CHARA Technical Report

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A CHARA Observation Planning Tool

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ABSTRACT: A graphical user interface (GUI) software tool written in the Interactive Data Language (IDL) has been developed to help plan interferometric observations with the CHARA array. The GUI allows the user to select: (1) the waveband for the observation, (2) the target HD number from Hipparcos catalogue, (3) an angular diameter, (4) a CHARA baseline, (5) the Pipes of Pan "POP" configuration, and (6) date. Once these options are specified, the user may plot, for a range of hour angles (-6^h to $+6^h$): (a) the (u, v)-plane coverage, (b) the spatial frequency coverage as a function of altitude, (c) the uniform disk visibility as a function of hour angle and Universal Time, (d) the uniform disk visibility as a function of spatial frequency, (e) the altitude versus azimuth, (f) the position angle as a function of hour angle and Universal Time, and(g) the altitude and OPLE delay as a function of Universal Time. The software calculates for which hour angles for which Optical Path-Length Equalizer (OPLE) delay compensation is possible and also calculates times of astronomical twilight.

1. INTRODUCTION

This technical report is an attempt to document this software tool: primarily to document what input data are used, what formulae are employed, and how the calculations are done. This document also provides a brief tutorial on using the GUI.

2. INPUT DATA

Computation of the projected baseline, geometric delay, and available delay compensation for a given target star and hour angle requires an astrometric solution for the array in order to calculate an accurate baseline length and bearing. Differential air/vacuum paths between telescopes are needed to compute the delay compensation required to obtain zero pathlength difference between two telescopes and produce a fringe. CHARA's Pipes of Pan "POP" mirrors allow fixed delay "chunks" of ~ 36.6 meters to be added or sometimes subtracted from the default air/vacuum path values. The available POP delays are telescope dependent. Below we list the astrometric solution, airpaths and POP configuration table used by the software.

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Listed below is astrometic solution for the CHARA Array (T.A. ten Brummelaar (2004), private communication), the airpaths, and "POP" table showing the delay offsets available for any given telescope combination.

```
#Date: Wed, 03 Mar 2004 11:26:46 -0800
#
# XOFFSET - East offset in microns from S1
# YOFFSET - North offset in microns from S1
# ZOFFSET - vertical (+ is up) offset in microns from S1
# AIRPATH - amount of airpath  in microns using default beam
#           Note that this assumes the default Beam dn default Pop are used
#
#S1
LONG    -118 3 25.31272
LAT       34 13 27.78130
XOFFSET 0.0
YOFFSET 0.0
ZOFFSET 0.0
AIRPATH 0.0
#S2
XOFFSET   -5748393.059
YOFFSET   33581340.790
ZOFFSET     643880.188
AIRPATH    4532654.762

#E1
XOFFSET   125349003.099
YOFFSET   305937513.274
ZOFFSET    -5898978.192
AIRPATH    15309717.902

#E2
XOFFSET    70400864.470
YOFFSET   269716660.932
ZOFFSET    -2787652.960
AIRPATH    26386214.626

#W1
XOFFSET -175068583.489
YOFFSET  216322063.446
ZOFFSET  -10827769.936
AIRPATH   29087218.284

#W2
XOFFSET -69088236.186
YOFFSET 199329322.146
ZOFFSET    451418.063
AIRPATH   -5413000.000
```

	POP1	POP2	POP3	POP4	POP5
S1	0.000 m	36.576 m	73.152 m	109.728 m	146.304 m
S2	-36.576 m	0.000 m	36.576 m	73.152 m	109.728 m
E1	0.000 m	36.576 m	73.152 m	109.728 m	146.304 m
E2	-73.152 m	-36.576 m	0.000 m	36.576 m	73.152 m
W1	-73.152 m	-36.576 m	0.000 m	36.576 m	73.152 m
W2	-146.304 m	-109.728 m	-73.152 m	-36.576 m	0.000 m

3. FORMULAE

3.1. Spatial Frequency and Delay

The spatial frequency and position angle coverage of a given star is derived from the CHARA Array's sampling of the u, v-plane. Following Dyck (1999), given baseline components B_{east}, B_{east}, and B_{up} (see `X(YZ)OFFSETS` above) the u, v spatial frequency values (in cycles/arcsecond) are

$$\begin{aligned} u &= (B_{east} \cos h - B_{north} \sin\phi \sin h + B_{up} \cos\phi \sin h)/(206265\, \lambda_0) \\ v &= (B_{east} \sin\delta \sin h + B_{north}(\sin\phi \sin\delta \cos h + \cos\phi \cos\delta) \\ &\quad -B_{up}(\cos\phi \sin\delta \cos h - \sin\phi \cos\delta))/(206265\, \lambda_0) \end{aligned}$$

where h is the hour angle, δ is the declination, ϕ is the latitude, and λ_0 is the central wavelength of the observation, Both B and λ_0 must have the same units. The spatial frequency, x, is defined

$$x = \sqrt{u^2 + v^2}$$

and the position angle on the sky is

$$\psi = \tan^{-1} u/v.$$

The geometric delay for a given baseline is

$$\begin{aligned} \Delta_{\rm geo} &= -B_{east} \cos\delta \sin h - B_{north}(\sin\phi \cos\delta \cos h - \cos\phi \sin\delta) \\ &\quad +B_{up}(\cos\phi \cos\delta \cos h + \sin\phi \sin\delta) \end{aligned}$$

Accessible spatial frequencies are those where needed delay can be provided by the OPLE carts. The delay required from carts is the sum of the geometric delay for the baseline, the airpath difference between the two telescopes and the delay provided by the POP mirrors:

$$\Delta_{\rm carts} = -\frac{1}{2}\Big[\Delta_{\rm geo} - \Delta_{\rm airpath} + {\rm POP(Tel.2)} - {\rm POP(Tel.1)}\Big]$$

where $\Delta_{\rm carts}$ must fall with in the range

$$-43 \text{ meters} < \Delta_{\rm carts} < +43 \text{ meters}$$

in order to achieve zero pathlength difference and obtain fringes. Δ_{airpath} is obtained for each baseline for the `AIRPATH` input data. The POP delay is obtained by summing the two delays provided by the POP settings associated with the telescope pair (see table above). At the time of this writing the W2 cart is stationary such that delay compensation is possible in the range -43 meters $< \Delta_{\text{carts}} < 0$ for all baselines which include the W2 telescope.

3.2. Visibility

For single stars, the squared visibility is assumed to be that of a uniform disk,

$$V^2 = \Big(2J_1(\pi x\theta_{\text{UD}})/(\pi x\theta_{\text{UD}})\Big)^2$$

where θ_{UD} is the uniform disk angular diameter in arcseconds. The visibility of a binary system (Boden 1999) is

$$V^2 = \frac{V_1^2 + r^2V_2^2 + (2rV_1V_2\cos(2\pi(u\Delta\alpha + v\Delta\delta)))}{(1+r)^2}$$

where r is the brightness ratio of the secondary to the primary and V_2^2 and V_1^2 are their squared visibilities, respectively. The right ascension and declination offsets are

$$\Delta\alpha = \rho\sin(\vartheta)$$
$$\Delta\delta = \rho\cos(\vartheta)$$

where ρ is the separation (in arcseconds) of the two components on the sky and ϑ is the position angle of a line connecting the two stars.

3.2.1. Binary Orbit

Following Aitken (1964, Chapter 4), the position angle is obtained from

$$\vartheta = \Omega + \tan^{-1}(\pm\tan(\upsilon+\omega)\cos i)$$

using $(+)$ when $\pi/2 \le \upsilon+\omega < 3\pi/2$ and $(-)$ when $\upsilon+\omega < \pi/2$ or $\upsilon+\omega \ge 3\pi/2$. Ω is the position angle of line of nodes, ω is the longitude of the line of apsides, υ is the true anomaly, and i is the orbital inclination.

