IRTF Wavefront Sensor Proposed Concept

Mike Connelley
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Abstract

IRTF needs a new guider/wavefront sensor to enable active wavefront control on off-axis guide stars as well as to acquire and guide on fainter targets. We propose to replace the current guider box with a new guider box to minimize down time. The new guider would have two cameras: one that will provide the functions of a 'live' video acquisition camera, and a second for off-axis wavefront sensing and possibly long exposure science imaging. A new filter wheel will have a pupil slicer prism array to enable Shack-Hartmann wavefront sensing. Where possible, we will reuse parts from the current guider to reduce cost and schedule risk. A significant amount of software development is necessary to ensure that the new guider is used to its full capability. This software effort may constitute the majority of the work required for this project.

1.0) Introduction

1.1) Current Guider

The current guider was made to support target acquisition, guiding, and science imaging. This was accomplished by having two channels: one leading to an image intensified TV camera, and the other leading to an Apogee CCD camera. The current guider layout is shown in Figure 1. Both cameras are on independent focus stages, and have their own re-imaging optics. The guider box also has a filter wheel for science imaging with the Apogee CCD and also to dim the image for the TV camera for bright targets and/or daytime observing. The pick-off-mirror is actuated to steer the pupil onto the pupil stop as the XY stage moves the assembly to find the guide star.

Although the TV camera is used for guiding, it was not originally meant to be used as the guider. I was told by Doug Toomey that the TV camera was meant for initial acquisition, but then it was expected that the TO would use the Apogee CCD for guiding since it's much more sensitive. However, that is not how the guider is used. The Apogee CCD is currently not used for guiding, nor is it used for science imaging due to its overall poor noise performance, and because switching to the Apogee CCD takes a long time.

The sensitivity of the current image intensified TV camera is fairly good; close to photon counting. They average over 4 image frames to average over the noise of the intensifier, and they adjust the intensifier gain to see fainter stars. Dave has been able to see magnitude 17.5 asteroids, and believes that on a good, dark night that a 19th magnitude star may be seen. He feels that the sensitivity of the camera has declined slightly over the years.

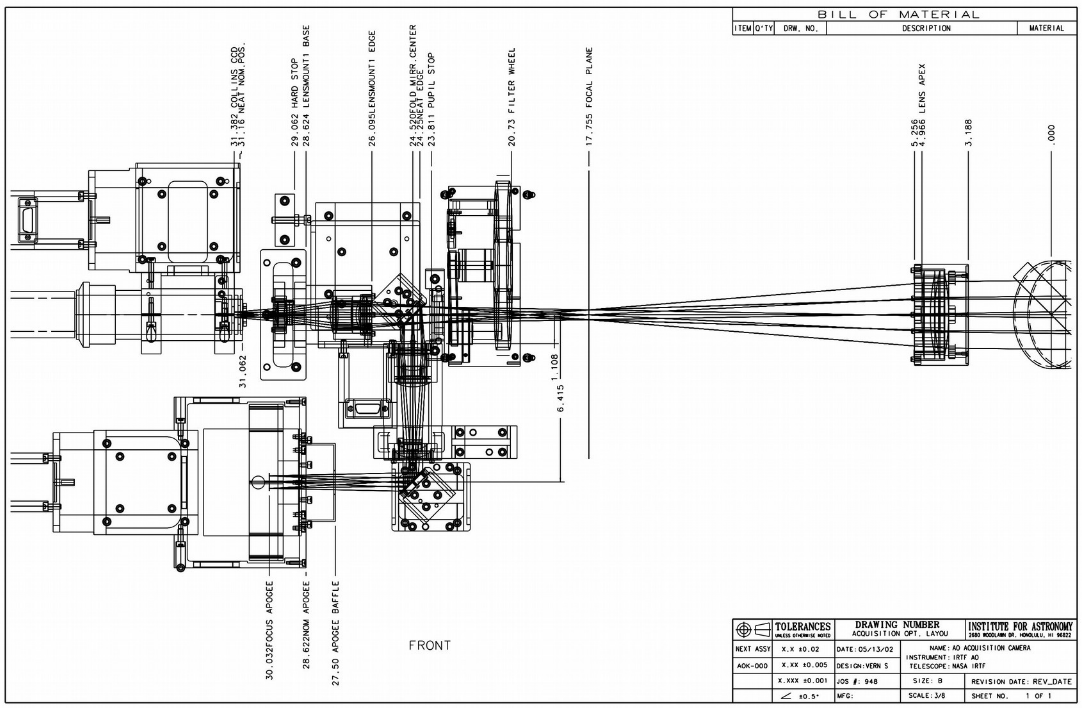

Figure 1: The layout of the current guider. Note the two channels, one for the intensified TV camera, and the other for the Apogee CCD.

