 2800 km. The satellites were detected in along-orbit scans, in which each trial field of view was held at the predicted satellite angular rate for the duration of the stare time, which was just two or three seconds. Both satellites were found less than a degree from their predicted positions. Bad weather forced us to stop experiments at this time.

A few problems occurred with the ETS for the daylight tracking experiment:

1. The accuracy requirement on the satellite ephemeris predictions are more stringent for DAYSAT than for deep space tracking operations. This is due to the small sensor FOV (0.23° diagonal) and also due to the relatively high speeds of the low altitude satellites.

The computer program SGP[16] routinely used at ETS for propagating satellite positions along orbit was found not to be accurate enough to be used for DAYSAT. Prediction offsets of more than 5° were observed when the low altitude element sets were more than a few days old. It was apparent that a more rigorous orbit propagation program had to be adopted.



RADIO ASTRONOMY-EXPLORER SATELLITE (S.D.C. No. 3307, Explorer-38) IN TRACK AT 2:40 pm ON 12 FEBRUARY 1981

ASTRONOMICAL MAGNITUDE: 6
RANGE: 7100 km

INSET PHOTO: EXPLORER-PRIOR TO LAUNCH ON 4 JULY 1968

Fig. 5. Radio Astronomy-Explorer satellite.

2. A special along orbit scan would be useful for low-altitude satellites which would allow the operator to scan, in addition to along the orbit, at ± a fixed angular distance from the velocity vector and parallel to the orbit. Since our FOV was only 0.23° (diagonal), the scan should be as efficient as possible.

3. A mathematical model to correct for mount droop characteristics to just four minutes of arc or less would be extremely useful. The operators had to re-calibrate the ETS telescope for every different region of the sky, and sometimes the mount would drift out of calibration during a satellite track, making it difficult to hold it in the FOV by manual corrections.

4. The Single Star Calibration Program (SSC) should have a daylight version which would select only stars brighter than $8\overset{m}{.}0$. This would enable calibrated positional data to be taken on satellites in the daytime for GEODSS operations then.

5. Mount vibration was a problem at the angular rates of typically 1.3°/sec and greater. Perhaps the servo loop could be modified or the telescope drive adjusted, to track more smoothly at the higher rates.

By mid-October, 1981, suggestions 2, 3, and 4 had been accomplished. To avoid the problem discussed in the first item, arrangements were made to obtain the most recent element sets on the satellites. During the period, 19-23 October, the daylight camera system was again taken to the ETS with the goal of taking calibrated positional data on as many satellites in daylight as possible to demonstrate the proof-of-concept of daylight GEODSS operations.

This was done. On Thursday, 22 October, from 9 a.m. - 5 p.m., 18 satellites were tracked (a total of 20 tracks), and calibrated positional data were taken on 13 of the tracks. Previously, on Tuesday, 20 October, after installation of our apparatus, similar data were taken on two satellites. Subsequently, the SDC told us[17] that all of our positional data were good, and that it correlated satisfactorily with previous data on the satellites in their file from other sensors. Indeed, SDC personnel were surprised to find the ETS active in daylight.

For this experiment, new element sets were requested from the SDC for 81 selected satellites. They were randomly selected from the SDC satellite catalog with mean motions in the 6.4 to 16 range, radar cross sections in the 0.06 to 185 m^2 range, and with inclinations at least 8° greater than the site latitude. It was felt that electro-optical detection of some of the satellites in daylight would be a good demonstration for projected daylight GEODSS operations.

Prior to the start of the experiment, ephemerides were generated on all the 81 satellites which indicated which of the satellites would be in site coverage during the experiment, when they would be, and positional information on them at 30 second intervals when in site coverage.

Table 6 is the satellite track record for the experiment. Brightness measurements were taken on almost all of them and the range of brightness recorded was close to the prediction in Section II based on the synchronous satellites. It is interesting to note that the brightnesses of all the satellites were either nearly constant or varied slowly over a period of minutes. This is in contrast to many deep space satellites with spin periods of a few seconds, which appear with flashing images.

TABLE 6

DAYSAT RECORD FOR TUESDAY, 20 OCTOBER (DAY 293), AND THURSDAY, 22 OCTOBER (DAY 295).

