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Project Report

ETS-3

A. S. Friedman

Determination of Specular Reflection
from Cylindrical Satellites
for Electro-optical Surveillance and SOI

8 October 1976

Prepared for the Department of the Air Force
under Electronic Systems Division Contract F19628-76-C-0002 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS



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The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, with the support of the Department of the Air Force under Contract F19628-76-C-0002.

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FOR THE COMMANDER



Raymond L. Loiselle, Lt. Col., USAF
Chief, ESD Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

DETERMINATION OF SPECULAR REFLECTION
FROM CYLINDRICAL SATELLITES
FOR ELECTRO-OPTICAL SURVEILLANCE AND SOI

A. S. FRIEDMAN

Group 94

PROJECT REPORT ETS-3

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ABSTRACT

Although electro-optical satellite surveillance depends primarily upon diffuse solar reflection, an understanding of specular reflection can lead to enhanced detection and identification capability.

An analysis of the timing and duration of observable specular reflections has been completed for the widely applicable case of the cylindrical satellite. A solution is presented for geosynchronous satellites which includes orbital elements and attitude as parameters. This solution, in turn, is broadened to encompass misalignment of spin axis and symmetry axis.

A realization of the above computation in readily accessible, command-structured format has been developed as a planning aid for the GEODSS Experimental Test System. Samples of its output are provided, which record the occurrence of observable specular reflections in a convenient, easily understood calendrical tabulation.

Predicting the timing and duration of observable specular reflections is of considerable interest in the conduct of electro-optical satellite surveillance. Since a satellite may appear many magnitudes brighter when seen by specularly reflected sunlight than when seen only by diffusely reflected sunlight, this interest is quite understandable. Before providing an explanation of this phenomenon, let us turn to an example.

Figure 1 depicts a strip chart segment containing the optical signature (or light curve) of satellite 83525, as observed on 6 May 1976. The horizontal coordinate represents time, here amounting to a span of 90 s, and the vertical coordinate is proportional to satellite brightness. One function of a GEODSS site is the collection of strip charts such as this for further SOI analysis. An examination of the full strip chart reveals that the satellite is performing some sort of periodic gyration, as evidenced by the light curve's period of 40 s.

In order to assign consistent numerical values to brightness measurements, calibration readings of selected stars of known color and brightness must also be taken. [Figure 3]. This procedure provides values for night sky brightness and atmospheric extinction as well.

Figure 2 shows the light curve of the same satellite, this observation made on 25 March 1976. Comparison with Figure 1 reveals an increase in peak brightness of two magnitudes, which can be attributed to specular reflections. In this example the observations are separated by 42 days, but such an effect could arise in the space of 42 hours or 42 minutes.

