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LIGHTPC ACCURACY STUDY

by

Capt Matthew C. Peterson

DECEMBER 1992

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Scott Air Force Base, Illinois, 62225-5116

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13. Abstract: This report documents the results of a USAFETAC study of the accuracy of LIGHTPC and ICE PC small computer programs, both of which were used to compute astronomical data such as sunrise, sunset, moonrise, and moonset. It presents error distributions for programs at and above 60° N. The LIGHTPC program solves fundamental astronomical equations to produce sunrise and sunset times; the ICE program allows accesses to an ephemeris calculated to high precision. The LIGHTPC program is less accurate than ICE in precision. The LIGHTPC program is less accurate than ICE in predicting sunrise and sunset times at all latitudes above 60° N. The report discusses weaknesses of the LIGHTPC program and errors in the ICE program. Techniques for using LIGHTPC to correct ICE to produce better sunrise, sunset, twilight end and twilight start, times than by using ICE alone are provided.

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PREFACE

In June 1991, the Strategic Air Command (now U.S. Strategic Command) asked USAFETAC to evaluate the accuracy of USAFETAC's LIGHTPC personal computer program at polar latitudes. The request (performed under USAFETAC project number 910639) was assigned to USAFETAC's Simulation and Techniques Branch (SYT). This report documents work done on the project and describes the results, which should be of interest to anyone who uses LIGHTPC or ICE to compute solar and lunar events at high latitudes.

USAFETAC/SYT analysts calculated not only the errors in USAFETAC's LIGHTPC (v3.1 and v3.2) PC program (which already cautions users on its accuracy above 60° N latitude), but in ICE v0.51 (beta), as well. Both programs compute sunrise, sunset, twilight start, twilight end, moonrise, and moonset at latitudes at and above 60° N. We used values provided by the Naval Observatories best mainframe computer program as "truth," and assumed that the Naval Observatory's mainframe program output was absolutely correct in all cases. Discussions with people at the Naval Observatory indicated that the algorithms used in this mainframe program are the best available anywhere for computing the solar and lunar events in which we are interested.

The author wishes to thank the Director of the Astronomical Applications Department of the U.S. Naval Observatory, Dr P.M. Janiczek, and his staff for providing USAFETAC with very helpful phone consultation, output of their mainframe program, and a copy of the ICE v0.51 beta software.

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1. INTRODUCTION

1.1 Purpose. This project report documents the results of a study done for USSTRATCOM/DOW, which tasked USAFETAC to:

- Determine the accuracy of LIGHTPC above 60° N latitude.
- Stratify accuracy values into 5° latitude bands from 60° to 90° N for both solar and lunar rise and set.
- Indicate accuracy of nautical twilight beginning and ending if different from sunrise and sunset accuracy.
- Locate and evaluate candidate alternative algorithms which provide improved accuracy above 60° N.

The study was to include a determination of each algorithm's accuracy at high latitudes and its portability to an MS-DOS microcomputer environment. Since the evaluation neglected atmospheric refraction, substantial differences could exist between when the sun or moon is geometrically above the horizon and when it can actually be seen.

1.2 LIGHTPC Program. This USAFETAC program was evaluated first. The algorithms used in LIGHTPC v3.2 are identical to those used in LIGHTPC v3.1, and the results are valid for both versions. LIGHTPC is maintained by USAFETAC and available from the Air Weather Service Technical Library (AWSTL), Bldg 859, Buchanan St., Scott AFB, IL 62225-5118. The LIGHTPC results presented there are for the entire year of 1990 at 0° W longitude and at 60°, 65°, 70°, 75°, 80°, 85°, 89° N latitude. The maximum sunrise errors of LIGHTPC at these latitudes are 3, 5, 24, 17, 10, 8, and 10 minutes.

1.3 Interactive Computer Ephemeris (ICE) Program. We also evaluated ICE v0.51 (beta). Although the ICE program is no longer maintained, it is still available from the Nautical Almanac Office, U.S. Naval Observatory, Washington, DC 20392. ICE was the brainchild of two former employees of the Nautical Almanac Office. The code was never released except as a beta (test) version. No changes or updates are planned. There are problems in the ICE software and its user interface is not very friendly. The maximum sunrise errors of ICE at the latitudes we studied (see 1.2) were 1, 1, 1, 1, 1, 3, and 15 minutes, respectively.

1.4 Navy Mainframe Program. The computer program that the Nautical Almanac Office at the Naval Observatory uses to calculate solar and lunar event times has not been validated at latitudes above 75° N, but Observatory spokespeople state that data from this program is the best currently available. Although the Naval Observatory does not normally release high latitude data or the software, they made an exception in our case. As of 1 December 1992, the Navy mainframe program no longer exists. It will be replaced in 1993 by a Nautical Almanac PC ephemeris program (MICA--Multi-Year Interactive Computer Almanac), that will be validated for high latitudes, as well.

2. PROGRAM DESCRIPTIONS

2.1 Navy Mainframe Program. A sample of the data from the Nautical Almanac Office's mainframe computer at the Naval Observatory is shown in Table 1, below. Although the original dataset had the entire year of events in one table, it was reduced to 1 month to save space here. The Naval Observatory ran their mainframe program for sunrise, sunset, twilight start, twilight end, moonrise, and moonset for 60°N, 65° N, 70° N, 75° N, 80° N, 85° N, and 89° N at 0° W for the entire year of 1990. We used the Naval Observatory output as "truth" for comparison with LIGHTPC and ICE. Although it was assumed that the Naval Observatory program's output was accurate at all latitudes to within 1 minute, its accuracy has not been absolutely determined at latitudes above 75° N.

TABLE 1. January 1990 Moonrise and Moonset for Longitude 0° W, Latitude 60° N. From the Nautical Almanac Office, U.S. Naval Observatory. "++++" indicates "no event, moon *above* horizon." "----" indicates "no event, moon *below* horizon.

Day	Rise h m	Set h m
1	1040	2104
2	1041	2238
3	1042	++++
4	1044	0014
5	1046	0154
6	1051	0339
7	1102	0528
8	1126	0713
9	1219	0832
10	1348	0914
11	1532	0932
12	1715	0940
13	1852	0944
14	2022	0946
15	2148	0947
16	2312	0947
17	----	0948
18	0035	0948
19	0200	0950
20	0327	0954
21	0457	1002
22	0624	1020
23	0734	1100
24	0816	1211
25	0836	1344
26	0845	1525
27	0849	1705
28	0851	1844
29	0853	2021
30	0854	2158
31	0855	2337

2.2 LIGHTPC Program.

LIGHTPC Dataset. A sample of the data from LIGHTPC is given in Table 2. LIGHTPC v3.2 computes all solar and lunar events using numerical algorithms to solve fundamental astronomical equations and determine solar or lunar event times. The algorithms used in LIGHTPC are more primitive than those on the Navy Mainframe and do not calculate solar and lunar event times as accurately. The LIGHTPC program does not list the original reference for the algorithms it uses.

Assumptions. The documentation for LIGHTPC v3.2 states that the program is accurate to within 2 minutes at latitudes below 60° and that "outside these boundaries (above 60° N/S), accuracy decreases as latitude increases." Since LIGHTPC is not recommended for use north of 60° N, this project made no attempt to improve the LIGHTPC software.

TABLE 2. Air Force Lunar Data. January 1990 Moonrise/Moonset and Percent Illumination. For Latitude 60° min N, Longitude zero degrees, zero minutes E, Flying Altitude: zero. The **** indicate non-events. Distinctions between "above or below the horizon" are not made. All times are Greenwich mean time percent illumination is given for 000C LST.

Day	Moon Rise	Moon Set	% Illum
1	1041	2104	15
2	1042	2238	24
3	1043	****	34
4	1044	0015	44
5	1046	0153	56
6	1051	0340	67
7	1100	0530	77
8	1121	0717	86
9	1214	0838	93
10	1343	0918	98
11	1528	0936	100
12	1713	0943	99
13	1849	0946	96
14	2021	0948	91
15	2146	0948	84
16	2311	0948	76
17	****	0949	67
18	0034	0949	58
19	0158	0951	48
20	0328	0956	39
21	0456	1003	30
22	0626	1018	22
23	0737	1100	15
24	0819	1210	8
25	0838	1341	4
26	0847	1523	1
27	0851	1705	0
28	0853	1842	2
29	0854	2020	6
30	0855	2156	12
31	0856	2337	20

2.3 ICE Program.

ICE Dataset. A sample of the ICE v0.51 (beta) data is given in Table 3. The ICE v0.51 (beta) software was tested to see if it could fulfill SAC's requirements for a microcomputer-based algorithm capable of +/- 2 minutes accuracy in predicting solar and lunar events at latitudes above 60° N. ICE v0.51 (beta) does not use numerical methods to solve the event times; instead, it uses a built-in 250-year ephemeris. We found that ICE is accurate to within +/- 2 minutes at polar latitudes, in some cases.

Assumptions. We made no assumptions about ICE. The copy of the software we received did not contain a users guide, and although the READ.ME file gave details of how to run the software and what hardware was required, it didn't warn of program deficiencies or of reductions in accuracy at certain latitudes. The ICE program also contained several software bugs; for example, ICE did not write all the correct twilight end times to a file when the program was run for latitudes at and above 70° N at 0° W longitude. The program writes "^@^@^@^@^@" for the twilight end times for specific dates instead of writing the actual time. ICE also misses some days when the moon does not set or rise when it writes the moonrise and moonset times to a file at all polar latitudes. All these software bugs caused problems in evaluating ICE program accuracy; in all cases, we were forced to insert values where ICE had written nonsense.

Conclusions. The Nautical Almanac Office does not plan to fix the problems described above. The ICE software is no longer supported or maintained, and the Navy has moved on to a new concept in interactive ephemeris programs. What ICE v0.51 does show is that microcomputer-based software can produce event times accurate to a few minutes at latitudes as far north as 85° N. Tighter software quality control and testing could easily yield a microcomputer-based ephemeris program with accuracies that are within a few minutes of the ephemeris values computed by the best astronomical computer programs. ICE v0.51 very nearly achieved this goal; it is unfortunate that it is no longer supported.

TABLE 3. Topocentric Ephemeris of Moon. January 1990 for Greenwich Meridian. Longitude 0 00.0, Latitude N 10 00.0, Time zone UT.

		TDT TIME			Rise			Trans			Set		
Day	TDT JD	h	m	s	h	m	(Alt)	h	m	(Alt)	h	m	(Azm)
1	2447893.154208	15	42	03.5	10	40	(109)	15	42	(s[illegible]2)	21	04	(256)
2	2447894.186371	16	28	22.4	10	41	(97)	16	28	(s28)	22	38	(270)
3	2447895.218799	17	15	04.3	10	42	(84)	17	15	(s35)	f 0	14	(283)
4	2447896.252440	18	03	30.8	10	43	(71)	18	04	(s41)	f 1	54	(297)
5	2447897.288218	18	55	02.0	10	46	(58)	18	55	(s47)	f 3	39	(310)
6	2447898.326827	19	50	37.9	10	51	(46)	19	51	(s52)	f 5	28	(323)
7	2447899.368379	20	50	28.0	11	01	(35)	20	50	(s56)	F 7	14	(333)
8	2447900.412035	21	53	19.9	11	24	(26)	21	53	(S57)	F 8	34	(337)
9	2447901.456025	22	56	40.5	12	18	(24)	22	57	(S57)	F 9	15	(332)
10	2447902.498322	23	57	35.0	13	47	(30)	23	58	(S55)	F 9	32	(322)
12	2447903.537538	0	54	03.3	p15	32	(40)	0	54	(s51)	9	40	(311)
13	2447904.573282	1	45	31.5	p17	15	(53)	1	46	(s46)	9	44	(299)
14	2447905.605930	2	32	32.4	p18	52	(65)	2	33	(s40)	9	46	(287)
15	2447906.636244	3	16	11.5	p20	22	(78)	3	16	(s35)	9	7	(276)
16	24479[illegible]7.665096	3	57	44.3	p21	48	(90)	3	58	(s29)	9	47	(264)
17	2447908.693347	4	38	25.2	p23	11	(102)	4	38	(s23)	9	48	(253)
18	2447909.721803	5	19	23.7	0	34	(114)	5	19	(s18)	9	49	(242)
19	2447910.751196	6	01	43.3	1	59	(125)	6	02	(s13)	9	51	(232)
20	2447911.782146	6	46	17.4	3	27	(136)	6	46	(s9)	9	55	(222)
21	2447912.815076	7	33	42.5	4	56	(146)	7	34	(s6)	10	03	(212)
22	2447913.850083	8	24	07.2	6	22	(154)	8	24	(s4)	10	22	(205)
23	2447914.886821	9	17	01.3	7	33	(158)	9	17	(s3)	11	01	(202)
24	2447915.924501	10	11	16.8	8	15	(155)	10	11	(s3)	12	12	(206)
25	2447916.962114	11	05	26.7	8	35	(147)	11	05	(s6)	13	45	(215)
26	2447917.998792	11	58	15.6	8	44	(137)	11	58	(s9)	15	25	(226)
27	2337919.034085	12	49	04.9	8	49	(126)	12	49	(s14)	17	05	(238)
28	2447920.068041	13	37	58.7	8	51	(113)	13	38	(s20)	18	44	(252)
29	2447921.101110	14	25	35.9	8	53	(101)	14	26	(s26)	20	21	(265)
30	2447922.134002	15	12	57.8	8	54	(88)	15	13	(s33)	21	58	(279)
31	2447923.167561	16	01	17.3	8	55	(75)	16	01	(s40)	23	37	(293)

NOTE: Although Day 11 seems to be missing from Table 3, with no moonrise of moonset times reported, the moon did rise on Day 11 and the table records it. The moonrise time for Day 12 is preceded by a "p," indicating the moon rose on the previous day (Day 11). ICE output is displayed using the Terrestial Dynamical Time Julian date (TDT JD) to keep track of the date. When the moon rises or sets on a different date than the TDT JD, the moonrise and/or set time is flagged "p" previous) or "f" (following) to indicate the difference. Both PCLIGHT and the Navy mainframe model use the date of moonrise to date the output. Keep this difference in model output methodology in mind when comparing model event times.

2.4 Comparisons. Both programs allow users to view event times on the screen or write them to a file. The LIGHTPC program is tailor-made for DoD users, while ICE was designed with the astronomy user in mind.

Table 4 gives January and February 1990 moonrise and moonset events for all three programs. The ICE# data contains the data used in our analysis. Table 4 shows how the model outputs (shown in Tables 1-3) were reformatted before being uploaded to USAFETAC'S IBM 3090 mainframe for SAS processing.

The method used to identify calendar days in ICE output was changed to match the method used in PCLIGHT, using date of moonrise as the output date label. ICE moonrise times flagged "p" were shifted ahead one day to match the PCLIGHT date. ICE moonset times flagged "f" were shifted back 1 day. Days in the ICE output with no moonrise or moonset events after the dates were shifted are filled in with asterisks. These date shifts ensure that ICE-PCLIGHT-NAVY moonrise and moonset comparisons are made between the same calendar dates.

TABLE 4. Moonrise/Moonset Events for January and February 1990, all Three Programs.