GMT Day	GMT H:M	Satellite SDC No.	SSC Positional Data Points to SDC*	SSC Stars Attempted	Comments
293	21:40	3257	0	0	Setting at low elevation.
293	23:44	3616	1	1	Time for 1 SSC.
293	23:56	3257	14	16	1/2 hour track, bright.
295	15:19	10515	0	0	Inadequate time for SSC.
295	15:23	10514	2	2	
295	15:28	9044	1	3	Lost track near pole.
295	16:32	12409	0	0	Lost track near pole, faint.
295	17:08	10973	0	0	Bright, set too quickly for SSC.
295	17:57	6993	0	0	Bad mount vibration.
295	18:17	12409	1	3	Lost track near pole.
295	18:26	10513	1	2	Mount vibration.
295	20:48	3257	3	11	Mount model inserted; inadvertently out since ~ 19.00
295	21:06	10011	1	5	
295	21:25	7714	0	0	Too fast.
295	21:32	11084	3	4	Faint.
295	21:43	12298	0	1	
295	21:47	3307	3	5	
295	22:04	7769	0	1	
295	22:13	12333	3	3	
295	22:27	11112	1	1	
295	22:45	12071	2	5	
295	22:54	11136	2	8	
295	23:09	10011	2	4	

* All data points were successfully correlated by SDC.

The brightness measurements were made from a VHS format cassette tape recording of the satellites and calibration stars. The observation times and elevations for each object were also recorded. The results are displayed graphically in Fig. 6. This figure includes all brightness measurements and estimates taken in the daytime from this experiment, the trip last February, and a brightness estimate of Salyut 6 (10382) when detected with a small lens at Lincoln Laboratory. The detection of Salyut 6 is described in the next section.

Table 7 shows a complete record of satellites tracked, approximate dimensions,[18] average radar cross section,[1] ranges, sun angles, and brightness measurements, or estimates. The standard deviation in each brightness measurement was estimated to be about $0\overset{m}{.}2$.

Most of the satellites were acquired near the predicted position, as expected, either in the nominal FOV, or within ± 2 seconds time from the predicted position along the orbit. Most searches were begun with a ± 5 second along-orbit scan, which was usually more than satisfactory. The new along-orbit scan worked well with just a two-second stare time; a satellite was detected moving into the FOV and sitting still in track for the stare time. The step size in the scan had to be very small (0.05°) because frequently the scan was diagonal to the rectangular FOV. A circular FOV would be useful for searches of this nature, or, if this would not be available, it would be useful to orient the TV camera in the direction of the search in progress. The latter task would require a motor drive and position indicator on the rotator ring of the ETS telescope, which would have to be designed. If this were implemented, the position indicator would have to be no better than a few degrees in accuracy.