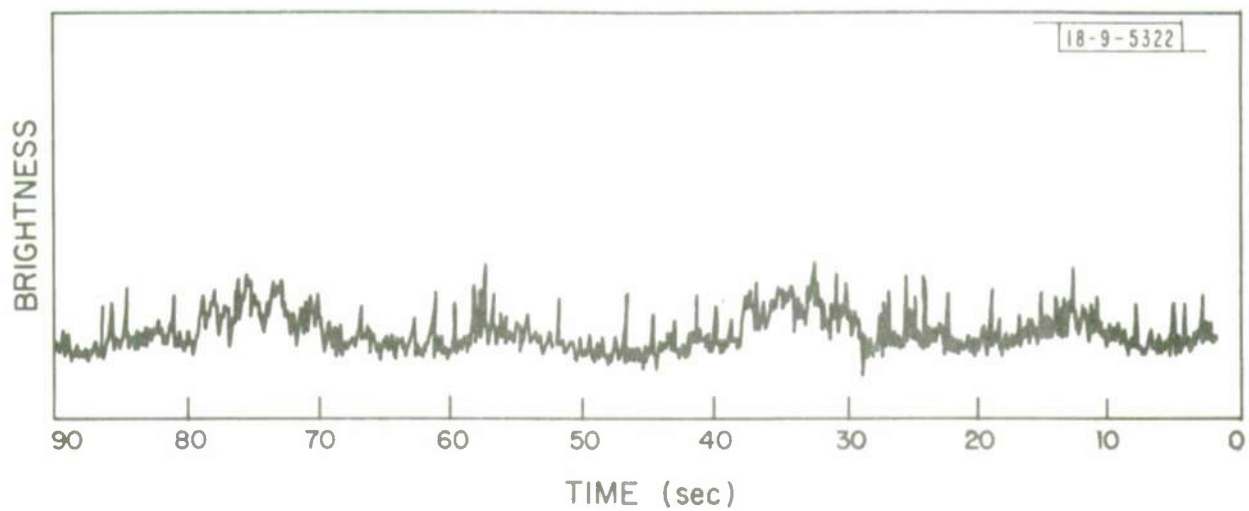


Fig. 1. Light curve of satellite, 83525 6 May 1976

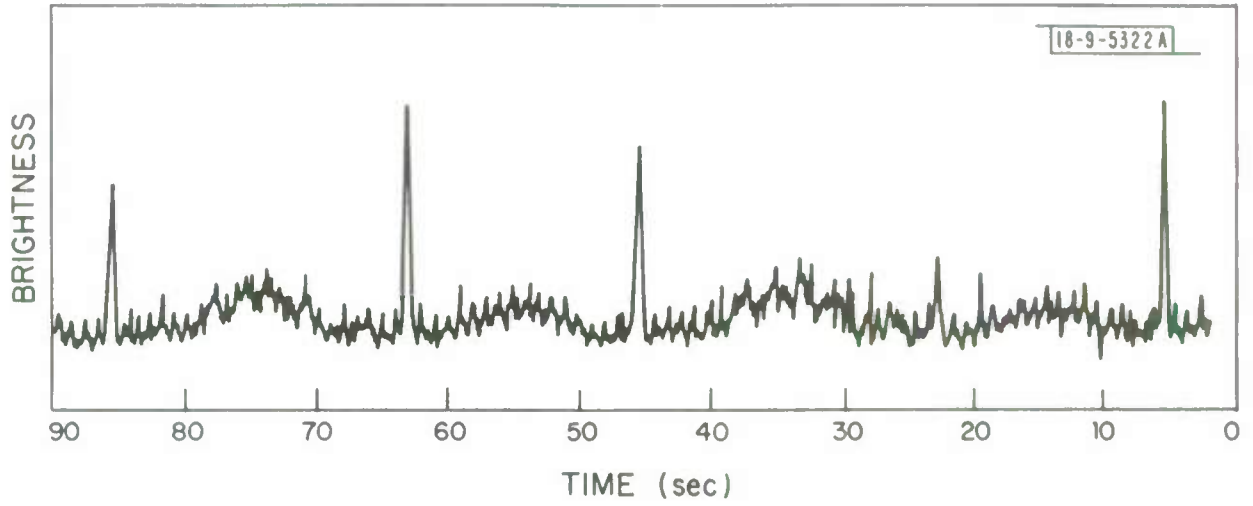


Fig. 2. Light curve of satellite, 83525 25 March 1976

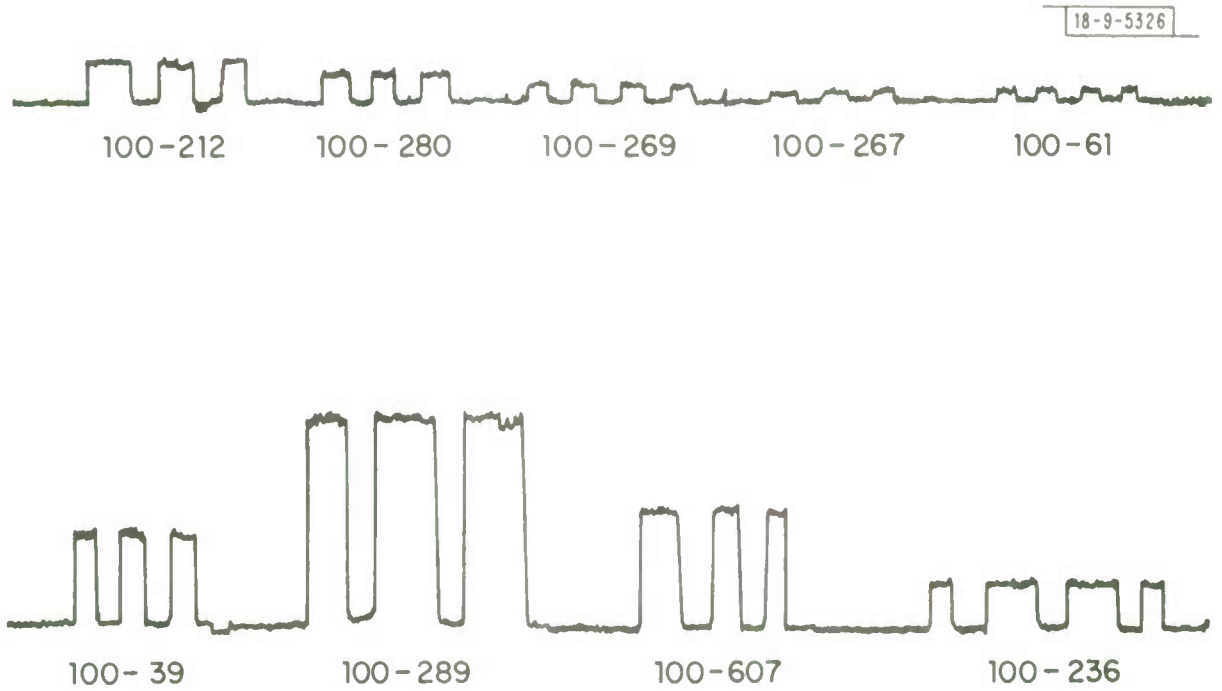


Fig. 3. Light curves, selected Landolt calibration stars

The mission of GEODSS does not include an SOI analysis of the fine structure of light curves, which is the domain of several other Air Force sponsored programs. But a preliminary examination of the light curve for such information as period and average brightness can vitally assist the surveillance role of GEODSS, by confirming the acquisition of a familiar satellite or by providing a means of distinguishing between satellites in the same vicinity. For this reason it is important to understand any phenomenon resulting in an anomalous change in brightness. Furthermore, a mastery of the timing of specular reflections can be a valuable scheduling asset, since maximum brightness should permit minimum search time. An extreme illustration is the case of satellite IMP-6, which was detected electro-optically on 24 October 1973 at a distance of 170,000 km - four times geosynchronous altitude - through the 31-inch telescope at Lowell Observatory. Had specular flashes not been visible, the satellite could not have been seen at all.

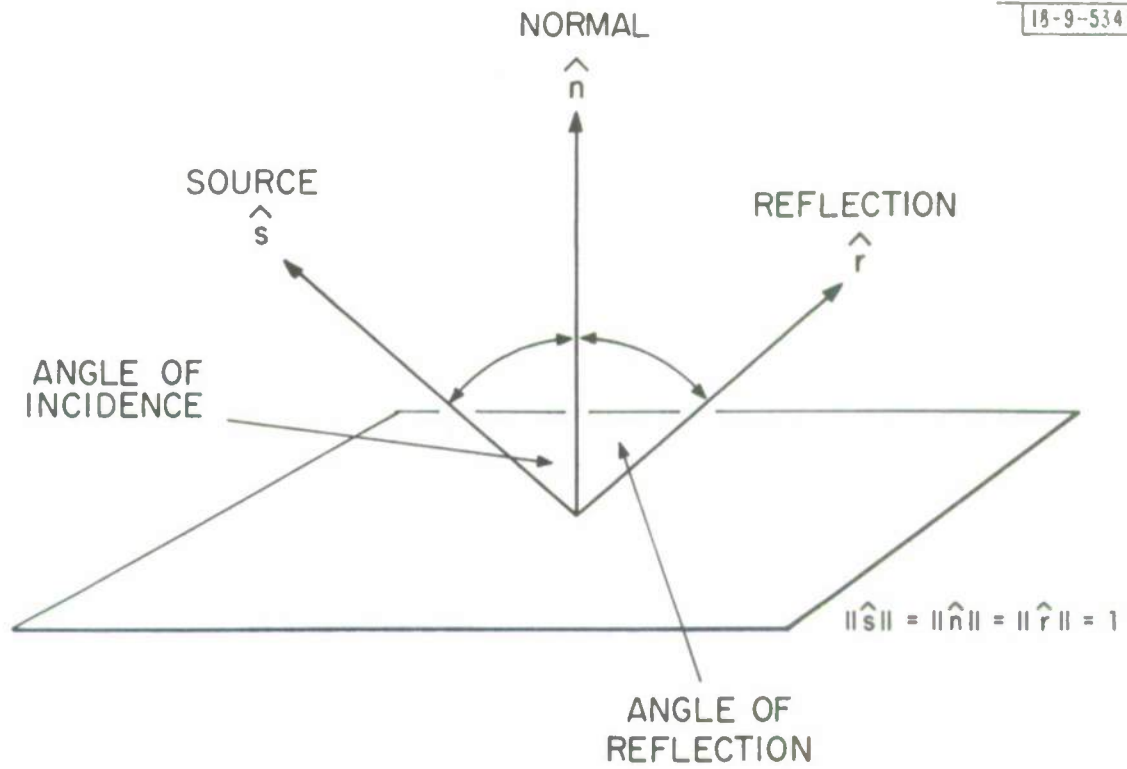
After so many repetitions of the term specular reflection, an explanation is now in order. Mirrorlike reflection from a shiny surface is termed specular, as distinguished from so-called diffuse reflection from an unpolished surface. Diffuse reflection is omnidirectional, while specular is limited in extent and consequently more concentrated. A single object may produce reflections of both types. With respect to satellites, it is diffusely reflected sunlight which ordinarily permits optical detection. Specular reflections, even if they occur, will be visible at a particular terrestrial location only when applicable geometric conditions are satisfied.

For a flat plate, the rule describing specular reflection is well-known: the angle of incidence equals the angle of reflection. This law is depicted in vectorial form in Figure 4. It may be readily extended to curved surfaces by measuring all angles from the normal at the point of reflection.