	ICE#		LIGHTPC		Navy Main		Uncorrected ICE		
Day	Rise	Set	Rise	Set	Rise	Set	Day	Rise	Set
1 Jan	1040	2104	1041	2104	1040	2104	1 Jan	1040	2104
2 Jan	1041	2238	1042	2238	1041	2238	2 Jan	1041	2238
3 Jan	1042	*****	1043	*****	1042	*****	3 Jan	1042	f0014
4 Jan	1043	0014	1044	0015	1044	0014	4 Jan	1043	f0154
5 Jan	1046	0154	1046	0153	1046	0154	5 Jan	1046	f0339
6 Jan	1051	0339	1051	0340	1051	0339	6 Jan	1051	f0528
7 Jan	1101	0528	1100	0530	1102	0528	7 Jan	1101	f0714
8 Jan	1124	0714	1121	0717	1126	0713	8 Jan	1124	f0834
9 Jan	1218	0834	1214	0838	1219	0832	9 Jan	1218	f0915
10 Jan	1347	0915	1343	0918	1348	0914	10 Jan	1347	f0932
11 Jan	1532	0932	1528	0936	1532	0932			
12 Jan	1715	0940	1713	0943	1715	0940	12 Jan	p1532	0940
13 Jan	1852	0944	1849	0946	1852	0944	13 Jan	p1715	0944
14 Jan	2022	0946	2021	0948	2022	0946	14 Jan	p1852	0946
15 Jan	2148	0947	2146	0948	2148	0947	15 Jan	p2022	0947
16 Jan	2311	0947	2311	0948	2312	0947	16 Jan	p2148	0947
17 Jan	*****	0948	*****	0949	*****	0948	17 Jan	p2311	0948
18 Jan	0034	0949	0034	0949	0035	0948	18 Jan	0034	0949
19 Jan	0159	0951	0158	0951	0200	0950	19 Jan	0159	0951
20 Jan	0327	0955	0328	0956	0327	0954	20 Jan	0327	0955
21 Jan	0456	1003	0456	1003	0457	1002	21 Jan	0456	1003
22 Jan	0622	1022	0626	1018	0624	1020	22 Jan	0622	1022
23 Jan	0733	1101	0737	1100	0734	1100	23 Jan	0733	1101
24 Jan	0815	1212	0819	1210	0816	1211	24 Jan	0815	1212
25 Jan	0835	1345	0838	1341	0836	1344	25 Jan	0835	1345
26 Jan	0844	1525	0847	1523	0845	1525	26 Jan	0844	1525
27 Jan	0847	1705	0851	1705	0849	1705	27 Jan	0849	1705
28 Jan	0851	1844	0853	1842	0851	1844	28 Jan	0851	1844
29 Jan	0853	2021	0854	2020	0853	2021	29 Jan	0853	2021
30 Jan	0854	2158	0855	2156	0854	2158	30 Jan	0854	2158
31 Jan	0855	2337	0856	2337	0855	2337	31 Jan	0855	2337
1 Feb	0857	*****	0858	*****	0857	*****	1 Feb	0857	f0120
2 Feb	0901	0120	0900	0121	0901	0120	2 Feb	0902	f0307
3 Feb	0909	0307	0907	0309	0909	0307	3 Feb	0909	f0453
4 Feb	0925	0453	0922	0453	0926	0452	4 Feb	0925	f0622
5 Feb	1004	0622	1003	0626	1006	0621	5 Feb	1004	f0716
6 Feb	1119	0716	1116	0719	1121	0714	6 Feb	1119	f0739
7 Feb	1258	0739	1255	0743	1259	0739	7 Feb	1258	f0750
8 Feb	1442	0750	1438	0752	1442	0749	8 Feb	1442	f0755
9 Feb	1620	0755	1619	0757	1621	0754			
10 Feb	1753	0757	1751	0759	1757	0757	10 Feb	p1620	0757
11 Feb	1921	0758	1921	0800	1922	0758	11 Feb	p1753	0758
12 Feb	2047	0759	2045	0759	2047	0759	12 Feb	p1921	0759
13 Feb	2211	0800	2211	0759	2211	0759	13 Feb	p2047	0800
14 Feb	2335	0800	2335	0800	2336	0800	14 Feb	p2211	0800
15 Feb	*****	0802	*****	0802	*****	0801	15 Feb	p2335	0802
16 Feb	0102	0805	0103	0804	0103	0804	16 Feb	0102	0805
17 Feb	0231	0811	0232	0810	0232	0810	17 Feb	0231	0811
18 Feb	0359	0824	0358	0821	0400	0823	18 Feb	0359	0824
19 Feb	0517	0852	0521	0850	0518	0851	19 Feb	0517	0852
20 Feb	0611	0949	0615	0944	0613	0947	20 Feb	0611	0949
21 Feb	0639	1112	0643	1110	0641	1111	21 Feb	0639	1112
22 Feb	0653	1250	0655	1247	0653	1249	22 Feb	0653	1250
23 Feb	0659	1431	0700	1429	0700	1430	23 Feb	0659	1431
24 Feb	0720	1611	0702	1611	0703	1611	24 Feb	0702	1611
25 Feb	0704	1715	0704	1749	0705	1751	25 Feb	0704	1751
26 Feb	0706	1931	0705	1930	0706	1930	26 Feb	0706	1931
27 Feb	0707	2112	0707	2113	0707	2112	27 Feb	0707	2112
28 Feb	0709	2257	0708	2256	0709	2257	28 Feb	0709	2257

3. METHODOLOGY

3.1 The Process. The project followed these steps:

- Run models for 365 days of 1990.
- Reformat the three models' output into a single file.
- Upload these files to USAFETAC IBM 3090 mainframe computer.
- Use SAS to process the files and produce frequency of error times in minutes.
- Download these frequency distributions to a microcomputer.
- Import the frequency distributions into Harvard Graphics 3.0.
- Produce graphs of frequency distributions.

3.2 Running the Models.

LIGHTPC and ICE. We installed the software on an 80386-based microcomputer and ran the programs for 1990. We ran the models for each latitude of interest on 0° W longitude, and saved the output to appropriately named files.

Navy Mainframe. We asked the Naval Observatory to run their mainframe program for the latitudes of interest for 1990 on the 0° W longitude. They ran the code, and provided us the output datasets in machine-readable form.

3.3 Reformatting the Output. Each of the three model's event times were initially saved in separate files in different formats. To subtract the LIGHTPC and ICE event times from the Navy mainframe event times, we reformatted the data into a single file of four columns: *Date, Navy mainframe event time, LIGHTPC event time, and ICE event time* (see Table 4).

3.4 Uploading the Files. Once all the model outputs were reformatted and placed in a single simple column format file, the column format files were uploaded to USAFETAC's IBM 3090 mainframe computers for processing.

3.5 SAS Processing. We used SAS v6.06 to calculate the difference in minutes between the microcomputer programs' event times and the Navy mainframe program's event times. We then used SAS to compute the frequency distribution of the minutes of error for both LIGHTPC and ICE.

TABLE 5. Example of SAS Error Frequency Distribution Table.

NARISE	Days	Percent	Cumulative Days	Cumulative Percent
-2	10	2.7	10	2.7
-1	66	18.1	76	20.8
0	159	43.6	235	64.4
1	81	22.2	316	86.6
2	35	9.6	351	96.2
3	14	3.8	365	100.0

1. NARISE — Minutes of error [(Navy mainframe event time) - (Air Force LIGHTPC event time)]
2. Days — Number of days with the minutes of error in NARISE column
3. Percent — Percent of days with minutes of error in NARISE column
4. Cumulative Days — Cumulative number of days from most negative to most positive minutes of error
5. Cumulative Percent — Cumulative percentage of days from most negative to most positive minutes of error

3.6 Downloading the Error Distributions. We downloaded the SAS-generated error frequency distributions (see Table 5) to a microcomputer for the final steps of producing tables and graphs for the report.

3.7 Producing Bar Charts Using Harvard Graphics 3.0. We imported the frequency distribution data into Harvard Graphics 3.0 and made bar charts of the error distributions for each latitude and each solar or lunar event.

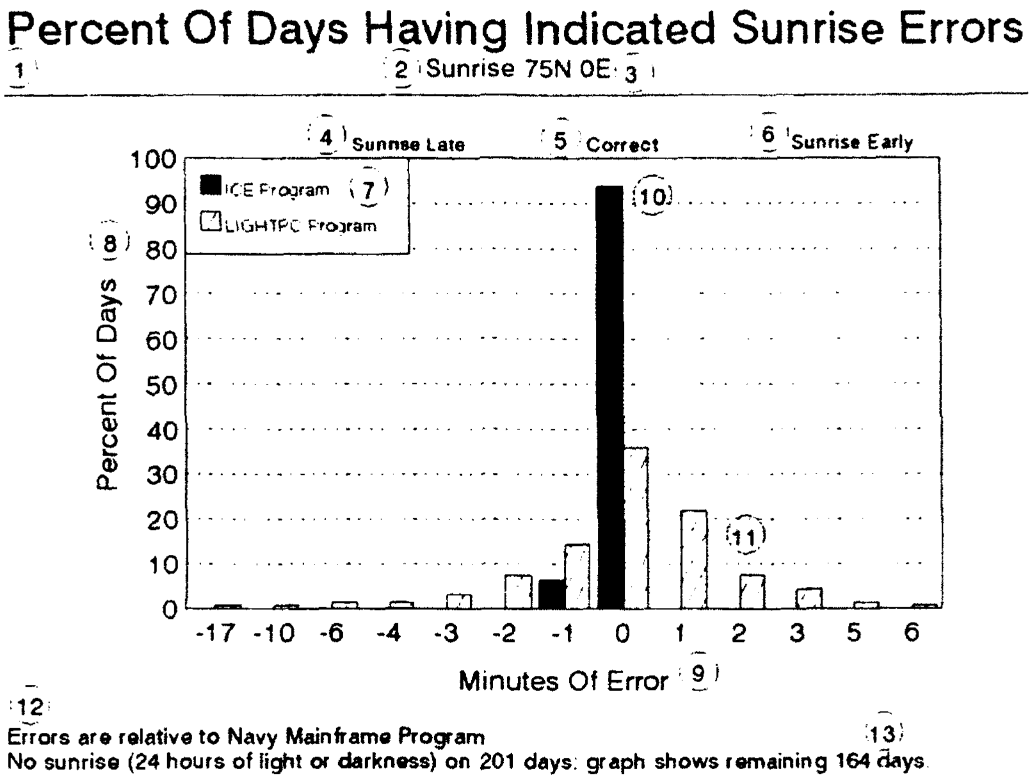


Figure 1. Example of Bar Chart and Key to Charts in Appendices A - F. Circled numbers provide keys to chart elements listed below.

1. Title
2. Event (Sunrise, Sunset, Twilight Start, Twilight End, Moonrise, Moonset)
3. Latitude and Longitude
4. Events predicted later than actual event
5. Events predicted correctly
6. Events predicted earlier than actual event
7. Bar graph legend.
8. Y-axis Title: Percentage of days on which event occurred
9. X-axis Title: Minutes of error between PC program and Navy mainframe program.
10. ICE data. Here, about 93% of the days with a sunrise had ICE predict the sunrise exactly correct, and about 7% of the days with a sunrise had ICE predict the sunrise late by 1 minute. (Note: there are only 164 days with a sunrise at 70° N, the sun was either above or below the horizon on the remaining 201 days.)
11. LIGHTPC data. Here, about 35% of the days with a sunrise had LIGHTPC predict the sunrise exactly. The remaining 65% of the days with a sunrise have LIGHTPC errors ranging from 17 minutes late to 6 minutes early.
12. Note reminding users that all errors are in minutes relative to the Navy mainframe program event times.
13. Note stating how many days the event occurred. In this example, the sun did not r-- on 201 days, but the remaining 164 days had a sunrise and are shown.

4. RESULTS

4.1 Summary. The results presented here are a synopsis of the full analysis. We analyzed the performance of two microcomputer programs that predict solar and lunar event times at latitudes 60°N to 89° N on the Greenwich Meridian (0°E). Results shown for 89° N should be used with caution because there are so few solar and lunar events at this latitude. There are bugs in the ICE software that cause large errors in twilight end times. Charts showing the error distributions of all the data are in the appendices. Overall, LIGHTPC is the more robust of the two programs. Although it has larger maximum errors and less perfect predictions, it does not suffer from the bugs that degrade ICE's predictions. ICE surpasses LIGHTPC in sunrise, sunset, moonrise, moonset and twilight start predictions, but LIGHTPC surpasses ICE in twilight end predictions. Neither program is very accurate for lunar events above 75° N.

4.2 Maximum Errors. The maximum errors of the ICE and LIGHTPC program are shown in Table 6. For sunrise, sunset, and twilight start, the ICE program is very accurate; most predictions have no errors. For twilight end, ICE has bugs that cause large errors in event prediction times. The LIGHTPC program is also accurate, with maximum errors occurring on days when the event is starting after a period of non-event. An example of this is when the Arctic transitions from winter to spring and the sun begins to rise in the far north after months of winter darkness. LIGHTPC will have a fairly large error (on the order of 10 minutes) on the first day that the sun rises after the long winter night. On subsequent days the error decreases to within a few minutes.

Maximum errors for twilight end could not be determined for ICE, which does not produce values for twilight end at and above 70° N.

Moonrise and moonset maximum errors for ICE are not available for 60, 65, 75, and 85° N because the datafiles were lost during this study. The demise (with no replacement) of the Navy mainframe model made it impossible for the lost files to be recreated.

TABLE 6. Maximum Minutes Early/Late at Each Latitude.

EVENT	LATITUDE						
	60°	65°	70°	75°	80°	85°	89°
Sunrise							
ICE	1/1	1/1	1/1	0/1	0/1	0/3	*/15
LIGHTPC	3/2	5/3	20/24	6/17	5/10	4/8	10/10
Sunset							
ICE	1/1	1/0	2/1	1/0	1/0	3/0	14/*
LIGHTPC	2/3	4/5	23/16	10/14	8/5	5/4	5/4
Twilight Start							
ICE	1/0	1/1	1/1	1/1	0/1	0/1	*/12
LIGHTPC	6/1	5/1	5/1	5/2	5/22	5/6	6/3
Twilight End							
ICE	1/0	1/0	1/?	1/?	?/?	?/?	?/?
LIGHTPC	1/16	2/14	2/15	2/17	6/21	6/7	5/5
Moonrise							
ICE	#	#	7/8	#	1/24	#	155/245
LIGHTPC	6/3	29/15	15/10	16/6	23/8	23/331	29/77
Moonset							
ICE	#	#	28/8	#	19/0	#	662/429
LIGHTPC	4/6	17/17	12/15	7/11	74/42	287/22	143/36

* Indicates no predictions in the appropriate early/late category.

? Indicates ICE ERRORS: No Values.

# Indicates missing predictions due to data loss.

4.3 Precision and Accuracy. The ICE program had at least 9 out of 10 perfect predictions for sunrise, sunset, and twilight start at latitudes below 80° N (see Table 7). This accuracy is truly outstanding for such high latitudes. ICE does worse for moonrise, moonset, and twilight end. It is worth noting that even with a software bug that affects twilight end, ICE had more perfect predictions than LIGHTPC in all but a few cases. LIGHTPC had, at most, 5 out of 10 perfect predictions for all the events studied here. LIGHTPC produces a distribution of event times for each event at each latitude (see Figure 1 and appendices). This means that while the LIGHTPC program may not be as *precise* as the ICE program, it is as *accurate*. "Precision" is a measure of the spread of data; it can be roughly estimated for the two programs by examining Tables 6 and 7. "Accuracy" is a measure of how close the maximum in the data distribution matches the value desired (here, zero minutes error), and can be estimated for the two programs by examining Table 7.

TABLE 7. Percent of Event Predictions Without Error at each Latitude.

EVENT	LATITUDE 60°	65°	70°	75°	80°	85°	89°
Sunrise							
ICE	95.3	87.7	92.1	93.8	80.6	70.6	0
LIGHTPC	43.6	34.2	36.5	36.0	34.0	29.4	9.1
Sunset							
ICE	92.9	91.8	93.4	91.5	90.4	74.5	0
LIGHTPC	35.3	31.5	34.9	37.2	36.5	27.5	9.1
Twilight Start							
ICE	99.3	97.6	98.1	97.9	97.7	89.5	0
LIGHTPC	53.3	45.3	51.9	38.2	32.6	35.1	9.1
Twilight End							
ICE	97.9	95.6	72.3	50.5	31.5	0	0
LIGHTPC	48.4	40.2	45.9	34.5	30.0	36.2	36.4
Moonrise							
ICE	#	#	34.8	#	10.7	#	11.1
LIGHTPC	18.4	13.9	15.7	9.7	3.5	2.2	7.1
Moonset							
ICE	#	#	51.3	#	8.4	#	0
LIGHTPC	18.7	16.2	15.8	8.3	6.0	0	0

# Indicates missing predictions due to data loss.

The LIGHTPC event prediction time distribution maximizes at zero minutes error in all solar events at and below 85° N. The accuracy of LIGHTPC is not as good for moonrise and moonset; its predicted maximum is usually no more than 3 minutes from the expected zero minutes of error (see the appendices).

The ICE program event prediction time distribution maximizes at zero minutes of error in all solar events at and below 85° N. The ICE error distribution maximizes at zero minutes error at 70° N, and at 1 minute of error at 80° N. The ICE predicted maximum is usually no more than 2 minutes from the expected error at 70° N, and no more than 3 minutes from the expected error at 80° N (see appendices). The results at 89° N are from too small a sample size to yield useful results.

4.4 Non-Event Predictions. "Non-event" days are those on which neither sunrise, sunset, twilight start, twilight end, moonrise, nor moonset occur. There are many non-event days at the polar latitudes. A good example is polar summer, when the sun may not rise or set for months, but is always above the horizon.

One question that SAC did not specifically ask, but that is important in assessing computer models that predict solar and lunar event times is, "Did the program correctly predict the days when nothing happens?" The answer to this question for LIGHTPC and ICE is "yes" for sunrise and sunset, "almost" for twilight, and "no" for moonrise and moonset.

Both programs correctly predict days with no sunrise and no sunset at all latitudes. LIGHTPC made one mistake in predicting twilight start and end; it occurred on March 3rd, when there were just 12 minutes of darkness between twilight end and twilight start. An ICE software bug results in many twilight end errors at and above 80° N. Both programs make errors in predicting days with no moonrise or no moonset.

LIGHTPC predicts moonrise and moonset when there are none for 31 December from 65° N to 75° N, but it seems to have a problem predicting instances when the moon sets for less than an hour before rising again. Except for the 31 December errors mentioned earlier, all LIGHTPC failures to correct to predict non-event days correctly occurred on days when the moon set for less than 1 hour. This happened three times at 65° N, three times at 70° N, once at 75° N, and twice at 85° N (see Table 8). On these days, LIGHTPC predicted a non-event day when the moon actually rose or set.

TABLE 8. Non-Event Prediction Error Table.

EVENT	LATITUDE						
	60°	65°	70°	75°	80°	85°	89°
Sunrise							
ICE	0	0	0	0	0	0	0
LIGHTPC	0	0	0	0	0	0	0
Sunset							
ICE	0	0	0	0	0	0	0
LIGHTPC	0	0	0	0	0	0	0
Twilight Start							
ICE	0	0	0	0	39	92	138
LIGHTPC	0	0	0	0	0	1	0
Twilight End							
ICE	0	0	0	0	0	0	0
LIGHTPC	0	0	0	0	0	1	0
Moonrise							
ICE	#	#	3	#	4	#	6
LIGHTPC	0	4	4	2	0	2	0
Moonset							
ICE	#	#	3	#	2	#	2
LIGHTPC	0	4	4	2	0	2	0

# Indicates missing predictions due to data loss.

5. RECOMMENDATIONS

5.1 Use LIGHTPC and ICE "as is." LIGHTPC is a robust program that produces accurate predictions of sunrise, sunset, twilight start, and twilight end times. It is also fairly precise for these events at and below 85° N. Most (90% or more) of the predictions are within 2 minutes of the actual event time.

