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TRITON STELLAR OCCULTATION CANDIDATES: 2000–2009

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ABSTRACT

As part of our ongoing program of predictions and observations of stellar occultations by solar system bodies, we have completed a search for candidates for occultations by Triton over the decade 2000 to 2009. Star positions near Triton's projected orbit as determined by the DE405 ephemeris and NEP016 orbit model were measured on (unfiltered) CCD strip scans recorded with the 0.6 m telescope at the George R. Wallace Astrophysical Observatory to a depth of 16th to 18th magnitude, depending on the quality of individual strip scans. Within 1″.0 of the predicted orbit of Triton during this period, 128 stars were found, including 12 stars brighter than 14th magnitude. Only appulses with geocentric minimum separations of less than about 0″.37 will result in an occultation visible from Earth, but potential errors in the ephemeris and in the positions of our candidates preclude accurate prediction of actual occultation events without further astrometry.

Key words: astrometry — occultations — planets and satellites: individual (Triton)

1. INTRODUCTION

Stellar occultations have been used many times in the past to study the rings and atmospheres of solar system bodies (Elliot, Dunham, & Olkin 1995; Elliot & Olkin 1996). The atmosphere of Triton has proved to be particularly interesting since from recent stellar occultation data we found that it exhibits an unexpectedly large ellipticity (Elliot et al. 1997) and an increasing pressure since the *Voyager* encounter (Elliot et al. 1998; Sicardy et al. 1998). The large ellipticity is likely due to winds circulating with nearly sonic velocities, while the increasing pressure is caused by a slight warming of the nitrogen surface frost, since this frost is in vapor-pressure equilibrium with the principal atmospheric gas.

In order to facilitate continued probing of Triton's atmosphere with the high spatial resolution afforded by stellar occultations, we have extended our identifications of potential occultations by Triton (McDonald & Elliot 1992, 1995) into the first decade of the next century. This paper presents 128 stars measured on CCD strip scans that lie within 1″.0 of the apparent path of Triton over the period of 2000 through 2009. Occultations observed for stars from our previous candidate lists (Table 1) show astrometric errors of a few tenths of an arcsecond, and at Triton's distance from Earth, the angles subtended by Triton's atmospheric half-light radius and by the radius of Earth are about 0″.07 and 0″.30, respectively. Hence, further astrometry of these candidates will be necessary before we can predict which will be involved in an occultation visible from Earth, and an even more extensive astrometric effort will be required to predict the path of Triton's shadow accurately enough to facilitate observations.

2. OBSERVATIONS AND ANALYSIS

This section gives an overview of the analysis procedures we used for this project, focusing on the changes introduced since the last Triton candidate paper (McDonald & Elliot 1995). Some of these procedures have become more automated.

The data were recorded with the 61 cm telescope at MIT's Wallace Astrophysical Observatory, located in Westford, Massachusetts. Our Portable CCD Camera (PCCD; Buie et al. 1993) has replaced the SNAPSHOT CCD camera (Dunham et al. 1985), which was used for previous candidate searches. Images were taken in strip-scan mode on the PCCD with no filter in order to maximize the number of stars detected. The typical full width at half-maximum of the star images was about 2 pixels, at an image scale of 2″.57 pixel^{-1}. Each strip-scan field overlapped its neighbors by 50% to get redundant coverage of the entire star field near Triton's orbit (see Fig. 1).

Each image was flattened in IRAF (Tody 1986) and processed by IRAF's DAOPHOT routines (Stetson 1987) to automatically identify and measure the positions and instrumental magnitudes of stars down to the limiting magnitude. Astrometric reduction of the strip scan is begun by visually inspecting the frame and establishing three correspondences with stars in the US Naval Observatory's A2.0 star catalog, which are then used for a preliminary astrometric solution. This solution is accurate enough so that all USNO-A2.0 stars detected on the frame (several thousand) can be identified, and a final astrometric solution is carried out. We find that the rms residual of the USNO-A2.0 star positions is about 0″.25. We have not found any significant systematic errors in the USNO-A2.0 catalog, so registering to a large number of stars should give us a good mean reference frame.

In previous astrometric analysis of CCD strip scans, we have observed deviations between the observed coordinates of stars on a single scan compared with either a good catalog of star positions or with a mean position taken from numerous observations of the same field (Dunham, McDonald, & Elliot 1991). These deviations are highly correlated for neighboring stars. On a CCD strip scan, each star image is exposed for a time interval that depends on its right ascension. Since the right ascension exposed within a strip scan is a linear function of time, a variation in right ascension and declination with respect to right ascension implies a time-dependent error in both coordinates. The

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TABLE 1

Results of Previous Occultations

Occulted Star	Occultation Date	Closest Approach (candidate search) Min. Sep. (arcsec)	Closest Approach (candidate search) P.A. of Triton (deg)	Closest Approach (observed) Min. Sep. (arcsec)	Closest Approach (observed) P.A. of Triton (deg)	Difference (arcsec)	References
Tr60	1993 Jul 10	0.02	360	0.03	180	−0.05	1, 2
Tr148	1995 Aug 14	0.42	348	0.28[a]	348	−0.14	2, 3
Tr176	1997 Jul 18	0.09	162	0.07	342	0.16	3, 4
Tr180	1997 Nov 4	0.06	158	0.21	338	0.27	3, 5

[a] Tr148 was discovered to be a double star; the observed minimum separation is calculated for the center of light.

References.—(1) McDonald & Elliot 1992; (2) Olkin et al. 1997; (3) McDonald & Elliot 1995; (4) Elliot et al. 2000; (5) Elliot et al. 1998.

pattern of deviation varies with each frame but generally exhibits irregular variability on timescales longer than 30 s. The best explanation we have for this effect is time-variable atmospheric distortion, which is consistent with both the local correlation and the timescale of the effect (each star is exposed for 90 s on our strip scans).

During most of our previous searches for occultation candidates that used CCD strip scans, we did not have an adequate star catalog to remove the variable deviation, and we could not take enough images to produce mean star positions, so we were unable to correct the positions of our occultation candidates for the deviation. However, the USNO-A2.0 catalog is dense enough for this purpose, so we were able to correct for the deviation in this candidate search. After registering each image against the catalog and converting the observed star positions into right ascension and declination, we plotted the remaining residuals from the catalog versus right ascension using Mathematica 3.0 (Wolfram 1996). We then fitted a Fourier series to the residuals in right ascension, and independently to the residuals in declination. The resulting functions were subtracted from the full set of observed star positions on the image to produce what we believe is an improved position for each star (see Fig. 2). This is of course critically dependent on the lack of systematic errors in the USNO-A2.0 catalog. If there are systematic errors in the catalog, this method will introduce them into our star positions.