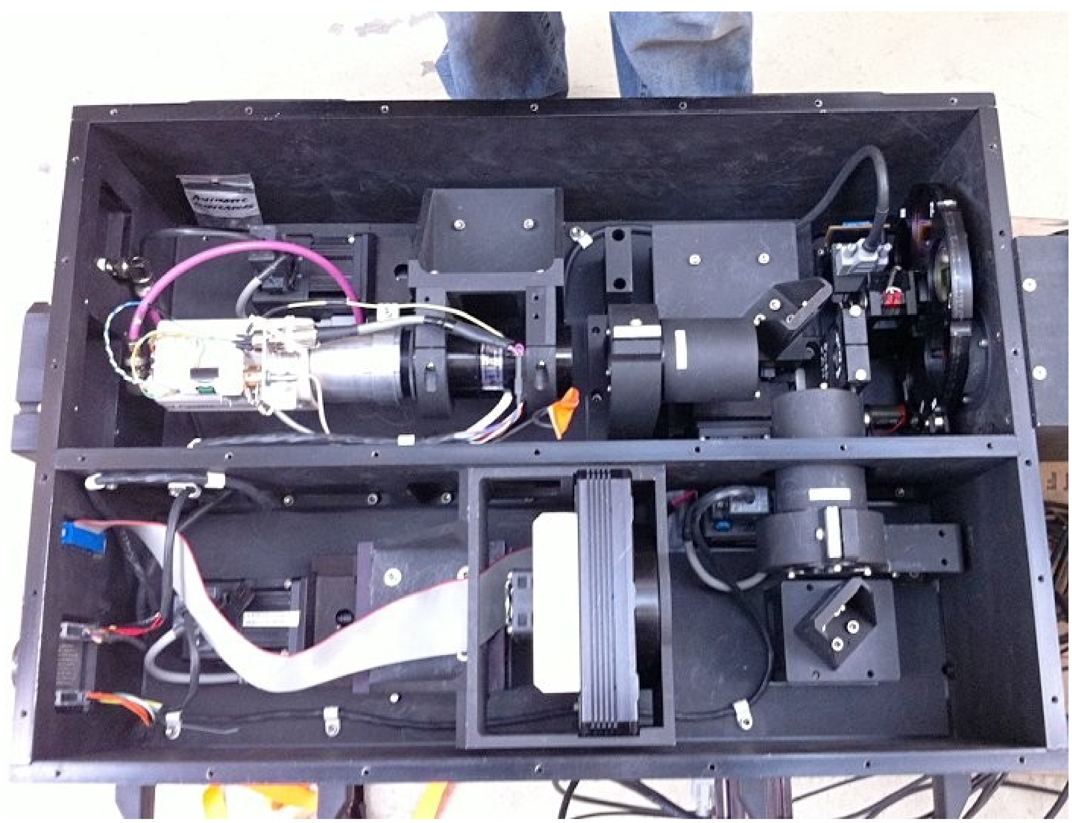

Figure 2: A photo of the current guider box.

1.2) Motivation For An Upgraded Guider/Wavefront Sensor

Active wavefront control is important to delivering optimal image quality. Image quality at IRTF is currently compromised by image jitter, defocus, astigmatism, and (sometimes) coma. As such, we need a wavefront sensor (WFS) that is sensitive to these aberrations, that is fast enough to correct them, and can work with all of the instruments with full sky coverage. A fast WFS will also allow us to correct tip-tilt, in conjunction with a future tip-tilt head on the hexapod. With active control of these aberrations, our image quality will then be limited by the seeing rather than by static or slowly dynamic telescope aberrations. The table below summarizes the current state of the image quality error budget.

Aberration	RMS wavefront error (microns)
Seeing	1.33
Fast Jitter	0.61
Focus (without model)	0.71
Astigmatism	0.53
Coma	0.34

A secondary goal of upgrading the guider is to improve the useful sensitivity of the acquisition and guide camera. There are times when the target is too faint for the TO to see, or the TO cannot find an off-axis guide star (most often due to the star catalogs being displayed incorrectly in Starcat, which has since been fixed). A camera with better exposure control will improve the ability to directly see faint targets. Although the current guider is close to photon counting, the analog output limits its usefulness for photometry and wavefront sensing.

