Limits to AO Observations from Altitude-Azimuth Telescope Mounts

KECK ADAPTIVE OPTICS NOTE 708

Christopher Neyman
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ABSTRACT

This note considers the limitation imposed by an altitude over azimuth telescope mount for observations with current and planned adaptive optics systems (NGAO) at Keck Observatory. Limitations imposed by field rotation as well as the effect of pupil rotation are discussed. A key result from this note concerns the special case that the desired zenith 'blind spot' from field rotation is no larger than the 'blind spot' from the telescope drive motors. In this case, the maximum instrument rotator tracking speed must be equal to maximum azimuth tracking speed. Systems utilizing an optical K-mirror must have a maximum drive speed equal to half the maximum azimuth drive speed, the image rotation is twice the physical rotation for such a device. The final sections give values for these limitations and propose requirements for future systems.

Revision History

Revision	Date	Author (s)	Reason for revision / remarks
1.0	February 10, 2010	C. Neyman	Initial release

1. Introduction

Traditionally, telescopes were constructed to have a mount with one axis aligned to the earth's axis of rotation, known as an equatorial mount. Telescopes, such as the two Kecks, constructed to give motions in azimuth and altitude have many advantages over an equatorial one. However, an altitude-azimuth mount suffers from the following drawbacks:

- Variable drive rates in two axes
- A 'blind spot' when tracking close to zenith
- Field rotation at the telescope foci
- Pupil rotation at images of the aperture stop

The 'blind spot' arises at zenith due to the large drive velocities and accelerations required to track objects moving at the sidereal rate through this location on the sky. The size and shape of the zenith 'blind spot' depends on the combination of maximum velocity and acceleration that telescope drive motors can achieve.

Current and future AO systems will be mounted on the Nasmyth deck of the Keck telescopes. These foci, as well as the Cassegrain foci, suffer from field rotation. One method to compensate for field rotation is to induce a compensating rotation of the image by optical or mechanical means. In the optical case, this is done with a rotating K-mirror or Dove prism assembly. Alternatively, one may mechanically rotate the science instrument mechanical structure directly. The maximum speed of mechanical rotation in either method will produce a 'blind spot' similar to the one caused by the telescope drives about the zenith.

As a result of using one of the above systems for eliminating field rotation, the image of the system aperture stop (the telescope primary mirror) will rotate at other pupils within the optical system. The issue of pupil rotation is particularly problematic with AO systems at Keck because of the irregular outside edge of the 36 hexagonal segments that make up the primary mirror. In particular, wavefront sensor subapertures can go from a condition of full, to non illumination as the edge of the primary rotates across the wavefront sensor subapertures. An illustration of this effect is shown in Figure 1 for a 6 degree rotation of the pupil. One method used to compensate for this effect is to recalculate the AO reconstruction matrices in real time as the illumination level on the wavefront sensor subapertures change. At Keck, this method was found to be effective as it can also accommodate imperfections of the upstream K-mirror, such as nutation of the illumination pattern. However, this flexibility is at the cost of additional computational burden of a matrix inversion every time the illumination changes on the wavefront sensor. The maximum speed of this computation will introduce its own 'blind spot' around zenith.