The observed stellar magnitudes were calibrated in a similar fashion. For most stars we have found that our unfiltered CCD observations follow the *R* magnitude scale

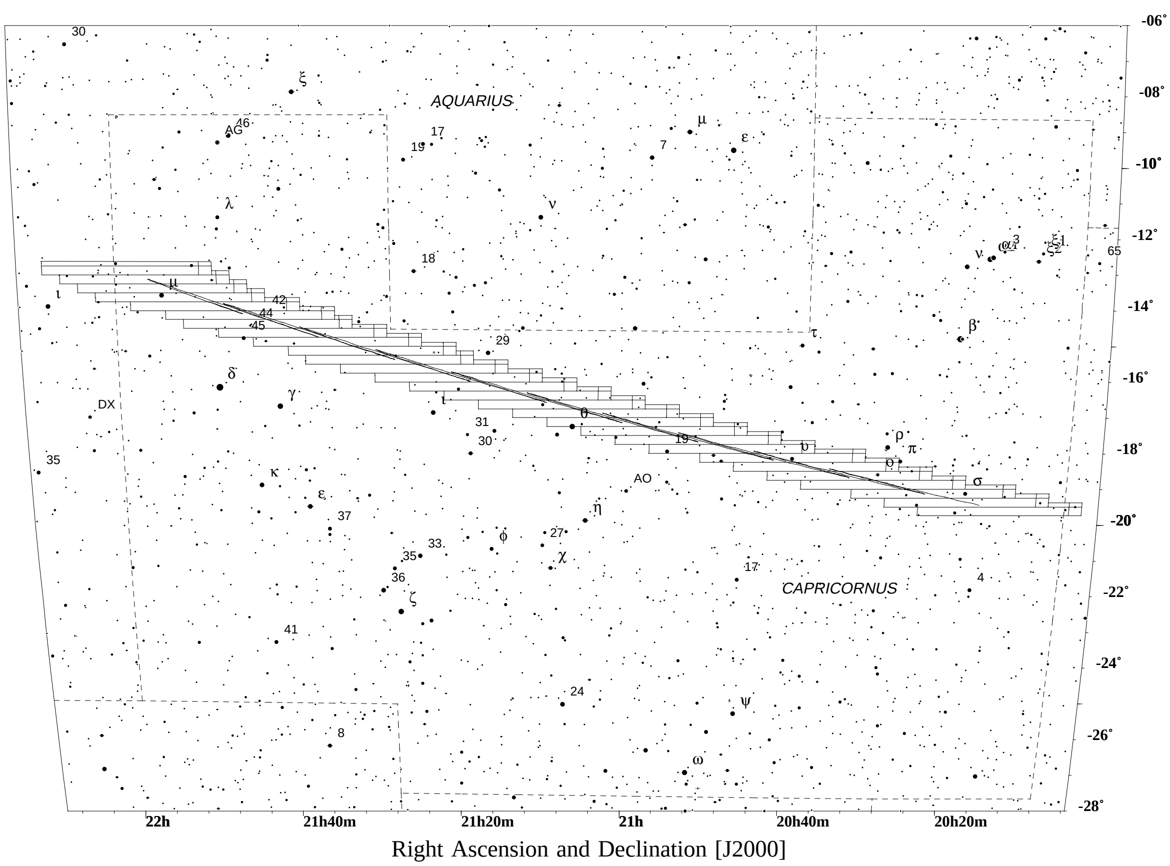

Fig. 1.—Layout of strip-scan fields. The odd-numbered fields are depicted, along with a plot of Triton's orbit from 2000 through 2009. Even-numbered fields overlap the odd-numbered fields by 50% on each side. Each field is about 15′ wide.

TABLE 2

Strip Scans Used in Search

Strip	Date	Magnitude Limit	Notes
04a......	1996 Aug 15	16.5	1
04b......	1996 Aug 6	16.7	
04c......	1996 Aug 23	16.7	1, 2
04d......	1998 Aug 22	17.9	
05a......	1996 Aug 6	17.7	
05b......	1996 Aug 23	17.0	1, 2
06a......	1996 Aug 6	17.0	3
06b......	1996 Aug 23	16.8	
06c......	1998 Sep 18	18.1	
07a......	1996 Aug 6	17.0	2
07b......	1996 Aug 22	17.1	
07c......	1998 Sep 18	17.9	
08a......	1996 Aug 7	17.1	
08b......	1996 Aug 23	17.1	2
08c......	1998 Sep 18	16.4	1
09a......	1996 Aug 7	16.5	
09b......	1996 Aug 23	17.1	
10a......	1996 Aug 7	17.1	
10b......	1996 Aug 23	17.1	
11a......	1996 Aug 7	17.0	
11b......	1996 Aug 23	17.3	
12a......	1996 Aug 7	17.0	
12b......	1996 Aug 23	17.1	
13a......	1996 Aug 8	16.5	
13b......	1996 Aug 22	17.2	
13c......	1996 Sep 4	17.0	
14b......	1996 Sep 4	17.2	3
15a......	1996 Aug 8	17.2	
15b......	1996 Sep 4	17.2	2
16a......	1996 Aug 9	17.3	1
16b......	1996 Aug 21	17.2	1
17a......	1996 Aug 9	17.8	
17b......	1996 Sep 4	17.5	
18a......	1996 Aug 9	17.9	
18b......	1996 Sep 4	17.6	2
18c......	1998 Aug 22	17.8	
19a......	1996 Aug 9	17.6	
19b......	1996 Sep 4	17.4	3
19c......	1998 Aug 22	17.6	
20a......	1996 Aug 7	17.0	
20b......	1996 Sep 4	17.2	3
20c......	1998 Aug 22	17.6	
21a......	1996 Aug 8	16.7	
21b......	1996 Sep 20	17.8	
21c......	1998 Jul 21	15.5	
22a......	1996 Aug 8	16.9	
22b......	1996 Sep 20	17.7	
22c......	1998 Aug 3	17.6	
23a......	1996 Aug 8	17.0	
23b......	1996 Sep 20	17.6	
23c......	1998 Aug 3	18.3	
24a......	1996 Aug 8	16.6	
24b......	1996 Sep 20	17.6	
24c......	1998 Aug 3	18.2	
25a......	1996 Aug 9	17.3	
25b......	1996 Sep 20	18.1	
25c......	1998 Aug 3	17.9	3
26a......	1996 Aug 9	17.3	
26b......	1996 Sep 20	17.5	
26c......	1998 Aug 3	17.9	3
27a......	1996 Aug 9	16.6	2
27b......	1996 Aug 21	17.4	
27c......	1998 Aug 3	18.1	