2.0) Proposed Concept

2.1) Overview

Summary: We'll build a new guider box to replace the current guider. The old Apogee CCD will be replaced with a new Andor iXON CCD, and replace the old image intensified video camera with a new video camera. We'll add a pupil viewing lens to check alignment, and a pupil slicer to the filter wheel to enable wavefront sensing. We'll install a faster flip mirror in the guide box. Software will be written to support wavefront sensing.

2.1) Requirements for Upgraded Guider (What Does This Thing Need to Do?)

2.1.1) Target Acquisition: Provide a 'live' image of the sky for target or reference star acquisition, with sensitivity at least as good as the current system.
2.1.2) Off-axis Guiding: Be able to guide on an off-axis guide star for any target (assuming it's not moving too fast). Sensitivity should be similar to MORIS.
2.1.3) Slow Wavefront Sensing. Measure tip/tilt, focus, astigmatism, and coma, @ ~ 1 Hz on off-axis guide star with full sky coverage, including for slowly moving targets. Sensitivity should be ~1 magnitude brighter than MORIS

2.1.4) High frame rate: Take images @ ~100 Hz on off-axis guide star for any target, to allow for future tip/tilt control.
2.1.5) Fast Wavefront Sensing: Wavefront measurement @ ~1kHz on bright stars for engineering, with POM in center position.
2.1.6) Science imaging: General purpose visible light imaging through discrete filters, with POM in center position. Sensitivity should be similar to MORIS.

2.2) Concept Description

The upgraded guider is expected to be used nightly for target acquisition, off-axis guiding, off-axis wavefront sensing, and general purpose science imaging. For each target that is observed with IRTF, we expect that the upgraded guider will be used for target acquisition and then for off-axis wavefront control during the observation. The TO would need to find an off-axis guide star for every target.

The three main design goals are 1) to reuse as many components as is practical of the current guider and 2) to have minimal operational down time, and 3) maintain the reliability of the current TV system.

We plan to reuse some of the parts from the current guider to reduce cost, time and risk. Although we plan to reuse many components, the components that we plan to reuse do not affect the use of the current guider. We plan to reuse the Apogee and TV channel's optics and optics mounts, as those components are of high quality and the Apogee optics are not used. We also plan to reuse the whole POM arm (pick-off mirror, mirror tilt mechanisms, camera lens), which should be a simple bolt-on swap. We also plan to re-use the video camera optics with the new system. We will also retain the current XY table that is guider rides on.

There are additional new components that are needed. We will need a pupil slicer to convert a single star image into a 3x3 grid of spots. We will install a pupil viewing lens on a flip mount to be able to see the alignment of the telescope pupil on the pupil stop.

As mentioned above, I would like to replace the POM actuators. The frame work around the mirror takes a lot of space, and reduces the field that the POM can survey without impacting the science instrument. A smaller tip/tilt mount, located behind the mirror, would give the POM a slimmer profile and increase the search field of the POM. This upgrade is desirable, but not necessary for off-axis wavefront sensing.

In summary, we'll modify the guider box to house a new camera, using the existing Apogee and TV camera optics. We'll reuse the POM arm as it currently exists, replacing the actuators. A flip mount near the re-imaging optics will allow for pupil imaging for engineering purposes.

2.3: How the Wavefront Sensor Works

The wavefront sensor (WFS) is essentially a Shack-Hartmann WFS, but uses a prism array instead of a lenslett array (see Figure 4). In a regular Shack-Hartmann WFS, a lenslett array is placed in a pupil plane to form an image of the sky on the detector for each sub-aberture of the pupil. In our case, we want to use the existing reimaging optics, which already put an image of the sky on the detector. These optics lie behind the pupil plane, so we can't replace one lens in the lens group with a lenslett array. Our solution is to put a zero-power prism array in the pupil plane to 'un-stack' the spots from different parts of the telescope pupil. This turns a single image of a star into a grid of images. The locations of these spots are sensitive to the local wavefront slope, and thus we have a Shack-Hartmann WFS. By mounting the prism array in the filter wheel, and locating the filter wheel at a pupil plane, we can quickly transition from imaging mode to wavefront sensing mode.