The true angular separation is

$$r = \vartheta_a\frac{(1-e^2)}{(1+e\cos\upsilon)}$$

where e is the orbital eccentricity. The apparent angular separation on the sky is

$$\rho = r\frac{\cos(\upsilon+\omega)}{\cos(\vartheta-\Omega)}$$

The true anomaly is computed from

$$\upsilon = 2\tan^{-1}\Big(\sqrt{\frac{1+e}{1-e}}\tan(E/2)\Big)$$

where E is the eccentric anomaly

$$E = M + \frac{e\sin(M)}{1 - e\cos(M)}$$

and M is the mean anomaly

$$M = \frac{2\pi}{P}(t - T_0)$$

where P is the orbital period, T_0 is the epoch of periastron, and t is the epoch of interest.

3.3. Time, the Sun's Position, and Twilight

In order to plan the best calendar dates and clock times for observations, we need to covert hour angles to Universal Time and compute the location of the sun for daylight and twilight calculations.

The Universal time associated with an hour angle and a calendar date is calculated as follows. Hour angles and Universal Time are linked through Greenwich Mean Sidereal Time, GMST. The calculation of GMST from the Julian Date is performed using formulae from the *Astronomical Almanac* (see TIME-SCALES: Relationships between universal and sidereal time, page B6).

```
# Julian centuries of 36525 days since ;J2000.0
tu=(mjd-51545.d0)/36525.d0

# Greenwich Mean Sidereal Time at 0h UT (in seconds)
gmst= 24110.54841d0 + (8640184.812866d0*tu) + (0.093104d0*tu*tu) + (6.2d-6*tu*tu*tu)
```

where `mjd` is the modified Julian Date, JD - 2400000.5. The modified Julian date at 0^h UT for a given calendar date is calculated by the routine `juldate.pro` (from the *IUE* satellite suite of IDL routines).

The Local Mean Sidereal Time at 0^h UT is

```
# Local Mean Sidereal Time in hours at 0h UT (longitude correction)
lmst_h=(gmst/3600.d0)+((long*180./!pi)/15.d0)
```

where `long` is the longitude of the CHARA Array in degrees. Thus, the hour angle of a star with right ascension `ra` at 0^h UT on this MJD is

```
#HA of star at 0h UT on MJD
ha_at_ut_zero=lmst_h-ra
```

Finally, the UT for a given hour angle h is

$$\mathrm{UT} = (h - \texttt{ha\_at\_ut\_zero})/1.002737$$

where 1.002737 is the conversion factor from sidereal hours to mean solar hours.

For the twilight calculations we use the "low precision formulas for the Sun's coordinates and the equation of time" from the *Astronomical Almanac* (1989, page C24). To calculate the times for the beginning and ending twilight we need to compute the zenith distance of the sun for a given date and for times which correspond to the hour angles of interest for the CHARA target star. Astronomical twilight is defined as the time between when the sun reaches zenith distance of 108° and sunrise or sunset. Our recipe is to first find those UT times when the sun has a zenith distance of 108°. If the zenith distance is increasing with time it is dusk, otherwise it is dawn. Once the times of dusk and dawn are located, the UT times are converted to LMST for ease of plotting. (see procedure `sunpos` in `chara_plan.pro` for the exact algorithm).

4. A BRIEF TUTORIAL

4.1. Getting Started

Start with the 'tar'ed and 'gzip'ed distribution. Gunzip and untar the distribution. That'll make a new directory in the current working directory. Change into the new directory and start IDL. Next compile `chara_plan.pro` and then run it. That's it! Here's an example in IDL 6.0 on a Mac G5 running OSX 10.3.2:

```
jaufdenb citlalicue \536> gunzip chara_plan_beta_1.4.tar.gz

jaufdenb citlalicue \537> tar xvf chara_plan_beta_1.4.tar
CHARA_PLAN_BETA_1.4/chara_plan.pro
CHARA_PLAN_BETA_1.4/README
CHARA_PLAN_BETA_1.4/hipp_ra_dec_hd_spec.idl

jaufdenb citlalicue \540> cd CHARA_PLAN_BETA_1.4
jaufdenb citlalicue \541> idl
IDL Version 6.0, Mac OS X (darwin ppc m32). (c) 2003, Research Systems, Inc.
Installation number: 209139.
Licensed for personal use by Jason Aufdenberg only.
All other use is strictly prohibited.

IDL> .run chara_plan
% Compiled module: PCHECK.
% Compiled module: IUEGETOPT.
% Compiled module: PARCHECK.
% Compiled module: TEN.
% Compiled module: CHARA_EVENT.
% Compiled module: CHARA_PLAN.
% Compiled module: CHARA_CONFIG.
% Compiled module: SUNPOS.
% Compiled module: ORBIT2.
% Compiled module: MYKEPLER.
% Compiled module: JULDATE.
% Compiled module: LEGEND.
IDL> chara_plan
% Compiled module: CW_FIELD.
% Compiled module: XMANAGER.
```

4.2. Working with the GUI

The following 11 figures are "screenshots" of the GUI in action. Please read the captions, they contain recommendations on how to further explore the GUI beyond the screenshots.

To get started, Figure 1 shows what the GUI should look like when it pops up after typing "chara_plan" at the IDL prompt. To quit, click the "QUIT " button to the middle right. The upper-left window contains basic help information. You type in the HD number of the target star and its angular diameter. The remaining settings are controlled by scroll- or drop-lists. There are 15 baselines to choose from, 5 POP settings per telecope, 7 plot settings, and the date. The HD number is looked up in the IDL savefile `hipp_ra_dec_hd_spec.idl` and star's coordinates and spectral type are returned. Next the formulae in Secetion 3 are employed to compute the data used to make the plots. A change of any input or list value will redraw the plot with the new set of parameters.

Figure 2 shows a plot of the (u, v)-plane for Sirius on the W2-E2 basline. To look at what visibilities and spatial frequencies are sampled, change the "Plot" droplist to "Vis. vs. Spatial Freq." and you'll see Figure 3. Another very useful plot is "Vis. vs. Hour Angle", shown in Figure 4. This is probably the single most useful plot for planning exactly when and what visibilties are sampled for a given baseline/POP configuration. Figure 5 shows the delay ($\Delta_{\rm carts}$, see above) as a function of UT time. This is very similar to the output of the Unix GUI `chara_plan` by T.A. ten Brummelaar. Figure 6 shows the track of Sirius in Alt-Az space and where delay compenstation is possible. This is a good plot mode to getting a feel for which baseline/POP configurations cover which parts of Sirius' path across the sky. Figure 7 shows another available plot mode "Spatial Freq. vs. Altitude" which can be useful for seeing what portions of the visibility curve are sampled at what altitudes. Figure 8 shows the position angle coverage of Sirius on the W2-E2 baseline. Figures 9 and 10 show the sampling of the 1st and 2nd lobes of Sirius with the E1-E2 and S2-W2 baselines as an alternative to the W2-E2 baseline.

Finally, Figure 11 shows the visibility as a function spatial frequency for the spectroscopic binary HD 116658 (α Vir, Spica) using the formulae from Section 3.2.1. Spica is the only star for which binary elements coded are present (see the procedure `orbit2` in the file `chara_plan.pro`), but in the future we plan to impliment manipulation of binary orbital elements for better binary star observation planning.

5. ACKNOWLEDGMENTS

Thanks to Greg Schwarz for getting me started with IDL GUIs. Thanks to Steve Ridgway for encouraging me to write this up and to Theo ten Brummelaar for the input data and for allowing access to his `chara_plan` program to test this code. Thanks to John Monnier and Theo for trying out beta versions of the code. Please send bugs, comments, and recommendations to jasona@noao.edu. Happy planning.

6. BREFERENCES

Aitken, R. G. (1964). *The binary stars*. New York: Dover Publication, 1964.