28a......	1996 Aug 12	16.4	1
28b......	1996 Aug 18	16.9	1, 2
28c......	1996 Aug 21	17.4	
28d......	1998 Aug 3	18.2	
29b......	1996 Aug 21	17.5	
29c......	1998 Aug 3	18.1	1
30a......	1996 Aug 19	17.6	
30b......	1996 Aug 23	17.1	
30c......	1998 Aug 3	17.5	1
31a......	1996 Aug 19	17.3	
31b......	1996 Sep 20	17.5	
31c......	1998 Jul 21	17.9	
32a......	1996 Aug 19	18.2	
32b......	1996 Sep 20	17.8	
32c......	1998 Aug 2	18.4	
33a......	1996 Aug 19	18.0	
33b......	1996 Sep 21	17.1	1
33c......	1998 Aug 2	17.7	
34a......	1996 Aug 19	18.1	
34b......	1996 Sep 21	17.2	
34c......	1998 Aug 2	18.2	
35a......	1996 Aug 19	17.4	
35b......	1996 Sep 21	17.6	
35c......	1998 Aug 2	17.9	
36a......	1996 Aug 19	18.1	
36b......	1996 Sep 21	17.4	
36c......	1998 Aug 2	17.9	
37a......	1996 Aug 19	17.8	
37b......	1996 Sep 21	17.3	
37c......	1998 Aug 2	18.0	
38a......	1996 Aug 19	17.3	
38b......	1996 Aug 21	17.9	
38c......	1998 Aug 2	17.6	
39a......	1996 Aug 19	18.1	
39b......	1996 Sep 21	18.1	
39c......	1998 Aug 2	17.7	
40a......	1996 Aug 19	18.1	
40b......	1996 Sep 21	18.3	
40c......	1998 Jul 25	17.8	
41a......	1996 Aug 19	18.1	
41b......	1996 Sep 21	18.0	
41c......	1998 Jul 21	18.1	
42b......	1996 Aug 21	17.0	2
42c......	1998 Jul 25	17.5	3
43a......	1996 Aug 20	17.9	1
43b......	1996 Aug 23	16.9	
43c......	1996 Sep 21	18.2	
43d......	1998 Jul 25	17.8	4
44a......	1996 Aug 20	17.9	1, 2
44b......	1996 Sep 21	18.0	
44c......	1998 Jul 25	18.1	
44d......	1998 Sep 17	17.0	
45a......	1996 Aug 20	18.0	
45b......	1996 Sep 21	17.8	
45c......	1998 Jul 25	17.6	
46a......	1996 Aug 20	17.5	
46b......	1996 Sep 21	17.6	
46c......	1998 Jul 25	17.5	
47a......	1996 Aug 20	17.6	3
47b......	1996 Sep 20	17.4	
47c......	1998 Jul 19	17.5	
48a......	1996 Aug 20	18.2	
48b......	1996 Sep 20	17.5	
48c......	1998 Jul 19	18.0	
49a......	1996 Aug 20	17.8	
49b......	1996 Sep 20	17.2	
49c......	1998 Jul 19	17.4	4
50b......	1996 Sep 20	17.3	
50c......	1998 Jul 19	17.7	
51a......	1996 Aug 20	17.9	
51b......	1996 Sep 20	17.1	
51c......	1998 Jul 19	17.6	
52a......	1996 Aug 20	18.2	3
52b......	1996 Sep 20	17.0	
52c......	1998 Jul 19	17.6	
53a......	1996 Aug 20	17.2	2
53b......	1996 Sep 21	17.4	
53c......	1998 Jul 19	17.5	
53d......	1998 Sep 29	17.7	
54d......	1998 Jul 19	17.1	5