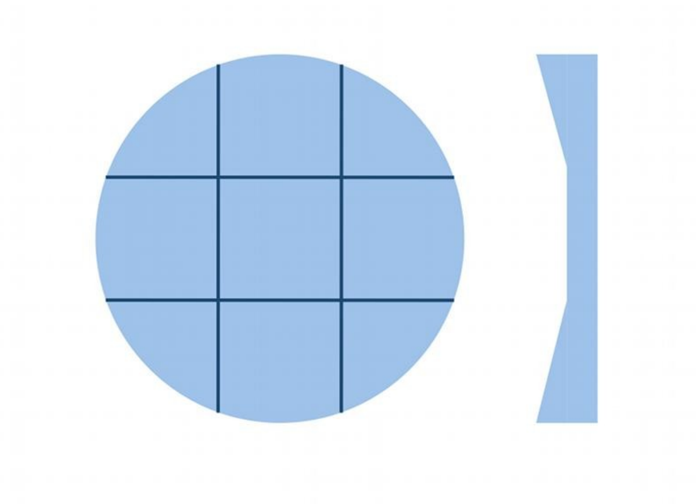

Figure 4: Illustration of the pupil slicer, with a cross section to the right with the slopes of the prisms greatly exaggerated. It is a prism array, such that the beam is deflected depending on the location in the pupil. Light passing through the upper third of the prism array is deflected upwards, whereas light passing through the lower third of the prism array is deflected downwards. Similar happens to light passing through the left third and right third of the array. Since the prism array is in a diverging beam, it needs to have the same thickness as the filters.

2.5) Upgraded Guider Box Layout

2.4) New Mechanisms for Upgraded Guider

2.4.1) Pick-off Mirror Tip/Tilt

The tip/tilt mount for the pick-off mirror allows for the pupil to be steered onto the pupil stop as the pick-off mirror is moved. The whole pick-off arm will be carried over from the current guider. The pick off arm is one large machined piece that bolts to the guider box

The goal is to replace the current, large tip/tilt mechanism with one that fits behind the POM mirror, which could then be made bigger. The current POM mirror is about 3.5” x 5.0”. The POM housing is ~6.3” wide (east-west) and 7.3” long (north-south).

<u>Requirements for the new POM mechanism</u>:

Range of motion:

Load in any orientation:

Size:

Candidate POM tip/tilt stages:
Thorlabs Motorized Pitch/Yaw Platform PY004Z8 ($2113)
Newport 8806 Blank plate Piezo Mirror Mount ($2051)
PI N-480 PiezoMike Linear Actuator w/ Kinematic Mirror mount ($ call)

2.4.2) In/Out Mirror stage

There is a small flat mirror that sends the light to the Apogee light path. This stage is currently very slow. This will be changed to a change that will allow the light path to the changed within about a second. This can be either a flip-in mount, or a translation stage.

Requirements for the new In/Out Mirror mechanism:
Range of motion: > 1.3”
Speed: About 1 second to insert into beam
Load in any orientation:
Size:

Candidate In/Out Mirror stages:
Newport 8893-K Motorized Flipper Mount ($1275)
Newport UTS50CC Mid-Range Travel Steel Linear Stage ($3800)
Thorlabs DDSM50 Linear Translation Stage, DC Direct Drive Motor ($2000)

2.4.3) Pupil Viewing Lens in Flip Lens Mount

The current guider does not have a way to check the alignment of the pupil image on the pupil stop. As such, the pupil is often misaligned to the pupil stop, causing vignetting. This lens will focus an image of the pupil stop onto the detector, allowing us to check the alignment of the pupil image onto the pupil stop. The pupil viewing lens will be mounted in a motorized flipper mount to allow it to be quickly inserted and removed from the beam. This motorized flipper mount from Newport seems to be a suitable option: ttp://www.newport.com/store/product.aspx?id=h955083&lang=1033

A lens just after the reimaging lens group needs to have a focal length 50-80 mm to image the pupil plane onto the detector. Newport has a 25mm diameter AR coated achromatic doublet (PAC043AR.14) with a focal length of 63.5 mm that will likely work. With this lens, the pupil image is 8 mm in diameter, fitting nicely within the 13mm detector with enough room to see the pupil stop.

