HET HOBBY ★ EBERLY TELESCOPE

HET Technical Report #90

Hobby - Eberly Telescope Trajectory Generation

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The University of Texas at Austin, The Pennsylvania State University,
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1. Introduction

Tracking trajectories for observed coordinates must be generated for the HET in a timely manner in order for the ambient conditions to be valid during the exposure. Also, since the HET's azimuth drive is designed to be precisely read but not precisely repeatable, telescope azimuth is best defined after positioning and settling have occurred. In addition to the azimuth encoders, tilt meters on the base wedge and tracker bearings will supply gravity-referenced information for small (az,el) corrections. Hence, trajectory generation depends upon whether the current azimuth setting is adequate for the observation. If it is, trajectory generation may proceed immediately; otherwise an operator must reset the telescope and then derive the object's trajectory once a new azimuth is calculated and corrected.

A 2 second time interval has been established as appropriate, as a result of extensive studies by the tracker vendor, OSC[1]. Their engineers' studies indicate that control information based on such a grid will guarantee the specified precision in the tracker servo, which of course inserts thousands of interpolated points between each successive pair of trajectory points. OSC's thesis is that even a linear interpolation is sufficient, given the nature of the HET's latitude, tracker limitations, and trajectory family.[2]

Since the planar tracking rates ($\dot{x}$, $\dot{y}$) cannot exceed about 1 mm/sec., not all of the trajectory points need to be present for the trajectory to begin.[3] Thus, with multi-tasking techniques, future points may be generated and delivered to the tracker control system while past points are being processed in real time. The issue of how and when to deliver trajectory points to the tracker's control system depends on the length of the proposed observation and the method of correcting from apparent to observed coordinates.

Another multi-tasking approach is to generate the next known trajectory while a previous tracking operation is in progress. This is possible only in the case that an azimuth reset is unnecessary for the next object. In the case of an impending reset, one may know with fair accuracy (current estimates are that the HET will achieve a predicted azimuth to 0.01°) a very close starting point for the tracker servo by basing servo settings on the predicted azimuth, so that the tracker can certainly be slewed during the azimuth reset time to a position very close to the next trajectory's initial point. Thus the bulk of the tracker's retraction is made more efficient.

2. Using SLALIB

The Positional Astronomy Library of software routines published by the Rutherford Appleton Laboratory, Particle Physics & Astronomy Research Council, Starlink Project, documented in Starlink User Note 67.26, by P. T. Wallace, February 20, 1995, gathers together in one FORTRAN- or C- callable library most of the information one needs to automate HET trajectory generation. Included are time scale conversions, mean-to-apparent and apparent-to-

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[1] Orbital Sciences Corporation, Phoenix, Arizona.

[2] For details on mean trajectory calculation, see, F. B. Ray, SST Setting and Tracking, HET Tech. report TR-940301, June 1994.

[3] ibid.

observed coordinate conversions for various types of almanacs, and a comprehensive set of utility routines tailored for use by the astronomy community's software engineers.

McDonald Observatory has recently adopted SLALIB after examining it thoroughly for consistency, usability, and accuracy. Software engineers report easily-obtained improvements in telescope pointing, mount models and data reduction due to SLALIB use.[4] It therefore seems reasonable to try and incorporate SLALIB into the HET's algorithms as much as possible, beginning with basic observed trajectory generation and continuing with the addition of mount models for additional HET-specific pointing correction.

3. Object "Observability"

Since the HET is a semi-transit telescope, any choice, by operator or programmed scheduler, of objects must consider its relatively small tracking space. This is most easily shown in equatorial coordinates.