ICE can be used to provide accurate sunrise and sunset times with high precision up to 85° N. ICE also produces accurate and highly precise twilight start times up to 85° N. Unfortunately, ICE has software deficiencies that make it unusable by itself for twilight end times. For these events, it may be possible to use both ICE with LIGHTPC to determine better event times than could be determined by either program alone.

For the twilight end times, use ICE for those dates on which it does not have errors, but use LIGHTPC for dates on which ICE *does* have errors.

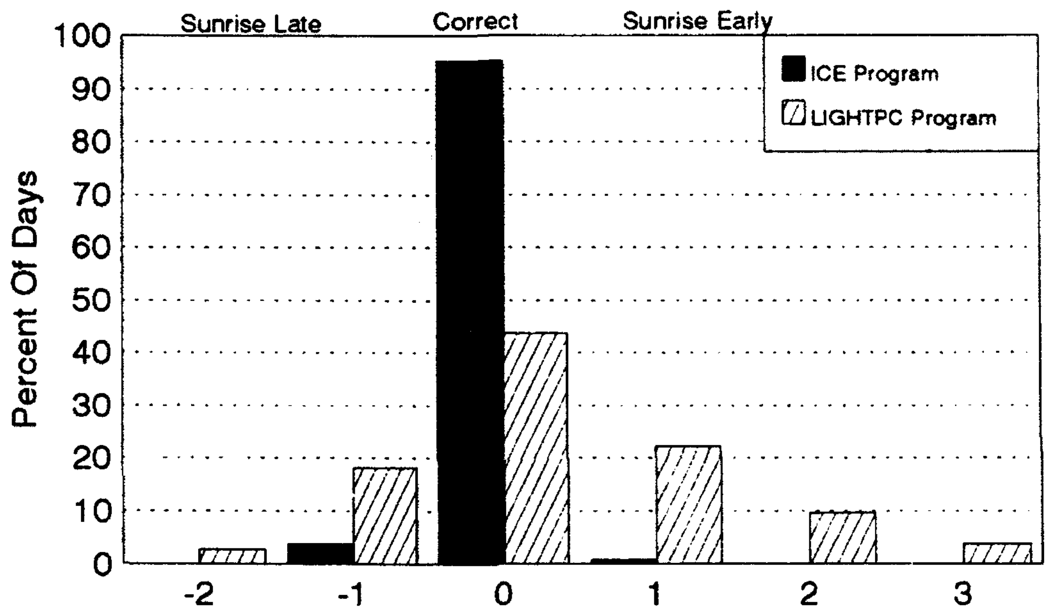
5.2 Other Solutions. The Naval Observatory is working on a new PC ephemeris program called "MICA" (Multi-year Interactive Computer Almanac) that should be released in 1993. This program should fix the problems with the ICE program, and will correct, as far as possible, errors in event times caused by atmospheric refraction at high latitudes. The MICA program will be available from the Nautical Almanac Office, U.S. Naval Observatory, Washington, D.C. 20392.

APPENDIX A

CHARTS OF INDICATED *SUNRISE* ERRORS

(Percent of Days)

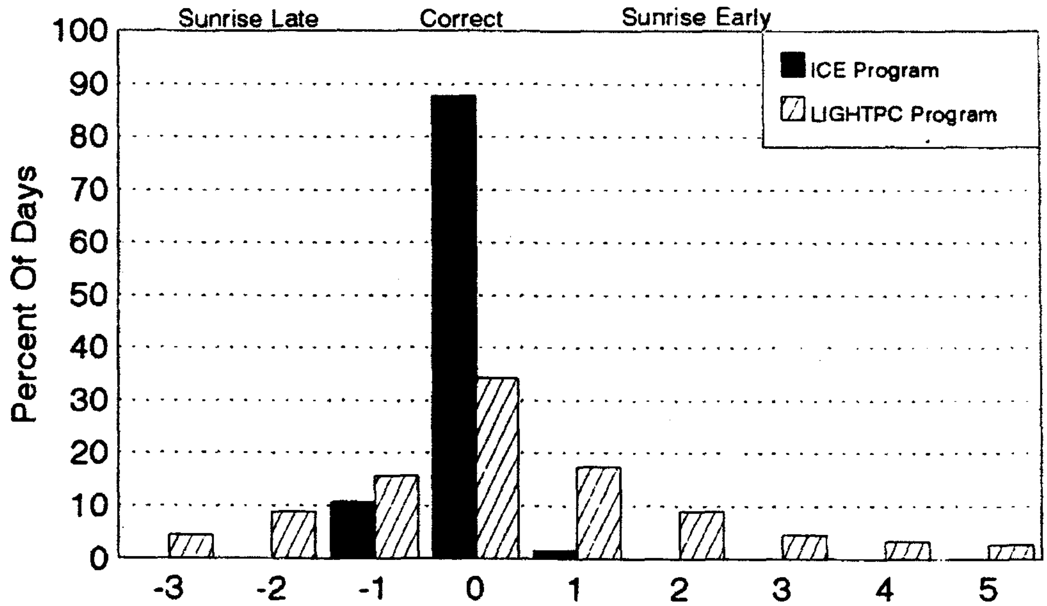
SUNRISE 60N 0E



MINUTES OF ERROR

Errors are relative to Navy mainframe program.
Sunrise on all 365 days; graph shows 365 days.

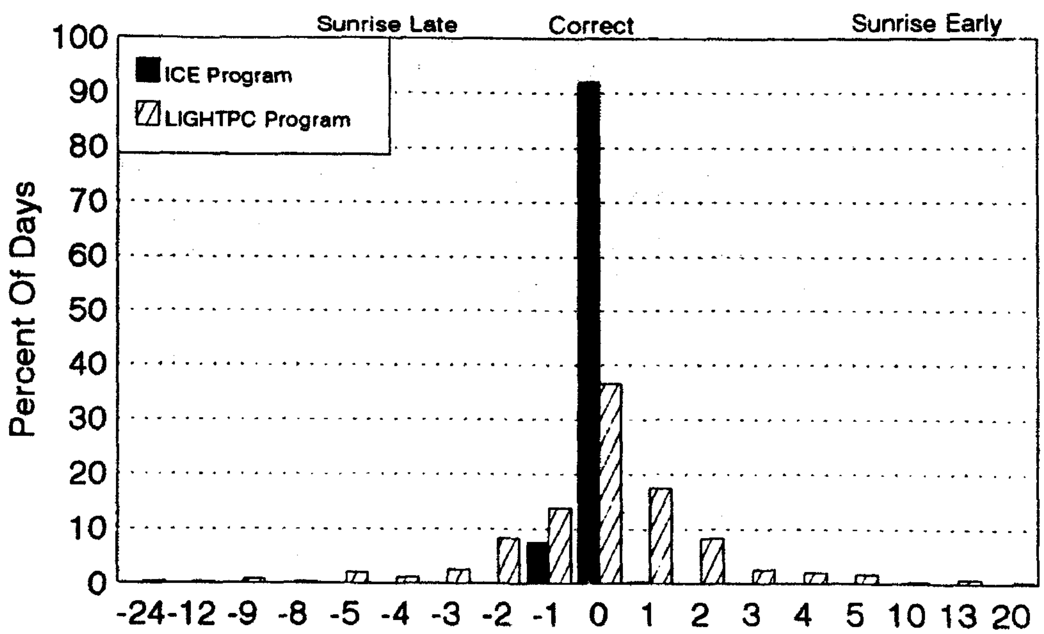
SUNRISE 65N 0E



MINUTES OF ERROR

Errors are relative to Navy mainframe program.
Sunrise on all 365 days; graph shows 365 days.

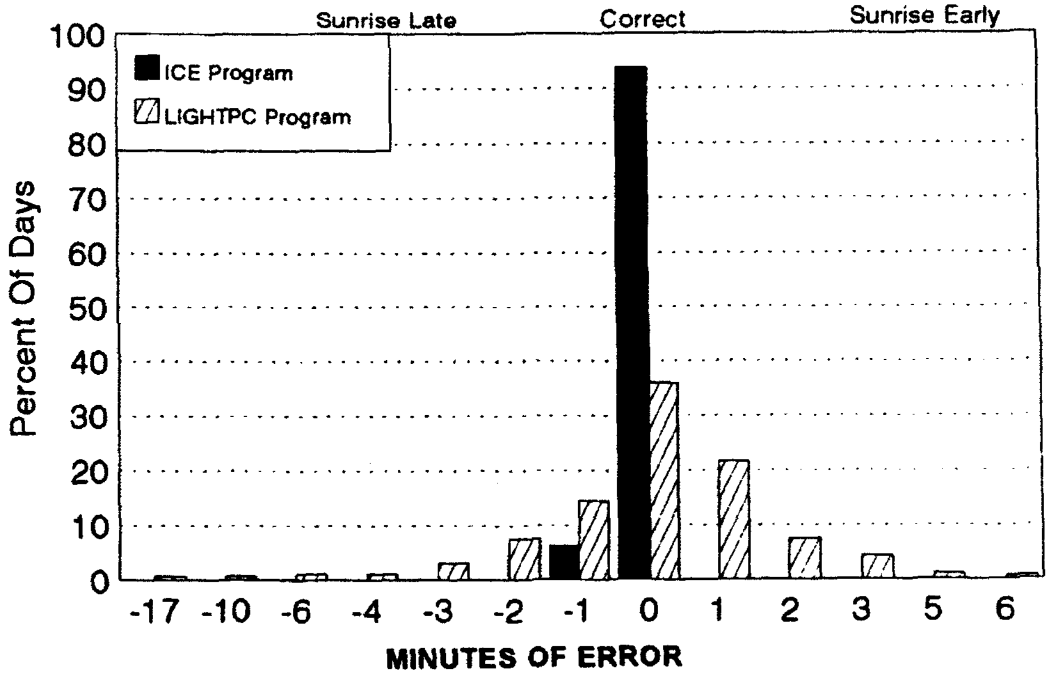
SUNRISE 70N 0E



MINUTES OF ERROR

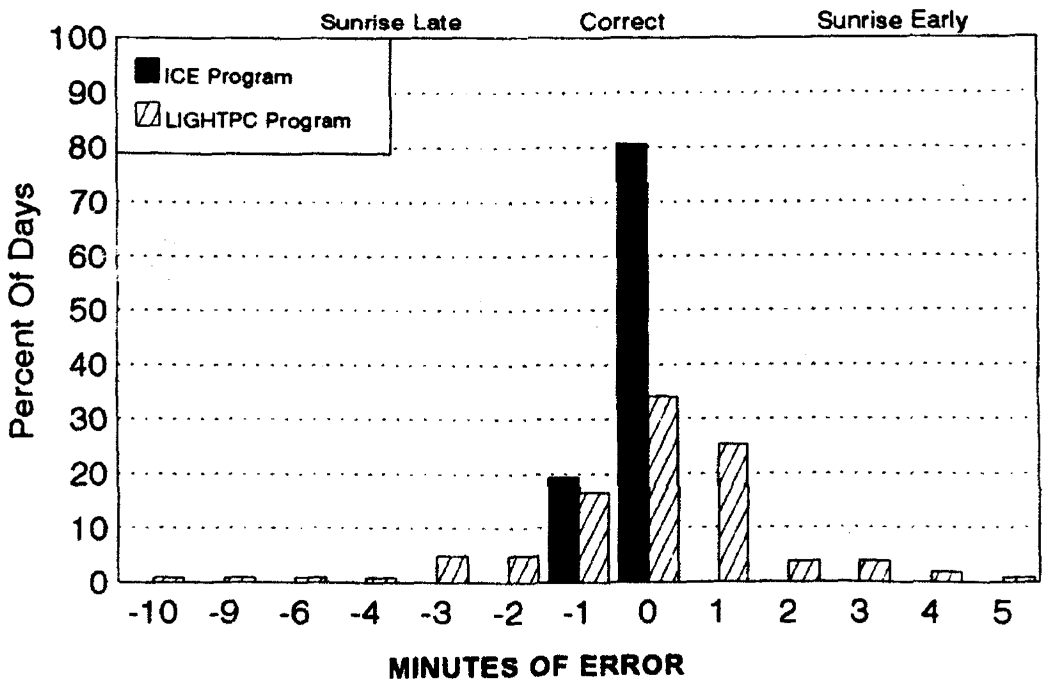
Errors are relative to Navy Mainframe Program.
No sunrise (24 hours of light or darkness) on 124 days; graph shows remaining 241 days.

SUNRISE 75N 0E



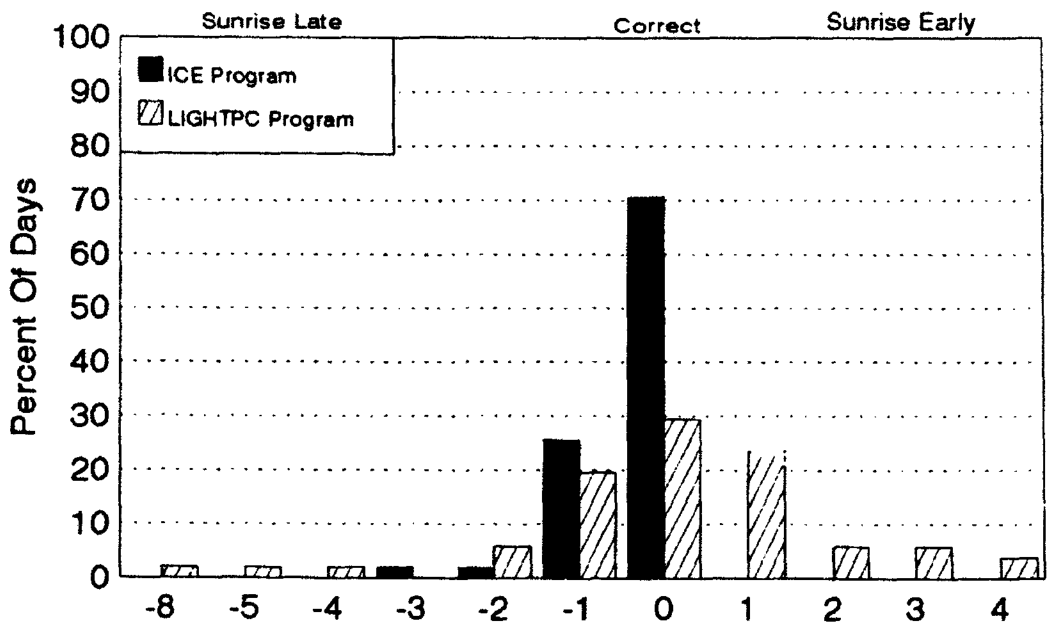
Errors are relative to Navy mainframe program.
No Sunrise (24 hours of light or darkness) on 201 days; graph shows remaining 164 days.

SUNRISE 80N 0E



Errors are relative to Navy Mainframe Program.
No sunrise (24 hours of light or darkness) on 262 days; graph shows remaining 103 days.

SUNRISE 88N 0E

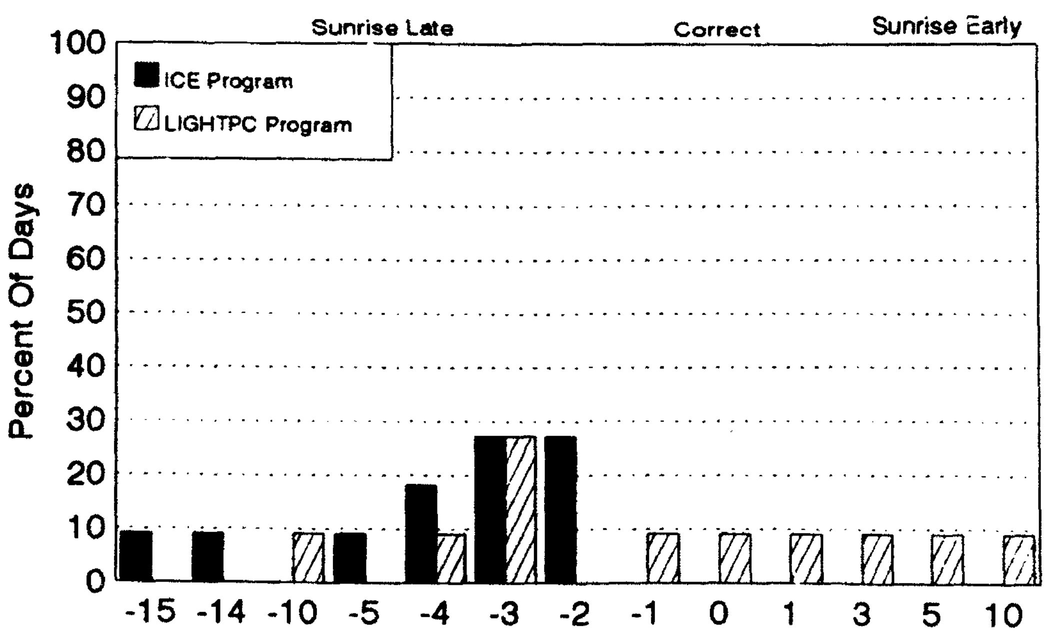


MINUTES OF ERROR

Errors are relative to Navy mainframe program.