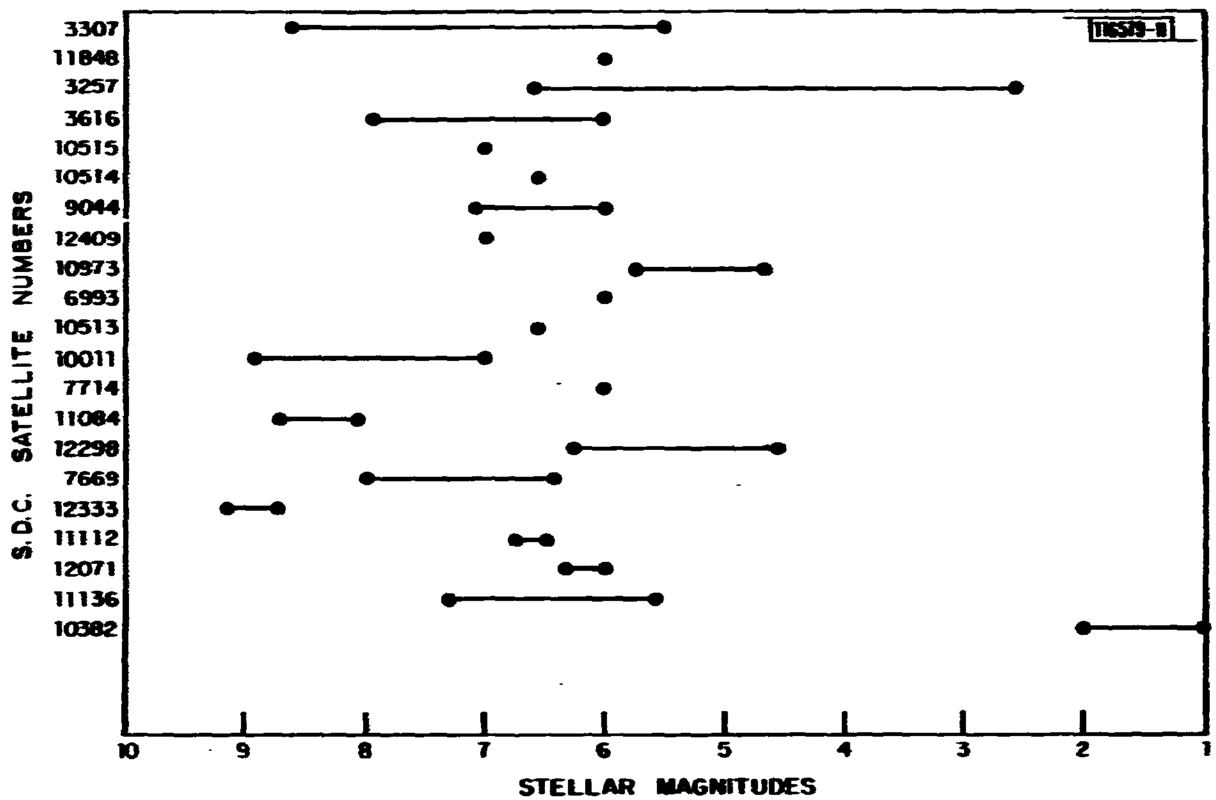


Fig. 6. Graphical indication of satellite brightness measured in the daytime.

TABLE 7

DAYLIGHT DETECTION AND TRACK RECORD OF SATELLITES

SATELLITE (SDC NO.)	NAME	APPROX. DIMENSIONS[18] (M)	RADAR CROSS SECTION (M^2)	NUMBER OF TRACKS IN DAYLIGHT	RANGE (KM)	SUN ANGLE (DEG)	BRIGHTNESS (MAGNITUDES)	POSITIONAL DATA TO SDC
3307	EXPLORER 38	1.5 X 1	37.09	5	6000-9000	21-113	5.5 - 8.7	X
11848	METEOR 1-30	-	19.0	1	2860	58	~6	
3257	PAGEOS FRAGMENT	-	181.0	2	8400-9300	106-126	3.7 - 6.7	X
3616	ESSA 8 RB	5.7 X 0.8	64.5	1	2700-3300	119-142	6.0 - 7.9	X
10515	METEOR 2-03 RB	3.8 X 2.6	61.1	1	1680-2020	100-139	7	
10514	METEOR 2-03	5 X 1.5	29.9	1	2000-2200	109-140	6.6	X
9044	COS 842 RB	7.4 X 2.4	42.5	1	1000-2300	62-111	6.0 - 7.1	X
12409	COS 1266	-	8.5	2	1400-2300	30-78	7.0	X
10973	COS 1025	-	22.0	1	1600-1625	107-116	4.6 - 6.0	
6993	COS 617 RB	6 X 2	39.2	1	1600-3200	45-114	~6	
10513	COS 967 RB	7.4 X 2.4	20.8	1	1350-2500	51-117	6.6+	X
10011	COS 816 RB	7.5 X 2.6	16.5	2	2020-4300	29-132	7.0 - 8.8	X
7714	METEOR 21	5 X 1.5	40.7	1	920-2200	46-124	~6	
11084	COS 1045	-	11.0	1	3100-3500	100-134	8.2 - 8.9	X
12298	COS 1244 RB	-	13.7	1	1760-2300	86-133	4.7 - 6.3	
7769	COS 729 RB	7.4 X 2.4	44.7	1	1020-2500	33-116	6.4 - 7.9	
12333	COS 839	4 X 2	0.81	1	1000-2500	61-89	6.4 - 9.2	X
11112	COS 1048 RB	7.4 X 2.4	10.3	1	900-1800	21-114	6.5 - 6.7	X
12071	COS 1222	-	18.4	1	770-1600	30-103	6.0 - 6.3	X
11136	COS 1051 RB	7.4 X 2.4	22.0	1	2100-3200	111-121	5.7 - 7.3	X
10382	SALYUT 6	14 X 4.2	185.8	3	570-740	73-108	1 - 2	