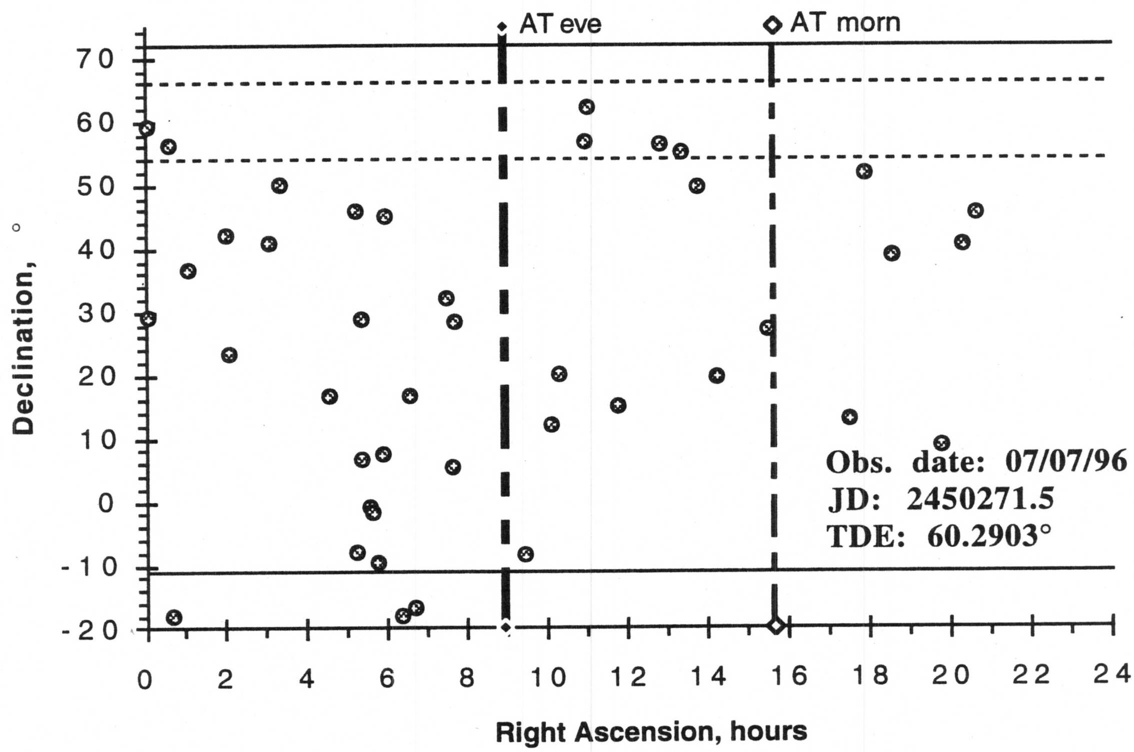

Figure 1. HET tracker space in equatorial coordinates. Astronomical twilight (computed by a method given in the Astronomical Almanac[5]) is plotted in RA for the date shown. The range of declinations for a telescope setting of TDE (telecentric distance from the Equator) corresponding to Az. = 24° is indicated by the horizontal dotted lines near the top of the figure. The four objects at center top are accessible in the night sky without an azimuth change.

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[4] T. Barnes, McDonald Summary of Activity, May 31, 1995.

[5] P. K. Seidelmann, *Explanatory Supplement fo the Astronomical Almanac*, US. Naval Observatory, Washington, D.C., Univ. Science Books, California, 1992, pp. 482 - 488.

Astronomical twilight is easily calculated by an algorithm given in astronomical almanacs, and is customarily based on a true solar altitude of -18° for rising and setting.[6] The procedure is very similar to that used in step 10 following, except that the hour angle h_{rs} of the sun at rise or set must be included in the UT estimator, e.g.

$$UT = UT_o - \frac{(GHA + \Phi \pm h_{rs})}{2\pi} \tag{1}$$

where GHA is the Greenwich hour angle, and Φ is east longitude.

4. Procedure for trajectory generation

We assume that the telescope has been previously set, and that its current azimuth A_o has been corrected for roll and pitch due to the unevenness of the pier (using tilt meters) and that some primitive mount model is available, providing at least an elevation correction Δa.

For the object, in order to judge how much time to allow in the exposure, a model must also exist for the flux delivery to an instrument. This will vary according to stellar magnitude and the nature of optical fibers (if present), slit openings, seeing, resolution, as well as other parameters. The vignetting due to the HET's spherical tracking geometry is well known and highly predictable from apparent or mean coordinates.[7]

Given the distributed computing environment applied to this problem, based on a master control system (MCS) computer and telescope control system (TCS) computer, parts of the algorithm may be used similarly, for example with mean or apparent coordinates and commensurate instrument models to calculate start, crossing and ending times for particular objects, as well as predicting an azimuth for those observations. In general, scheduling the HET for observations falls within the purview of operations and observer groups, and will be implemented on the MCS computer.