Boden, A. F. (1999). Elementrary theory of interferometry. In P. R. Lawson, editor, *Principles of Long Baseline Stellar Interferometry*, pages 9–29. National Aeronautics

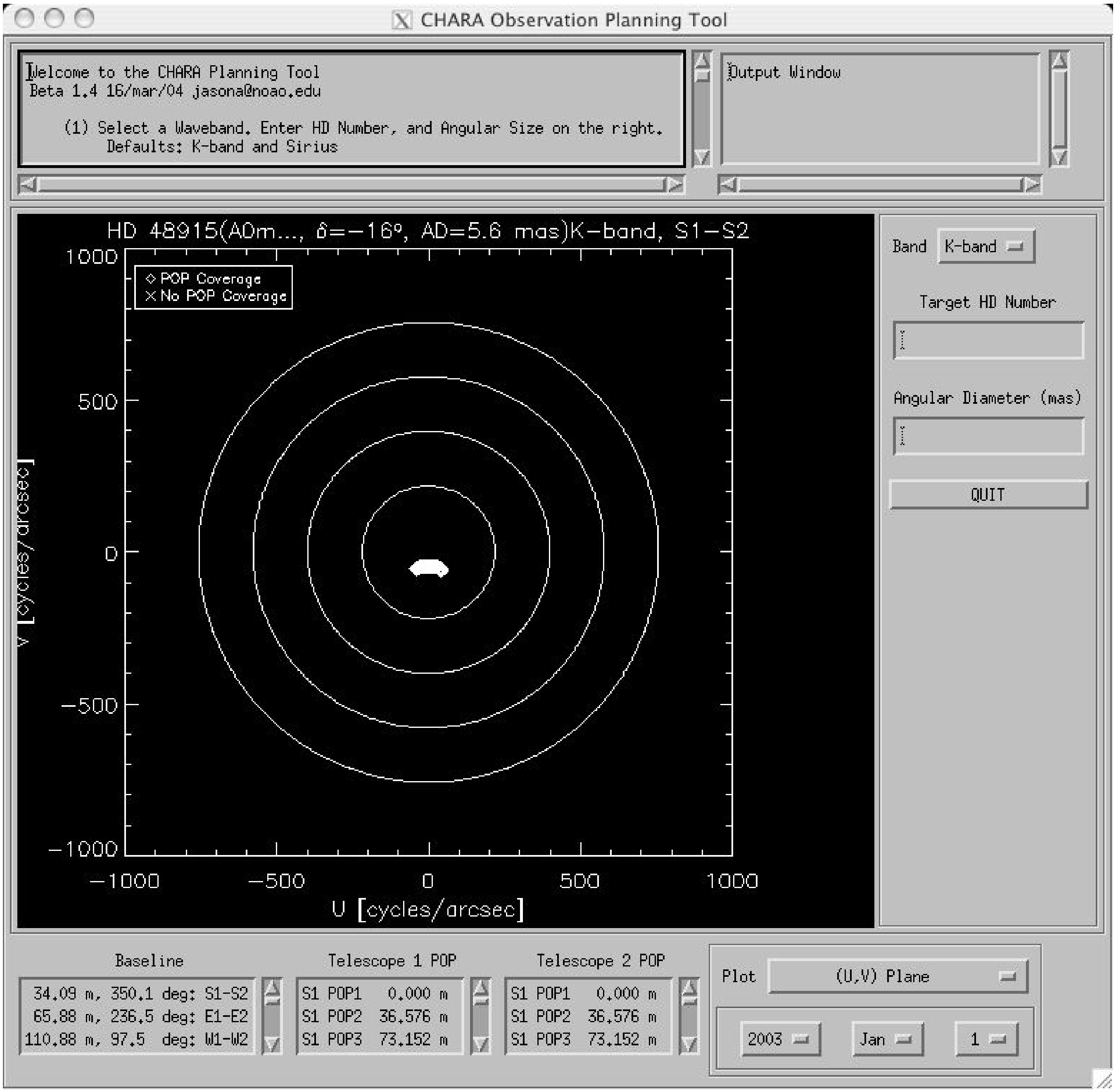

FIGURE 1. A screen shot of the IDL GUI when it first pops up. The initial setting is for Sirius on the shortest baseline, S1-S2, in the K-band. The (u, v)-plane plot is initially shown. The type of plot and date are set by the buttons at the lower right. Above this on the right are the settings for the waveband, HD number, and angular diameter. The lower-left scroll lists allow the user to select the baseline and POP setting for each telescope. The upper left box contains basic instructions and the "Output Window" diplays (x, y) values from any plot when the user clicks in the plot window.

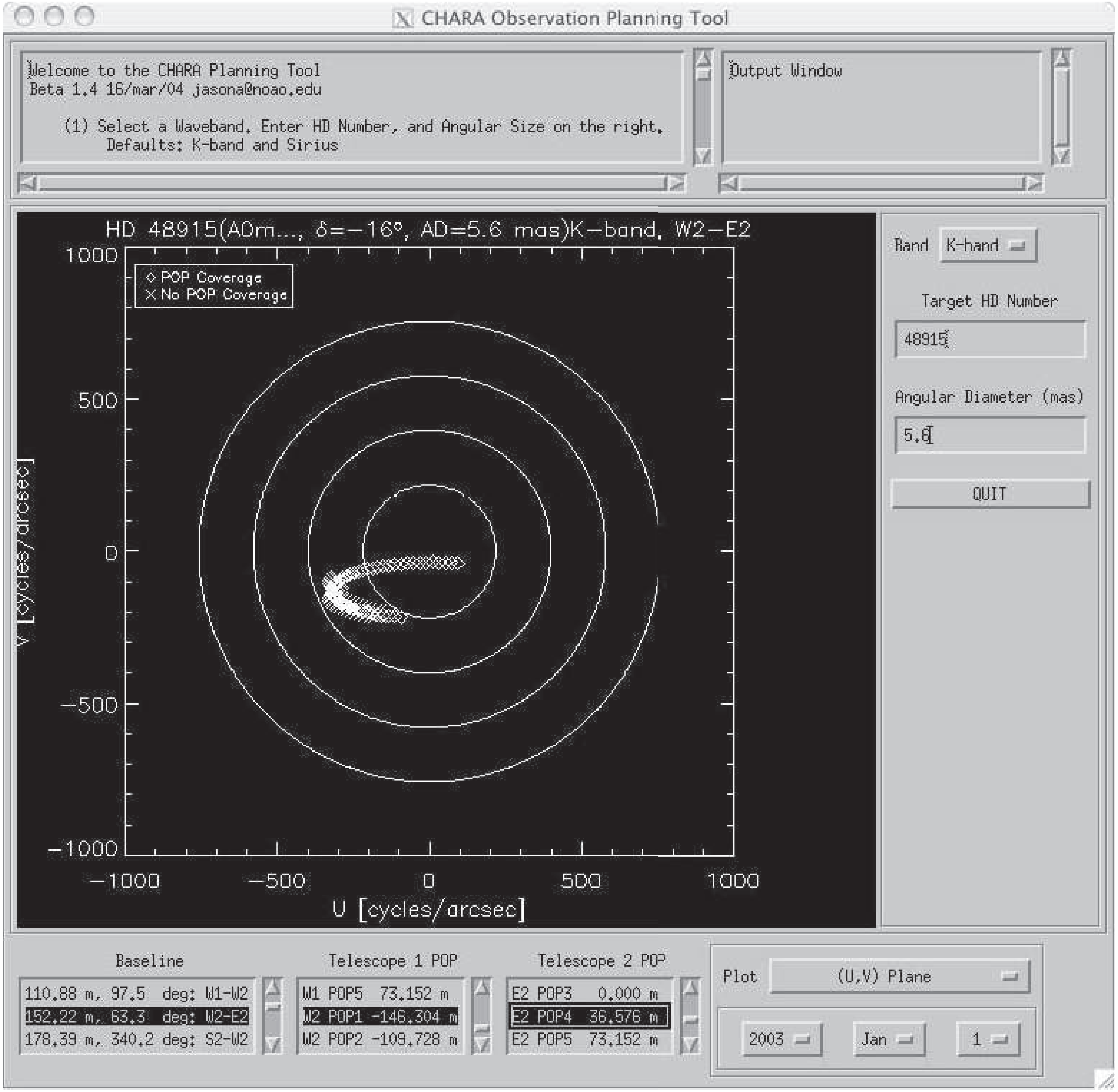

FIGURE 2. A (u, v)-plane plot for Sirius, this time on the W2-E2 baseline. The baseline was selected from the scroll list "Baseline" at the bottom-left corner of the GUI. W1 POP1 has been selected from scroll list "Telescope 1 POP" and E2 POP4 from the scroll list "Telescope 1 POP". Sirius' HD number has been explicitly entered to the right, along with its angular diameter. On this baseline, over 12 hours (hour angles -6^h to $+6^h$ in 15 minute steps) the (u, v)-plane track sweeps through a good portion of the 1st and 2nd lobes of the visibility function. The open diamonds show locations in the (u, v)-plane where OPLE/POP delay compensation is possible. The overplotted 'X's mark (u, v)-plane positions where delay compensation is not possible. Try changing the POP configuration via the scroll lists to see how the OPLE/POP coverage changes. Also try switching to the H-band, using the button on the upper right, to see how the (u, v)-plane track changes.