Notes.—(1) High background (>15% of saturation); (2) part of image washed out; (3) haze or clouds; (4) focus problems; (5) low altitude.

TABLE 3

Possible Occultations by Triton

Event	Closest Approach: Date	UT	Minimum Separation (arcsec)	P.A. of Triton (deg)	Shadow Velocity (km s^{-1})	CCD Mag.	S/N[a]	Solar Angle (deg)	East Long. (deg)	R.A. (J2000)	Decl. (J2000)	Distance (AU)	Strips
Tr205	2000 Mar 11	2214	0.19	163	30.6	17.0	6	46	164	20 32 3.171	−18 37 30.41	30.80	08c, 09a
Tr206	2000 Apr 16	0201	0.29	338	15.0	17.2	7	80	74	20 35 02.565	−18 26 50.43	30.27	10a
Tr207	2000 May 19	1056	0.15	354	7.9	17.2	9	112	−93	20 35 27.882	−18 25 46.76	29.72	10b
Tr208	2000 Jun 7	2019	0.81	178	9.9	16.8	12	131	107	20 34 35.855	−18 28 41.05	29.44	10a, b, 11a, b
Tr209	2000 Jun 17	0029	0.27	162	21.3	17.6	4	140	35	20 33 58.645	−18 31 21.69	29.33	09a, 10b
Tr210	2000 Jul 4	0803	0.30	340	25.4	17.3	5	157	−96	20 32 25.803	−18 37 03.63	29.18	08b, c, 09b
Tr211	2000 Jul 18	2055	0.05	174	20.2	17.7	4	171	57	20 30 51.994	−18 42 29.95	29.11	08a
Tr212	2000 Jul 19	2235	0.45	163	19.9	15.5	27	172	31	20 30 46.033	−18 42 46.59	29.11	08a, b, 09a, b
Tr213	2000 Jul 25	0429	0.98	350	19.6	16.6	10	177	−63	20 30 10.520	−18 44 58.77	29.10	07b, 08a, b, c
Tr214	2000 Aug 17	1332	0.03	174	17.9	16.2	16	160	137	20 27 37.930	−18 54 13.84	29.16	06a, b, 07b
Tr215	2000 Aug 18	1132	0.94	342	18.5	17.7	4	159	166	20 27 33.389	−18 54 30.25	29.17	07c
Tr216	2000 Aug 22	1159	0.50	355	20.3	17.3	5	155	156	20 27 07.934	−18 56 14.55	29.19	07c
Tr217	2000 Sep 15	2005	0.80	357	9.3	14.7	81	131	10	20 25 08.771	−19 03 19.91	29.44	05a, b, 06a, b
Tr218	2000 Oct 12	1210	0.11	148	1.0	17.4	22	104	102	20 24 13.646	−19 07 17.35	29.85	04d
Tr219	2000 Nov 3	0635	0.86	359	11.7	16.6	13	83	164	20 24 37.895	−19 05 58.52	30.22	04d, 05a, b, 06a, b, c
Tr220	2000 Nov 25	2032	0.89	166	25.1	16.1	14	60	−67	20 26 09.560	−19 01 01.15	30.58	05a, b, 06a, b
Tr221	2000 Dec 6	1623	0.03	160	27.7	16.9	7	50	−15	20 27 15.159	−18 57 32.53	30.74	06c, 07c
Tr222	2001 Mar 26	0553	0.02	342	17.5	13.5	148	57	38	20 42 20.538	−18 03 54.44	30.63	13a, b, c, 14b
Tr223	2001 Apr 1	0220	0.98	349	14.9	17.2	7	63	86	20 42 52.466	−18 01 55.46	30.55	14b
Tr224	2001 Apr 4	2139	0.96	171	20.3	14.1	85	67	153	20 43 11.018	−18 00 21.30	30.48	13a, b, c, 14b
Tr225	2001 Apr 12	1231	0.89	176	9.6	17.1	10	74	−78	20 43 43.380	−17 58 40.24	30.36	13b, c
Tr226	2001 Jun 16	2157	0.95	346	20.1	17.5	4	137	76	20 43 09.808	−18 01 19.97	29.35	13b, c, 14b
Tr227	2001 Jul 14	1547	0.52	337	24.0	17.4	4	164	141	20 40 38.446	−18 10 58.19	29.12	12b
Tr228	2001 Jul 25	0954	0.02	163	20.8	17.2	6	175	−142	20 39 27.812	−18 15 19.39	29.09	11b
Tr229	2001 Aug 4	0143	0.31	172	23.9	16.8	8	175	−29	20 38 22.363	−18 19 45.39	29.09	12a
Tr230	2001 Aug 21	0139	0.88	350	24.6	17.5	4	159	−45	20 36 34.052	−18 26 49.32	29.16	11a
Tr231	2001 Aug 25	2148	0.29	162	25.1	12.9	186	154	7	20 36 06.539	−18 28 35.54	29.19	09b, 10a, 11a
Tr232	2001 Aug 26	1048	0.92	166	24.8	10.9	598	153	172	20 36 02.776	−18 28 50.10	29.19	09b, 10a, b, 11a, b
Tr233	2001 Nov 20	1734	0.10	176	17.4	17.0	7	68	−15	20 34 35.093	−18 35 14.85	30.46	09a
Tr234	2001 Nov 20	2236	0.98	177	16.5	14.6	65	68	−91	20 34 36.136	−18 35 13.14	30.46	09a, b, 10a, b
Tr235	2001 Dec 15	0957	0.53	170	23.5	17.5	4	43	76	20 37 02.534	−18 26 47.84	30.81	11a
Tr236	2001 Dec 20	2210	0.98	172	26.4	16.6	9	38	−113	20 37 44.025	−18 24 14.53	30.87	10b, 11b
Tr237	2001 Dec 25	1552	0.82	171	32.8	17.1	5	33	−23	20 38 21.181	−18 21 45.77	30.91	11a, b, 12a
Tr238	2002 Feb 27	1504	0.46	166	35.8	17.1	5	29	−72	20 47 49.549	−17 46 04.14	30.95	15a, 16a
Tr239	2002 Mar 5	1848	0.12	167	33.5	13.8	85	35	−134	20 48 39.581	−17 42 51.71	30.90	16a, b, 17a, b
Tr240	2002 Mar 21	0358	0.66	337	24.9	18.1	2	50	74	20 50 29.414	−17 35 58.60	30.72	17b
Tr241	2002 Apr 10	0110	0.19	170	19.3	17.9	3	69	97	20 52 19.332	−17 28 31.30	30.43	18b
Tr242	2002 Apr 21	0321	0.97	162	15.0	17.3	6	80	54	20 52 58.812	−17 25 54.69	30.25	18b, 19a, c
Tr243a...	2002 May 4	1702	0.38	31	2.4	17.9	9	93	−165	20 53 27.958	−17 24 19.72	30.02	19c
Tr243b...	2002 May 21	1816	0.99	113	6.8	17.9	5	110	160	20 53 27.958	−17 24 19.72	29.74	19c
Tr244	2002 Jun 29	0346	0.14	353	18.9	14.0	99	147	−21	20 51 18.528	−17 33 33.46	29.23	17a, b, 18a, b, c
Tr245	2002 Jul 17	1029	0.74	352	20.0	17.0	7	165	−140	20 49 32.086	−17 40 42.26	29.11	16b, 17b
Tr246	2002 Jul 25	1002	0.09	337	23.3	17.3	5	173	−142	20 48 42.857	−17 44 03.37	29.08	15a
Tr247	2002 Aug 7	0951	0.55	160	27.8	16.2	13	175	−152	20 47 17.170	−17 50 05.72	29.08	15b
Tr248	2002 Aug 7	1227	0.29	161	28.0	15.2	29	175	169	20 47 16.368	−17 50 10.08	29.08	15a, b, 16a, b
Tr249	2002 Oct 28	0418	0.04	218	3.0	17.1	16	94	−151	20 42 20.635	−18 10 13.30	30.01	13a