No Sunrise (24 hours of light or darkness) on 314 days; graph shows remaining 51 days.

SUNRISE 89N 0E



MINUTES OF ERROR

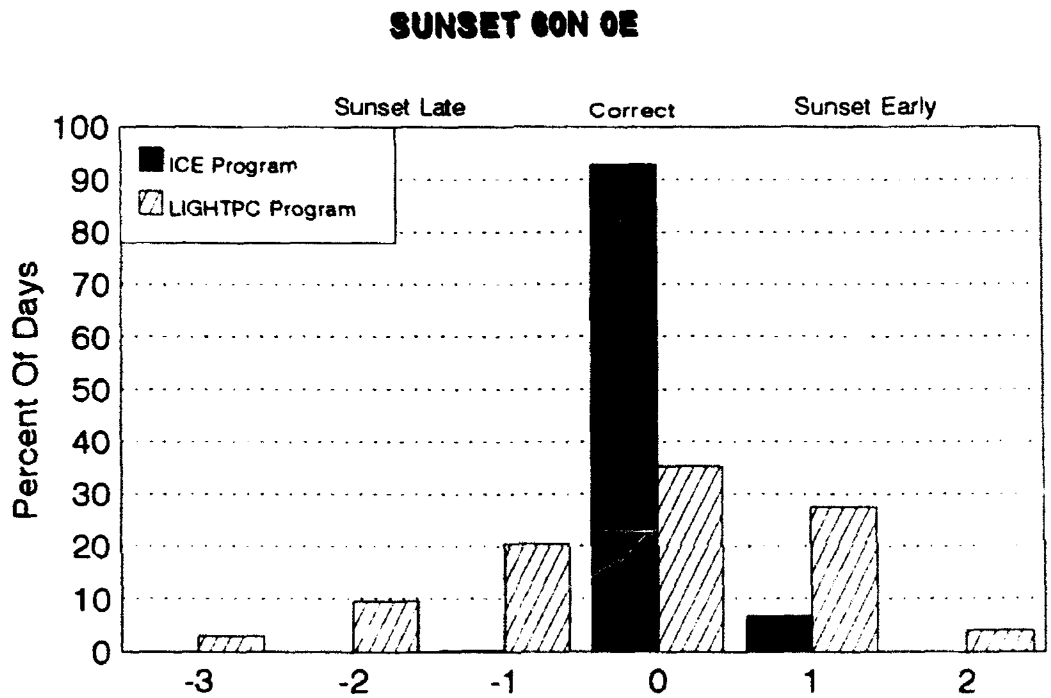
Errors are relative to Navy Mainframe Program.

No sunrise (24 hours of light or darkness) on 354 days; graph shows remaining 11 days.

APPENDIX B

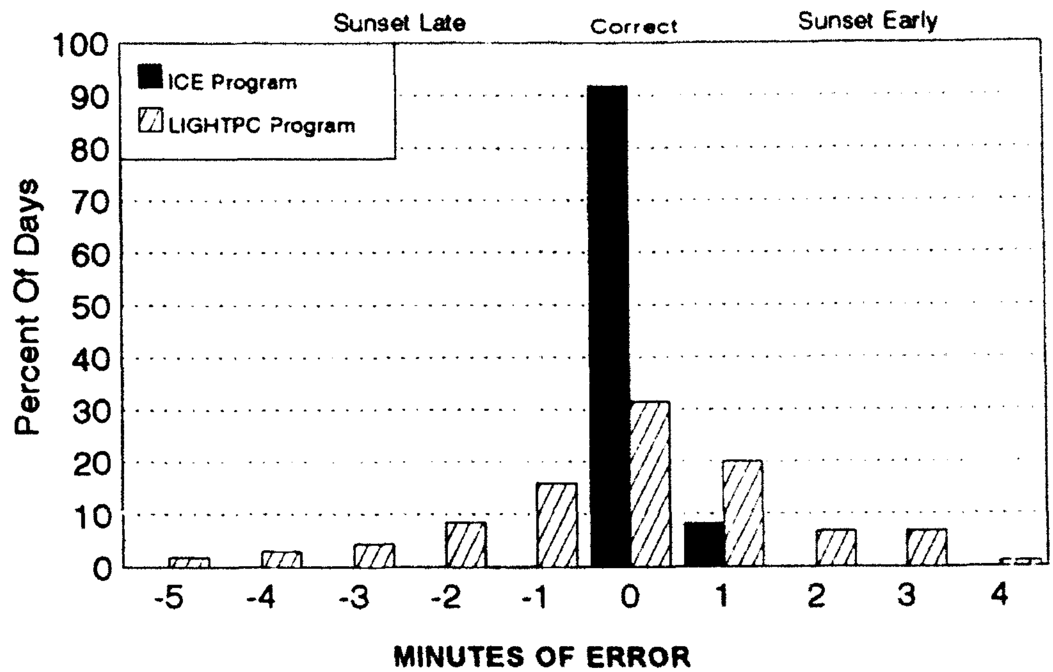
CHARTS OF INDICATED *SUNSET* ERRORS

(Percent of Days)



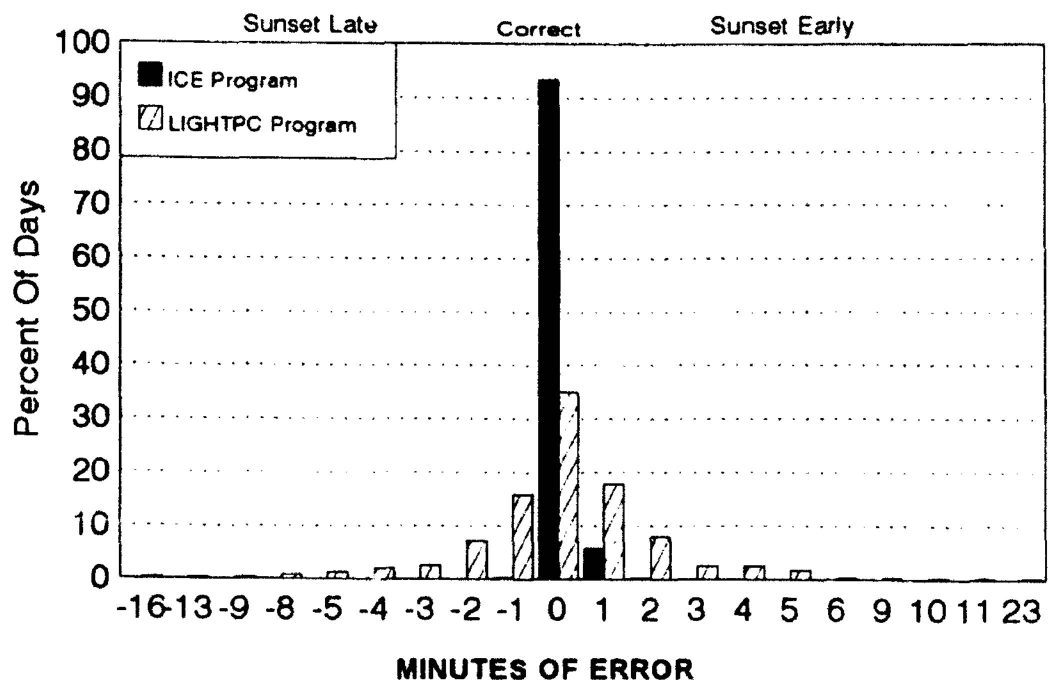
MINUTES OF ERROR
Errors are relative to Navy mainframe program.
Sunset on all 365 days; graph shows 365 days.

SUNSET 66N 0E



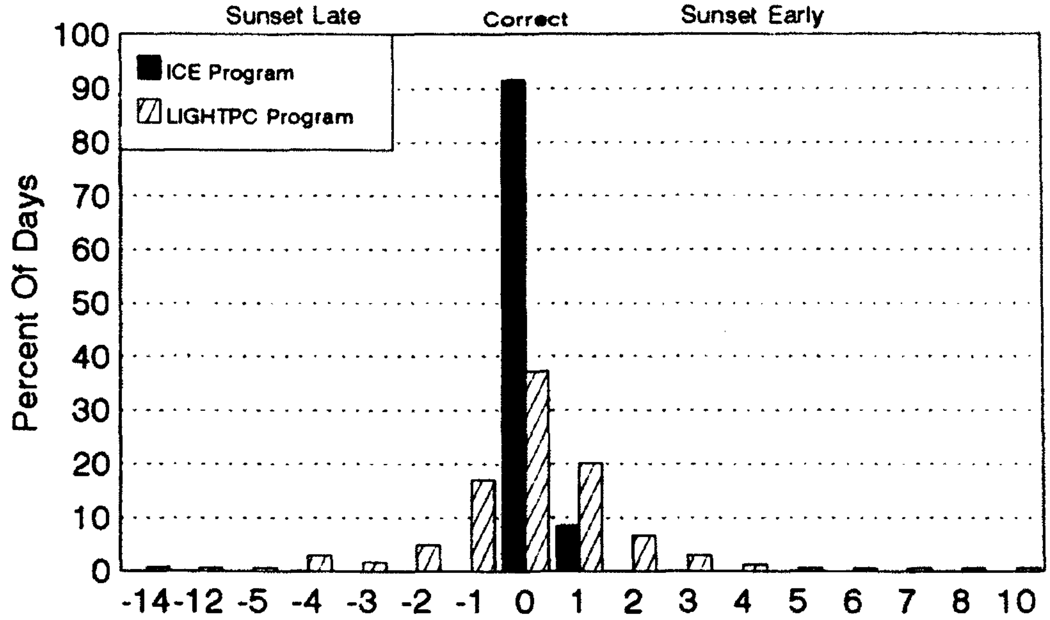
Errors are relative to Navy mainframe program.
Sunset on all 365 days; graph shows 365 days.

SUNSET 70N 0E



Errors are relative to Navy Mainframe Program.
No sunset (24 hours of light or darkness) on 124 days; graph shows remaining 241 days.

SUNSET 78N 0E

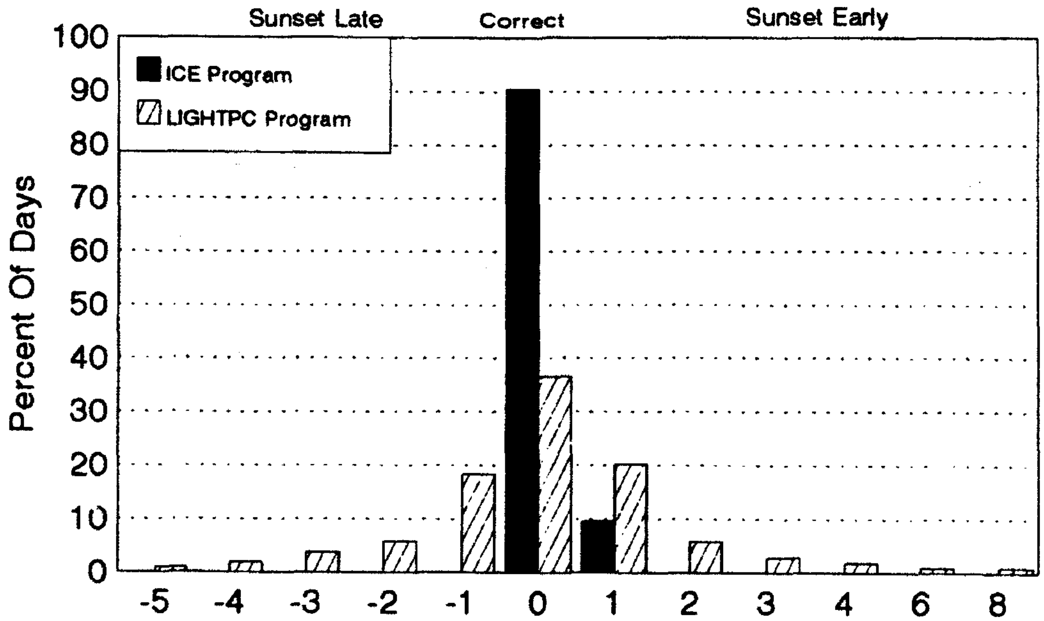


MINUTES OF ERROR

Errors are relative to Navy mainframe program.

No sunset (24 hours of light or darkness) on 201 days; graph shows remaining 164 days.

SUNSET 80N 0E

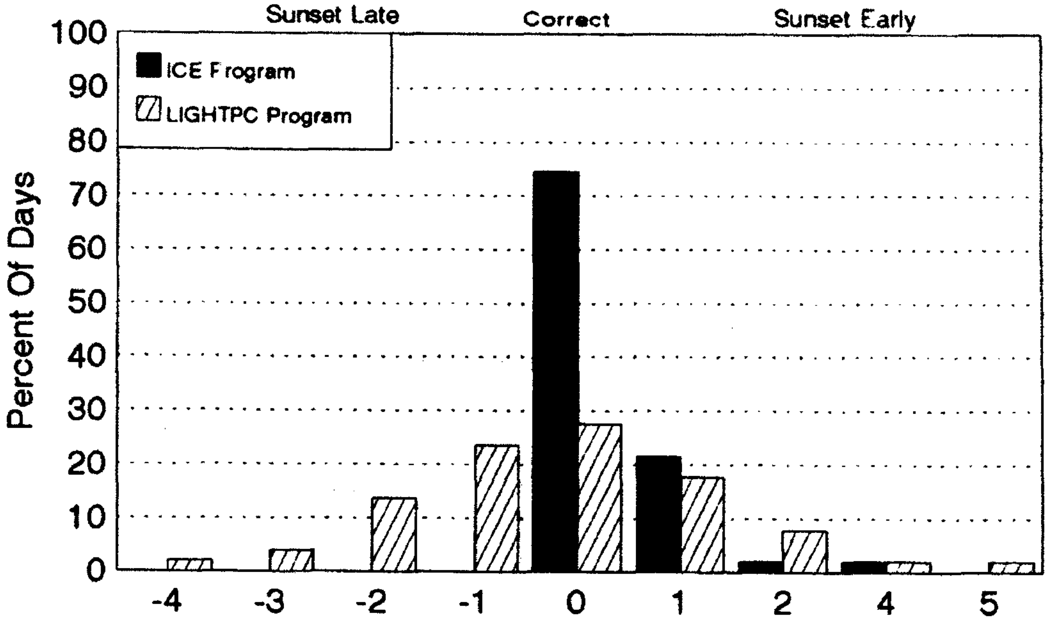


MINUTES OF ERROR

Errors are relative to Navy Mainframe Program.

No sunset (24 hours of light or darkness) on 261 days; graph shows remaining 104 days.

SUNSET 88N 0E

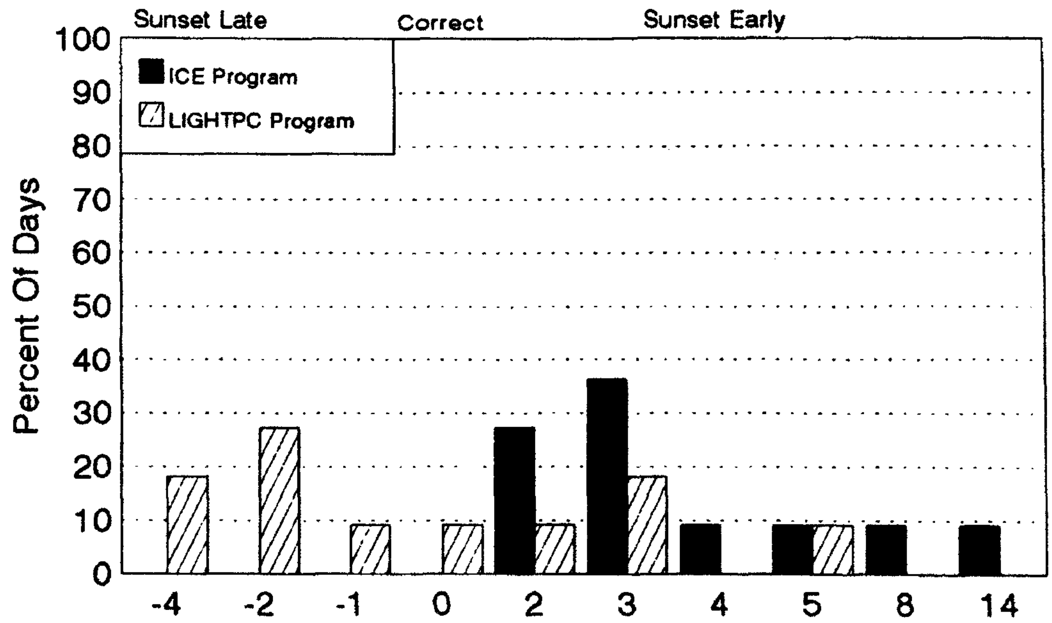


MINUTES OF ERROR

Errors are relative to Navy mainframe program.

No sunset (24 hours of light or darkness) on 314 days; graph shows remaining 51 days.