The chart in Figure 5 describes the current deployment of geosynchronous satellites launched before 1 January 1976. Observe that the large majority have cylindrical bodies. Such satellites are usually faced with solar cells, which are known to be specular reflectors, and for these a specularly reflecting cylinder serves as a good mathematical model. We will limit our attention to this important category, diagrammed in Figure 6. Light rays incident upon the cylinder from a single direction diverge, after reflection, in a multidirectional configuration whose shape is approximately conical. As seen from a sufficiently great distance, that configuration can be regarded as a perfect right circular cone, coaxial with the cylinder and making the same angle with its axis as does the incoming light. [Figure 7].

In the case of solar illumination, the sun may be considered a remote disk of angular diameter one-half degree. Its reflected light thus constitutes a "thickened" cone, of angular thickness one-half degree, as illustrated in Figure 8. Let us now inquire how these reflections impinge upon the earth.

As a preliminary simplification, Figure 9 depicts a spherical earth and an ideal geosynchronous satellite, cylinder axis parallel to the



$$\hat{r} = -\hat{s} + 2(\hat{s} \cdot \hat{n})\hat{n}$$

Fig. 4. Specular reflection from a flat plate-vector representation

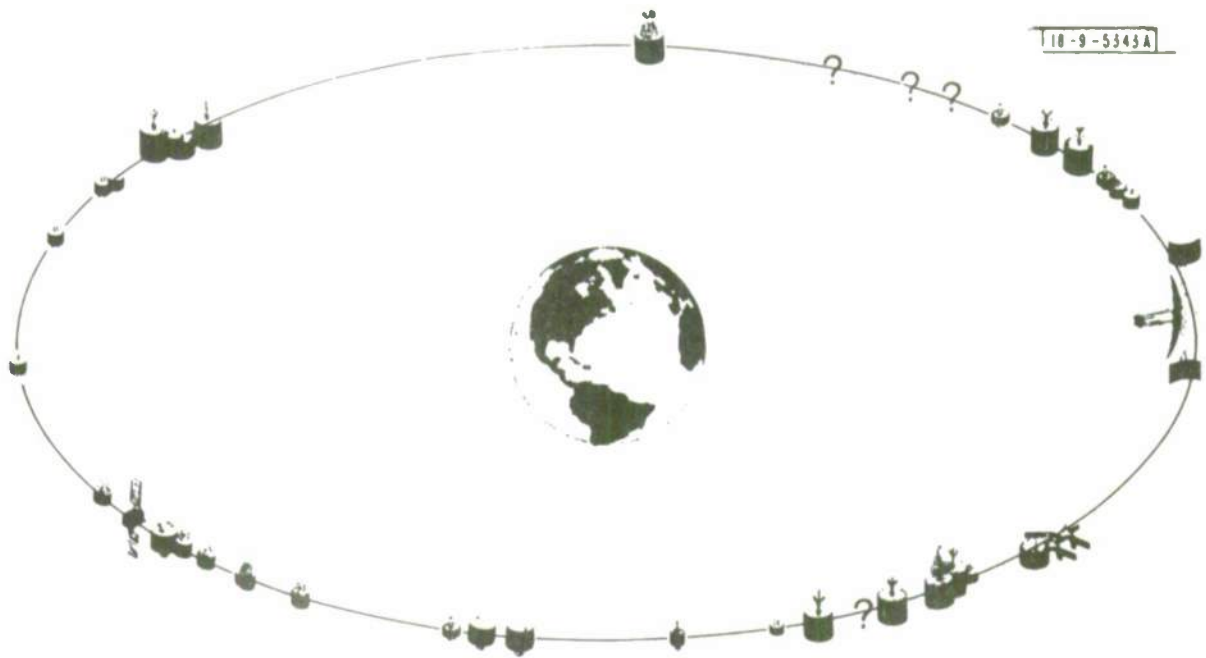
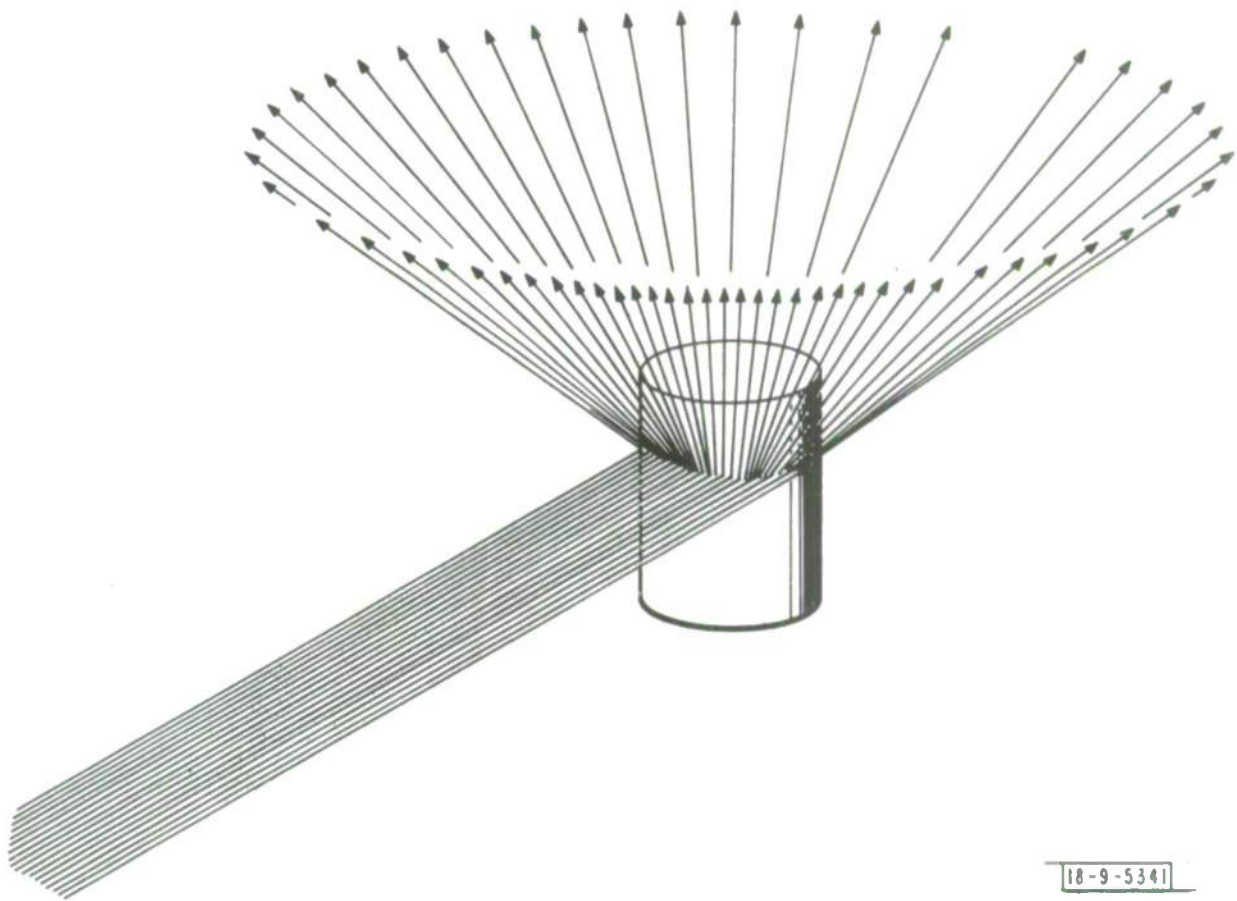