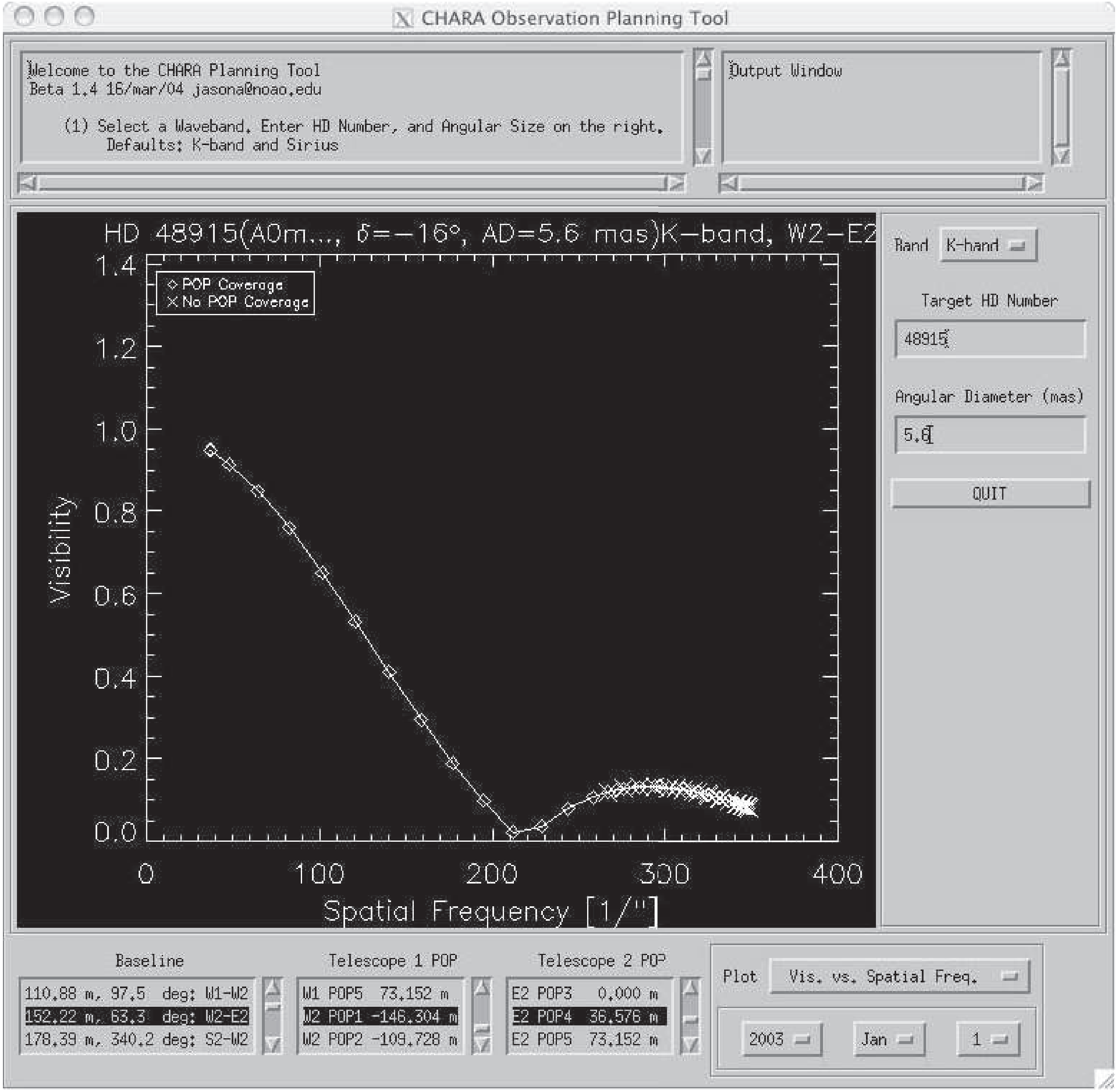

FIGURE 3. Here's a plot of the visibility as a function of spatial frequency for Sirius on the W2-E2 baseline. The plot type is selected from the "Plot" droplist at the bottom right of the GUI. Indeed, the visibility coverage is quite good, as suggested in Figure 2. However, with this OPLE/POP setup there is no delay available to cover most of the 2nd lobe. Again, try changing the POP configuration via the scroll lists to see how the OPLE/POP coverage changes. Also try switching to the H-band, using the button on the upper right, to see what portions of the visibility curve are sampled compared to the K-band.