SUNSET 89N 0E



MINUTES OF ERROR

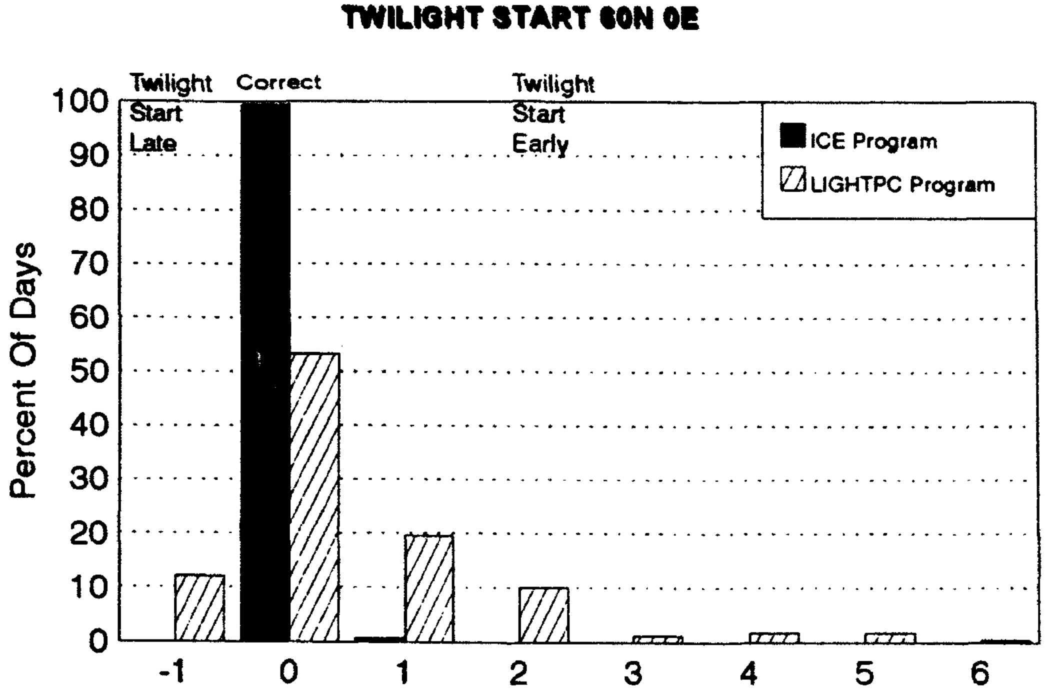
Errors are relative to Navy Mainframe Program.

No sunset (24 hours of light or darkness) on 354 days; graph shows remaining 11 days.

APPENDIX C

CHARTS OF INDICATED *TWILIGHT START* ERRORS

(Percent of Days)

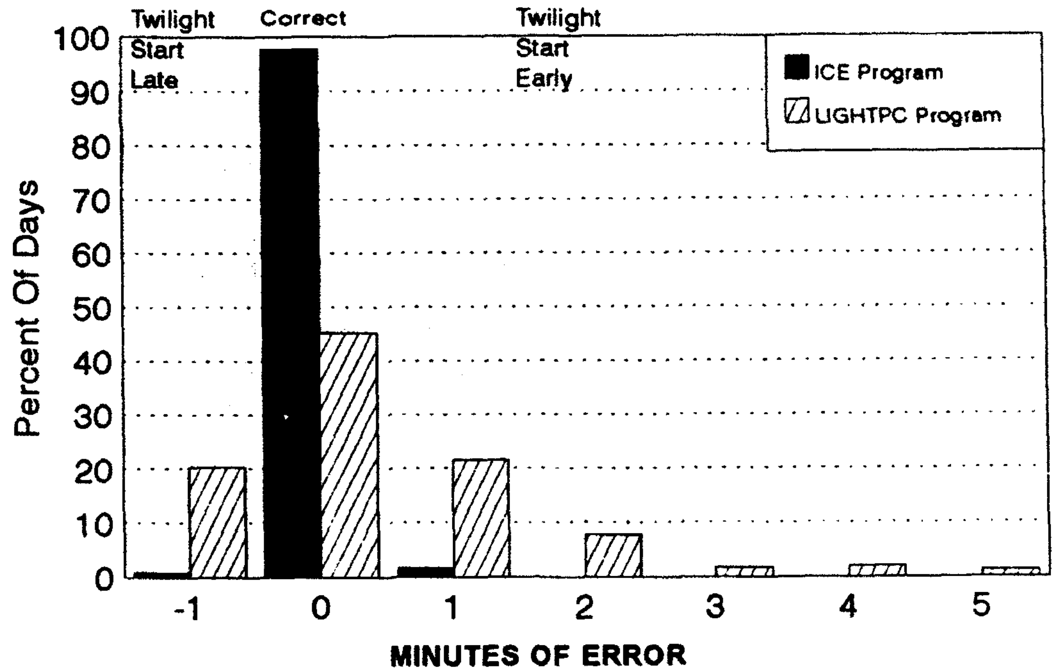


MINUTES OF ERROR

Errors are relative to Navy mainframe program.

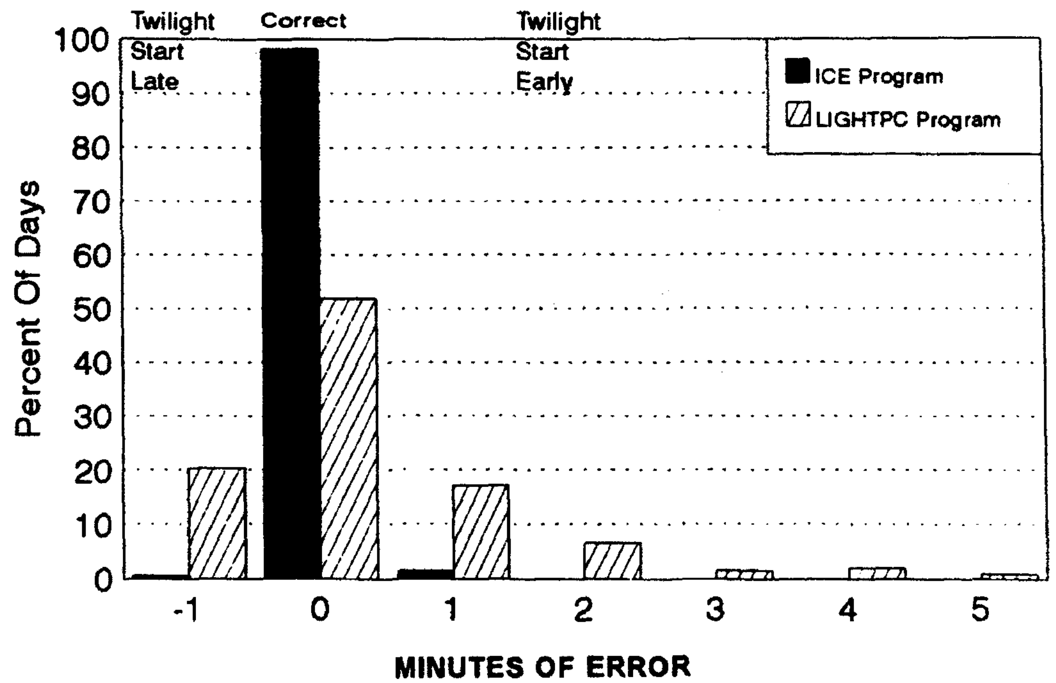
Twilight start criterion not met on 89 days; graph shows remaining 276 days.

TWILIGHT START 68N 0E



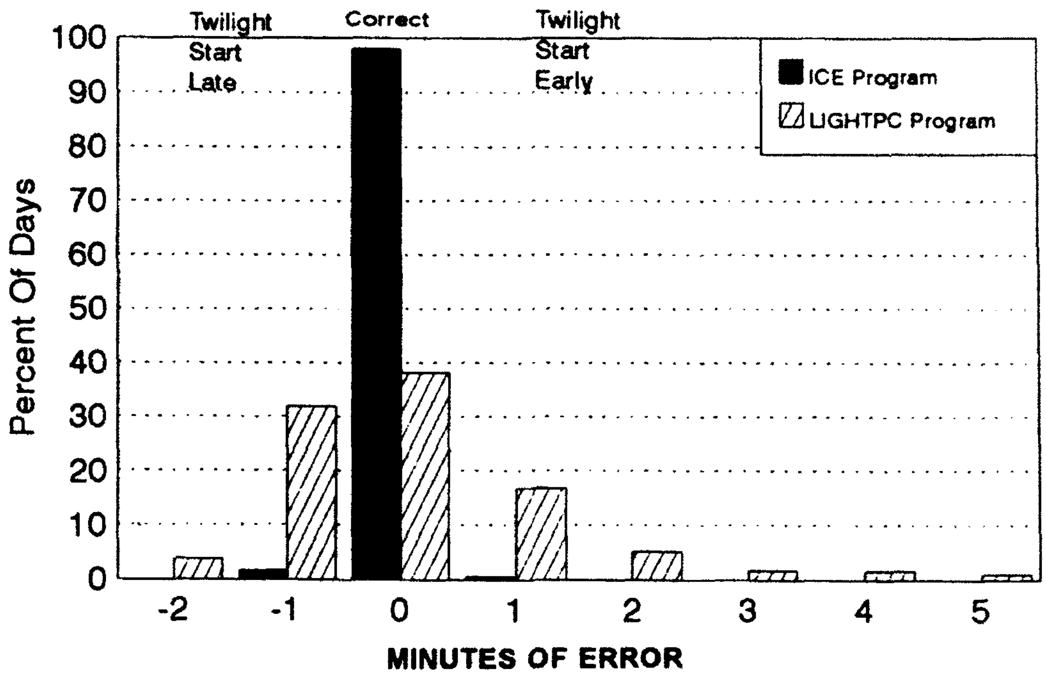
Errors are relative to Navy mainframe program.
Twilight start criterion not met on 120 days; graph shows remaining 245 days.

TWILIGHT START 70N 0E



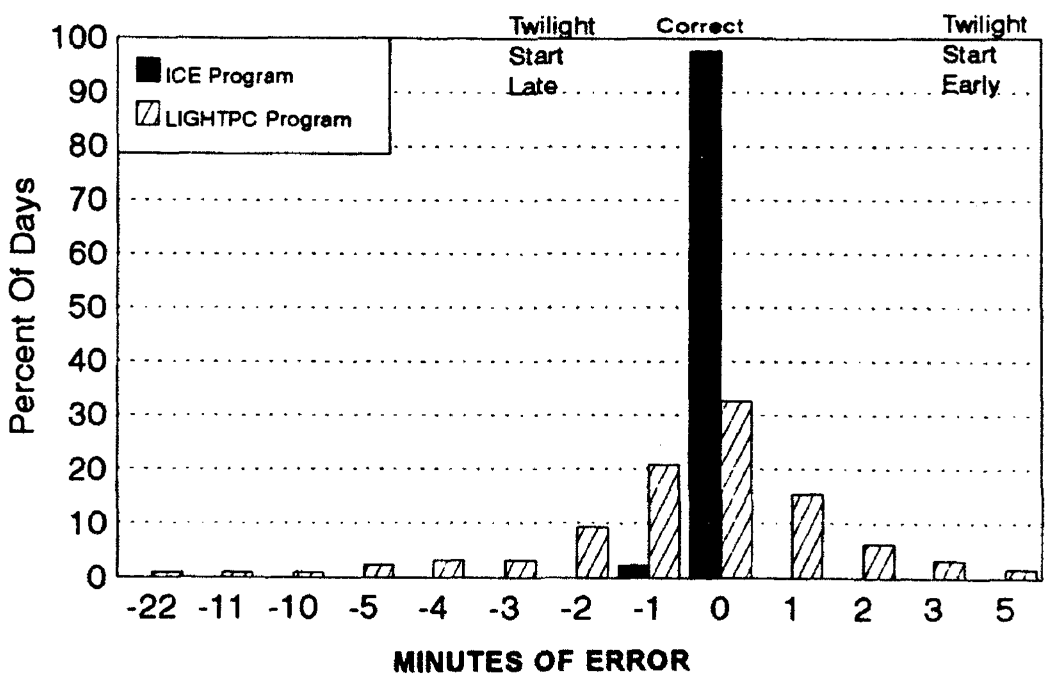
Errors are relative to Navy Mainframe Program.
Twilight start criterion not met on 149 days; graph shows remaining 216 days.

TWILIGHT START 78N 0E



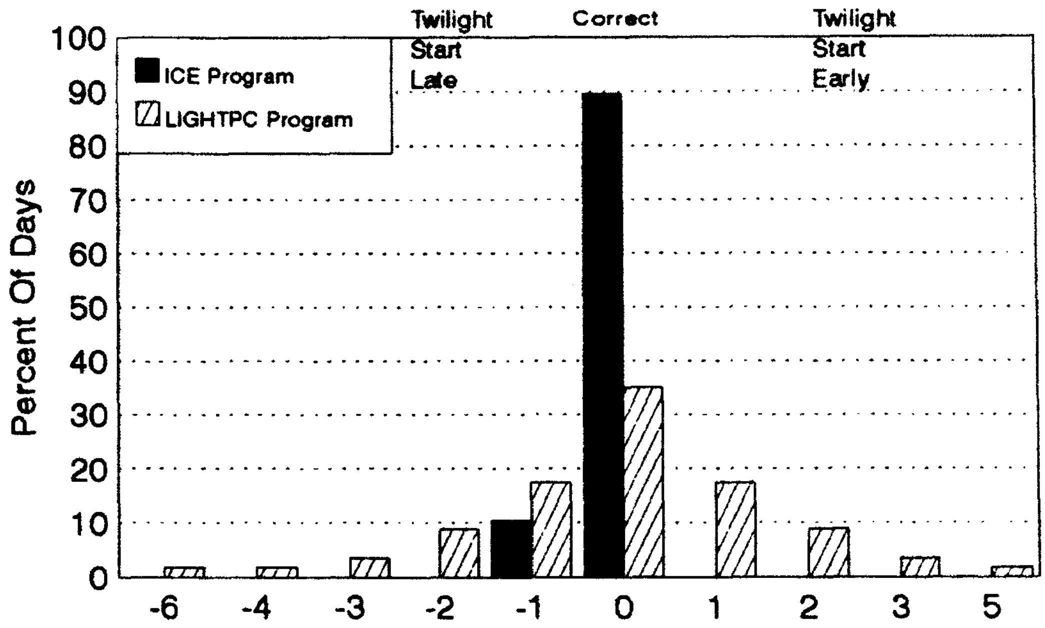
Errors are relative to Navy mainframe program.
Twilight start criterion not met on 174 days; graph shows remaining 191 days.

TWILIGHT START 80N 0E



Errors are relative to Navy Mainframe Program.
Twilight start criterion not met on 236 days; graph shows remaining 129 days.

TWILIGHT START 88N 0E

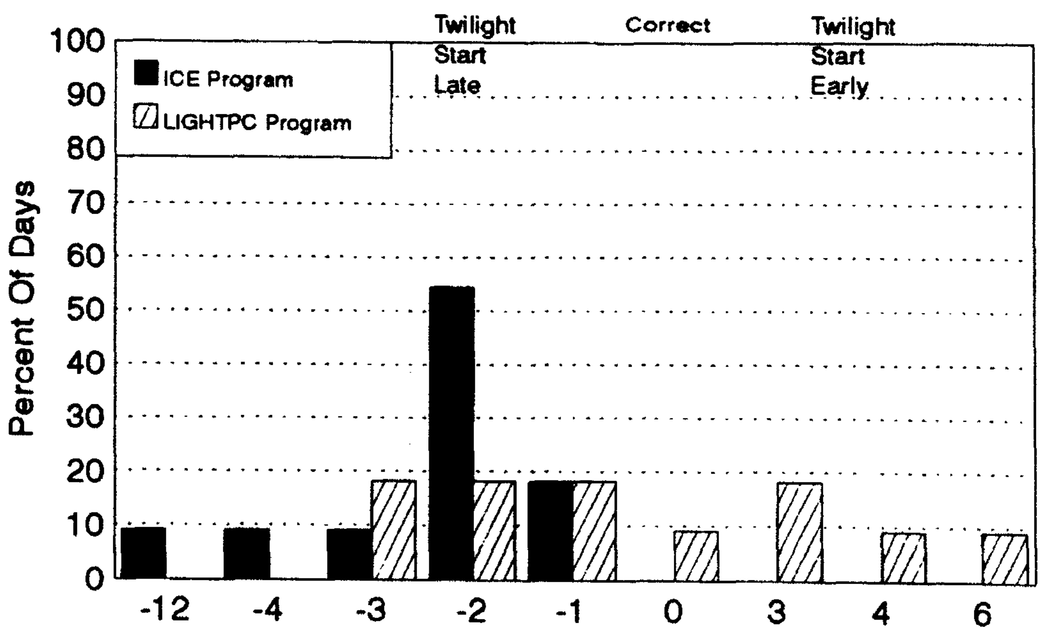


MINUTES OF ERROR

Errors are relative to Navy mainframe program.

Twilight start criterion not met on 308 days; graph shows remaining 57 days.