Fig. 5. Geosynchronous satellites launched before 1 January 1976
[Adapted from Comsat Technical Review, vol. 6, no. 1, pp. 196-197]



18-9-5341

Fig. 6. Specular reflection from a cylinder (close up view)



Fig. 7. Specular reflection from a cylinder

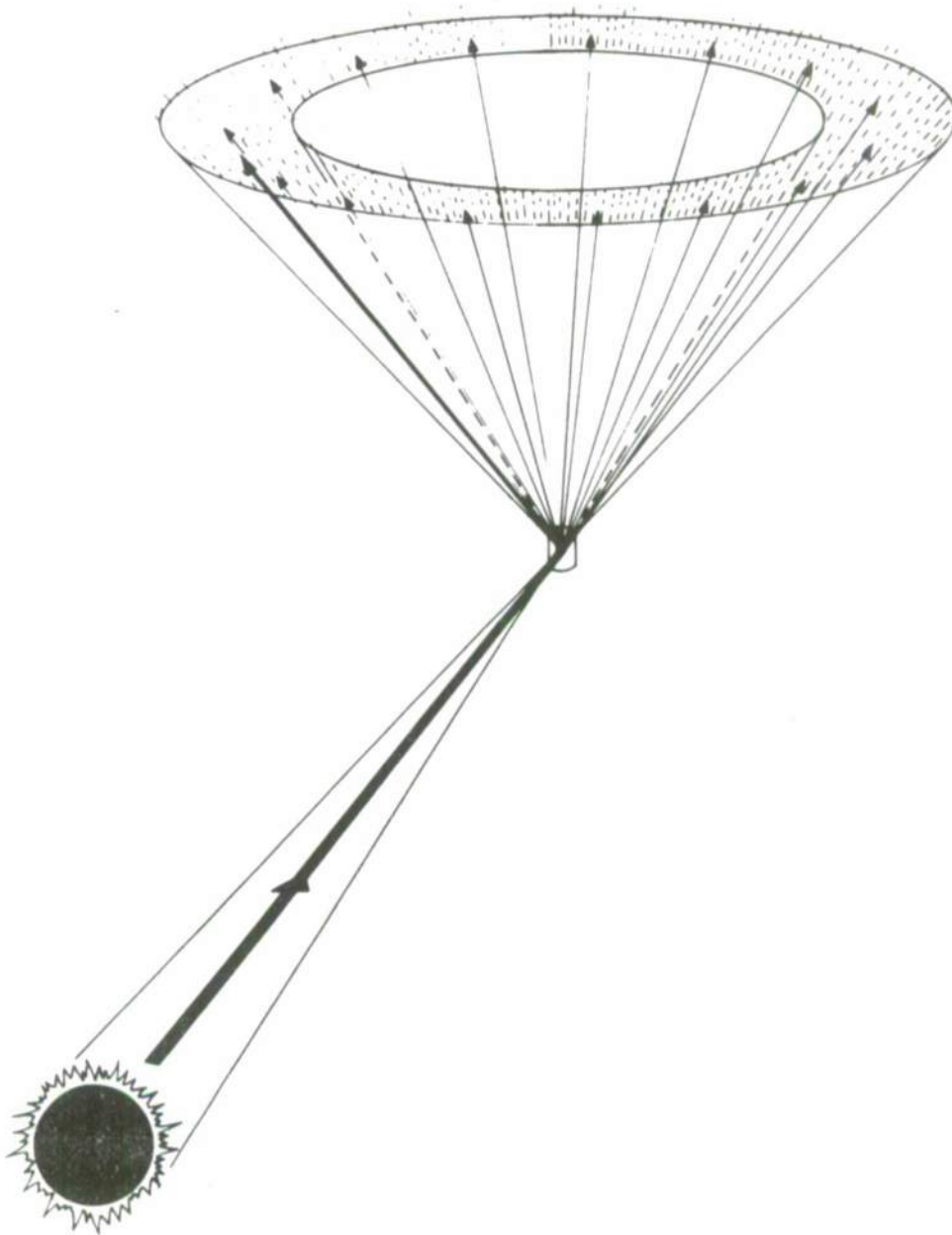


Fig. 8. Solar specular reflection from a cylinder (not to scale)

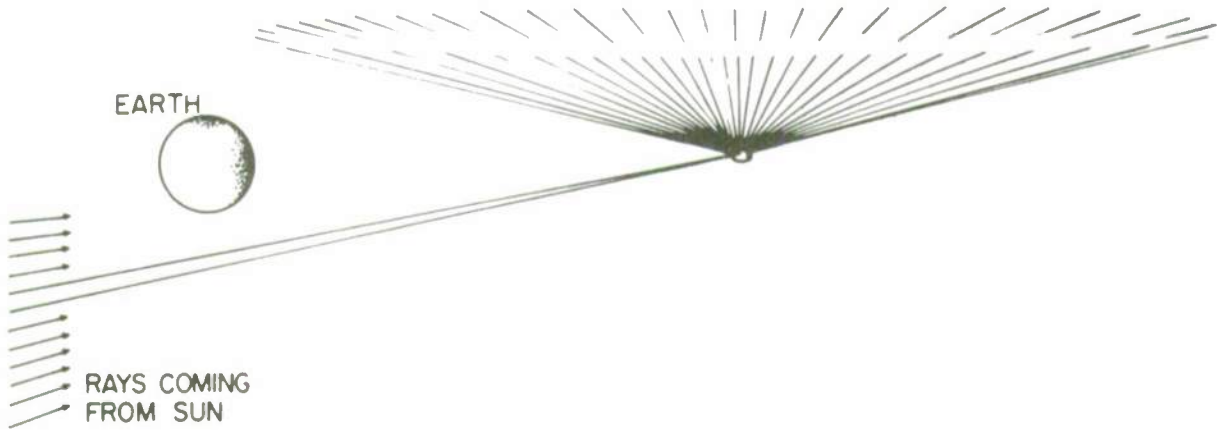


Fig. 9. Terrestrial visibility of solar specular reflection (unfavorable solar declination)

earth's. The sun's declination is such that no specularly reflected rays reach the terrestrial observer. In Figure 10, however, the opposite case is shown, only the rays striking the earth being included. According to the indicated trigonometric relationships, specular reflections are observable at a site of latitude ϕ and sub-satellite longitude if and only if the declination of the source, δ , satisfies the following equation:

$$\tan \delta = \frac{\sin \phi}{\cos \phi - (R_s/R_e)} \quad , \quad (A)$$

where $R_s \approx 42,164$ km is geosynchronous distance, $R_e \approx 6,378$ km is the earth's radius, and hence $(R_s/R_e) \approx 6.61$. Since the source may be any location on the sun's disk, equation (A) is equivalent to the following constraint on solar declination, δ_\odot :

$$\left| \delta_\odot - \arctan \left(\frac{\sin \phi}{\cos \phi - 6.61} \right) \right| \leq 0.5^\circ. \quad (B)$$

Hence, specular reflections are observable at just those times when δ_\odot assumes values in a specific interval, functionally related to site latitude.