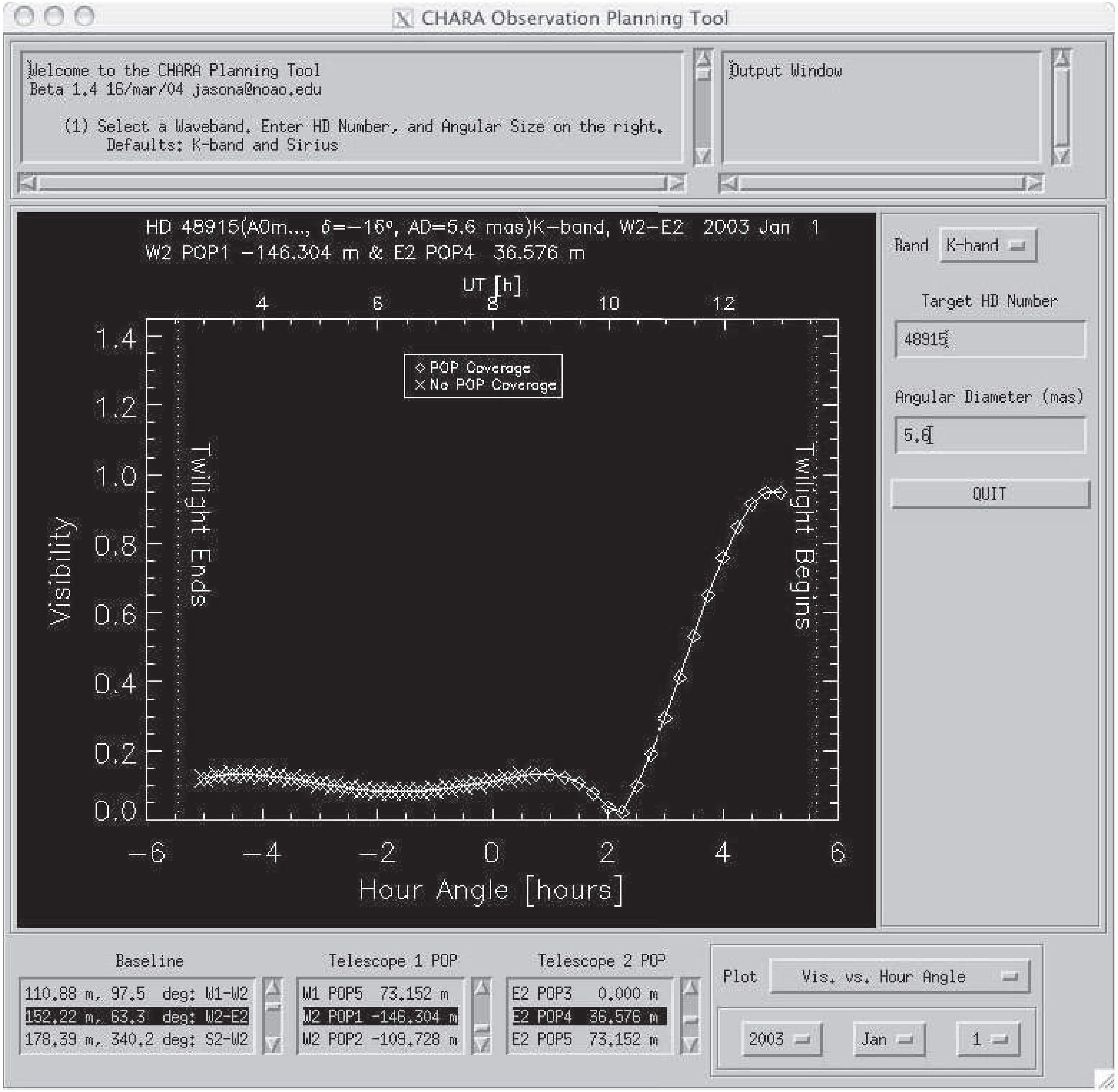

FIGURE 4. Here's a plot of the visibility vs. hour angle for Sirius on the W2-E2 baseline on January 1, 2003. This is another of the plot types available from the "Plot" droplist at the bottom right of the GUI. This particular plot is packed with useful information for planning. It shows the hour angles and UTs when delay compensation is available and the location of dawn and dusk. While the W2-E2 baseline provides good coverage of the 1st lobe, it does so only at hour angles greater than 2 hours. For the relatively low declination of Sirius, this isn't the best baseline to use since the altitude will quite low at these hour angles. Again, try changing the POP configuration via the scroll lists to see how the OPLE/POP coverage changes. Can you adjust the POP coverage such that observations can be made centered around Sirius' transit? Try changing the "Month" and "Day" buttons. How far into the year can you observe before morning twilight is a problem?

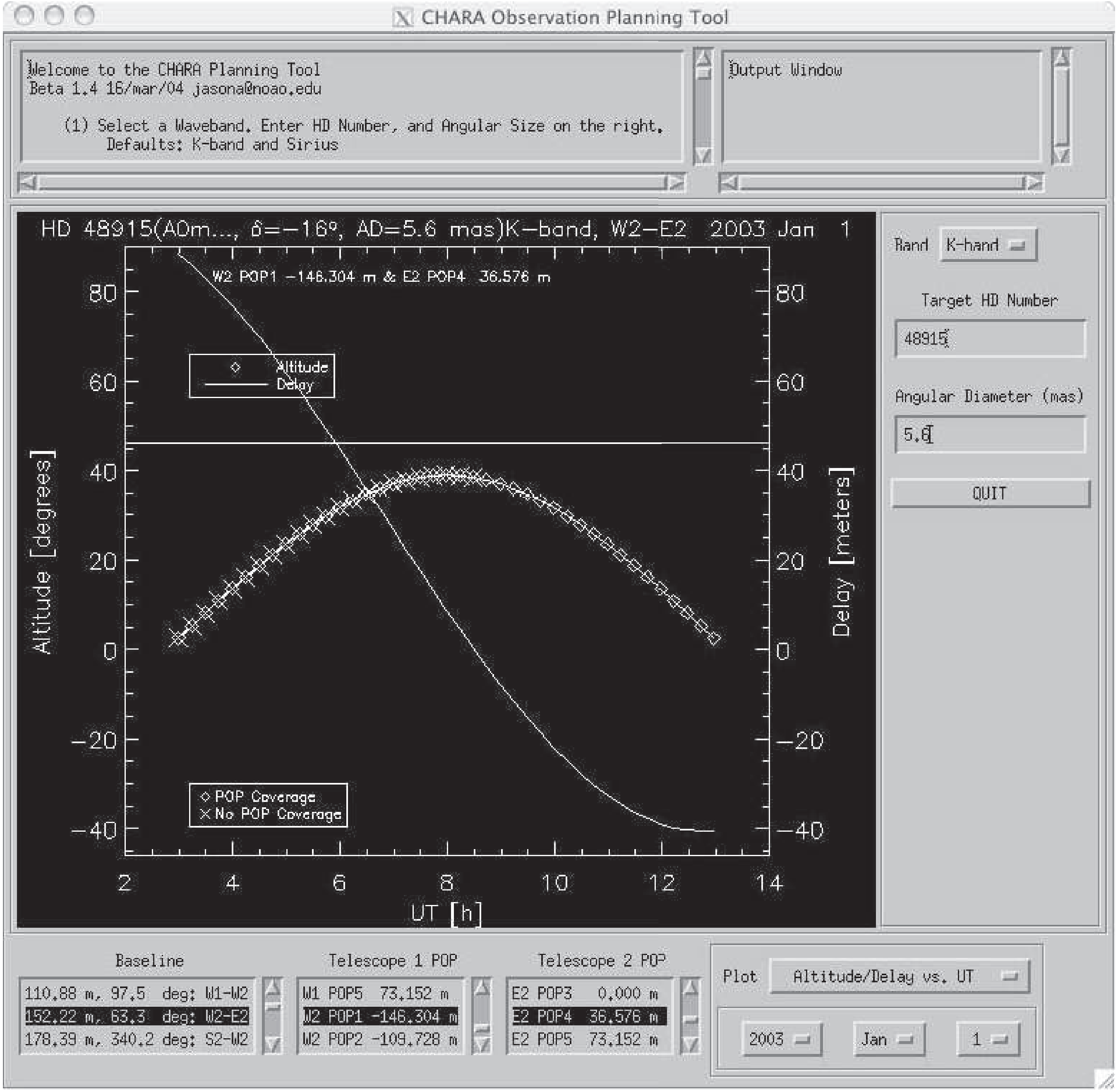

FIGURE 5. This plot shows explicitly the available delay (white line) from the OPLE carts as a function of UT for a given baseline/POP configuration. Changing the date will change the run of UT time along the x-axis, but not the plotted quantities which are only declination dependent. The diamonds show the altitude of the target star as a function of time. Those diamonds with overplotted 'X's show those times when no delay compensation is available. Try changing the POP configuration via the scroll lists to see how the delay changes.