TWILIGHT START 89N 0E



MINUTES OF ERROR

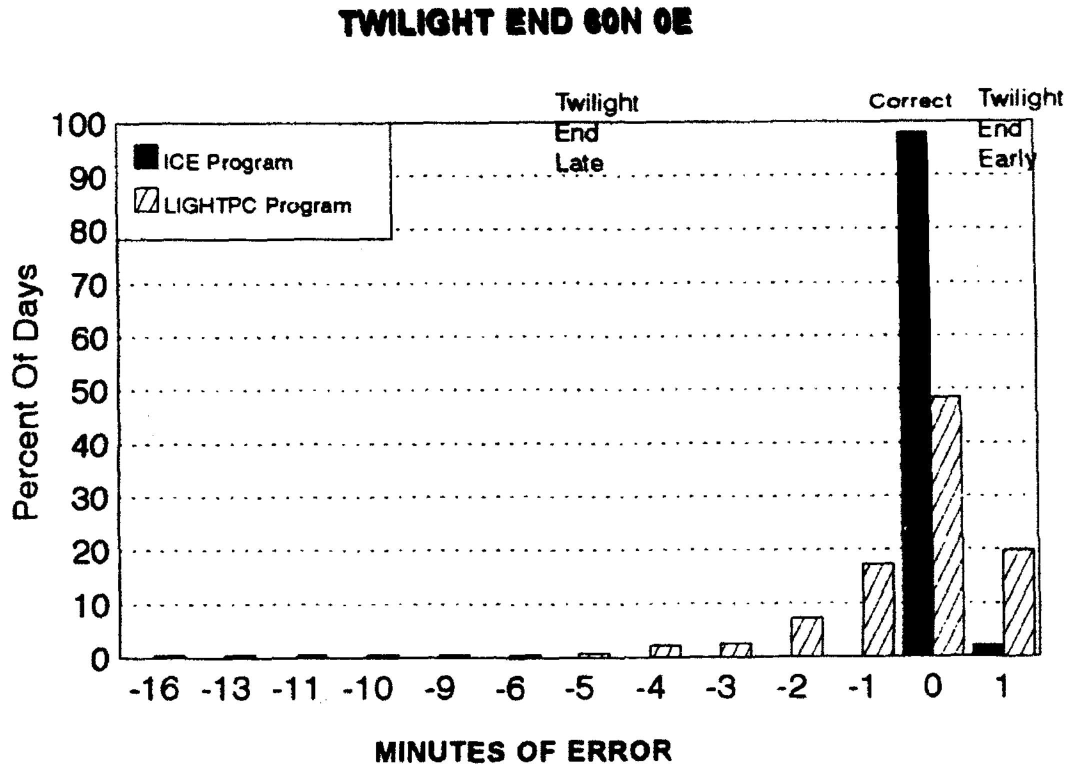
Errors are relative to Navy Mainframe Program.

Twilight start criterion not met on 354 days; graph shows remaining 11 days.

APPENDIX D

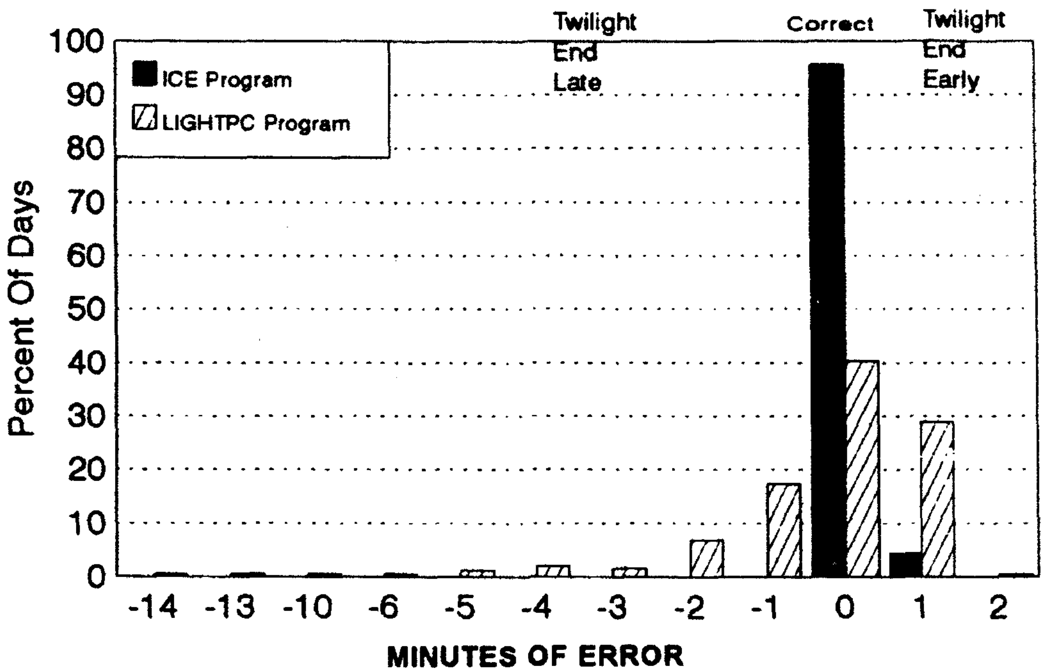
CHARTS OF INDICATED *TWILIGHT END* ERRORS

(Percent of Days)



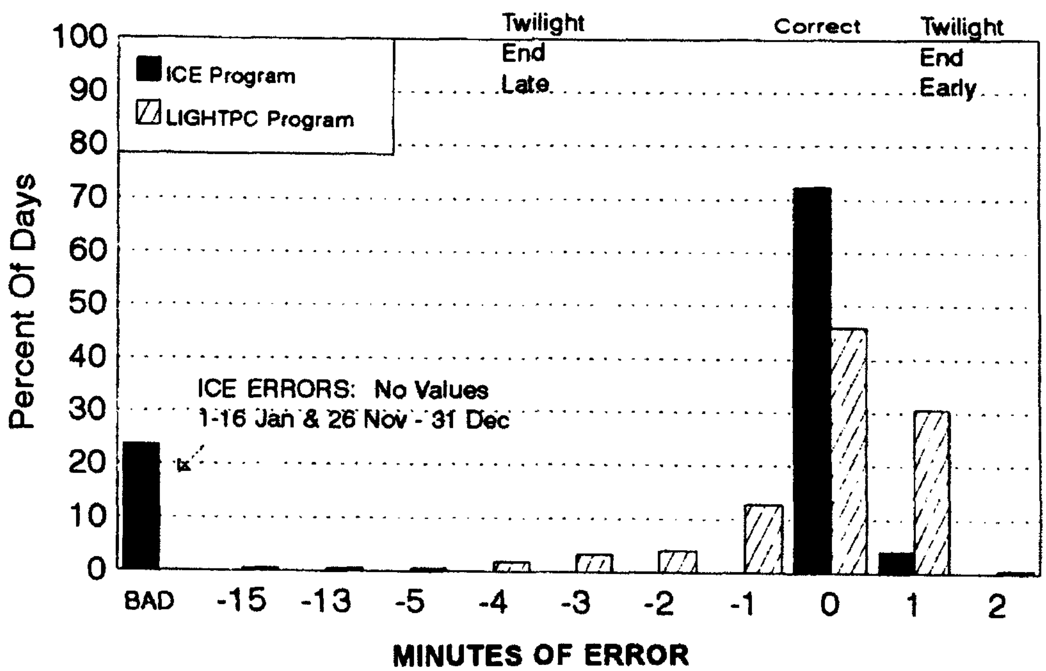
Errors are relative to Navy mainframe program.
Twilight end criterion not met on 82 days; graph shows remaining 283 days.

TWILIGHT END 68N 0E



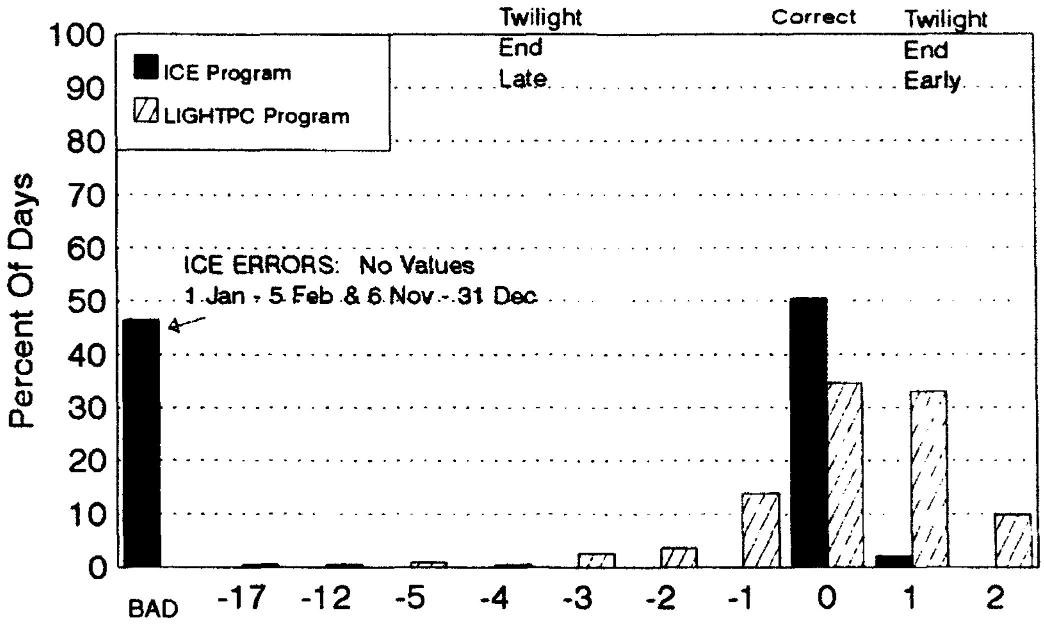
Errors are relative to Navy mainframe program.
Twilight end criterion not met on 116 days; graph shows remaining 249 days.

TWILIGHT END 70N 0E



Errors are relative to Navy Mainframe Program.
Twilight end criterion not met on 145 days; graph shows remaining 220 days.

TWILIGHT END 78N 0E

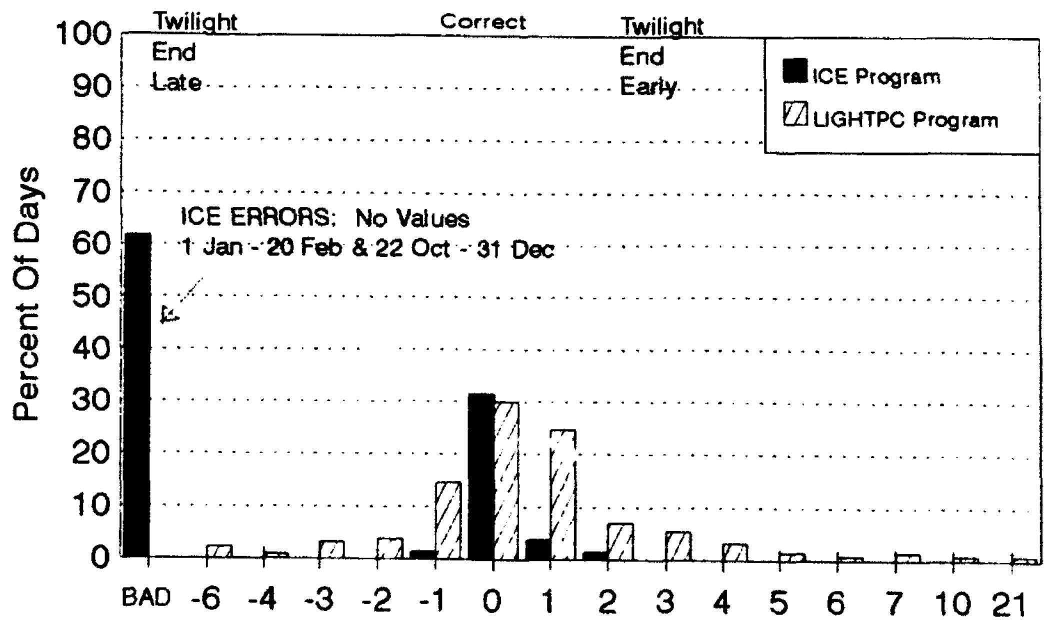


MINUTES OF ERROR

Errors are relative to Navy mainframe program.

Twilight end criterion not met on 171 days; graph shows remaining 194 days.

TWILIGHT END 80N 0E

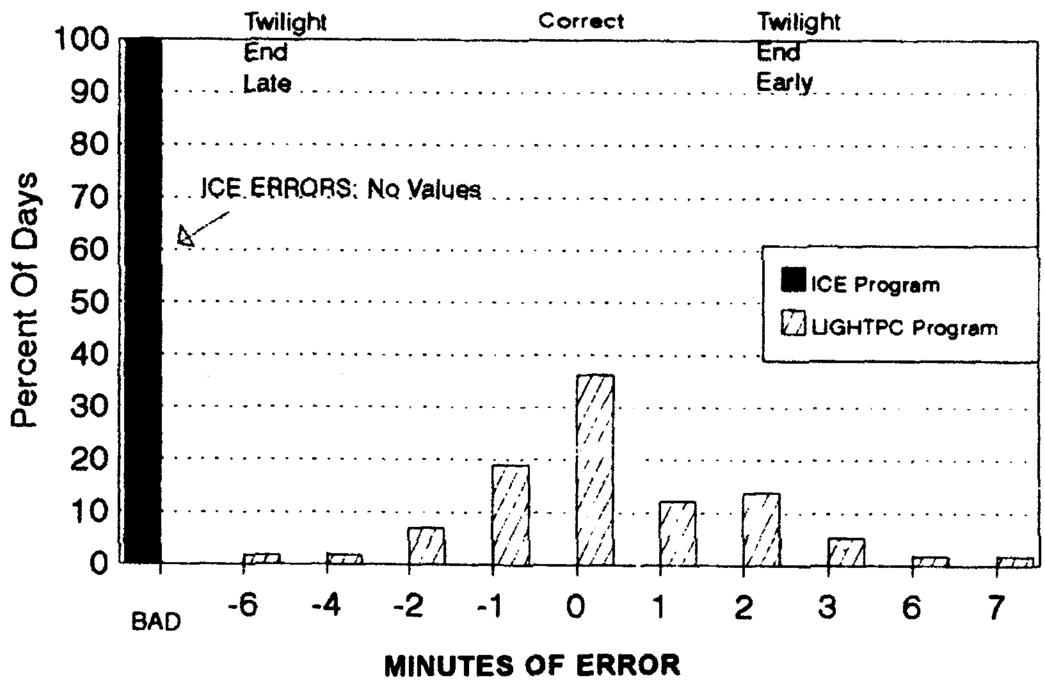


MINUTES OF ERROR

Errors are relative to Navy Mainframe Program.

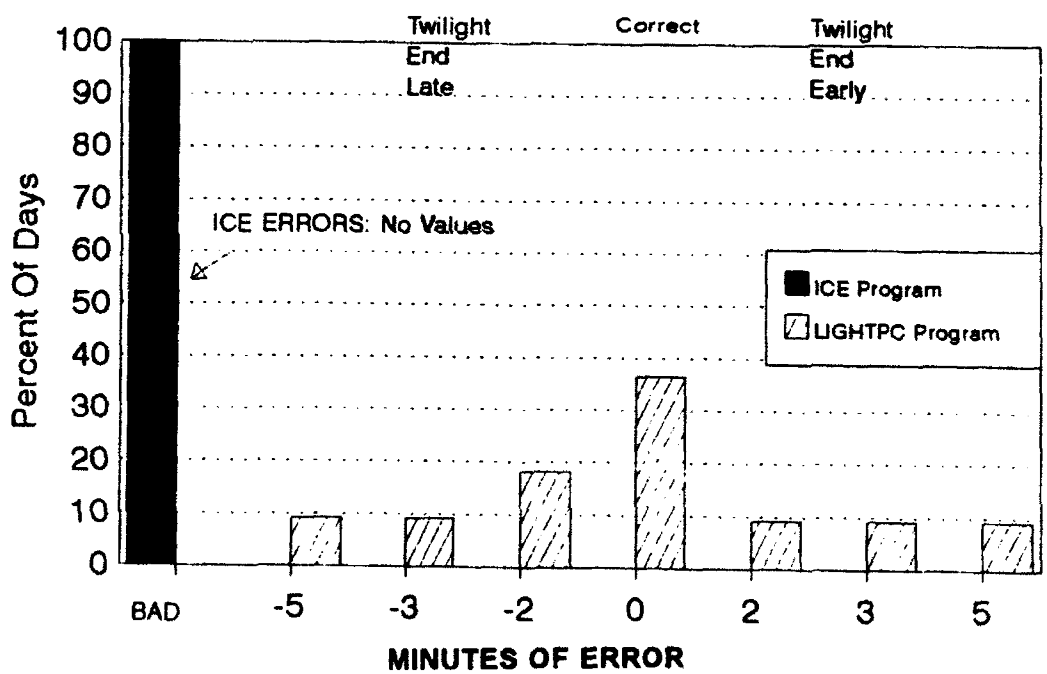
Twilight end criterion not met on 234 days; graph shows remaining 130 days.

TWILIGHT END 88N 0E



Errors are relative to Navy mainframe program.
Twilight end criterion not met on 307 days; graph shows remaining 58 days.