The cyclic variation of solar declination is an aspect of the annual course of the seasons, as shown in Figure 11. As a result, each value of solar declination corresponds to two dates. When ϕ is restricted to northern temperate latitudes, for example, the limitations on δ_\odot imposed by equation (B) are seen to confine specular observability

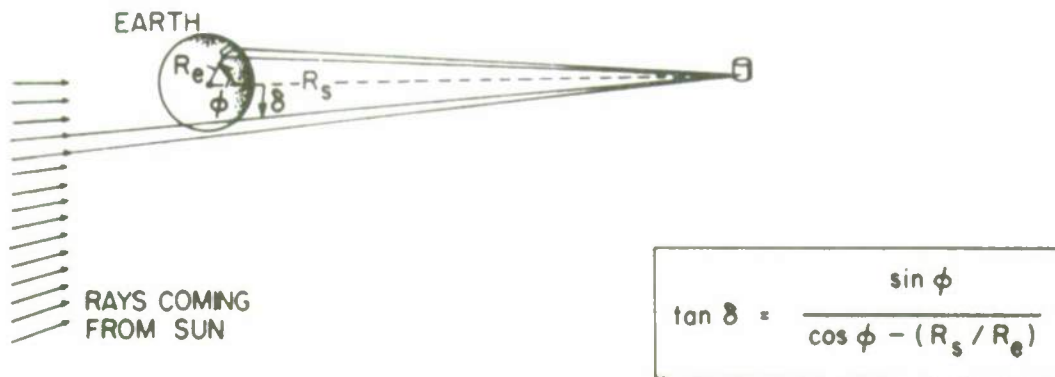


Fig. 10. Terrestrial visibility of solar specular reflection (favorable solar declination)

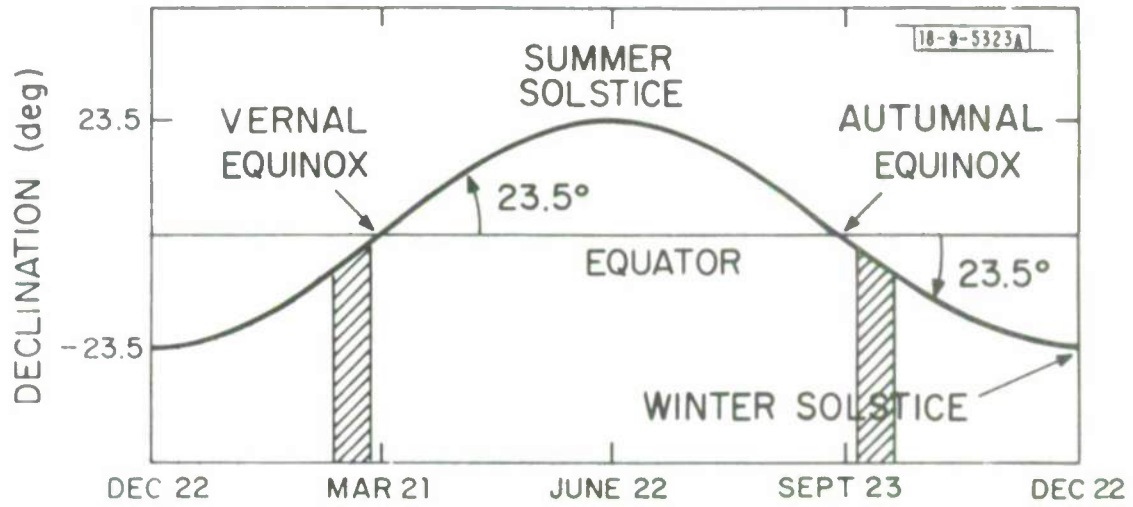


Fig. 11. Annual cycle of solar declination

to one period shortly before the vernal equinox and another shortly after the autumnal, each lasting less than two weeks. The mean rate of change of δ_{\odot} then being about $.38^{\circ}/\text{day}$, the duration of specular observability at any individual site will be approximately 32 hours, part of which will occur during daylight.

Although in the real world the above simplifying assumptions do not hold, the following valid conclusion can be drawn: at a north temperate zone site (such as the Lincoln Laboratory GEODSS Test Site), specular reflections will be prevalent around the time of the equinoxes, particularly before the vernal and after the autumnal. As a corollary, if system detection capability is to be tested under least favorable brightness conditions, sensitivity measurements should be taken near the summer solstice.

A more accurate model of specular timing must take account of all deviations of the satellite orbital elements from true geosynchronous. Likewise, variations in spin axis orientation (also called attitude) must be considered. Satellites which are not perfectly balanced may in addition seem to wobble, as shown in Figure 12. This motion represents a misalignment of the cylinder's spin axis and symmetry axis, which can significantly lengthen the specular viewing period.

The above computational requirements can best be satisfied by a computer program. If it is to serve as a practical planning tool, it must be readily accessible at each GEODSS site, and its results must be provided in a convenient format. The author has written such a program

18-9-5340

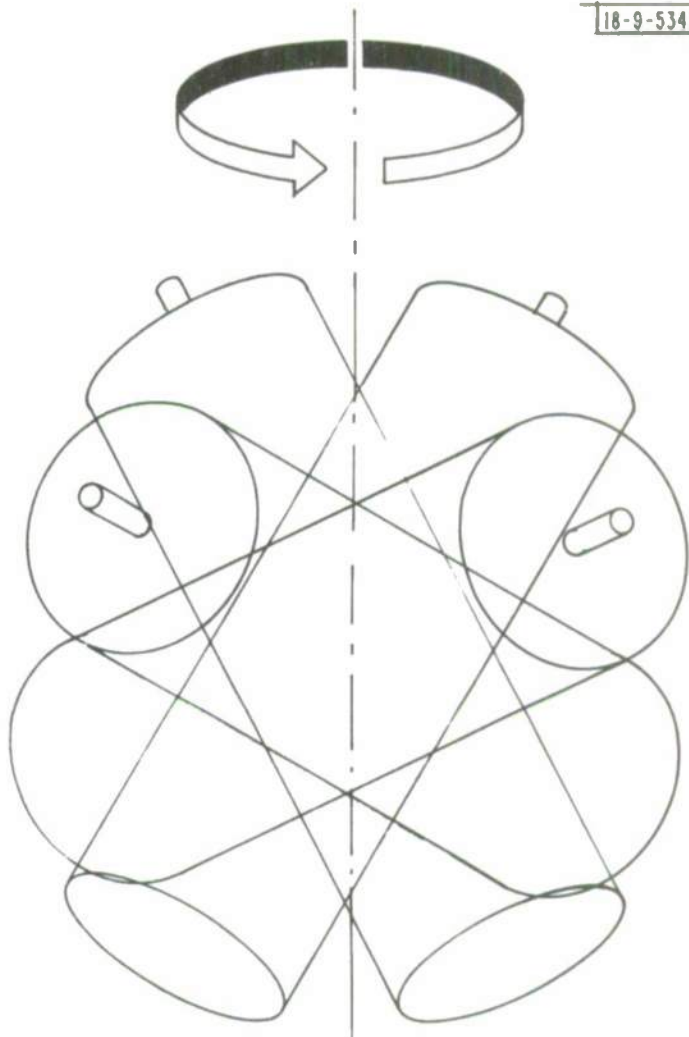


Fig. 12. Wobbling cylinder (spin axis and symmetry axis misaligned)

for the MODCOMP IV minicomputer, an example of whose output is shown in Figure 13. It takes the form of a graphic table, each row representing an observing night, each column an observing time, at ten minute intervals. In addition to observable specular reflections, indicated by (*), the chart specifies the following phenomena: sunset/sunrise (S), twilight (T), eclipse by earth (E), and (for satellites with strong sublongitude drift) descent below horizon (X). The program is interactive and command structured. The computation of a month's specular reflections takes under a minute.