Trajectories are generated using the following computational steps:

1. Obtain the mean coordinates $(\alpha,\delta)_{mean}$ for an object.

Comment: There are various methods of accomplishing this, ranging from keying mean coordinates into a text field on the computer screen to having a pull-down menu trigger a message to an on-line almanac. Mean coordinates may also be supplied from a scheduler. Provisions exist in SLALIB for converting from various types of almanacs to the FK5 system, equinox J2000, and it is suggested that the HET adopt the same as a standard for mean coordinates. Some discussion will probably be necessary to decide which other systems (FK4, GCS, etc.) of mean coordinates will be processed by the HET's trajectory generator (and on which computer). Obviously, to apply the trajectory immediately to the tracker, the mean coordinates must be in an appropriate time window, taking into account twilight, dawn, and the expected time necessary to set up a trajectory, slew the tracker, and possibly do an azimuth reset. In some cases, one may wish to generate a trajectory which is not applicable, just for the record or as a trial. ***Coordinates from a scheduler will have previously been tested for HET observability.***

2. Obtain the date of observation.

Comment: The date of the observation must be determined, either by default or entry, and if entered (for example, by keyboard), should be processed for efficacy. For example, if one wishes to generate a trajectory for a future (or past) date for which the ambient conditions are unknown or assumed, the operations or scheduling program interface should warn the operator of the limitations of such a trajectory. A suitable time system should be chosen, such as UTC or

[6] ibid.

[7] F. B. Ray, "SST Setting and Tracking", HET Tech. report TR-940301, June 1994.

UT1, paying attention to leap seconds. There are no doubt some uses for generating such trajectories, even though they may be used only for comparison and never applied to the tracker.

3. Obtain the site parameters, elevation, barometric pressure, geodetic coordinates, etc.

Comment: Many of the site parameters are fixed and may be kept as either hard-coded or "sticky" parameters, with the proper protection and klaxons for changing them. Time-dependent variables should be controlled from external monitors such as a weather station, thermometer, etc. SLALIB has several routines to aid the programmer here.

4. Convert to apparent coordinates $(\alpha,\delta)_{app}$.

Comment: All of the inputs, mean coordinates, proper motions, parallax, radial velocity, epoch and equinox of star data, and the date, either for an applied or unapplied trajectory are available at this stage. SLALIB's **SLA_MAP** can be used for full correction here.

5. Is the current azimuth A_o adequate? If so, go to step 9.

Comment: Using A_o, from which we may compute H_o and TDE_o,[8] and the apparent coordinates, the observer can be made aware of (1) whether the object will cross the HET's field, and (2) if it does, what exposure time will be necessary for a given signal/noise ratio using the model of a particular instrument set-up. For δ_{app} close to TDE_o, there is less inherent vignetting by the HET due to its unfilled aperture. And of course, if δ_{app} is more than 6° removed from TDE_o, the trajectory will not fall within the HET's observing range. If a scheduling program on the MCS is supplying a pre-computed azimuth, we may assume that as the target azimuth, and also that it is adequate for the observer's purpose.

6. (Az. needs to be changed). Setting TDE_o to δ_{app}, we can compute and suggest an azimuth giving a telecentric crossing. Operator or programmatic input for pertinent variables may also be accepted here, and a new target azimuth derived.

Comment: Depending on the context of the trajectory generation, the operator may accept a telecentric crossing, make a correction (in any consistent manner) or depend on a scheduling program to select azimuths to optimize throughput of a sequence of objects. In any case, after step 6 a target azimuth is selected.

7. After the telescope has been commanded, lifted, rotated, and lowered, determine from encoders, tilt meters, thermometers, mount models, etc., what the resting azimuth actually achieved is, and store that value in A_o. A tracker slew to a "ready" position a small amount west of the beginning of the next trajectory may also occur at the same time.

Comment: Research and modeling by the tracker vendor OSC has shown that acceleration of the large tracker masses is easily achieved due to the low velocities expected, and slewing to a "ready" position should be a simple matter of a fixed westward offset. No elaborate "over-the-shoulder" trajectory matching will be required in any case anticipated, and the tracker should have settled into an open-loop stable rate in less than 4 seconds. Details of how much westward to offset the "ready" position are yet to be determined.