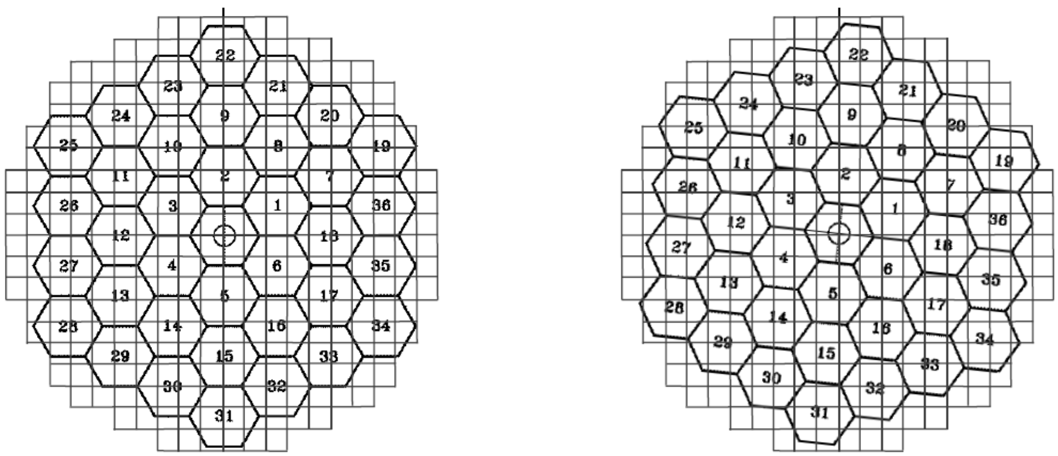

Figure 1: The pattern of the 36 segments (hexagons) superimposed on the subapertures of the current Keck wavefront sensors. The image on the right has a rotation of the Keck Pupil of 6 degrees with respect to the left hand image. An example of a dramatic illumination change is the subaperture at the top left side of segment 22. It goes from partial illumination to almost no illumination as the pupil rotates in the images above.

Other devices and control systems may also need to know or compensate for rotations of the image, the pupil or the vertical angle, the direction of the zenith, as the telescope tracks. One example of this type of system is the image rotation compensation needed by the off axis lasers in a multi laser guide star projection system. Another example is atmospheric dispersion correctors (so called ADCs) which need to know the vertical angle in order to position themselves to the correct orientation. These and similar systems may also suffer 'blind spots' due to finite speed of correction of the particular method or mechanism used. These functions and devices will need to be studied on a case by case basis and are not mentioned further in this note. However, it is likely that these systems will need to have similar rotation drive requirements as given at the end of this document.

2. The Telescope Tracking 'Blind Spot'

The goal of this section is to list the relevant mathematical relations for telescope drive rates. The section also will list the equations for image and pupil rotation rates. The basic relations required to derive the size of the various 'blind spots' have already been developed elsewhere [1, 2] and only the relevant results are repeated here. The basic quantities are denoted as follows:

- azimuth, A
- altitude, a
- zenith distance, z
- hour angle, h
- declination, δ
- parallactic angle, p
- latitude, ϕ

Azimuth is measured eastwards from north; the hour angle is measured westwards from the south. The locations of these quantities are shown in Figure 2. These definitions, in particular those for the directions of azimuth and hour angle, are **not universally applied** and many other conventions are in use. This note follows the standard conventions for Keck Observatory [1,4]. The reader is warned that other references [2, 3] use different conventions.

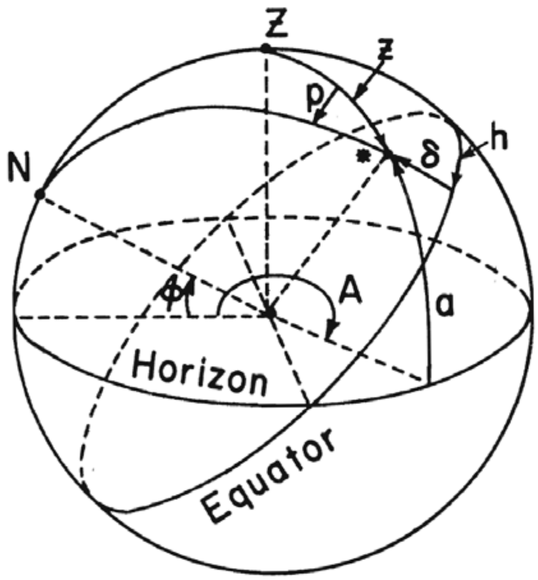

Figure 2: Standard altitude-azimuth coordinate system. The azimuth (A) angle above is defined to start at north moving through east as the positive direction. This is the standard at Keck [1,4]. Other references have different conventions [2,3].