The chart in Figure 13 refers to the true geosynchronous case described above, as seen from a site of latitude 35° and longitude 0° . Figures 14-16 illustrate timing changes resulting from the alteration of a single parameter. The respective modifications are: site moved to latitude 25° ; orbital inclination of 0.5° introduced; axial offset of 0.2° introduced.

When the orbital elements or other parameters are not known exactly, the specular predictions will also contain uncertainty. For example, a change of 0.1° in inclination may cause a shift of as much as six hours in specular observability, and a like change in attitude may have a 12 hour response. When the objective is to recognize a satellite by its known diffuse return, a reasonable precaution is to augment the predicted specular period by a buffer period incorporating recognized uncertainty. When the objective is to capitalize on specular brightness for detection, one should schedule observations near the center of the longest specular

MISSION: REFLECTION FROM LUNAR SURFACE SATELLITE: SPIN AXIS = SYMMETRY 6010
 70000, USE 017E LASS
 OBJECT: HYPOTHETICAL GEOSTATIONARY SATELLITE

9-5425

EPHNO 1976 200 01 01 0.0
 No 1.0027790M AM 6.6105 LM 0.0000000 IM 0.0000
 ORBITAL 0.0000 046PKR 0.0000 MR 0.0000

MOONRA 1.00 NARA 0.00 UCLAA 90.00 RISSLANAX 0.00
 OFFSET FROM ORN NCHNL 0.00 LONG FROM ANOUC 0.00

SATELLITE GRAPHIC TIME TABLE
 FROM SEP 1976 THROUGH NOV 1976

1976	LOCAL MEAN SOLAR TIME												1976					
	16	17	18	19	20	21	22	23	0	1	2	3		4	5	6	7	8
1 SEP 200			6															2 SEP 206
2 SEP 201			5															3 SEP 207
3 SEP 202			6															4 SEP 208
4 SEP 203			6															5 SEP 209
5 SEP 204			6															6 SEP 210
6 SEP 205			6															7 SEP 211
7 SEP 206			6															8 SEP 212
8 SEP 207			6															9 SEP 213
9 SEP 208			6															10 SEP 214
10 SEP 209			6															11 SEP 215
11 SEP 210			6															12 SEP 216
12 SEP 211			6															13 SEP 217
13 SEP 212			6															14 SEP 218
14 SEP 213			6															15 SEP 219
15 SEP 214			6															16 SEP 220
16 SEP 215			6															17 SEP 221
17 SEP 216			6															18 SEP 222
18 SEP 217			6															19 SEP 223
19 SEP 218			6															20 SEP 224
20 SEP 219			6															21 SEP 225
21 SEP 220			6															22 SEP 226
22 SEP 221			6															23 SEP 227
23 SEP 222			6															24 SEP 228
24 SEP 223			6															25 SEP 229
25 SEP 224			6															26 SEP 230
26 SEP 225			6															27 SEP 231
27 SEP 226			6															28 SEP 232
28 SEP 227			6															29 SEP 233
29 SEP 228			6															30 SEP 234
30 SEP 229			6															1 OCT 20
1 OCT 21			6															2 OCT 21
2 OCT 22			6															3 OCT 22
3 OCT 23			6															4 OCT 23
4 OCT 24			6															5 OCT 24
5 OCT 25			6															6 OCT 25
6 OCT 26			6															7 OCT 26
7 OCT 27			6															8 OCT 27
8 OCT 28			6															9 OCT 28
9 OCT 29			6															10 OCT 29
10 OCT 30			6															11 OCT 30
11 OCT 31			6															12 OCT 31
12 OCT 32			6															13 OCT 32
13 OCT 33			6															14 OCT 33
14 OCT 34			6															15 OCT 34
15 OCT 35			6															16 OCT 35
16 OCT 36			6															17 OCT 36
17 OCT 37			6															18 OCT 37
18 OCT 38			6															19 OCT 38
19 OCT 39			6															20 OCT 39
20 OCT 40			6															21 OCT 40
21 OCT 41			6															22 OCT 41
22 OCT 42			6															23 OCT 42
23 OCT 43			6															24 OCT 43
24 OCT 44			6															25 OCT 44
25 OCT 45			6															26 OCT 45
26 OCT 46			6															27 OCT 46
27 OCT 47			6															28 OCT 47
28 OCT 48			6															29 OCT 48
29 OCT 49			6															30 OCT 49
30 OCT 50			6															31 OCT 50
31 OCT 51			6															1 NOV 50
1 NOV 52			6															3 NOV 507
2 NOV 503			6															4 NOV 509
3 NOV 504			6															5 NOV 510
4 NOV 505			6															6 NOV 511
5 NOV 506			6															7 NOV 512
6 NOV 507			6															8 NOV 513
7 NOV 508			6															9 NOV 514
8 NOV 509			6															10 NOV 515
9 NOV 510			6															11 NOV 516
10 NOV 511			6															12 NOV 517
11 NOV 512			6															13 NOV 518
12 NOV 513			6															14 NOV 519
13 NOV 514			6															15 NOV 520
14 NOV 515			6															16 NOV 521
15 NOV 516			6															17 NOV 522
16 NOV 517			6															18 NOV 523
17 NOV 518			6															19 NOV 524
18 NOV 519			6															20 NOV 525
19 NOV 520			6															21 NOV 526
20 NOV 521			6															22 NOV 527
21 NOV 522			6															23 NOV 528
22 NOV 523			6															24 NOV 529
23 NOV 524			6															25 NOV 530
24 NOV 525			6															26 NOV 531
25 NOV 526			6															27 NOV 532
26 NOV 527			6															28 NOV 533
27 NOV 528			6															29 NOV 534
28 NOV 529			6															30 NOV 535
29 NOV 530			6															1 DEC 38
30 NOV 531			6															

0=SUNSET/SUNRISE
 T=TWILIGHT
 *S=SPECULAR REFLECTION 61 SITE
 *E=ECLIPSED BY EARTH
 *M=ALTITUDE LESS THAN 5 DMS

Fig. 13. Specular reflection visibility chart

LPURP 1975 205 01 01 0.00
 RE T.00211907 AP 3.5105 LE 0.000000 IP 0.0000
 ANJUI 0 0.0000 ARSPEM 0.0000 RA 0.0000
 HURAD 0.00 KAAZ 0.00 WECAZ 90.00 MISALONAR 0.00
 UPFECT FROM LHO HURPLE 0.00 LONG FROM ANQUE 0.00