8. Return to step 5 and check A_o again for adequacy.

9. Compute new values for H_o, a (telescope elevation) TDE_o, p_c, the telecentric parallactic angle, and all of the other "static" telescope parameters.

Comment: At this point, there should be enough time before starting the track to generate enough of a trajectory to satisfy the tracker's need for data, perform a minor slew and set, and acquire the object.

10. Using **SLA_AOP**, and by an iterative procedure on the time variable (in the form of a modified Julian date MJD), find the "crossing" time τ_x when the observed hour angle (which includes all possible corrections) equals H_o. The last values for SLALIB output parameters "hob" and "dob", the observed hour angle and declination at the crossing time, respectively,

[8] H_o is the HET telecentric distance from the meridian and TDE_o is its telecentric crossing time, respectively

computed by **SLA_AOP**, are denoted by h_x and δ_x. A robust method of iteration (usually converging in ~3 cycles), as suggested by the Astronomical Almanac, modified to use SLALIB routines, follows:[9]

10.1 $\varepsilon = 5 \times 10^{-8}$ radians $\approx$ 0.01 arcsec.
10.2 $UT_o = MJD + 0.5$ add a half day to start the iteration.
10.3 Call **SLA_AOP** (..., UT_o, ... , h_{obs},...) to initialize h_{obs}, the observed hour angle.
10.4 $UT = UT_o - MJD - \frac{(h_{obs} - H_o)}{2\pi}$ initializes the crossing time estimator.
10.5 If $| h_{obs} - H_o | < \varepsilon$, terminate. *UT is the crossing time.*
10.6 Normalize UT to lie in the interval [0 , 1] with appropriate shifts of integral days.
10.7 $UT_o = UT$
10.8 Call **SLA_AOP** (..., $MJD + UT_o$, ... , h_{obs}, d_{obs}...) to update h_{obs}, and d_{obs}., the observed hour angle and declination, respectively.
10.9 $UT = UT_o - \frac{(h_{obs} - H_o)}{2\pi}$ estimates the crossing time.
10.10 Go to step 10.5.

Comment: We will call τ_x = UT from step 10, the "crossing time" to avoid confusion.[10] It is similar to the transit time (time of meridian crossing) but differs in that refraction and other astrometric offsets affect both observed hour angle and observed declination. Finding the crossing time whose accuracy corresponds to 0.01 arcseconds requires 3-4 iterations.

11. Using δ_x as the new observed crossing declination (returned parameter "dob" from the last call to **SLA_AOP**) calculate the maximum offset from H_o, $h_{c.max}$.[11] The constants C1 - C6 used in the trajectory calculation are first updated for the ambient thermal conditions as follows:

$$C1 = \sin(\delta_x - TDE_o),\ C2 = \sin TDE_o,\ C3 = \cos \delta_x,\ C4 = C2\ C3,$$
$$C5 = C1 + C4, \text{ and } C6 = \cos TDE_o \tag{11.1}$$

Comment: The dimension L as defined in the following sequence may be used to compute the available tracking time ATT, given a particular telescope setting and object declination. The elliptical projection for a sidereal trajectory has the symmetrical form

$$\frac{r^2}{a^2} + \frac{d^2}{b^2} = 1 \tag{11.2}$$

where, for a tracking sphere of radius F_s,

$$a = C3\ F_s \quad \text{and} \quad b = C2\ C3\ F_s \tag{11.3}$$

and since the center of the ellipse is at the pole, we may express d in terms of r as

$$d = b\left[1 - \frac{\sqrt{a^2 - r^2}}{a}\right] + c \tag{11.4}$$

if we let

$$c = F_s\,[\,C5 - C2\cos(\delta_x)\,]\ . \tag{11.5}$$

The radius of the limiting circle is given by

$$r_{max} = F_s \sin\left(6^\circ\sqrt{2}\right) \tag{11.6}$$

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[9] Seidelmann, p. 487.