TABLE 3—*Continued*

Event	Closest Approach: Date	UT	Minimum Separation (arcsec)	P.A. of Triton (deg)	Shadow Velocity (km s^{-1})	CCD Mag.	S/N[a]	Solar Angle (deg)	East Long. (deg)	R.A. (J2000)	Decl. (J2000)	Distance (AU)	Strips
Tr250…	2002 Nov 12	0010	0.94	154	15.2	15.7	25	79	−103	20 42 49.584	−18 08 22.50	30.26	12a, b, 13b, c
Tr251…	2002 Dec 3	1845	0.52	343	18.5	15.9	20	57	−43	20 44 28.390	−18 02 39.27	30.61	13a, b, c, 14b
Tr252…	2002 Dec 10	0932	0.77	158	23.7	15.8	18	51	89	20 45 08.315	−18 00 02.58	30.70	13a, b, c, 14b
Tr253…	2003 Jan 2	1247	0.17	342	29.4	14.6	46	28	18	20 48 02.572	−17 49 02.20	30.95	15a, b, 16a, b
Tr254…	2003 Mar 12	0150	0.67	351	27.7	18.4	2	39	118	20 58 04.245	−17 09 00.07	30.85	21b
Tr255…	2003 Mar 13	2124	0.43	341	25.2	14.9	39	41	−178	20 58 16.384	−17 08 20.84	30.83	20a, b, c, 21a, b, c
Tr256…	2003 Apr 13	1106	0.32	333	18.1	15.3	35	70	−53	21 01 15.189	−16 55 56.14	30.41	22a, b, c, 23a, b, c
Tr257…	2003 Jun 28	0844	0.78	172	18.6	16.4	12	144	−92	21 00 29.354	−17 00 06.08	29.26	21b
Tr258…	2003 Jul 7	1822	0.44	335	23.1	16.1	14	153	114	20 59 41.739	−17 03 32.62	29.17	22a, b, c
Tr259…	2003 Aug 10	0710	0.10	344	19.6	17.8	4	174	−112	20 56 09.143	−17 18 23.59	29.07	19a
Tr260…	2003 Aug 17	0634	0.69	156	22.8	16.7	9	167	−110	20 55 25.238	−17 21 36.23	29.09	18a, b, c, 19a, c, 20b, c
Tr261…	2003 Aug 20	1441	0.60	172	21.7	13.8	102	164	125	20 55 02.084	−17 23 19.00	29.10	18a, b, c, 19a, b, c
Tr262…	2003 Aug 30	0827	0.71	340	25.2	16.5	10	155	−152	20 54 05.262	−17 27 30.70	29.16	18c, 19b, c
Tr263…	2003 Sep 28	2313	0.31	160	15.4	14.9	53	125	−43	20 51 50.370	−17 36 58.03	29.49	16a, b, 17a, b, 18b
Tr264…	2003 Nov 18	2017	0.86	172	16.4	17.4	5	75	−49	20 52 02.859	−17 36 18.32	30.32	17b, 18a, b
Tr265…	2003 Nov 19	1526	0.47	178	13.2	17.1	8	74	23	20 52 06.390	−17 36 14.38	30.34	16b
Tr266…	2003 Nov 29	0348	0.21	158	22.5	13.3	154	64	−172	20 52 45.900	−17 33 33.97	30.49	17a, b, 18a, b, c
Tr267…	2004 Mar 7	1848	0.45	338	33.3	13.7	92	33	−131	21 06 09.425	−16 38 36.65	30.90	24a, b, 25b
Tr268…	2004 Mar 20	1443	0.19	163	30.8	17.4	4	46	−82	21 07 45.312	−16 31 40.15	30.76	25a, b, c
Tr269…	2004 Mar 30	2140	0.48	335	23.9	17.3	5	56	163	21 08 50.116	−16 27 17.83	30.62	26b, c, 27c
Tr270…	2004 Apr 16	1045	0.09	157	12.6	17.8	4	72	−49	21 10 12.715	−16 21 37.69	30.37	28d
Tr271…	2004 Jun 27	0745	0.70	354	14.9	15.9	22	141	−75	21 09 32.672	−16 25 17.40	29.27	26a, b, 27a, b, c
Tr272…	2004 Jul 18	1511	0.18	159	26.7	16.8	8	162	152	21 07 38.055	−16 34 10.82	29.10	25b, 26a, b, c
Tr273…	2004 Jul 27	0427	0.94	349	19.7	17.0	7	170	−55	21 06 42.850	−16 37 57.72	29.07	24c, 25a, b
Tr274…	2004 Aug 14	1613	1.00	342	19.8	17.5	4	172	109	21 04 43.688	−16 46 42.34	29.07	23b
Tr275…	2004 Aug 19	0028	0.60	351	21.8	16.8	8	167	−19	21 04 14.812	−16 49 01.60	29.08	23c
Tr276…	2004 Aug 24	0147	0.55	348	24.9	17.6	4	162	−44	21 03 43.756	−16 51 28.68	29.11	23b, c
Tr277…	2004 Sep 4	0306	0.53	343	24.4	16.9	7	151	−75	21 02 39.879	−16 56 12.14	29.18	22b, 23b
Tr278…	2004 Sep 7	0423	0.61	162	15.8	15.9	22	148	−97	21 02 23.111	−16 56 57.58	29.21	22b, 23b, c
Tr279…	2004 Oct 5	1402	0.92	186	5.1	15.5	53	120	90	21 00 29.199	−17 05 21.48	29.55	21a, 22a, b, c
Tr280…	2004 Oct 8	1811	0.69	152	11.6	17.1	9	117	24	21 00 23.883	−17 06 03.95	29.60	20c, 21b, 22b
Tr281…	2004 Oct 19	1945	0.53	117	5.4	17.4	10	106	−10	21 00 09.443	−17 07 02.79	29.78	20c, 22b, c
Tr282…	2005 Apr 30	1618	0.62	351	11.4	12.8	296	83	−144	21 19 39.403	−15 42 59.95	30.17	32a, b, c, 33a, b, c
Tr283…	2005 Jun 17	0923	0.46	147	14.4	15.2	43	129	−87	21 19 13.821	−15 45 49.55	29.41	31b, 32a, b, c
Tr284…	2005 Jul 2	1729	0.39	172	15.1	14.8	57	144	136	21 18 07.662	−15 51 04.91	29.23	30a, 31a, b, c, 32b, c
Tr285…	2005 Jul 7	1612	0.06	348	20.7	15.8	21	149	150	21 17 42.737	−15 53 16.58	29.19	30a, c, 31a, b
Tr286…	2005 Jul 18	0436	0.72	160	26.3	17.2	5	159	−46	21 16 44.980	−15 57 54.01	29.11	30a, 31c
Tr287…	2005 Aug 5	1646	0.53	346	26.6	15.5	24	177	112	21 14 48.016	−16 06 57.88	29.05	28a, b, c, d, 29c, 30a, c
Tr288…	2005 Nov 5	1632	0.97	20	3.3	16.0	44	91	24	21 09 06.876	−16 32 53.74	30.02	25a, b, c, 26a, b
Tr289…	2005 Nov 9	1239	0.15	334	11.5	18.0	4	88	78	21 09 11.278	−16 32 24.09	30.08	25b
Tr290…	2005 Dec 13	1457	0.27	155	24.0	15.9	18	54	11	21 11 29.357	−16 22 40.64	30.63	26b, 27c
Tr291…	2006 Mar 18	0238	0.64	156	31.3	17.7	3	39	106	21 24 26.581	−15 24 17.16	30.83	34a, c, 35b, c
Tr292…	2006 Mar 24	0552	0.58	337	30.2	15.3	26	45	51	21 25 10.639	−15 20 52.98	30.76	34a, b, 35a, b, 36b, c
Tr293…	2006 Jun 29	1925	0.74	157	20.9	17.0	7	138	113	21 27 20.714	−15 12 35.28	29.29	36a, b, c, 37b, c
Tr294…	2006 Jul 19	0243	0.22	170	21.2	15.2	32	157	−16	21 25 39.785	−15 20 44.02	29.11	34a, b, 35a, b, c, 36b, c
Tr295…	2006 Aug 3	1203	0.86	155	27.1	17.6	3	172	−172	21 24 07.383	−15 28 16.21	29.05	34a, 35b