SATELLITE GRAPHIC TIME TABLE
 FROM SEP 1975 THROUGH NOV 1975

DATE	LOCAL MEAN SOLAR TIME														TIME			
	16	17	18	19	20	21	22	23	0	1	2	3	4	5		6	7	8
2 SEP 240																		2 SEP 246
3 SEP 247																		3 SEP 247
4 SEP 248																		4 SEP 248
5 SEP 249																		5 SEP 249
6 SEP 250																		6 SEP 250
7 SEP 251																		7 SEP 251
8 SEP 252																		8 SEP 252
9 SEP 253																		9 SEP 253
10 SEP 254																		10 SEP 254
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14 SEP 258																		14 SEP 258
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27 SEP 271																		27 SEP 271
28 SEP 272																		28 SEP 272
29 SEP 273																		29 SEP 273
30 SEP 274																		30 SEP 274
1 OCT 275																		1 OCT 275
2 OCT 276																		2 OCT 276
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27 NOV 332																		27 NOV 332
28 NOV 333																		28 NOV 333
29 NOV 334																		29 NOV 334
30 NOV 335																		30 NOV 335

S=SUMMIT/SUNRISE
 T=TWILIGHT
 *S=SPECULAR REFLECTION AT SITE
 A=ECLIPSE BY EARTH
 #=ALTIITUDE LESS THAN 0 ULS

Fig. 14. Specular reflection visibility chart (change in site latitude of 10°)
 20

SPECULAR REFLECTION FROM CYLINDRICAL SATELLITE SPIN AXIS - SYMMETRY AXIS
 70000, USA SITE LOSS
 ULLTRA HYPOMETRIC GEOSTATIONAROUS SATELLITE

9-5277

LPDR# 1976 200 UT UT 0.0
 No 1.00277909 AO 3.0105 LO 0.0000000 I# 0.5805
 ANUOLE 0.0000 ONSPEMO 0.0000 MO 0.0000
 HNU# 0 1.00 HAAK# 00.00 DELA# 00.00 RISALBNAK# 0.58
 OFFSLY FNU# 000 NOMAL# 0.20 LONG FROM ANUOLE 90.98

SATELLITE GRAPHIC TIME TABLE
 FROM SEP 17 THROUGH NOV 1976

Date	LOCAL MEAN SOLAR TIME												Date				
	16	17	18	19	20	21	22	23	24	25	26	27		28			
1 SEP 245			S										IT	S			2 SEP 246
2 SEP 246			S										IT	S			3 SEP 247
3 SEP 247			S										IT	S			4 SEP 248
4 SEP 248			S										IT	S			5 SEP 249
5 SEP 249			S										IT	S			6 SEP 250
6 SEP 250			S										IT	S			7 SEP 251
7 SEP 251			S										IT	S			8 SEP 252
8 SEP 252			S										IT	S			9 SEP 253
9 SEP 253			S										IT	S			10 SEP 254
10 SEP 254			S										IT	S			11 SEP 255
11 SEP 255			S										IT	S			12 SEP 256
12 SEP 256			S										IT	S			13 SEP 257
13 SEP 257			S										IT	S			14 SEP 258
14 SEP 258			S										IT	S			15 SEP 259
15 SEP 259			S										IT	S			16 SEP 260
16 SEP 260			S										IT	S			17 SEP 261
17 SEP 261			S										IT	S			18 SEP 262
18 SEP 262			S										IT	S			19 SEP 263
19 SEP 263			S										IT	S			20 SEP 264
20 SEP 264			S										IT	S			21 SEP 265
21 SEP 265			S										IT	S			22 SEP 266
22 SEP 266			S										IT	S			23 SEP 267
23 SEP 267			S										IT	S			24 SEP 268
24 SEP 268			S										IT	S			25 SEP 269
25 SEP 269			S										IT	S			26 SEP 270
26 SEP 270			S										IT	S			27 SEP 271
27 SEP 271			S										IT	S			28 SEP 272
28 SEP 272			S										IT	S			29 SEP 273
29 SEP 273			S										IT	S			30 SEP 274
30 SEP 274			S										IT	S			1 OCT 275
1 OCT 275			S										IT	S			2 OCT 276
2 OCT 276			S										IT	S			3 OCT 277
3 OCT 277			S										IT	S			4 OCT 278
4 OCT 278			S										IT	S			5 OCT 279
5 OCT 279			S										IT	S			6 OCT 280
6 OCT 280			S										IT	S			7 OCT 281
7 OCT 281			S										IT	S			8 OCT 282
8 OCT 282			S										IT	S			9 OCT 283
9 OCT 283			S										IT	S			10 OCT 284
10 OCT 284			S										IT	S			11 OCT 285
11 OCT 285			S										IT	S			12 OCT 286
12 OCT 286			S										IT	S			13 OCT 287
13 OCT 287			S										IT	S			14 OCT 288
14 OCT 288			S										IT	S			15 OCT 289
15 OCT 289			S										IT	S			16 OCT 290
16 OCT 290			S										IT	S			17 OCT 291
17 OCT 291			S										IT	S			18 OCT 292
18 OCT 292			S										IT	S			19 OCT 293
19 OCT 293			S										IT	S			20 OCT 294
20 OCT 294			S										IT	S			21 OCT 295
21 OCT 295			S										IT	S			22 OCT 296
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23 OCT 297			S										IT	S			24 OCT 298
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30 NOV 335			S										IT	S			1 DEC 336

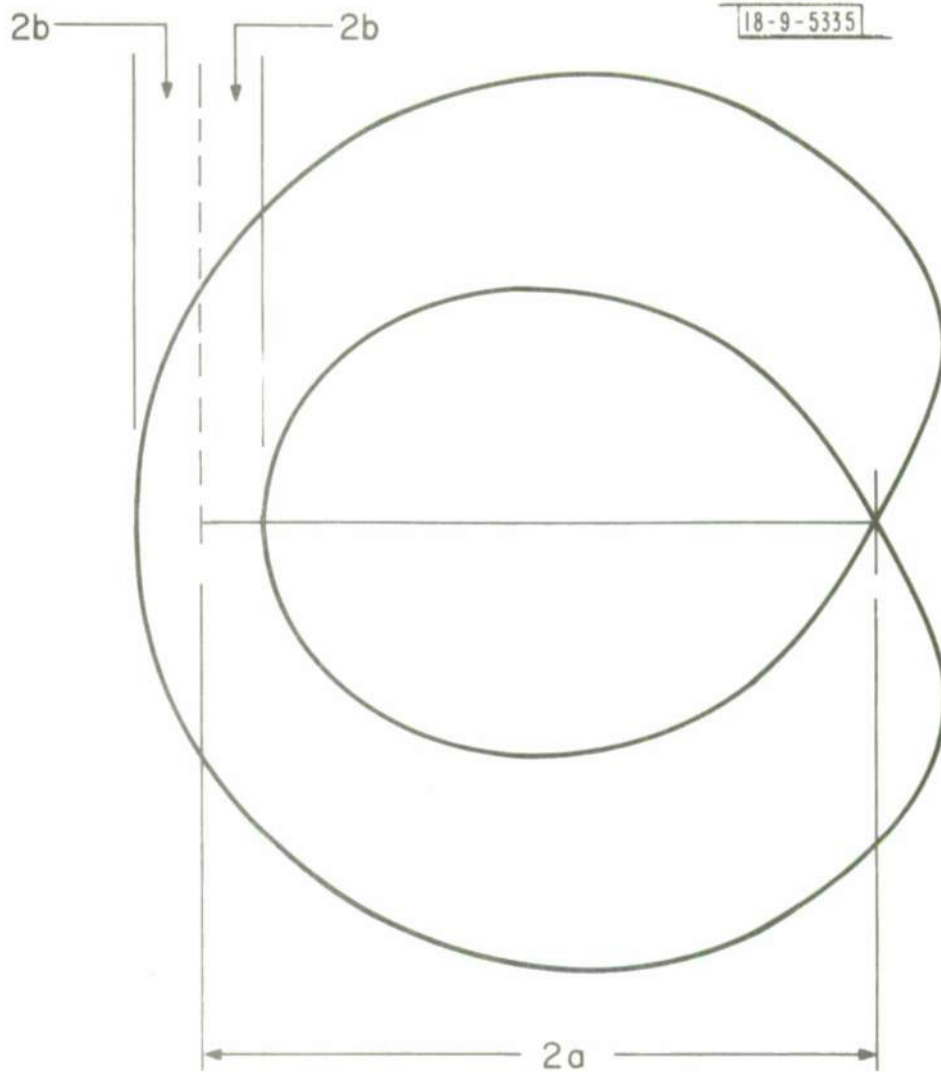
SUNSET/SUNRISE
 (T) (I) (S)
 *SPECCULAR REFLECTION AT SITE
 (E) (C) (I) (S) (E) (I) (M)
 (S) (A) (L) (I) (T) (U) (E) (L) (S) (I) (M) (A) (N) (0) (U) (L) (E)