The quantities needed to derive the zenith ‘blind spots’ are: ***a***, ***A***, ***p***, their velocities and accelerations. Derivatives with respect to time are denoted with dot notation: one dot over the symbol to denote velocity, two dots for acceleration. The limits from the altitude axis velocity and acceleration are much smaller than the limits imposed by the motion in azimuth and the parallactic angle and are not given here. The relevant equations from reference [1] are:

$$\frac{\dot{\mathbf{A}}}{\omega_0} = \mathbf{sin}\,\phi - \mathbf{tan\,a\,cos\,A\,cos}\,\phi \tag{1}$$

$$\frac{\dot{\mathbf{p}}}{\omega_0} = -\frac{\mathbf{cos}\,\phi\,\mathbf{cos\,A}}{\mathbf{cos\,a}} \tag{2}$$

$$\frac{\ddot{\mathbf{A}}}{\omega_0^2} = -\mathbf{tan}^2\,\mathbf{a\,sin}\,2\mathbf{A\,cos}^2\,\phi + \frac{1}{2}\mathbf{tan\,a\,sin\,A\,cos}\,2\phi - \frac{1}{2}\mathbf{sin}\,2\mathbf{A\,cos}^2\,\phi \tag{3}$$

$$\frac{\ddot{\mathbf{p}}}{\omega_0^2} = \frac{\mathbf{sin\,A\,sin}\,2\phi}{2\,\mathbf{cos\,a}} - \frac{\mathbf{sin\,a\,sin}\,2\mathbf{A\,cos}^2\,\phi}{\mathbf{cos}^2\,\mathbf{a}} \tag{4}$$

The natural sidereal rate is $\dot{\mathbf{h}} \approx 15\,\mathbf{deg/hr}$ and is denoted $\boldsymbol{\omega_0}$.

Given the mechanical drive limits which fix the maximum values for $\dot{a}, \dot{A}, \dot{p}$ and $\ddot{a}, \ddot{A}, \ddot{p}$ equations 1-4 can be used to define a set of parametric curves in the azimuth-altitude coordinate system. The area within these curves defines the telescope and rotator related ‘blind spots’. Examples are given in references [1] and [2] and in section 5 of this note. The total ‘blind spot’ is the composite of all 4 curves, one for each equation 1-4. We will not repeat that analysis here but note the key points in the next paragraph.

Notice that the equations 1-4 above all approach infinity as the altitude, **a**, approaches 90 degrees. In reality, the limitations of the drive motors in azimuth will prevent this from happening, causing the ‘blind spot’ around zenith. The expressions (1) and (2) become identical as the altitude approaches 90 degrees. Equations (3) and (4) also behave the same way at high altitudes. This means that the field rotation ‘blind spot’ will be identical to the azimuth drive ‘blind spot’ if the relevant telescope and rotator drives have the same maximum velocity and acceleration.

3. Telescope Slewing ‘Blind Spot’

In many cases, the telescope drive motors will have different maximum speeds for tracking an object than when slewing to a new target on the sky. Although the Keck telescope is equipped with friction drives so that slewing and tracking use the same motors and drive mechanisms, the effective maximum tracking rate is considerably slower [5,6] than the maximum slew rate because of excessive image smearing from telescope jitter when it is operated near maximum speed. Because of this difference in tracking and slewing speeds, the resulting ‘blind spots’ must be considered separately.

If a telescope tracks an object into the ‘blind spot’ and one desires to keep tracking the object on the other side of the meridian, once the object is lost then the telescope must slew in azimuth until it catches up to the object. The resulting slewing ‘blind spot’ is asymmetrical about the meridian. An alternative is to leave the star before the peak tracking rate is reached, slew across the meridian and be ready to acquire the star on the other side of the meridian. This note assumes a symmetrical solution. The expressions for the exact shape of the slewing ‘blind spots’ are shown graphically in reference [1] and [2] along with the mathematical expressions used to derive them. Reference [2] gives more details on the slewing problem.

4. Current and Future Telescope Drive Limitations

The current Keck drive velocity limits [5] are given in Table 1. The maximum azimuth velocity and acceleration represents the maximum attainable with the current tuning of the telescope drive system. It is planned to retune these servos as part of the Telescope Control System (TCS) upgrade project at the Observatory resulting in better tracking. The project is scheduled to occur over the next two years. The current maximum tracking speed is estimated from DCS/TCS night logs [6] from periods when the telescope is tracking objects during observing. This value (~0.3 deg/s) results in a zenith 'blind spot' of 0.75 degrees centered on the zenith (max altitude of 89.25). The next section has a plot of the current limits.