TABLE 3—*Continued*

Event	Closest Approach: Date	UT	Minimum Separation (arcsec)	P.A. of Triton (deg)	Shadow Velocity (km s^{-1})	CCD Mag.	S/N[a]	Solar Angle (deg)	East Long. (deg)	R.A. (J2000)	Decl. (J2000)	Distance (AU)	Strips
Tr296...	2006 Aug 9	0848	0.52	156	27.3	18.0	2	178	−129	21 23 29.779	−15 31 17.36	29.04	34a
Tr297...	2006 Aug 18	1721	0.02	164	19.4	15.7	22	173	93	21 22 27.965	−15 35 54.64	29.05	32a, b, 33a, b, 34b, c
Tr298...	2006 Aug 21	1626	0.97	339	27.8	16.7	8	170	104	21 22 10.365	−15 37 43.99	29.06	32a, b, c, 33b
Tr299...	2006 Aug 27	0832	0.19	338	26.9	18.2	2	164	−143	21 21 35.131	−15 40 29.10	29.08	32c
Tr300...	2006 Sep 9	1600	0.49	349	21.2	16.8	8	151	91	21 20 16.105	−15 46 39.48	29.17	31c, 32a, b
Tr301...	2006 Sep 12	0058	0.72	157	16.7	17.3	6	148	−46	21 20 04.533	−15 47 13.15	29.19	31b
Tr302...	2006 Sep 25	1632	0.99	335	19.2	17.0	7	135	67	21 19 01.135	−15 52 35.25	29.34	30a, c, 31a, b
Tr303...	2006 Oct 4	0409	0.65	359	7.8	17.8	5	126	−116	21 18 28.590	−15 54 50.80	29.45	31c
Tr304...	2007 Jan 7	1516	0.32	165	34.6	14.1	67	31	−15	21 22 58.803	−15 34 19.35	30.88	33a, b, 34a, b, c
Tr305...	2007 Mar 12	0826	0.11	160	35.6	16.6	8	31	27	21 32 08.227	−14 51 22.44	30.90	38b, 39a, c, 40c
Tr306...	2007 May 6	0926	0.13	185	5.3	14.0	188	84	−41	21 37 10.411	−14 27 53.06	30.15	41a, 42b, c, 43a, b, c, d
Tr307...	2007 Aug 24	1336	0.75	159	19.9	18.0	3	169	146	21 30 53.446	−15 00 17.13	29.05	37a
Tr308...	2007 Aug 29	0325	0.14	169	20.1	17.1	7	165	−66	21 30 23.936	−15 02 51.47	29.07	38b, c
Tr309...	2007 Sep 4	0549	0.07	350	18.3	16.4	12	159	−108	21 29 47.374	−15 05 48.12	29.10	36a, 37a, c
Tr310...	2007 Sep 12	2217	0.68	154	23.2	18.0	3	150	−4	21 29 00.506	−15 09 49.95	29.17	36b
Tr311...	2007 Sep 19	0452	0.66	156	22.3	16.9	8	144	−109	21 28 28.223	−15 12 31.37	29.23	36a, b, c, 37a
Tr312...	2007 Sep 21	0303	0.03	174	16.8	13.4	161	142	−84	21 28 17.238	−15 13 17.49	29.25	35a, b, c, 36a, b, c, 37b
Tr313...	2008 Mar 13	2207	0.59	343	27.1	16.4	10	31	−179	21 40 52.441	−14 12 43.63	30.89	44a, 45b
Tr314...	2008 Apr 7	0437	0.11	337	21.0	15.4	29	54	61	21 43 40.841	−13 58 57.57	30.62	45b, c, 46b, c, 47b, c
Tr315...	2008 Apr 17	1920	0.16	169	14.5	16.4	14	64	−170	21 44 38.728	−13 54 15.37	30.46	46c, 47b, c
Tr316...	2008 May 21	0146	0.30	174	0.8	12.9	1031	96	61	21 46 11.038	−13 46 45.61	29.91	47b, c, 48b
Tr317...	2008 Aug 1	2123	0.15	338	27.5	17.3	5	167	54	21 42 10.348	−14 09 04.72	29.05	44a, c, d, 45a
Tr318...	2008 Aug 23	1338	0.95	154	22.5	17.1	6	172	148	21 39 53.604	−14 20 25.45	29.04	43a, c, d, 44a, b, c, d
Tr319...	2008 Sep 22	1144	0.46	330	19.1	18.1	3	142	146	21 37 04.571	−14 34 47.70	29.24	40a, 42c
Tr320...	2009 Jan 6	2207	0.71	167	26.7	17.3	4	36	−114	21 39 52.482	−14 21 01.32	30.83	42c
Tr321...	2009 Jun 18	2353	0.26	142	9.5	18.0	4	121	63	21 54 25.438	−13 08 51.71	29.49	53d
Tr322...	2009 Jul 7	1547	0.36	149	19.5	17.2	6	140	165	21 53 20.836	−13 15 09.95	29.25	51a, b, c, 52c
Tr323...	2009 Aug 29	0837	0.25	152	24.8	17.9	3	169	−140	21 48 14.645	−13 42 30.55	29.04	49c
Tr324...	2009 Sep 14	2021	0.55	158	17.4	17.9	3	152	27	21 46 37.092	−13 50 46.93	29.13	47b
Tr325...	2009 Sep 20	2238	0.38	155	16.6	16.5	13	146	−13	21 46 05.505	−13 53 31.47	29.19	46c, 47b, c
Tr326...	2009 Sep 24	0816	0.32	348	18.7	16.4	12	143	−161	21 45 47.819	−13 55 23.13	29.22	46b, c, 47b, c
Tr327...	2009 Sep 26	1809	0.82	155	14.6	15.6	28	140	48	21 45 37.769	−13 55 53.32	29.25	46a, b, c, 47b, c
Tr328...	2009 Oct 14	1634	0.10	325	9.8	15.0	60	122	54	21 44 33.143	−14 01 26.32	29.48	45a, c, 46a, b, c
Tr329...	2009 Dec 2	1007	0.58	351	10.4	17.5	6	74	103	21 44 55.478	−13 59 44.15	30.29	46b, c
Tr330...	2009 Dec 2	1041	0.11	172	10.4	17.4	7	74	94	21 44 55.536	−13 59 43.30	30.29	46b
Tr331...	2009 Dec 24	0828	0.07	346	25.8	17.2	5	52	106	21 46 43.462	−13 50 09.14	30.62	47a, c, 48b, c
Tr332...	2009 Dec 29	0604	0.35	160	30.4	16.9	6	47	138	21 47 13.619	−13 47 29.41	30.69	47a, b, c, 48c

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] The signal-to-noise ratio for the light curve has been calculated for an averaging interval of 20 km (the approximate scale height of Triton's atmosphere), based on the expected performance of HOPI on SOFIA (see text). Potential observers should evaluate the S/N for the telescope and photometric equipment planned for use.

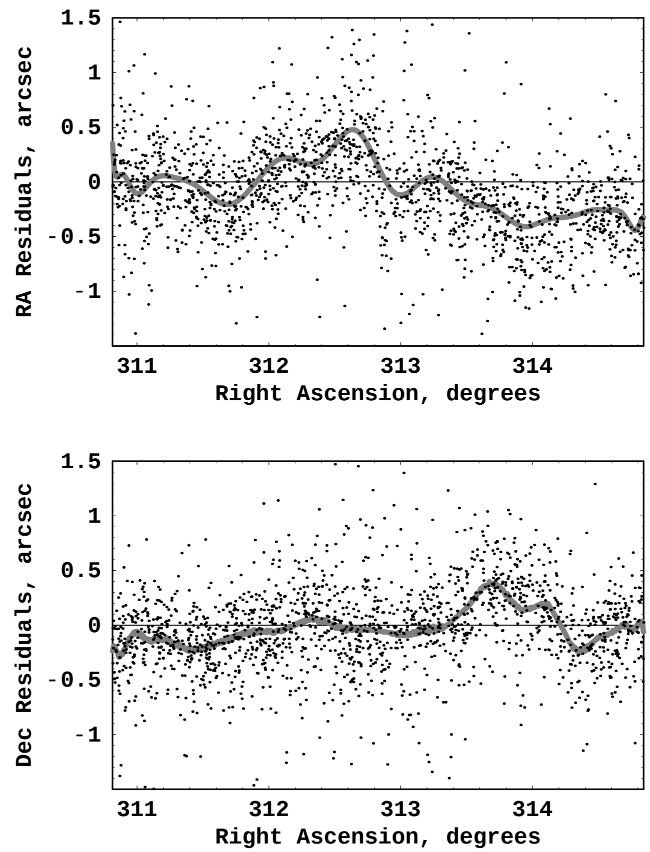

FIG. 2.—Residuals vs. right ascension, before correction. These two plots show a typical example of the systematic deviation of the observed position from the catalog position with respect to R.A. The pattern of the deviation changes with each observation, but all show residuals in R.A. and decl. that independently vary systematically along the length of the strip (i.e., along R.A. or time). Also plotted is a Fourier series fit to the residuals that we use to correct our astrometry.

within a few tenths of a magnitude. Hence, we used the *R* magnitudes for the sample of USNO-A2.0 stars within each strip scan as standard stars to obtain approximate *R* magnitudes for our candidates. Since each strip scan was 25 minutes long, the seeing could change considerably from the beginning of the strip to the end. We corrected for time-variable seeing conditions over the course of each strip scan by fitting a Fourier series to the magnitudes as a function of right ascension, analogous to our corrections for the time-dependent positional deviation.