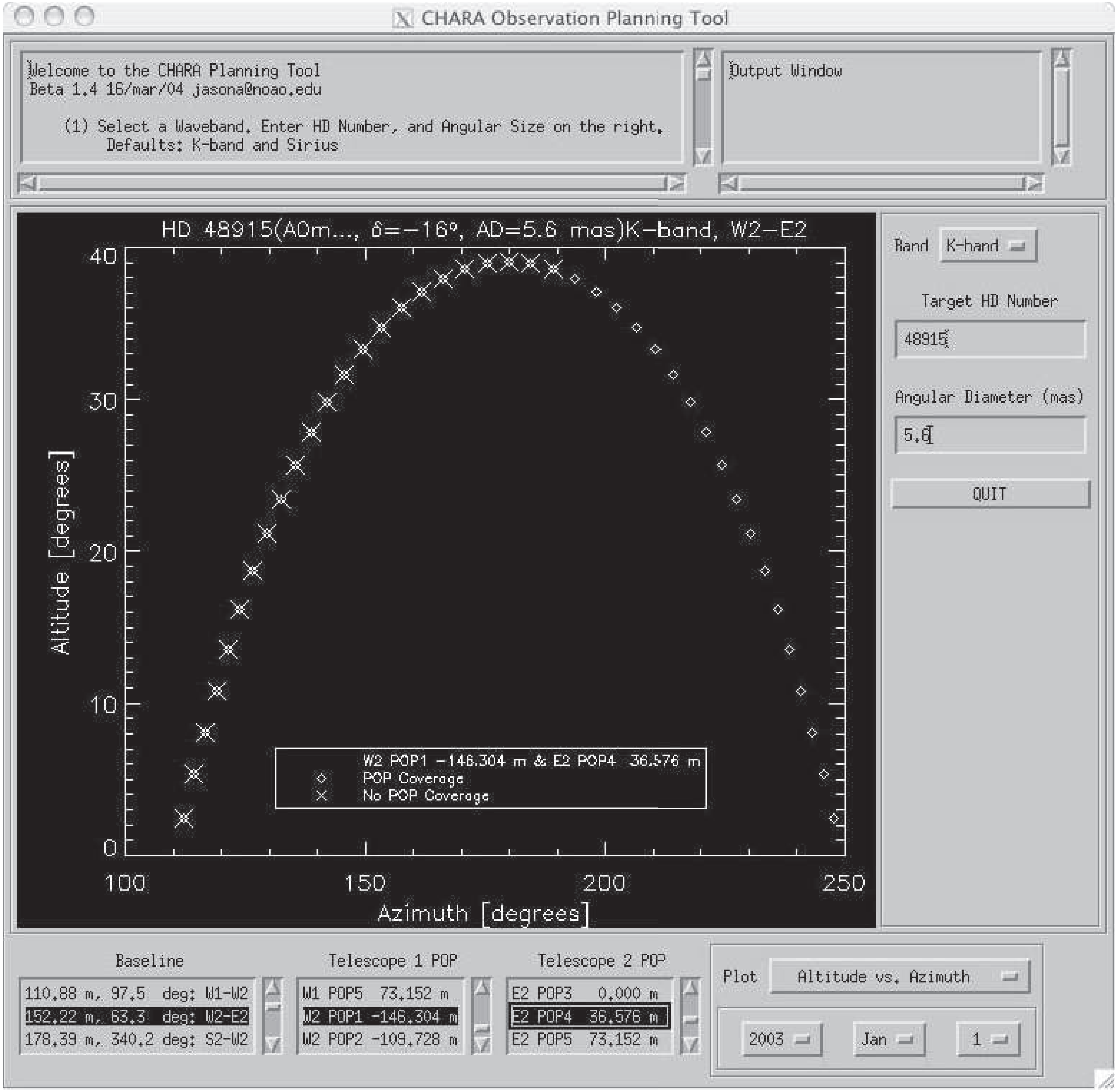

FIGURE 6. Here's another plot mode, showing the altitude versus azimuth track for Sirius. Also shown is the delay coverage for the W2-E2 baseline and one POP configuration. This shows that delay compensation is only available west of the meridian in this configuration. Try changing the POP configuration via the scroll lists to see how the delay coverage changes.

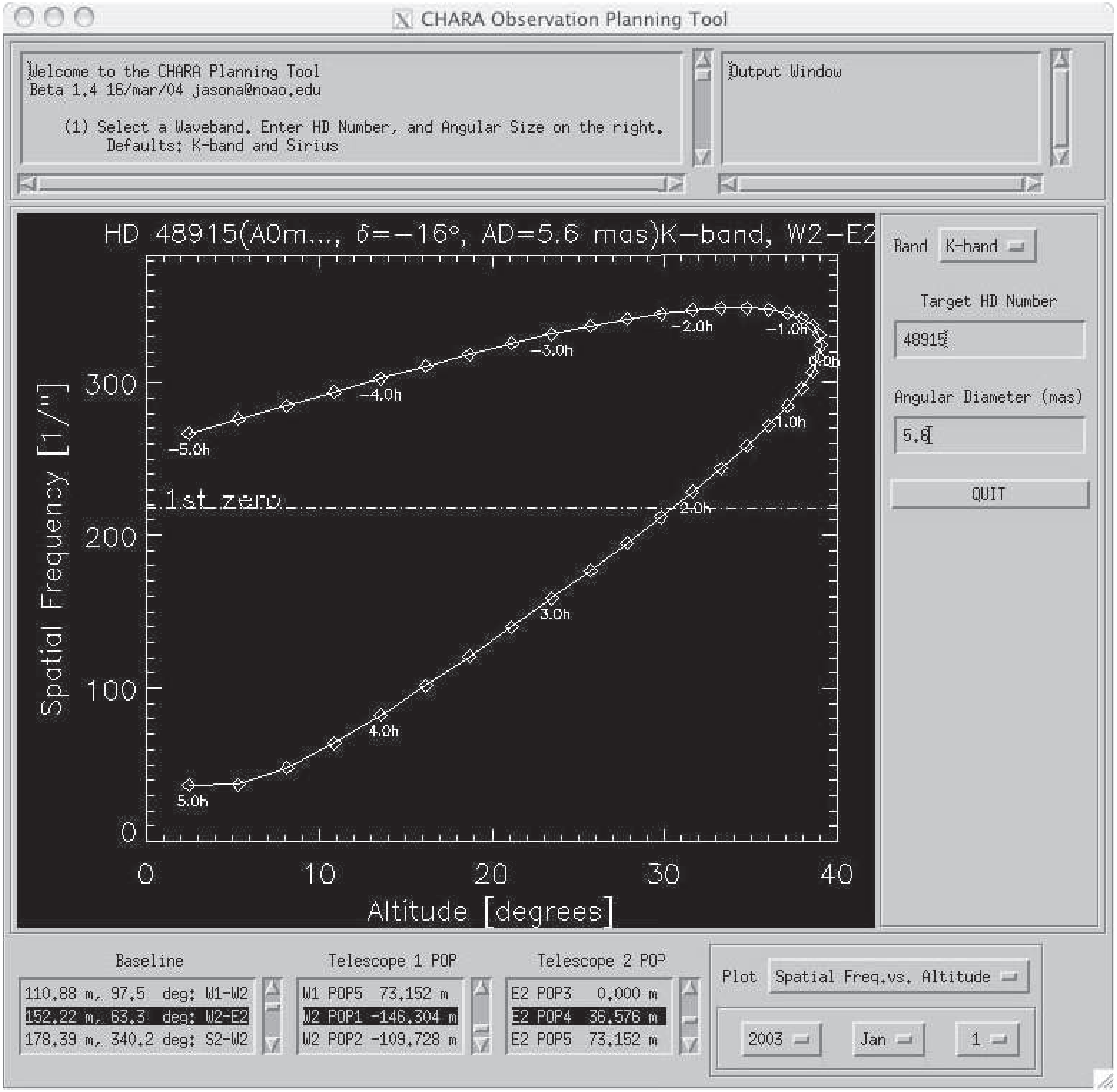

FIGURE 7. Here's a handy plot mode that shows the spatial frequency sampled by a baseline as a function of altitude. This is another way to learn that the 1st lobe coverage (below the 1st zero) on the W2-E2 baseline occurs at low altitudes.