[10] In some previous reports, the use of the word "transit" evokes the meridian transit, but it is the *crossing* of hour angle H_o which is germane to the HET.

[11] F. B. Ray, "SST Setting and Tracking", HET Tech. report TR-940301, June 1994.

therefore a point of intersection between the trajectory's elliptical projection and the limiting circle must also satisfy the circular form

$$r^2 + d^2 = r_{max}^2 . \tag{11.7}$$

Solving for r and substituting in equation 11.4 we find

$$d = b\left(1 - \frac{\sqrt{d^2 - r_{max}^2 + a^2}}{a} \right) + c \tag{11.8}$$

and also that after rearranging, squaring, and collecting terms, d must be a root of the quadratic polynomial

$$(a^2 + b^2) d^2 + \left[-2a^2 (b + c) \right] d + a^2 c^2 + 2 a^2 b c + b^2 r_{max}^2 \tag{11.9}$$

explicitly,

$$d = \frac{a^2 (b + c) - b \sqrt{a^4 - a^2\left(r_{max}^2 - c^2 - 2bc\right) + b^2 r_{max}^2}}{a^2 - b^2} \tag{11.10}$$

which we will call d_{lim}. Then, from equation 11.7 we can solve for r_{lim}, lying on a circular boundary, so that the equation for L is

$$\frac{L}{2} = r_{lim} = \sqrt{r_{max}^2 - d_{lim}^2} \tag{11.11}$$

and in turn, for $h_{c.max}$, the maximum available hour angle offset at the current setting,

$$h_{c.max} = \sin^{-1}\left[\frac{r_{lim}}{F_s \cos \delta_x} \right] \tag{11.12}$$

finally achieving an expression for the available tracking time (ATT), in hours, as follows:

$$ATT = \frac{24}{\pi} h_{c.max} . \tag{11.13}$$

$H_o + h_{c.max}$ and $H_o - h_{c.max}$ represent the limits of travel in hour angle for the tracker at the current azimuth setting. Therefore, they may be used to derive limiting start and stop times for a full trajectory. These limits will normally be overridden by a scheduling algorithm in the MCS, but it is instructive to relate the HET tracking time limits to astronomical coordinates in any case, just to provide a time window.

12. In a fashion similar to step 10, **SLA_AOP** may be used to converge to values for τ_{start} and τ_{end}, the start and ending times related to $H_o + h_{c.max}$ and $H_o - h_{c.max}$, respectively.

Comment: One could, for example, write step 10 as a subroutine which returns the UT crossing time for a given hour angle. The same subroutine may be used for start, crossing and ending times.

13. Grid points at integral UTC seconds are calculated for starting and ending times near the exact values for τ_{start} and τ_{end} just calculated and stored back in the same variables, thus aligning the tracker's clock with UTC second pulses. In order for there to be an integral number of 2-second intervals in the trajectory, $(\tau_{end} - \tau_{start})$ mod 2 must equal 0.

14. The remaining trajectory points are then generated in observed coordinates, calling **SLA_AOP** (or alternatively **SLA_AOPQK** and using in-line refraction correction) at discrete intervals to obtain h_{obs} and δ_{obs}. If $\hat{t}$ represents the time "tick" generated by the system clock at

some appropriate interval, and with the telescope tracker constants C1 - C6 as before, we have the computational sequence[12]

$$r(\hat{t}) = -F_S \cos \delta_{obs}(\hat{t}) \sin \left[h_{obs}(\hat{t}) - h_x\right] \quad (14.1)$$

$$d(\hat{t}) = F_S \left[C5 - C2 \cos \delta_{obs}(\hat{t}) \cos \left[h_{obs}(\hat{t}) - h_x\right]\right] \quad (14.2)$$

providing the Cartesian coordinates in the tracker's reference frame,

$$x(\hat{t}) = r(\hat{t}) \cos p_c - d(\hat{t}) \sin p_c \quad (14.3)$$

$$y(\hat{t}) = r(\hat{t}) \sin p_c + d(\hat{t}) \cos p_c \quad (14.4)$$

$$z(\hat{t}) = F_S \left[1 - \cos \beta(\hat{t})\right] \quad (14.5)$$

where the angular distance from the line of sight to the telecentric axis is

$$\beta(\hat{t}) = \cos^{-1} \left[C2 \sin \delta_{obs}(\hat{t}) + C6 \cos \delta_{obs}(\hat{t}) \cos \left(h_{obs}(\hat{t}) - h_x\right)\right] \quad (14.6)$$