The observed star positions were then compared with a Triton ephemeris to produce a list of candidates. We used the NEP016 ephemeris solution for Triton (Jacobson, Reidel, & Taylor 1991) combined with the DE405 ephemeris for Neptune and Earth. The ephemerides were supplied to us by JPL's Navigation Ancillary Information Facility (Acton 1990). All stars lying within 1″.0 of the ephemeris and more than 20° from the Sun at the time of the closest approach of Triton were retained as occultation candidates. We examined each of these candidates on our images and on the Digitized Sky Survey and rejected several that appeared to be nonstellar.

3. RESULTS AND DISCUSSION

Table 2 provides information about each of the strip-scan images used in this occultation candidate search. Table 3 contains information about each occultation candidate we found in our search. The format of the table is similar to that used in McDonald & Elliot (1995). Each candidate has been given an identification label beginning with "Tr" and followed by a sequence number. The next columns show the date and time of Triton's closest approach to the star and the minimum separation and position angle of Triton relative to the star (measured north through east) at that time for a geocentric observer. The CCD magnitude of the star in the next column is approximately equivalent to an *R* magnitude as described above. The velocity of the occultation shadow relative to the geocenter is in the next column.

An estimate for the expected signal-to-noise ratio (S/N) for the occultation event using the high-throughput mode for the High-Speed Occultation Photometer and Imager (HOPI; Dunham, Elliot, & Taylor 1998) on the Stratospheric Observatory for Infrared Astronomy (SOFIA; Becklin 1997) is given in the next column. For this calculation, the signal is that expected from the unocculted star over a time interval corresponding to 20 km of shadow motion, and the noise is the photon noise expected from the combined light of Triton and the star. We have not removed candidates with signal-to-noise values lower than the minimum of 20 that is necessary for atmospheric modeling of the light curve, because higher values could be obtained if the occultation proves to be visible with a telescope larger than SOFIA. Also, the colors of these stars are not known, and a very red or very blue star may provide better signal-to-noise ratios if observed in the infrared or ultraviolet, respectively.

The next column contains the solar elongation of Triton at event time. Then comes the observed coordinates of the star in J2000 equinox. The next column is the substar Earth longitude of the star at the time of the event. The substar Earth latitude is the same as the star's declination. The last column contains a list of the CCD strip images on which the candidate was measured.

Our previous occultation candidate search papers have included finder charts for the candidates. However, there is no longer a need to publish such finder charts with the current availability of the Digitized Sky Survey and other charting resources. Figure 3 contains a view of Earth from Triton at the time of closest approach to the star. The shadowed region shows the area from which the Sun is more than 12° below the horizon. This figure is useful for seeing where on Earth the event might be visible, but we have not shown an actual path of the occultation shadow (which has a width about a quarter of Earth's diameter).

For a geocentric observer, an appulse by Triton to a star closer than about 0″.37—the angle subtended by the sum of the radii of Earth and Triton at the mean distance of Triton—would produce an occultation event observable from somewhere on Earth. To be sure of not missing any potential occultations due to astrometric errors, our occultation candidate list includes events with minimum geocentric separations up to 1″.0. The minimum separations in Table 3 are only our best estimates, and they may be affected by errors in our observations, the USNO-A2.0 catalog, and the ephemeris. In our earlier work we estimated the total effect of these errors would be a few tenths of an arcsecond (McDonald & Elliot 1992), an estimate that has been substantiated by several observed occultations (Table 1). Since the error is substantially larger than the angle subtended by the half-light radius in Triton's atmo-