The pointing model[19] constructed for the ETS B-telescope worked very well for our purpose; the pointing error was almost always less than two minutes of arc over the regions of sky that we operated. With the mount model in use, the new Bright Star Single Star Calibration (SSC BRI) program worked well and quickly, provided the calibration star could be seen. As indicated from Table 6, a number of SSC boresights were made without a star appearing. Usually repeated attempts at different locations of the track would result in one appearing, however. Possibly some of the SSC stars not seen were near the preset faint limit of $8^{m}.0$ and blue in color, which may have made them considerably fainter for the near-IR filtered silicon target camera tube. Perhaps it would be useful to set the brightness limit to $7^{m}.5$, and require stars between $7^{m}.0$ and $7^{m}.5$ to have B-V values > 0.6. Also, the new model may make a less dense and brighter selection of stars useable for the SSC accuracy requirement. This would make night operations easier as well.

This experiment required highly dynamic scheduling. Some of the satellite passes were only a few minutes in duration, and sometimes several were up at once. The satellite tracks had to be planned in real time because it was not known exactly how long the system would have to remain on any given track to complete the SSC positional data. Avoiding the sun in track and between tracks was done by manually driving the telescope around the R.A. and Dec of the sun if it was determined that the computer was going to drive the telescope near it. It is clear that a new automated dynamic scheduler will be essential for tracking near-earth satellites. Hopefully this can be obtained by modification of the existing dynamic scheduler in use at the ETS for deep space operations. The provision to automatically steer the telescope to avoid the sun must be incorporated in the ETS software.

The most severe and persistent problem was telescope vibration in track. A number of satellites were detected on the video monitor as a bar image two or three arc minutes long in displacement. A faint satellite would not have been detected because of this smearing. Reversing torque motors usually made some improvement, but sometimes, especially during high rate tracks, the telescope could not be prevented from vibrating. In spite of this problem, the telescope drive was certainly useable for the experiment.

VII. ATMOSPHERIC PHENOMENA EFFECTS ON DAYLIGHT DETECTION

1. Atmospheric "Angels"

During experiments conducted at Lincoln Laboratory beginning in November 1980 in which the star Polaris was detected in daylight, bright and faint point images, which appeared to be wind blown, were frequently visible in the field. They were visible only in daylight. The frequency of occurrence was as low as one every few minutes up to about 200 in the field at a time. Some of the objects appeared to be in focus just a few hundred feet away.

2. The Use of Parallax as a Tool

To investigate these objects or "angels" further, a parallax apparatus was constructed with two cameras and lenses to determine the altitude distribution of them. The baseline was 35 inches, which was limited by the width of the window in Room L-024 of Lincoln Laboratory. Figure 7 is a block diagram of the apparatus. The apparatus is set up such that any object closer than about 14,000 feet will appear as two images on the monitor, and the range of any object closer than this distance can be measured from the separation between the images. The two lenses used were 500 mm f/5.6 Celestron "C-90" telephoto lenses which resulted in 1.8° diagonal FOV for each sensor. Figure 8 is a photograph of the parallax apparatus.

The parallax apparatus indicated that the altitude of the "angels" varied from about 100 feet to more than 7000 feet, with most "angels" detected within these bounds. In addition, on both trips to the ETS, the angels were seen with the 31-inch telescope at slant ranges farther than 6km, as indicated by the diameter of the out-of-focus "donut" images produced.