tilts,

$$\theta(\hat{t}) = \tan^{-1}\left[\frac{y(\hat{t})}{F_S \cos \beta(\hat{t})}\right], \quad \phi(\hat{t}) = \tan^{-1}\left[\frac{x(\hat{t})}{F_S \cos \beta(\hat{t})}\right]. \quad (14.7)$$

and field rotation

$$\rho(\hat{t}) = -\sin^{-1} \left[\sin \delta_{obs}(\hat{t}) \sin \left(h_{obs}(\hat{t}) - h_x\right)\right] \quad (14.8)$$

Comment: The HET's limited zenith angle range ($\zeta \leq 43.5°$) may be used to advantage if refraction calculations during the generation take too long. A simple model for refraction

$$R = A_R \tan \zeta \quad (14.10)$$

will suffice, giving corrections accurate to $0^s.014$ RMS and $0^s.07$ max. (see Figure 2). If this error is acceptable as a worst case (parallactic angle = 90°), the programmer may use **SLA_AOPPA** to pre-compute apparent to observed place parameters in an array AOPRMS, then during the generation, recover the zenith angle ζ at each time step, using **SLA_ZD** for example, and use the pre-computed AOPRMS(11) as the coefficient A_R in the refraction equation. The routine **SLA_AOPQK** is then called at each time interval for observed positions. In this way latitude, height, ambient temperature, pressure, relative humidity, wavelength, lapse rate, and longitude are not redundantly calculated for each time tick. At each interval, the observed hour angle and declination may then be corrected by adding $R \cos p_c$ and $R \sin p_c$, respectively.

[12] ibid.

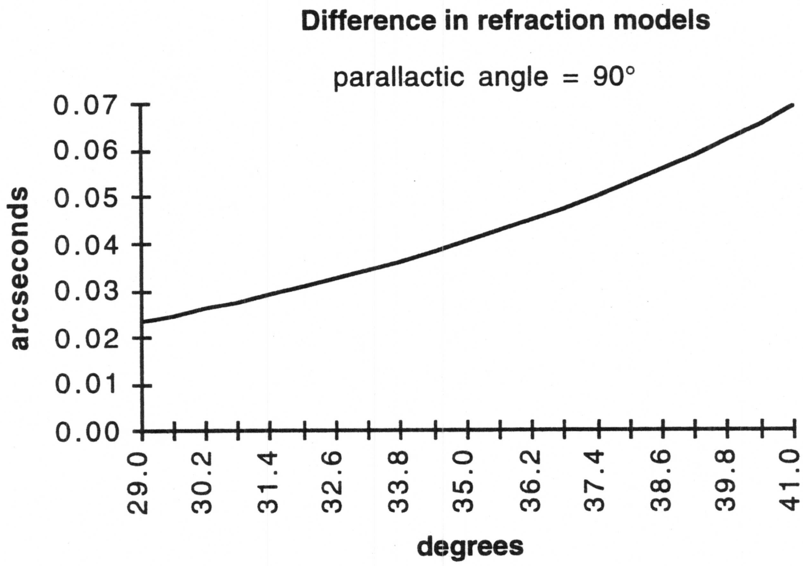

Figure 2. Difference in refraction models between the simple model in equation 14.10 and a more accurate Newton-Raphson solution used in SLALIB. The trajectory, having a parallactic angle of 90° has the maximum zenith distance variation possible in the HET.

5. Test stars

The following table gives a range of bright stars and the dates when they are on the meridian at 2100 hours local mean time. Coordinates are also given in radians for convenient debugging. Column "Mer." is the date when the star is on the meridian at about 9 p.m. local time. Knowing H_o, one may quickly estimate the crossing time τ_x.