	Keck I		Keck II	
	Current	TCS upgrade	Current	TCS Upgrade
Max Az. Vel. Slew (deg/s)	1.0	2.0 (goal)	1.3	2.0 (goal)
Max Alt. Vel. Slew (deg/s)	1.0	1.0	1.0	1.0
Max Az. Acc. (deg/s/s)	0.05	0.05	0.05	0.05
Max Alt. Acc. (deg/s/s)	0.05	0.05	0.05	0.05
Max Az. Vel. Tracking (deg/s)	~0.3	0.5 (estimate)	~0.3	0.5 (estimate)
Max Alt. Vel. Tracking (deg/s)	N/A	N/A	N/A	N/A

Table 1: The current values for telescope velocity and accelerations. The goal values from the TCS upgrade project are also shown. The maximum altitude tracking velocity required is much less than the achievable velocity of the telescope drives and is designated as N/A for not applicable in the table.

5. Current Keck I and II Performance

The current AO systems on Keck I and Keck II have K-mirrors for field rotation compensation. These mirrors were specified [7] to have a physical rotation maximum slew speed of 3 degrees/sec and a maximum tracking speed of 0.18 degrees per second. The optics of a K-mirror is such that image rotation is twice the physical rotation of the device. Therefore, the corresponding image rotation would be 6 degrees per second when slewing and 0.36 degrees per second when tracking. The changing pupil illumination is compensated by computation of the AO reconstruction matrices. Current estimates [8] for the update rate of the Keck NGWFC reconstructor are 1 update per second; this includes the matrix inversion computation as well as the overhead for the loading of the new reconstructor into the real-time hardware from IDL.

	Keck I	Keck II
	Current	Current
Max Az. Vel. Slew (deg/s)	1.0	1.3
Max Az. Tracking (deg/s)	~0.3	~0.3
Max Az. Acc. (deg/s/s)	0.05	0.05
AO K-mirror Tracking (deg/s)	0.18	0.18
AO K-mirror Image Tracking (deg/s)	0.36	0.36
AO NGWFC Update (s)	1.0	1.0

Table 2: The values that determine the zenith 'blind spot' for the current Keck I and Keck II adaptive optics systems.

Using the values from Table 2 and the equations from reference [1], the values for the 'blind spots' were computed for the Keck II telescope. The most relevant curves are shown in the polar plot of Figure 3**.** That figure uses azimuth in degrees as the angular coordinate (theta) and zenith distance in degrees as the radial coordinate (r). The figure plots the area of the celestial sphere **within only one degree of zenith** looking down from above. East, 90 degrees azimuth, is at the right hand side of the figure, opposite the astronomical convention. The area between any curve and the zenith represents a ‘blind spot’ where the particular limit is exceeded. The area defined by the outer boundary of all 4 curves extending up to the zenith is the total ‘blind spot’.

The limitations from the finite velocity and acceleration of the telescope azimuth drive when tracking are shown in Figure 3, see the purple and blue curves. The velocity curve has two lobes centered on zenith. The shape of this curve implies that objects with declinations equal to the latitude of the Keck telescope (19 degrees 50 minutes) can be tracked closer to zenith than ones whose declinations are approximately 0.5 degrees greater or approximately 0.5 degrees less, at the peak width of the blue curve in Figure 3. One can understand the shape of this curve by considering the special case of a telescope on the Earth’s equator. Here a star with a declination equal to the telescope’s latitude, one exactly on the celestial equator, rises due east and the telescope would only need to track in altitude as the star rises. The azimuth is perfectly stationary, until the zenith is reached. Then an impossible instantaneous move of 180 degrees would be needed. The azimuth speed limit was not exceeded until the zenith was reached. If the star is slightly off zenith, it will need to change azimuth at an ever-increasing rate as the star rises and at some point will exceed the velocity limit of the telescope drive. Hence, this star will have a larger azimuth velocity limit area on the sky even though it passes the meridian further from zenith than a star with a declination exactly equal to the telescope’s latitude. An analogous situation is represented by the azimuth velocity limits shown in Figure 3 for the Keck II Telescope. The limitations from finite acceleration restrict a relatively small area of the sky and limit the telescope only when it is already limited by the telescopes finite velocity limits, see Figure 3.

The limitations from the finite slew speed of the Keck II telescope around the zenith cause the telescope to actually need to leave the star early before it reaches the maximum tracking rate and slew around and pick up the star symmetrically on the other side of the zenith (as it ‘sets’). The azimuth slew limit is also shown in Figure 3. The cusps of the slew limit curve at 90 and 270 degrees azimuth are caused by assuming that the telescope takes the ‘shortest way around’ the zenith. Two solutions exist depending on whether the slew is through north or south. Only the section of each solution representing the shortest path is plotted in Figure 3.