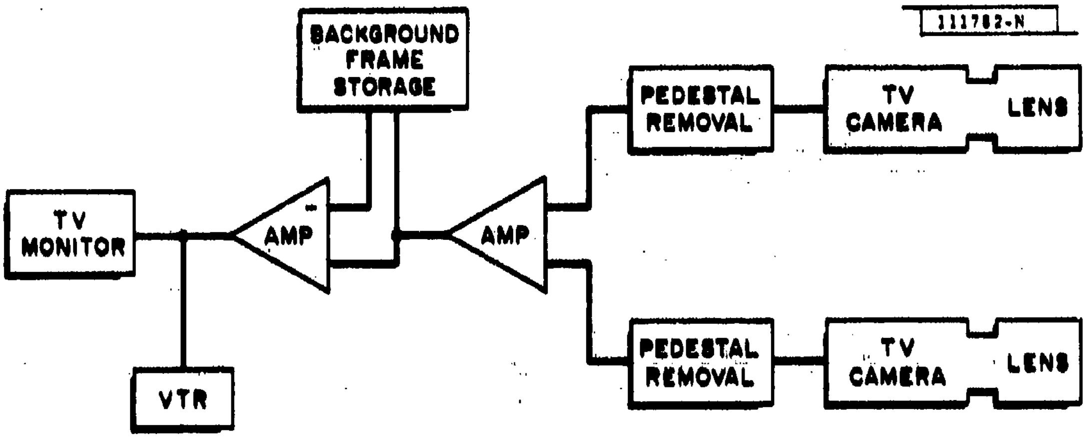


Fig. 7. Parallax TV system for discriminating near and far objects, and for measuring distance of near objects.

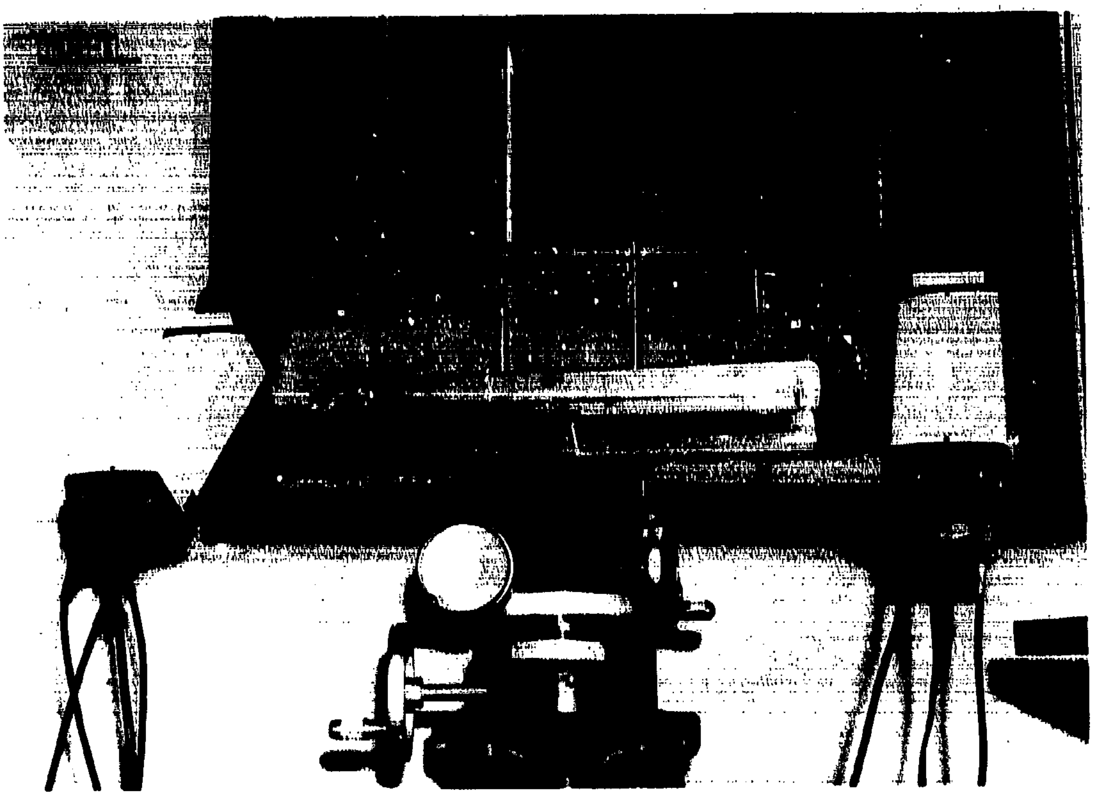


Fig. 8. The parallax apparatus aligned on the North Star from the window in Room L-024 of Lincoln Laboratory.