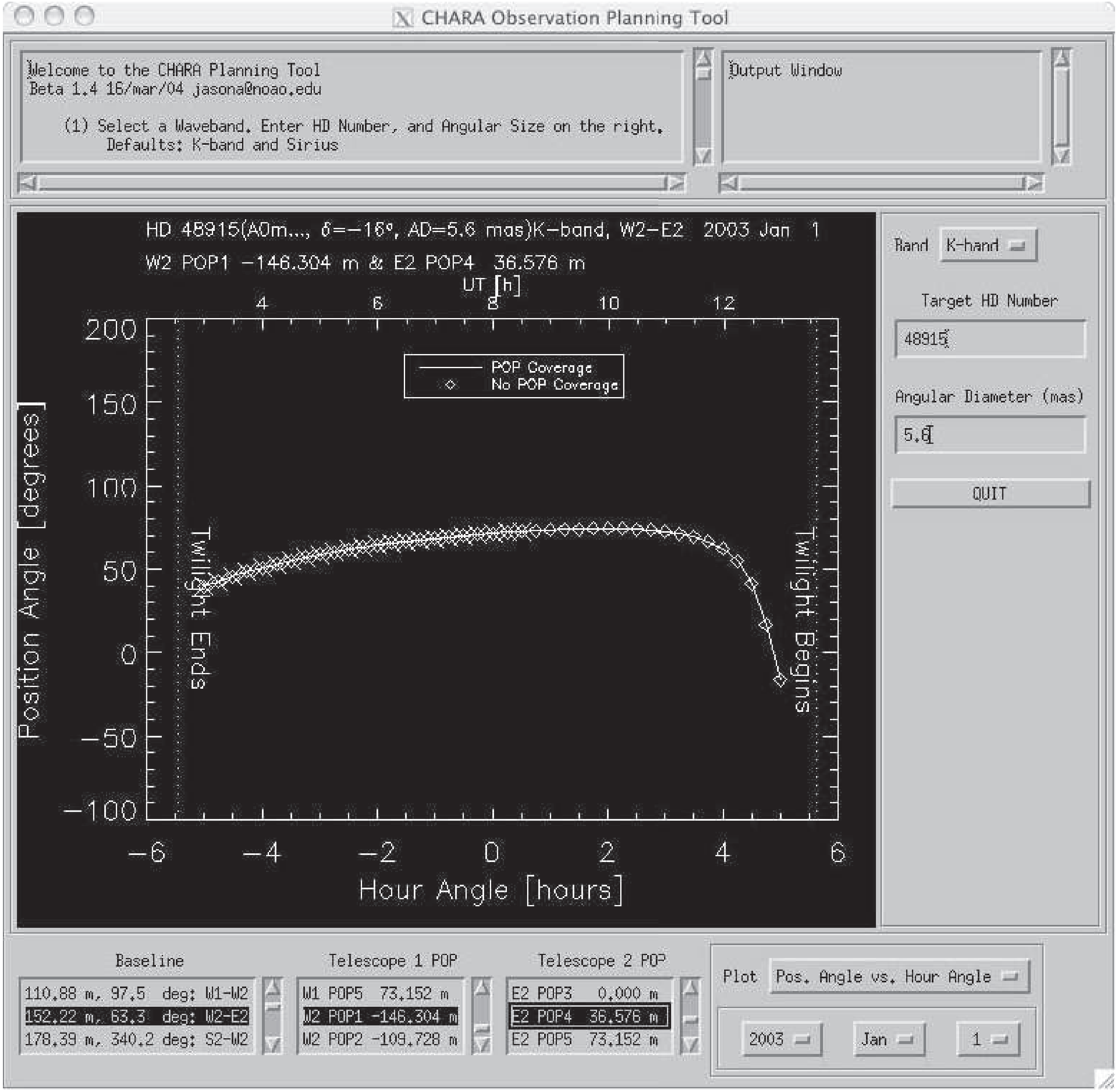

FIGURE 8. Here's a plot of the position angles sampled by the W2-E2 baseline as a function of hour angle. This plot mode us useful for planning observations of asymmetric sources such as rapidly rotating stars. Try changing the "Baseline" to see how the position angle coverage changes with baseline orientation.

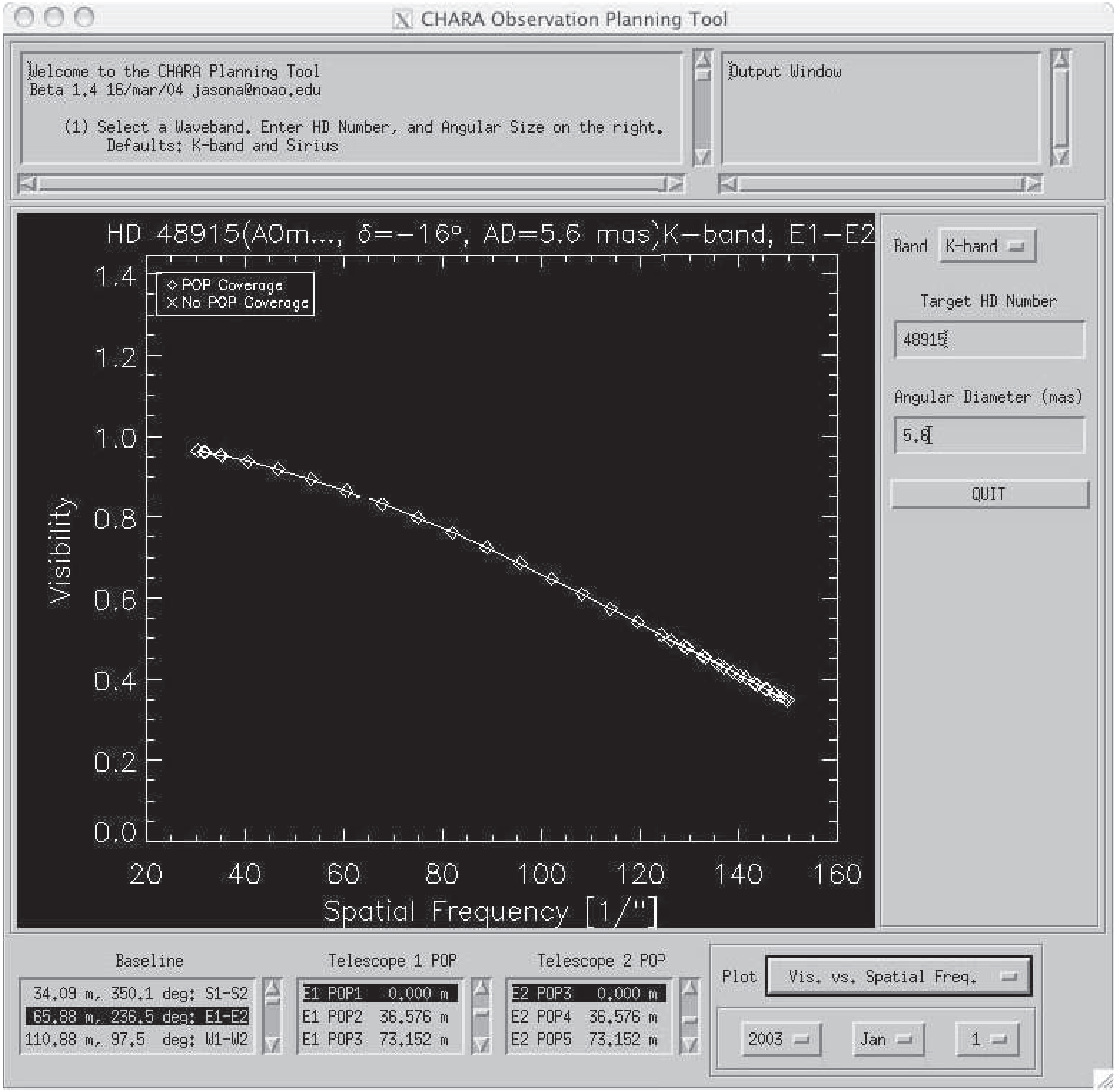

FIGURE 9. Here's a plot of visibility versus spatial frequency for the E1-E2 baseline which, like W2-E2, samples the 1st lobe of Sirius quite well and in this POP configuration shows no delay coverage constraints. Try changing the "Plot" option to find the range of visibilities that are sampled near the meridian and over what range of UT clock times these observations would be made on this date.