Fig. 16. Specular reflection visibility chart (change in satellite attitude of 0.2°)

periods available. In either case, the program facilitates tentative parameter modification, so that alternate predictions may be obtained for comparison.

The case of the wobbling satellite deserves further comment. As the satellite spins about a fixed axis, its symmetry axis revolves about that spin axis because of their misalignment. As a result, the geometric requirements for specular reflection may be satisfied during some portions of a spin period and unsatisfied during others. The relevant concept is the envelope of all specular rays which may periodically be reflected. This envelope is closely related to the classical limaçon of Pascal (cf. Figure 17) and can be described by a closed parametric formula. The shape of the resulting envelope is approximated in Figure 18. It still resembles a thickened cone, but the thickening is uneven and depends upon the amount of misalignment. Figure 19 shows our standard example with an introduced misalignment of 0.5° . Figure 20 shows a less artificial example, with orbital inclination of 5.7° , offset of 2.8° , and misalignment of 0.5° .

Extensive observations based on the above analysis are planned for the 1976 autumnal equinox. Already at hand are data from February and March, 1976, concerning Lincoln Experimental Satellite 6. LES-6 is particularly interesting because of its large misalignment of 2.2° and its unfavorable altitude at the Lincoln GEODSS site of less than 12° above the horizon. Pronounced specular returns were obtained at the times indicated in Figure 21, which are quite compatible with predicted



$$r = 2(b - a \cos \theta)$$

$$(x^2 + y^2 + 2ax)^2 = 4b^2(x^2 + y^2)$$

Fig. 17. Limaçon of Pascal

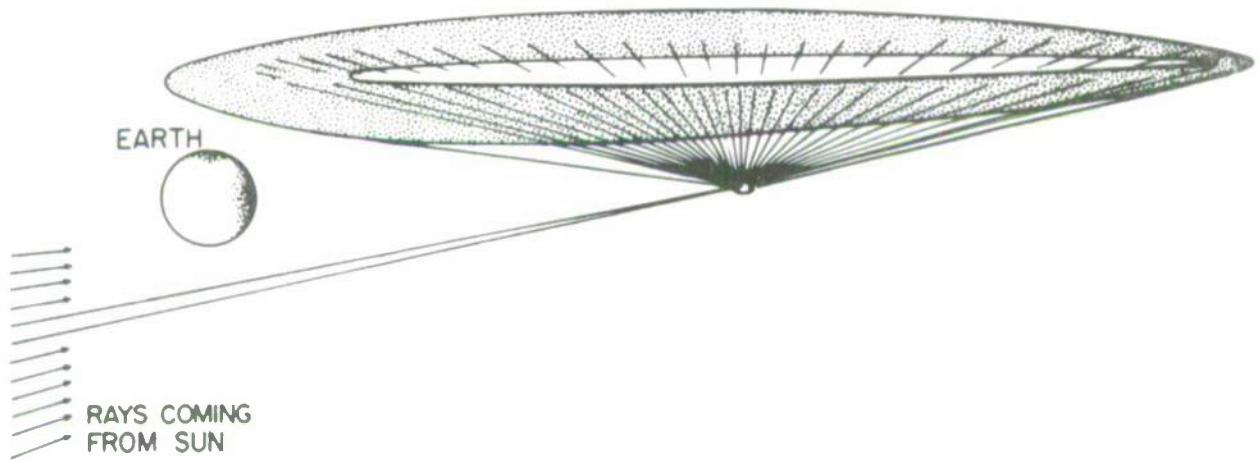


Fig. 18. Terrestrial visibility of solar specular reflection (wobbling satellite)

EPOCH: 1976 265 01 01 U.U
 NS 1.04277905 AS 3.6105 ES 0.00000000 IS 0.0000
 ANUUS 0.0000 ANGLPMS 0.0000 MS 0.0000

MO*AS 1.00 MAAS 0.00 DECAE 94.00 MISALNABD 0.50
 OFFSET FROM DBB NORMALS 0.00 LONG FROM ANGLE 0.00

SATELLITE GRAPHIC TIME TABLE
 FROM SEP 1976 THROUGH NOV 1976

	LOCAL MEAN SOLAR TIME																
	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8
1 SEP 240																	
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0=SUNSET/SUNRISE
 1=TWILIGHT
 2=SPECULAR REFLECTION AT SITE
 3=ECLIPSE BY SHAD
 4=ALTITUDE LESS THAN 0 DEG

Fig. 19. Specular reflection visibility chart (misalignment of 0.5° introduced)

timing. A record of unsuccessful observation attempts for similar comparison would have been most desirable and will be included in the fall observing program.

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ESD-TR-76-308	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Determination of Specular Reflection from Cylindrical Satellites for Electro-optical Surveillance and SOI		5. TYPE OF REPORT & PERIOD COVERED Project Report
		6. PERFORMING ORG. REPORT NUMBER Project Report ETS-3
7. AUTHOR(s) Alan S. Friedman		8. CONTRACT OR GRANT NUMBER(s) F19628-76-C-0002
9. PERFORMING ORGANIZATION NAME AND ADDRESS Lincoln Laboratory, M. I. T. P. O. Box 73 Lexington, MA 02173		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element No. 63428F Project No. 2128
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Systems Command, USAF Andrews AFB Washington, DC 20331		12. REPORT DATE 8 October 1976
		13. NUMBER OF PAGES 34
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Electronic Systems Division Hanscom AFB Bedford, MA 01731		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES None		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) specular reflection electro-optical surveillance cylindrical satellites space object identification (SOI)		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) An analysis of the timing and duration of observable specular reflections from cylindrical satellites is presented, taking into account orbital elements, attitude, and axial misalignment (wobble). Results are displayed in the form of computer-generated graphic tables.		