In the spring, summer and fall of 1981, sometimes two or three hundred "angels" would be in the FOV at a time which was surprising. Figure 9 is a photograph of "angels" from the parallax apparatus when the density was high. Each "angel" is shown by two side-by-side images. Data taken so far indicates that the density of "angels" is in the same range at both Lincoln Laboratory and the ETS.

The "angels" are thought to be primarily ice crystals in winter, and insects and seed transport vehicles in the warmer months. There are too many "angels" observed to be accounted for as airplanes or birds. In addition, the "angels" are frequently too bright to be dust particles. Sometimes they are observed to be several times brighter than Polaris. They were also visible to the eye through 5-inch or 8-inch Celestron telescopes as occasional silvery-white sparkling points.

Properties of the "angels" are summarized in Table 8.

The "angels" present no problem for satellite detection in GEODSS Type I Surveillance, in which the orbits of sought after satellites are known. The satellite detection experiments conducted and reported up to here are examples of GEODSS Type I Surveillance; it involves searches for satellites with known element sets. The "angels" simply do not track at the predicted rates for the satellites.

The "angels" would affect any search for satellites in which the orbits are unknown, i.e., the GEODSS Type II Surveillance mission, and a parallax technique, such as that described here, would have to be employed to discriminate the nearer atmospheric "angels" from satellites.

Fig. 9. TV monitor display of "angels" detected on 20 May 1981 with the parallax apparatus. Most "angels" are seen as a pair of images.

TABLE 8

PROPERTIES OF "ANGELS"

APPEARANCE:	MOSTLY POINT IMAGES, BUT SOME ARE THIN FILAMENTS ∿ 25-100" LONG.
BRIGHTNESS:	∿ $+4^m$ to -3^m
RANGE:	∿ 25M TO BEYOND 6KM
MOTION:	∿ 0-10 DEG/SEC; MOST ARE APPARENTLY WINDBLOWN.
DENSITY:	UP TO 1 IN 10^4 FT^3
PLACED OBSERVED:	LINCOLN LAB AREA; HARVARD CENTER FOR ASTROPHYSICS; LINCOLN ETS AND HEL FIELD SITES, NM
SKY CONDITIONS:	DAYTIME SKY, EITHER CLEAR OR WITH VERY THIN CLOUDS.
DATE OF DISCOVERY:	NOVEMBER 1980
TIME OBSERVED:	ALMOST CONTINUOUSLY IN VARYING DENSITIES.
DETECTORS:	1. SILICON VIDICON AND CCD TV CAMERAS WITH LENSES OF AT LEAST 150 MM FOCAL LENGTH. 2. HUMAN EYE AND TELESCOPE OF AT LEAST 3.5" APERTURE.

<u>POSSIBLE CANDIDATES</u>

1. ICE CRYSTALS
2. INSECTS
3. SEED TRANSPORT VEHICLES
4. DUST
5. LEAF FRAGMENTS
6. BIRDS
7. AIRPLANES
8. SATELLITES

It is interesting to note that the "angels" were used advantageously in the satellite tracking experiments. If "angels" appeared wobbly as they streaked across the FOV, then a satellite image would also be wobbly, and the telescope was vibrating. Smooth, gliding "angels" provided the indication that the telescope was tracking smoothly during a search. To some extent, star images could be used for the same purpose, but they were far more infrequent. The angels almost always appeared as distinct "donuts", i.e. point objects in the field too close to be in focus. A few were distinguishable as point images, indicating a range greater than ∿ 6 km.

A version of the Lincoln Laboratory computer program ANODE[20] was successfully implemented to update element sets of low altitude satellites. In conjunction with a test of this program, the parallax apparatus (Fig. 6 and 7) was set to an azimuth and elevation near Polaris where and when the satellite Salyut 6 (10382) was predicted to pass. The star served as a calibrated position reference. Salyut 6 was thought to be bright enough to be detected by the parallax apparatus, which had a detection sensitivity of about $4^{m}.0$. This experiment would also demonstrate the discrimination between a satellite and "angels" by parallax, as would have to be done in GEODSS Type II Surveillance in daylight.