The K-mirror rotator tracking velocity limits were also computed. These limits are also shown in Figure 3 as the red curve. The limits from K-mirror slewing and NGWFC updates are not significant in comparison to the other limits and are not plotted in Figure 3. The composite ‘blind spot’ has an irregular extent with the maximum value extending out to 0.75 degrees from zenith in the direction of due north and due south.

6. Suggested Requirements for Future AO Field and Pupil Rotation Compensation

Based on the equations of section 2, we can adopt the following rule for specifying field rotation and pupil rotation compensation rates:

> If the AO system is to have a ‘blind spot’ no larger than the one produced by the telescope drives, then the field rotation compensation rates and accelerations must be the same or greater than the maximum azimuth telescope drive speed and acceleration. Similarly, the AO pupil rotation compensation rate and accelerations must be the same or greater than the maximum azimuth telescope drive speed and acceleration.

For example, if the maximum tracking rate of the telescope in azimuth is 0.5 degrees/sec, a mechanical instrument rotator must be able to meet all its other relevant specifications while tracking at 0.5 degrees/sec. For the case of an optical rotator, such as a K-mirror, the optical rotation of the image is twice the physical rotation of the device. In this case, the maximum mechanical speed for the K mirror must be only half the mechanical instrument rotator or 0.25 degrees/sec.