TWILIGHT END 89N 0E

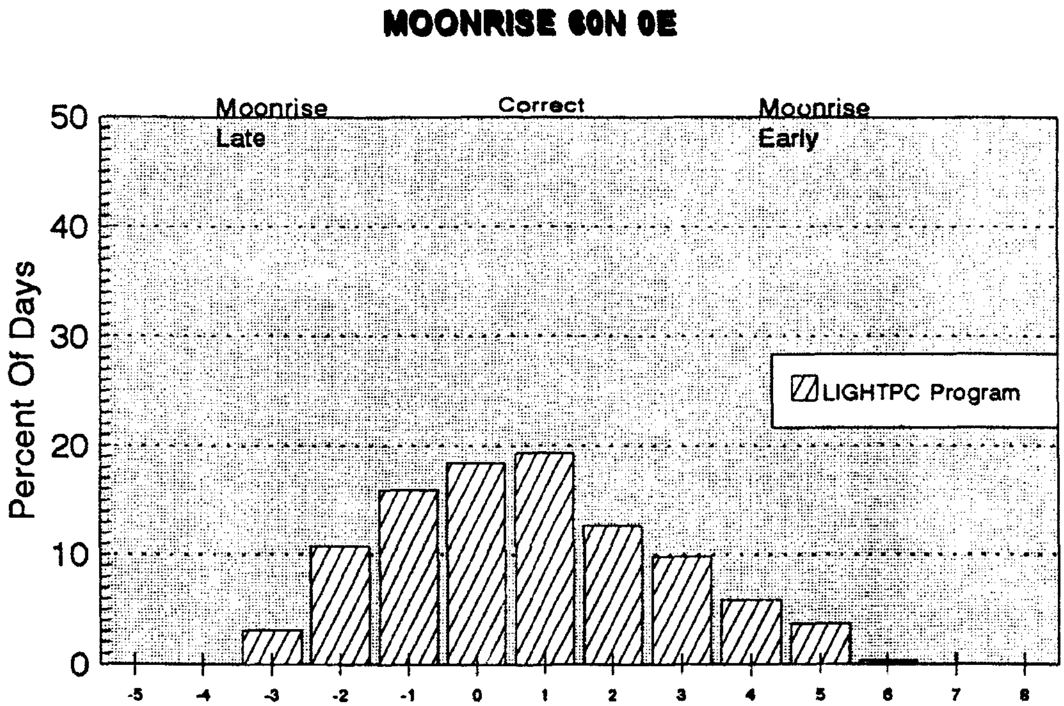


Errors are relative to Navy Mainframe Program.
Twilight end criterion not met on 354 days; graph shows remaining 11 days.

APPENDIX E

CHARTS OF INDICATED *MOONRISE* ERRORS

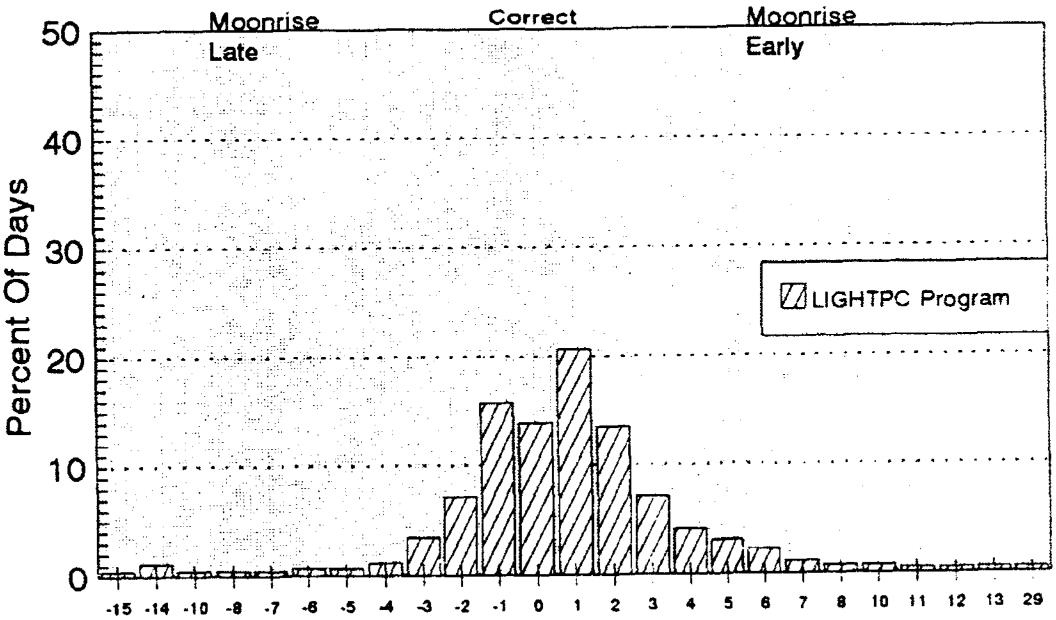
(Percent of Days)



MINUTES OF ERROR

Errors are relative to Navy mainframe program.
Moonrise did not occur on 12 days; graph shows remaining 353 days.

MOONRISE 65N 0E

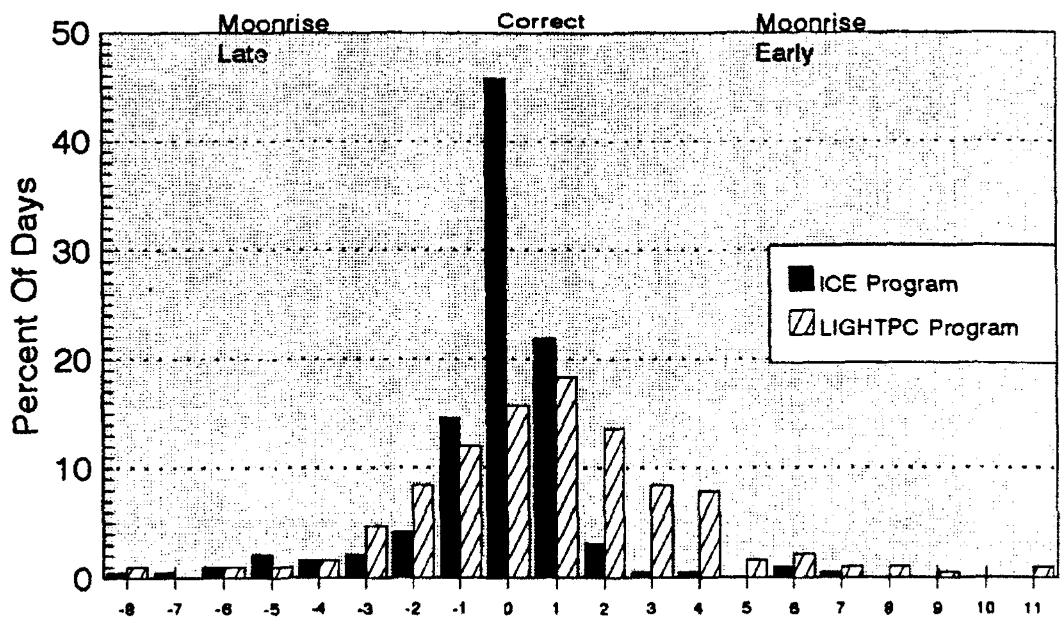


MINUTES OF ERROR

Errors are relative to Navy mainframe program.

Moonrise did not occur on 98 days; graph shows remaining 267 days.

MOONRISE 70N 0E

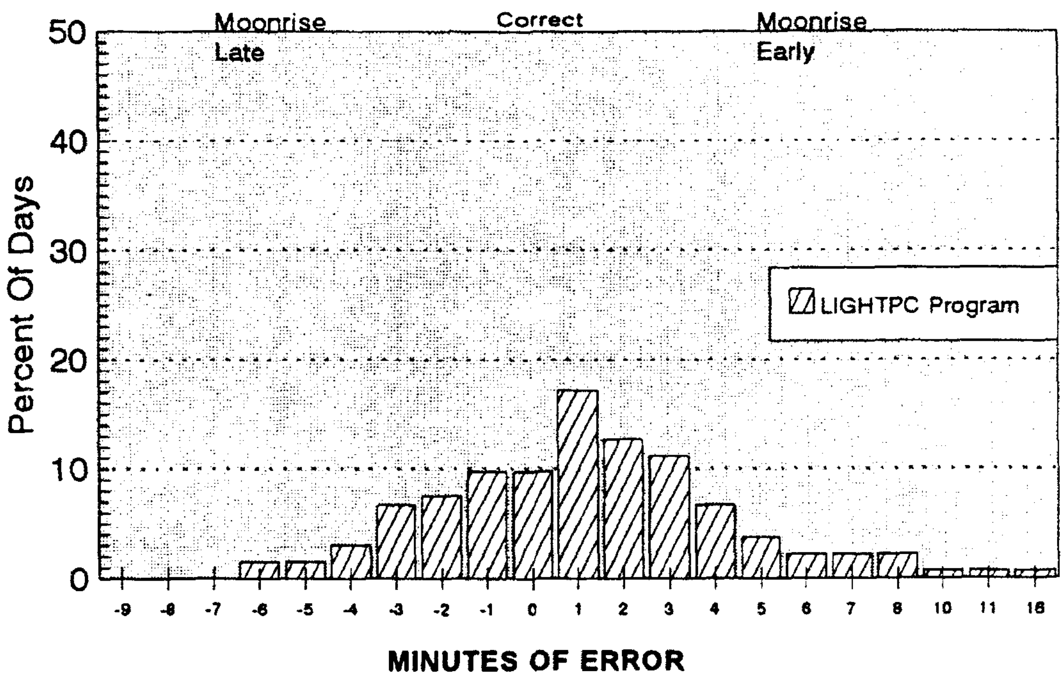


MINUTES OF ERROR

Errors are relative to Navy Mainframe Program.

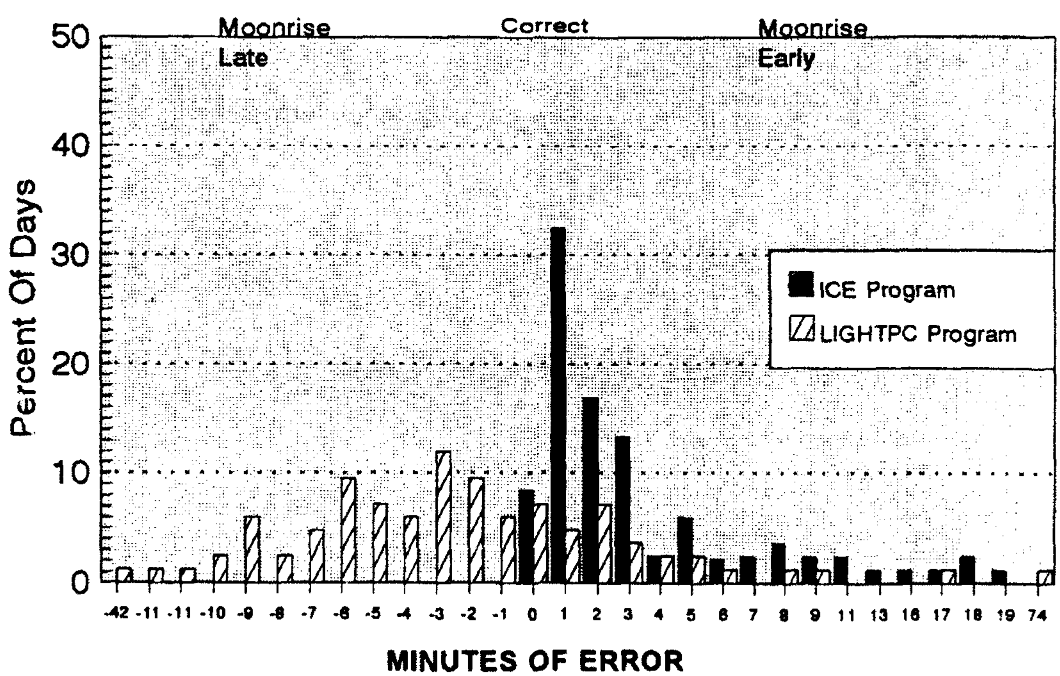
Moonrise did not occur on 174 days; graph shows remaining 191 days.

MOONRISE 75N 0E



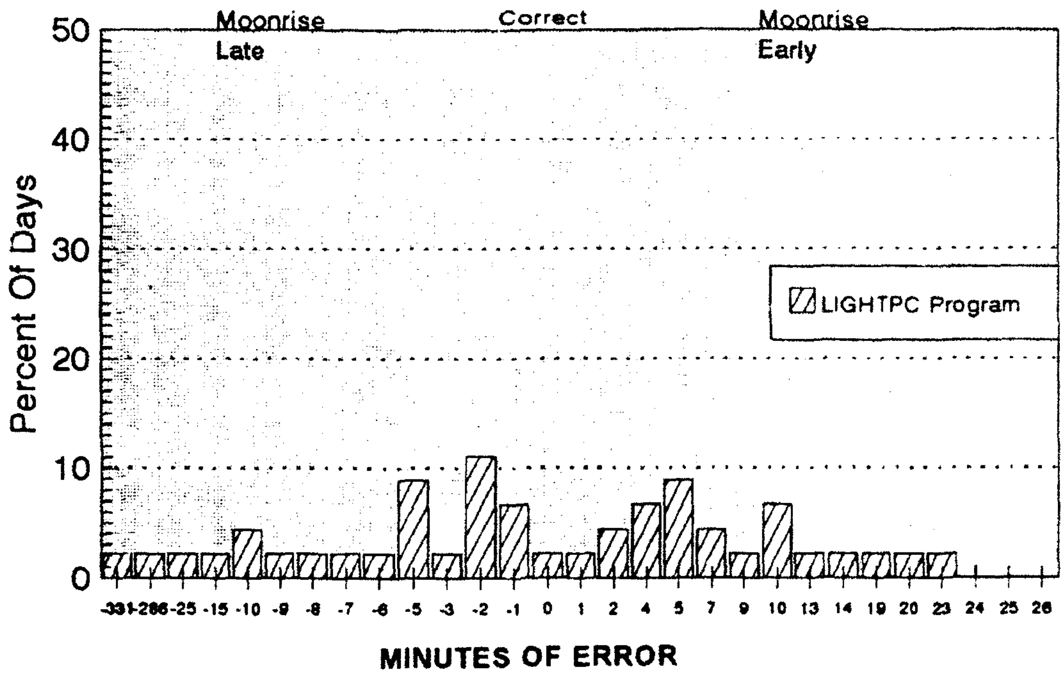
Errors are relative to Navy mainframe program.
Moonrise did not occur on 131 days; graph shows remaining 134 days.

MOONRISE 80N 0E



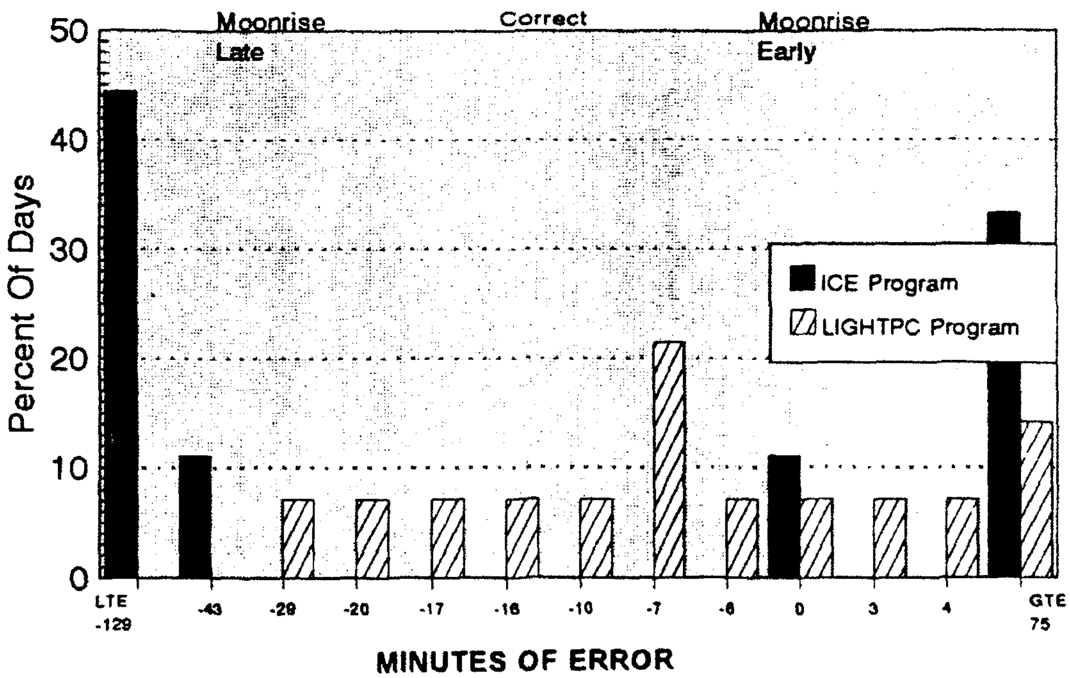
Errors are relative to Navy Mainframe Program.
Moonrise did not occur on 280 days; graph shows remaining 85 days.

MOONRISE 85N 0E



Errors are relative to Navy mainframe program.
Moonrise did not occur on 320 days; graph shows remaining 45 days.