	Right ascension				Declination				
Star	**h**	**m**	**α, h**	**α, rad.**	**°**	**m**	**δ, °**	**δ, rad.**	**Mer.**
Alpheratz	0	7	0.1167	0.0305	28	54	28.9000°	0.5044	11/7
Caph	0	7	0.1167	0.0305	58	58	58.9667°	1.0292	11/7
Schedar	0	39	0.6500	0.1702	56	21	56.3500°	0.9835	11/15
Diphda	0	42	0.7000	0.1833	-18	10	-18.1667°	-0.3171	11/16
Mirach	1	8	1.1333	0.2967	36	26	36.4333°	0.6359	11/23
Almak	2	2	2.0333	0.5323	42	10	42.1667°	0.7359	12/6
Hamal	2	5	2.0833	0.5454	23	18	23.3000°	0.4067	12/7
Algol	3	6	3.1000	0.8116	40	50	40.8333°	0.7127	12/23
Mirfak	3	22	3.3667	0.8814	49	45	49.7500°	0.8683	12/27
Aldeberan	4	34	4.5667	1.1956	16	27	16.4500°	0.2871	1/14
Rigel	5	13	5.2167	1.3657	-8	14	-8.2333°	-0.1437	1/24
Capella	5	14	5.2333	1.3701	45	48	45.8000°	0.7994	1/24
Bellatrix	5	23	5.3833	1.4094	6	19	6.3167°	0.1102	1/26
Elnath	5	24	5.4000	1.4137	28	35	28.5833°	0.4989	1/27
Alnilam	5	34	5.5667	1.4573	-1	13	-1.2167°	-0.0212	1/29
Alnitak	5	39	5.6500	1.4792	-1	58	-1.9667°	-0.0343	1/30
κ Orion	5	46	5.7667	1.5097	-9	41	-9.6833°	-0.1690	2/1
Betelgeuse	5	53	5.8833	1.5403	7	24	7.4000°	0.1292	2/3

Menkalinan	5	57	5.9500	1.5577	44	57	44.9500°	0.7845	2/4
Mirzam	6	21	6.3500	1.6624	-17	56	-17.9333°	-0.3130	2/10
Alhena	6	36	6.6000	1.7279	16	26	16.4333°	0.2868	2/14
Sirius	6	44	6.7333	1.7628	-16	40	-16.6667°	-0.2909	2/16
Castor	7	32	7.5333	1.9722	31	58	31.9667°	0.5579	2/28
Procyon	7	38	7.6333	1.9984	5	19	5.3167°	0.0928	3/2
Pollux	7	43	7.7167	2.0202	28	7	28.1167°	0.4907	3/3
Alphard	9	26	9.4333	2.4696	-8	31	-8.5167°	-0.1486	3/29
Regulus	10	7	10.1167	2.6485	12	8	12.1333°	0.2118	4/8
Algeiba	10	18	10.3000	2.6965	20	1	20.0167°	0.3494	4/11
Merak	11	0	11.0000	2.8798	56	34	56.5667°	0.9873	4/22
Dubhe	11	2	11.0333	2.8885	61	56	61.9333°	1.0809	4/22
Denebola	11	47	11.7833	3.0849	14	46	14.7667°	0.2577	5/4
Alioth	12	53	12.8833	3.3728	56	9	56.1500°	0.9800	5/20
Mizar	13	23	13.3833	3.5037	55	6	55.1000°	0.9617	5/28
Alkaid	13	46	13.7667	3.6041	49	29	49.4833°	0.8636	6/3
Arcturus	14	14	14.2333	3.7263	19	22	19.3667°	0.3380	6/10
Alphecca	15	33	15.5500	4.0710	26	50	26.8333°	0.4683	6/30
Rasalhague	17	33	17.5500	4.5946	12	35	12.5833°	0.2196	7/30
Eltanin	17	56	17.9333	4.6949	51	30	51.5000°	0.8988	8/5
Vega	18	36	18.6000	4.8695	38	45	38.7500°	0.6763	8/15
Altair	19	49	19.8167	5.1880	8	47	8.7833°	0.1533	9/3
Sadr	20	21	20.3500	5.3276	40	9	40.1500°	0.7007	9/11
Deneb	20	40	20.6667	5.4105	45	9	45.1500°	0.7880	9/16

6. Filenames

This document is archived in the following files:

Text: TR950607
Spreadsheets: TRACKER SS
HET refraction
HET observability