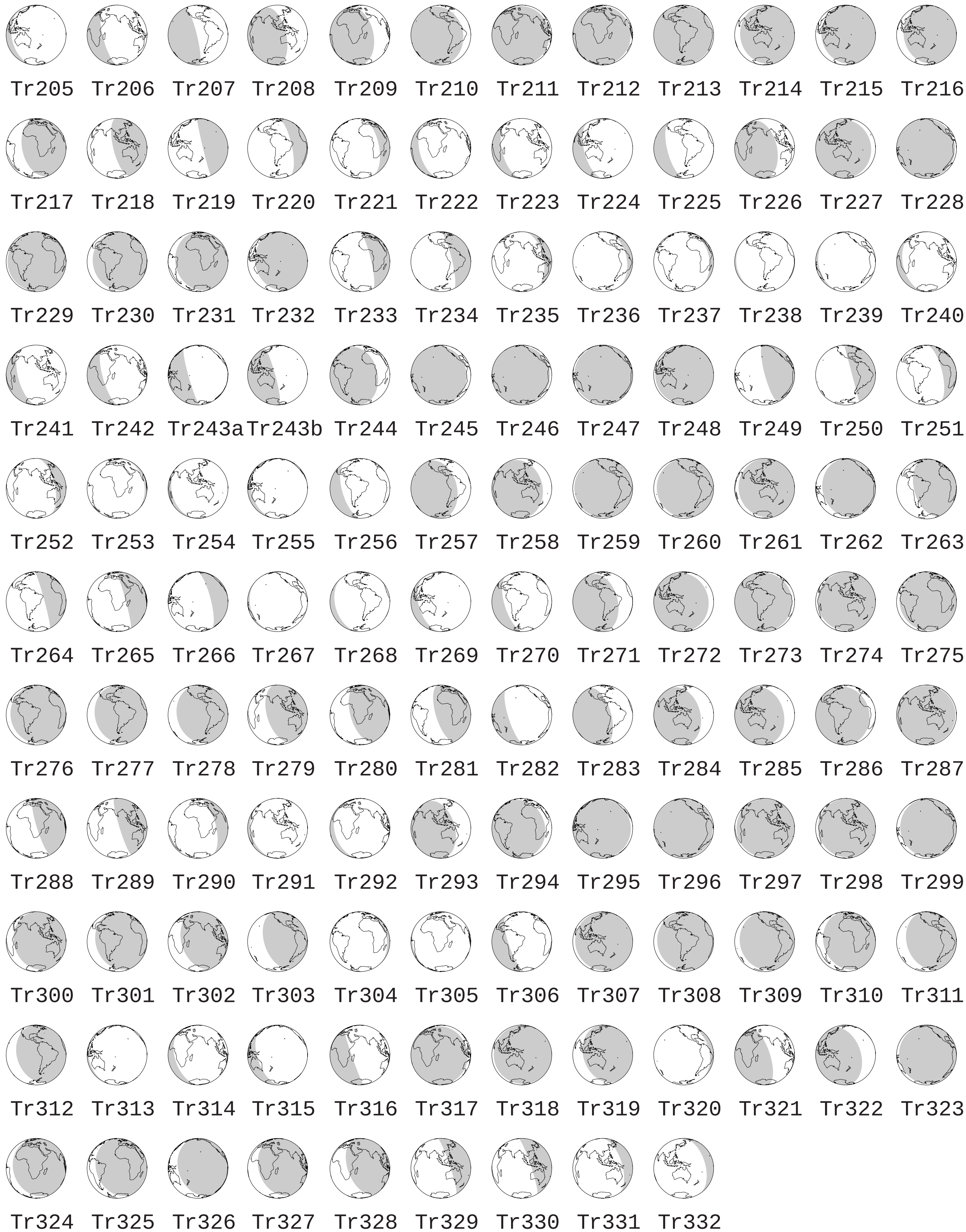

FIG. 3.—Visibility zones for Triton appulse and occultation events. Each frame in this figure shows Earth as seen from Triton at the time of closest approach of Triton to the designated star. The shaded region of Earth indicates the areas where the Sun is more than 12° below the horizon.

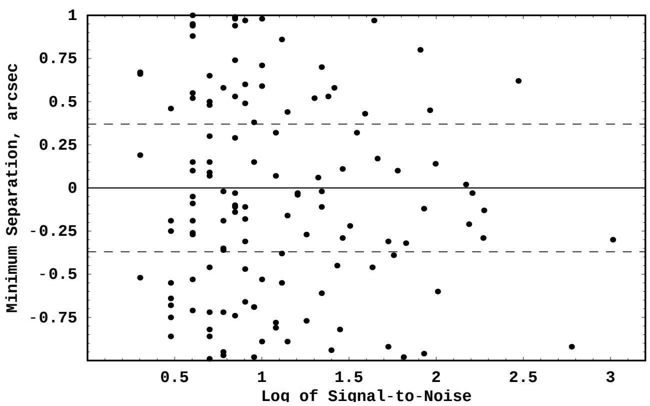

FIG. 4.—Signal-to-noise ratio vs. geocentric minimum separation. The horizontal axis is the logarithm (base 10) of the signal-to-noise values listed in Table 3. Negative values of minimum separation indicate events with position angles greater than 90° and less than 270°, i.e., events that pass south of the center of Earth. Two horizontal lines indicate plus and minus 0".37. If our astrometry had no errors, those events between the two lines would be occultations visible from somewhere on Earth, while those outside the lines would be appulses. However, uncertainties in the astrometry and ephemeris mean that the actual minimum separations will differ from those marked on this figure.

sphere, considerable astrometric refinement will be necessary to produce a prediction sufficiently accurate to observe an occultation.

Taking the ratio of 0".37 to the 1".0 search path we used, we would expect about 47 stars from our candidate list to be occulted by Triton (visible from Earth). Of these events, several will likely be visible from existing large telescope facilities. Occultations of the brightest stars can be observed with portable instruments (see, e.g., Elliot et al. 2000). Figure 4 plots our estimated signal-to-noise ratios for each event (taken from Table 3) versus the nominal minimum separation.

The most interesting events are those that would have the highest signal-to-noise ratios and permit observation of the "central flash" (Elliot et al. 1977). The events with the best potential signal-to-noise ratio are, in decreasing order, Tr316, Tr232, Tr282, Tr306, Tr231, Tr312, Tr266, Tr222, and Tr261. Of these, six have nominal minimum separations less than 0".37: Tr222, Tr312, Tr306, Tr261, Tr231, and Tr316, in order by increasing minimum separation. Tr316 is a particularly promising event, with a magnitude 12.9 star and a geocentric shadow velocity of only 0.8 km s^{-1}. In the next 2 years, Tr222 and Tr231, in 2001, provide the best opportunities, unless a significant correction to the ephemeris or to the position of Tr232 shifts the expected path of its occultation shadow onto Earth. One other star of note in the candidate list is Tr243, which provides two appulses by Triton in 2002 separated by 17 days (Tr243a and Tr243b). Unfortunately, this star is magnitude 17.9 and neither appulse is currently expected to produce an occultation visible from Earth.

4. CONCLUSIONS

We have found 128 stars within 1".0 of Triton's ephemeris over the years 2000 to 2009. Of these, 47 can be expected to produce occultations visible from Earth. We emphasize that these stars should be considered only candidates for occultations, and that further astrometric observations are necessary to determine whether any specific candidate is likely to be occulted and where it would be visible. We have provided views of Earth at the event times to aid in selecting the most promising occultations for further study.

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REFERENCES

Acton, C. H., Jr. 1990, in Second International Symposium on Space Information Systems, ed. L. A. Tavenner (Washington: American Inst. Aeronaut. Astronaut.), 1029
Becklin, E. E. 1997, in The Far Infrared and Submillimetre Universe, ed. A. Wilson (ESA SP-401) (Noordwijk: ESA), 201
Buie, M. W., et al. 1993, BAAS, 25, 1115
Dunham, E. W., Baron, R. L., Elliot, J. L., Vallerga, J. V., Doty, J. P., & Ricker, G. R. 1985, PASP, 97, 1196
Dunham, E. W., Elliot, J. L., & Taylor, B. W. 1998, BAAS, 30, 1109
Dunham, E. W., McDonald, S. W., & Elliot, J. L. 1991, AJ, 102, 1464
Elliot, J. L., Dunham, E. W., & Olkin, C. B. 1995, in ASP Conf. Ser. 73, Airborne Astronomy Symposium on the Galactic Ecosystem: From Gas to Stars to Dust, ed. M. R. Haas, J. A. Davidson, & E. F. Erickson (San Francisco: ASP), 285
Elliot, J. L., French, R. G., Dunham, E., Gierasch, P. J., Veverka, J., Church, C., & Sagan, C. 1977, ApJ, 217, 661
Elliot, J. L., et al. 1998, Nature, 393, 765
Elliot, J. L., & Olkin, C. B. 1996, Ann. Rev. Earth Planet. Sci., 24, 89
Elliot, J. L., et al. 2000, in preparation
Elliot, J. L., Stansberry, J. A., Olkin, C. B., Agner, M. A., & Davies, M. E. 1997, Science, 278, 436
Jacobson, R. A., Riedel, J. E., & Taylor, A. H. 1991, A&A, 247, 565
McDonald, S. W., & Elliot, J. L. 1992, AJ, 104, 862
———. 1995, AJ, 109, 1352
Olkin, C. B., et al. 1997, Icarus, 129, 178
Sicardy, B., et al. 1998, BAAS, 30, 1107
Stetson, P. B. 1987, PASP, 99, 191
Tody, D. 1986, Proc. SPIE, 627, 733
Wolfram, S. 1996, The Mathematica Book (3d ed.; New York: Cambridge Univ. Press)