MOONRISE 89N 0E

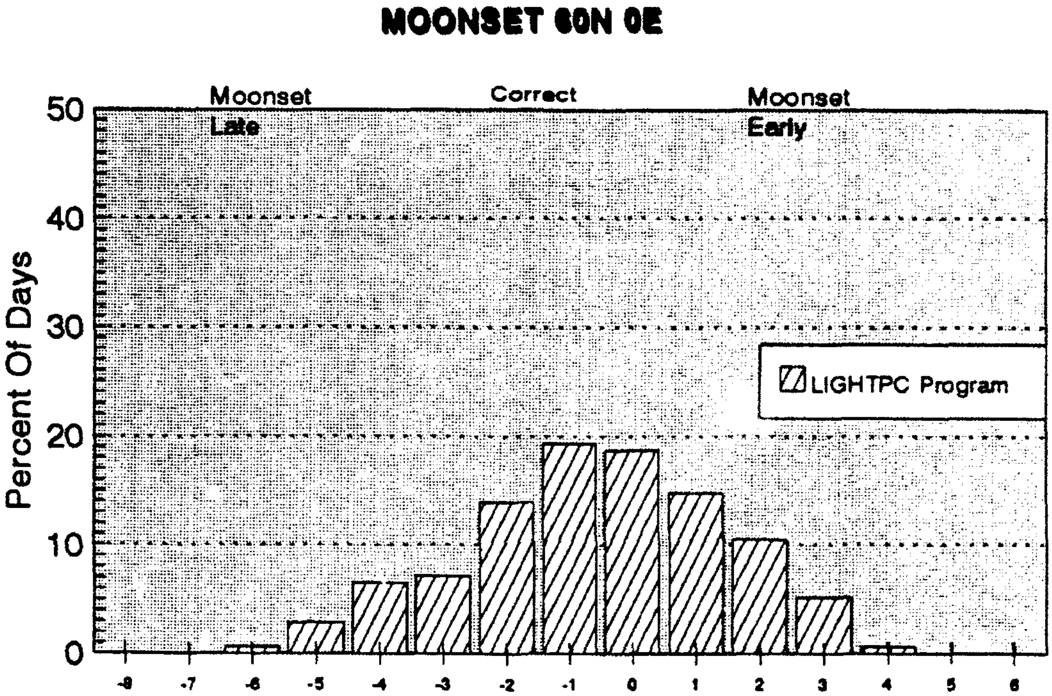


Errors are relative to Navy Mainframe Program.
Moonrise did not occur on 351 days; graph shows remaining 14 days.

APPENDIX F

CHARTS OF INDICATED *MOONSET* ERRORS

(Percent of Days)

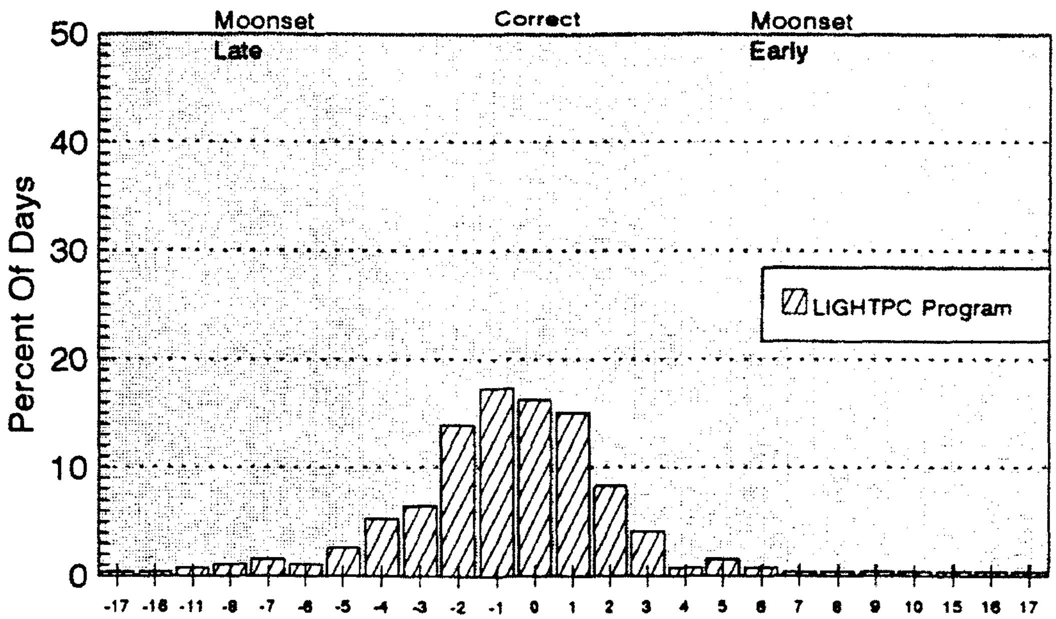


MINUTES OF ERROR

Errors are relative to Navy mainframe program.

Moonset did not occur on 12 days; graph shows remaining 352 days.

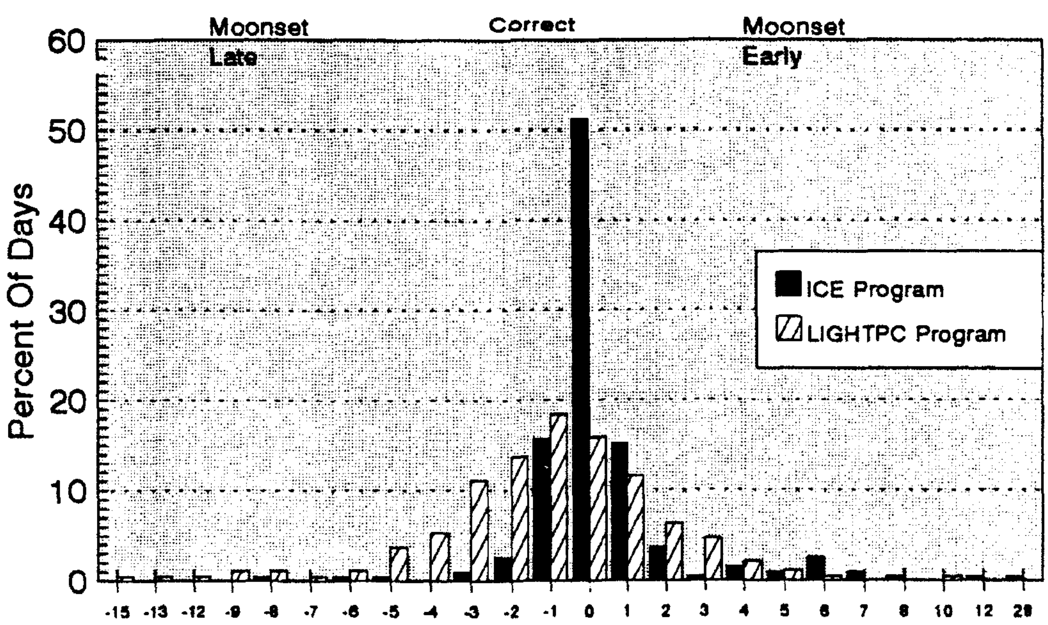
MOONSET 65N 0E



MINUTES OF ERROR

Errors are relative to Navy mainframe program.
Moonset did not occur on 99 days; graph shows remaining 266 days.

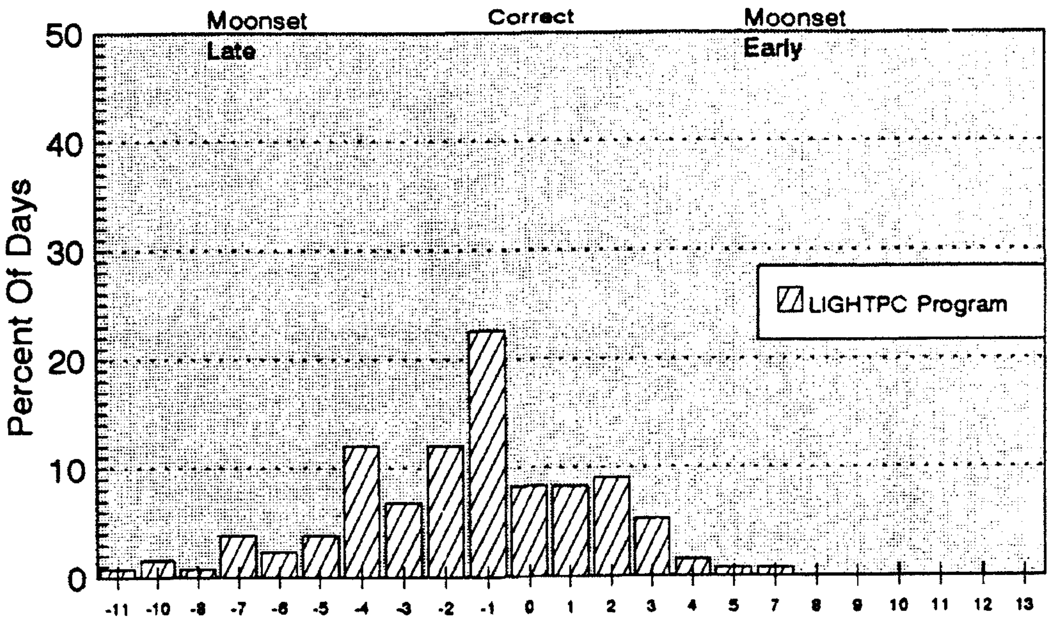
MOONSET 70N 0E



MINUTES OF ERROR

Errors are relative to Navy Mainframe Program.
Moonset did not occur on 175 days; graph shows remaining 190 days.

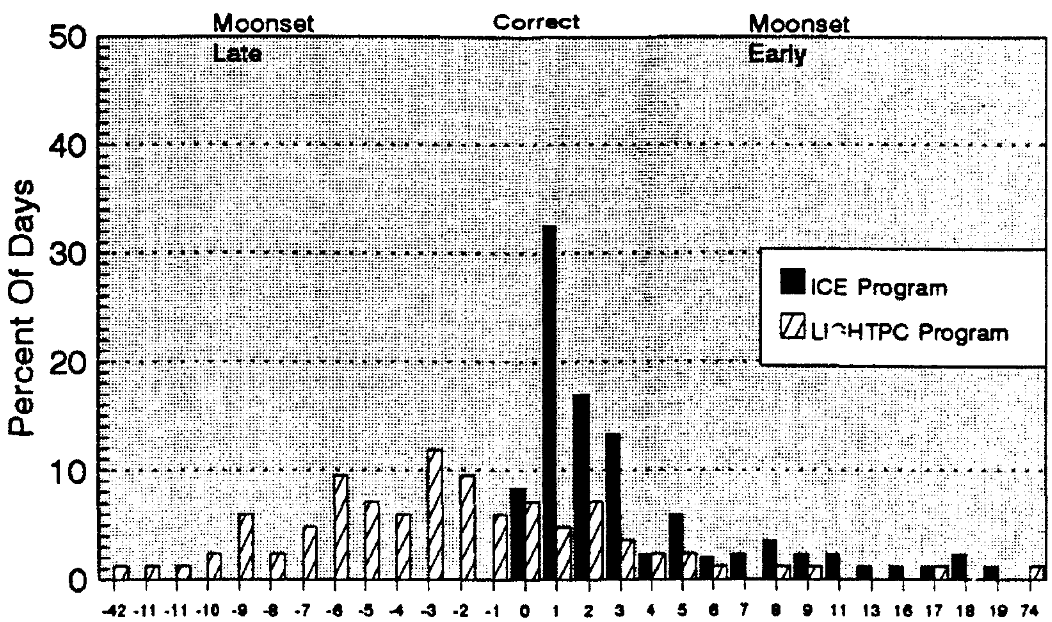
MOONSET 78N 0E



MINUTES OF ERROR

Errors are relative to Navy mainframe program.
Moonset did not occur on 232 days; graph shows remaining 133 days.

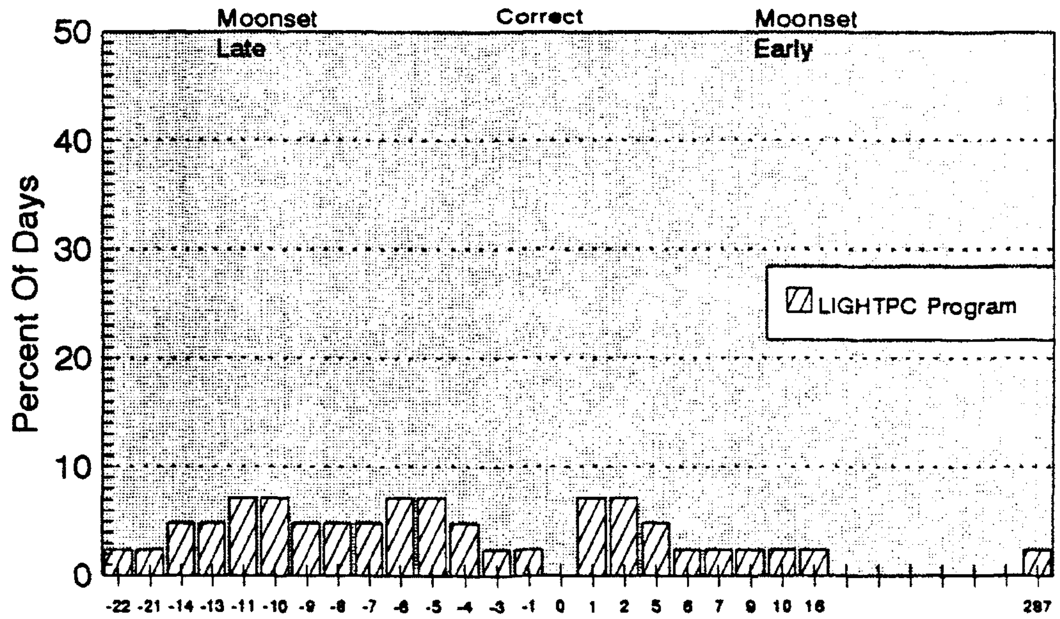
MOONSET 80N 0E



MINUTES OF ERROR

Errors are relative to Navy Mainframe Program.
Moonset did not occur on 281 days; graph shows remaining 84 days.

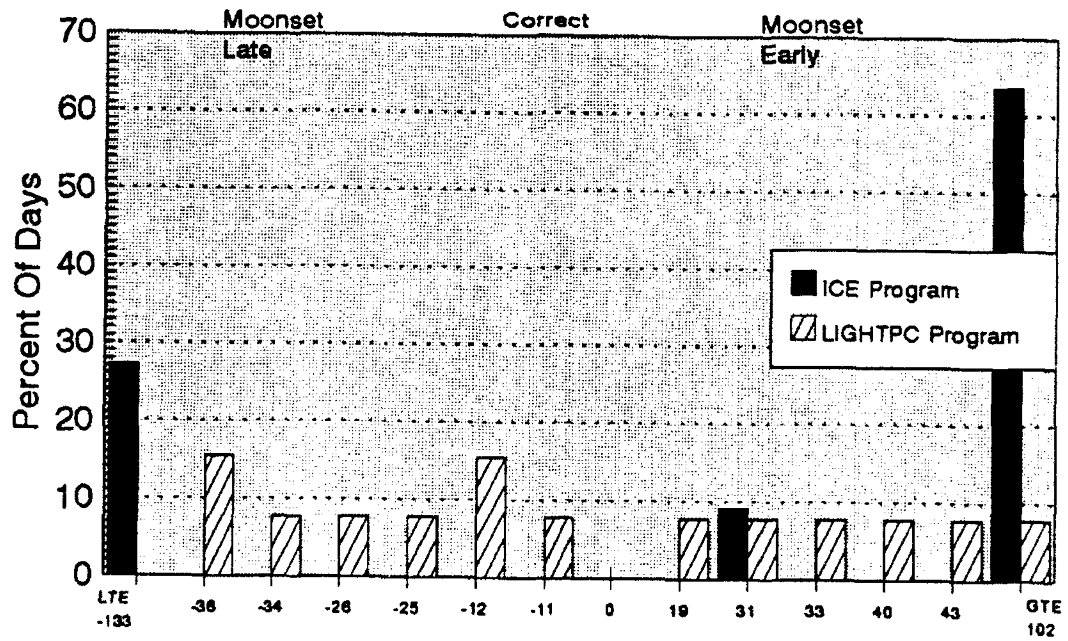
MOONSET 88N 0E



MINUTES OF ERROR

Errors are relative to Navy mainframe program.
Moonset did not occur on 323 days; graph shows remaining 42 days.

MOONSET 89N 0E



MINUTES OF ERROR

Errors are relative to Navy Mainframe Program.
Moonset did not occur on 352 days; graph shows remaining 13 days.

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GLOSSARY

Accuracy	How closely the maximum in a distribution of data matches the expected value that the data is meant to represent.
Event	*For rises and sets:* An occurrence in which the horizon of the earth intersects a specified portion of the disk of the sun or moon. *For twilight start or end:* An occurrence in which the sun is a specified number of degrees below the horizon of the earth.
ICE	A Naval Observatory PC program for accessing and displaying solar and lunar event times from a computer ephemeris.
LIGHTPC	An Air Weather Service PC program for computing solar and lunar event times.
Minutes of Error	Actual event time minus PC-program-predicted event time
Moonrise	The time at which the upper limb of the moon just appears over the horizon of the earth.
Moonset	The time at which the upper limb of the Moon just disappears over the horizon of the Earth.
Navy mainframe	What we call the Naval Observatories program for computing solar and lunar event times.
Non-Event	When the sun does not rise or set, when twilight does not begin or end, or when the moon does not rise or set on a given day.
PC	personal computer
Precision	The spread of data around its maximum value.
Sunrise	The time at which the upper limb of the sun just appears over the horizon of the earth.
Sunset	The time at which the upper limb of the sun just disappears over the horizon of the earth.
Twilight	Here, twilight means *nautical* twilight.
Twilight Start	Nautical twilight starts when the sun is 12° below the horizon before sunrise.
Twilight End	Nautical twilight ends when the sun is 12° below the horizon after sunset.

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