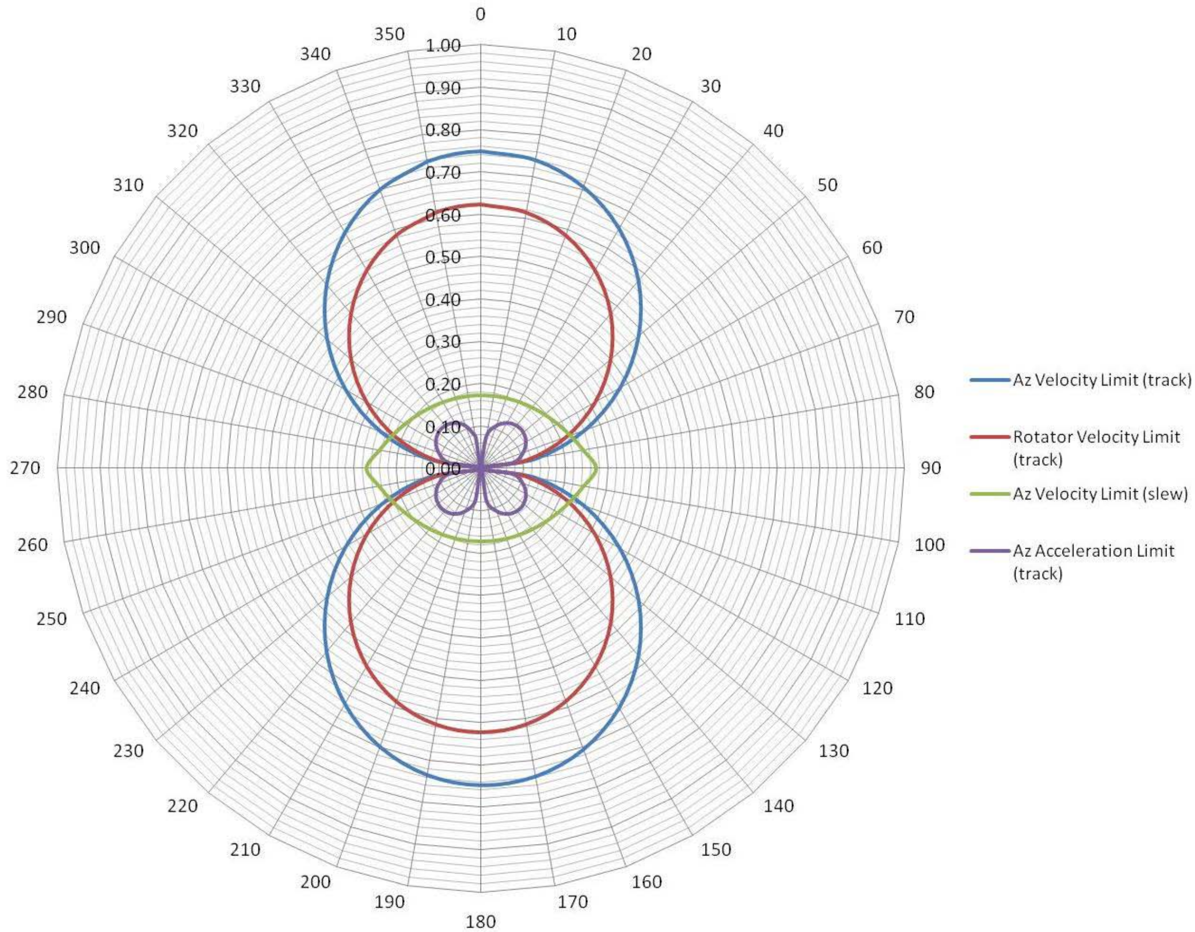

Figure 3: A polar plot of the zenith 'blind spot' for the Keck II telescope. The values from Table 2 were used to generate these contours. The radius is the value of the zenith distance in degrees; it shows only the area within one degree of zenith. The area between any curve and the zenith represents a 'blind spot' where the particular limit is exceeded. The area defined by the outer boundary of all 4 curves extending towards the zenith is the total 'blind spot'. The total 'blind spot' has an irregular extent with the maximum value extending out to 0.75 degrees from zenith.

7. Proposed NGAO Requirements

Based on the value for the telescope drive rates given in Table 1, the following rates are proposed for NGAO field and pupil rotation compensation. These numbers represent **minimum acceptable values** so that the telescope drive rates are the limiting factor in determining the zenith ‘blind spot’. The proposed values for NGAO instrument rotor and K-mirror velocity specifications are for the times when the telescope is tracking an object. It is assumed that related specifications on nutation and image jitter applicable to observing should be met at the same time. The slew specifications are for times when the telescope is moving to a new location, requirements associated with observing would not need to be met at these times. The RTC update is the time for the RTC subsystem assigned the reconstruction task to load a new active subaperture map, compute the appropriate reconstructors, and load that information back into the hardware that is responsible for updating the respective deformable mirrors. At present, the exact speed of the update depends on several factors, but because of the generally smaller subaperture in NGAO as compared to the current Keck I and II systems, it is likely that the RTC should be capable of responding to changes in subaperture illumination at least once a second.

	Keck I		**Keck II**	
	Current	TCS upgrade	Current	TCS Upgrade
Max Rotator Vel. (deg/s)	0.3	0.5	0.3	0.5
Max Rotator Slew (deg/s)	1.0	2.0	1.3	2.0
Max K-mirror Vel. (deg/s)	0.15	0.25	0.15	0.25
Max K-mirror Slew (deg/s)	0.5	1.0	0.65	1.0
Max RTC Update (s)	1.0 (TBC)	1.00 (TBC)	1.00 (TBC)	1.00 (TBC)

Table 3: The proposed values for NGAO. The rotor and K-mirror velocity specification apply when the telescope is tracking a target. The slewing (slew) values apply when moving the telescope to a new target. RTC update time is an estimate and should be confirmed with detailed simulation of the NGAO RTC system.

References

1. J. Nelson, “Geometric Relations for an Altitude-Azimuth Telescope”, Keck Observatory Report 49 (KOR 49), 1981.
2. F. G. Watson, “The Zenithal Blind Spot of a Computer-Controlled Altazimth Telescope”, Monthly Notices of the Royal Astronomical Society, 183, pp. 277-284, 1978.
3. K. R. Lang, Astrophysical Formulae, pp. 503-505, Springer-Verlag, 1974.
4. W. Lupton, “DCS Coordinate Systems”, Keck Software Document 40 (KSD 40), 2002.
5. T. Krasuski, email January 6, 2010.
6. T. Krasuski, personal communications, January 26, 2010.
7. E. Wetherell, personal communications, January 14, 2010, values taken from report, “AO Motion Stages” WMKO archives instrument shelf, author Kevin Y. Ho. The same values are also given in KAON 93 and KAON 98.
8. R. Campbell, personal communications.