This experiment was done successfully on August 18, 20, and 21, 1981. Salyut 6 appeared as a single image at the right times and directions as verified by the current element set predictions. The Millstone Radar verified that the satellite was within 0.2 sec of the element set prediction on the 18 August detection.[21]

The brightness of Salyut 6 varied from about 1 to 2 stellar magnitudes during the three detections in daylight. The last detection was a significant accomplishment for the parallax technique because the satellite was easily discriminated against about 100 angels detected in the same FOV.

VIII. CONCLUSIONS

A proof-of-concept that daylight operations are feasible for GEODSS has been demonstrated. This was done by acquiring 20 satellite tracks during one day in full daylight, and transmitting correct positional data on 13 of the tracks to the NORAD Space Defense Center. Even though our electro-optical system achieved a nominal detection sensitivity of $8^{m}.3$, satellites as faint as $9^{m}.2$ were able to be tracked. This demonstration was an example of GEODSS Type I Surveillance, in which a specific orbital element set is used to search for a particular satellite. This type of surveillance constitutes most GEODSS missions.

The measured detection sensitivity, while not declared to be the best theoretically attainable for daylight, was adequate for these experiments. The results indicate that detection sensitivity was limited either by beam current or preamplifier dynamic range, and not target storage capacity.

Presently, a special 32 mm diameter target silicon vidicon camera, with high beam current capability and with a special preamplifier of wide dyanmic range, is being developed by Lincoln Laboratory and Westinghouse for daylight use.[22] It will quadruple the area of the field of view, and it should have comparable or better detection sensitivity than the present device. It should be a significant addition to both Type I and Type II daylight surveillance projects in progress at Lincoln Laboratory.

APPENDIX I

Contrast Improvement with Red and Near-IR Spectral Filters

It was clear that the use of the near-IR Kodak Wratten #87 filter[14] improved the contrast between Polaris and the blue daytime sky. For example, with the above filter in the light path of the 150 mm test lens on a silicon vidicon camera, the best SNR produced by the image of Polaris was about 6. The lens aperture was set so the camera was operating just below saturation, which was usually f/8 for the new RCA "Ultricon" camera. When the filter was removed, the lens aperture had to be set to f/22 to avoid saturation, and the star could not be detected. The focus of the lens was adjusted for the proper optical and near-IR focus positions.

To determine contrast improvement from the spectral filter, a test lens was needed which would enable the TV camera to detect Polaris with a measurable SNR in daylight without the filter. For this purpose, a 400 mm f/4 Pentax telephoto lens was obtained; its longer focal length enabled Polaris to be detected at f/22 in daylight with no filter. The contrast improvement in SNR with the filter varied from 1.5x to 2.5x, on several occasions, apparently depending on atmospheric clarity.

Additional experiments were conducted and more are in progress with other red and near-IR filters. In addition to the Kodak #87 filter, we obtained Kodak filters[14] #23a, 25, 29, 89b, 87c, 87b, and 87a. The conclusion so far is that the best detection sensitivity occurs when the reddest filter in the group is selected which allows the TV camera to operate at near saturation for the largest lens aperture available. It appears more important to keep the camera operating near saturation with a less red filter than to reduce the background, even slightly, with a redder filter when the lens aperture is fixed. However, experiments indicate that contrast improvement from spectral filtration varies considerably with atmospheric clarity.

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atmospheric optical clutter

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An electro-optical sensor consisting of the ETS 31-inch f/5 telescope, a readily-available silicon vidicon TV camera, and a video signal processing system was used to acquire and track low altitude satellites in daylight from reflected sunlight. The limiting magnitude was $8^{m}_{.}3$. In demonstrating this, a total of 20 satellite tracks on 18 different satellites was achieved in full daylight during one day, and accurate precision positional data on 13 of the tracks were sent to the NORAD Space Defense Center. This demonstrated proof-of-concept might provide an enhanced GEODSS daylight operation.

In connection with experiments in daylight space surveillance, an atmospheric phenomenon was encountered which consists primarily of point images, apparently windblown, moving through the field-of-view. The leading candidates are seed vehicles, insects, and ice crystals. A parallax technique has been demonstrated to separate these objects, dubbed "angels," from artificial satellites.

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