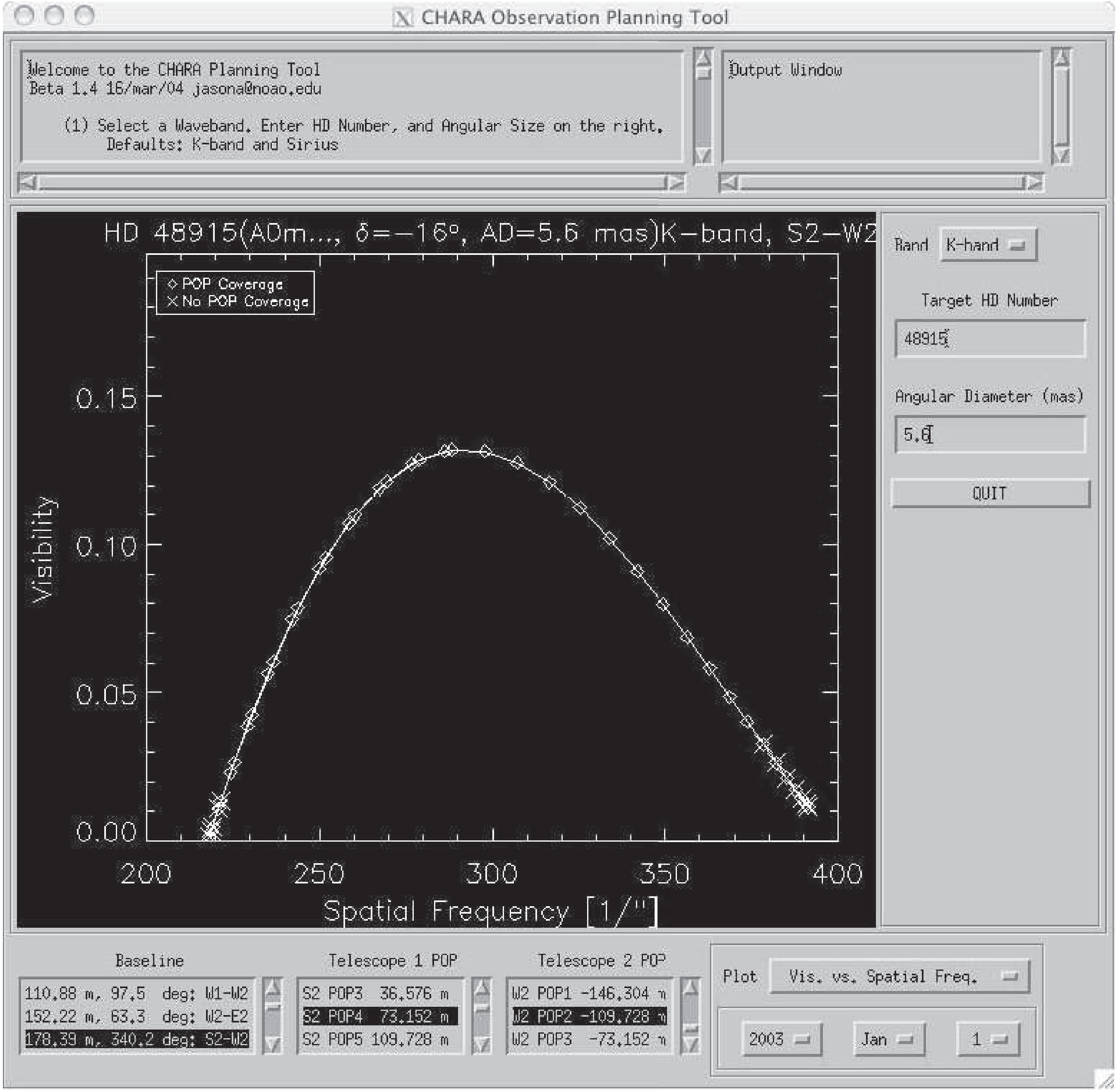

FIGURE 10. Here's another visibility versus spatial frequency plot for the S2-W2 baseline which samples the 2nd lobe of Sirius' visibility function. In this POP configuration, all but the ends of the 2nd lobe are free from delay constraints. The pairs of diamonds on the left side of the 2nd lobe indicate these spatial frequencies are sampled twice as Sirius rises and sets. Try changing to the "Visibility vs. Hour Angle" plot mode to see at what hour angles this occurs. Over what range of UT values is the 2nd lobe sampled. Will the altitude of Sirius be a problem?

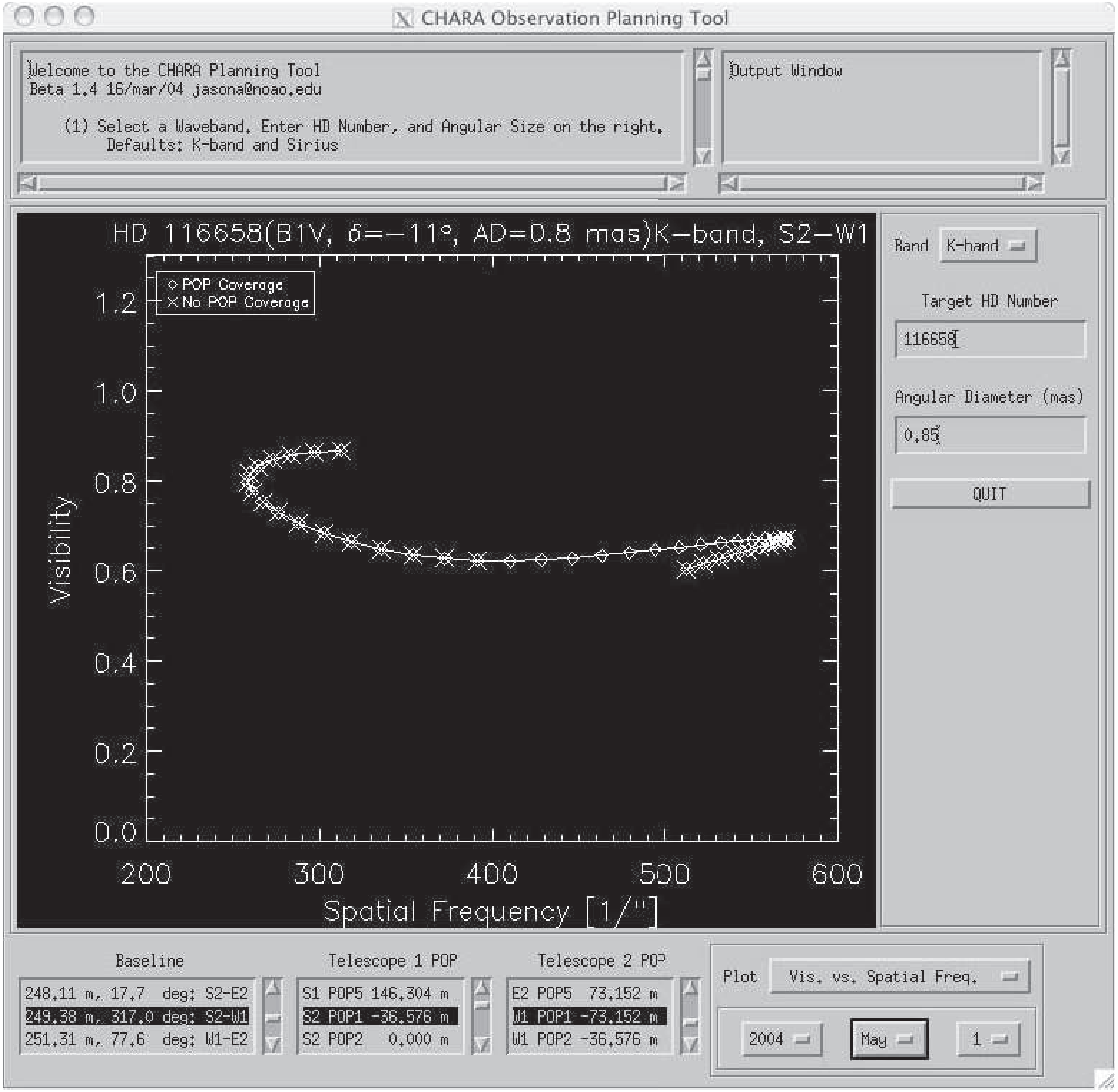

FIGURE 11. Here's a curious plot of visibility versus spatial frequency for the 4.0-day period binary Spica. Over the 12 hour (u, v)-plane track the asymmetric of the source is revealed *and* the orientation of the binary on the sky changes. Try changing the "Day" to see how the visibilities change over the orbital period.

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