Requirements for the new In/Out Lens mechanism:
Range of motion: > 1.3”
Speed:
Load in any orientation:
Size:

Candidate In/Out Lens stages:
Newport 8892-K Motorized Flipper Mount

2.4.4) Remaining Old Mechanisms

We will keep several old mechanisms. These are the XY table that the guider moves on, the filter wheel, and the focus stages for the two cameras.

2.5 The Cameras

2.5.1: CCD Wavefront Sensor Camera

The cameras are the most important physical component of this project. The camera must satisfy several requirements regarding detector size, pixel size, sensitivity, and readout rate. We prefer to use an Andor iXon CCD. This is the camera used on MORIS, which works well and which we have experience integrating the camera control software into our GUIs. Both the iXon Ultra 888 and 897 models satisfy the requirements for the camera. The following table summarizes the properties of these cameras, with the iXon 888 being fed with the Apogee optics and the iXon 897 being fed with the Collins (TV) optics. The limiting magnitudes of these two cameras, in various operating modes, is summarized in Tables 2 and 3.

Table 1: Characteristics of the iXon Ultra 888 and 897 cameras

Category	iXon Ultra 888	iXon Ultra 897	Comment
Pixel Count	1024 x 1024	512x512	
Pixel Size	13 microns	16 microns	
Detector Size	13.3 mm x 13.3 mm	8.2 mm x 8.2 mm	
Field of View	69.5 arcsec	105.3 arcsec	
Pixel Scale	0.068 arcsec/pixel	0.206 arcsec/pixel	
Frame rate, full frame, unbinned	26 Hz	56 Hz	
Frame rate, full frame, binned 3x3 (0.20”/pixel)	70 Hz	Camera used unbinned	Mode for target acquisition, guiding, wavefront sensing, and science imaging
Frame rate, 12” square window	290 Hz	397 Hz	Mode for fast wavefront sensing for engineering

2.5.2: Video Camera

It is desirable to maintain a dedicated video camera, as there are fewer things that can go wrong (e.g. computers to reboot, software to crash).

Sensitivity of old camera: Dave believes that on a good dark night, he could see a 19th magnitude star. The camera effectively runs at a 6 Hz frame rate.

<u>Video Camera Requirements</u>

- See as faint as current camera, preferably fainter
- Video output

- Be able to use camera without a computer
- Color desirable
- Frame rate adjustable from 10 Hz to 0.1 Hz
- Useful for daytime observing (with ND filters or short exp. time)

Candidate Cameras

Mallincam Exterminator: Web site says it can see a 17th magnitude star in 2 seconds with a 6” telescope. Assuming this is read noise limited, then we should expect to see a V=20.8 star in 1/6th of a second. Cost: $1800

2.6 Reused Components

2.6.1: “George Mount” and XY Table

The George Mount and XY table both work well. Since we only replacing the guider box, these components can be used for the upgraded guider. The upgraded guider box will bolt onto the XY Table just as the current guider does.

2.6.2: POM Arm

The POM arm is an important mechanism to keep since it has the necessary parts to steer the pupil onto the pupil stop as the POM moves around. It also has the first lens that makes the first focal plane and the first pupil plane. These parts work well, and should be a bolt-on component to the new guider box. If we choose the iXon 897 camera, we will need to increase the size of the field stop in the POM arm.

2.6.3: Apogee Optics

The apogee optics were well designed and deliver good image quality. Since we are reusing these optics, the image quality of the upgraded guider has been modeled in Zemax using the Zemax file.

2.6.4: TV Camera Optics

The TV camera optics were well designed and deliver good image quality. Since we are reusing these optics, the image quality of the upgraded guider has been modeled in Zemax using the Zemax file. Rather the removing these lenses from the current guider, which may increase down time, we could fabricate a new set.

2.7) Baffling

Dave reports that it can be difficult to find a faint off-axis guide star nearby a bright target, such as when observing Mars. It will be useful to reduce scattered light an improve baffling where possible. In the case of observing a faint off-axis guide star near a bright star, none of the light from the bright star should hit the POM since the POM is clear of the center beam. Any light from the bright star likely has scattered off of the mirrors or the spider.

There are already two baffles between the first lens in the POM and the field stop. Adding more baffles here is unlikely to help. Revising the pupil stop can be effective, such as by 1) making the pupil stop slightly under size, 2) adding a central dark spot to mask light scattered by the edge of the central obstruction, and 3) masking out the spiders to block light that they scatter. Adding baffles between the camera and the end of the reimaging optics can also be helpful.

2.8) Upgrade work and operations
2.8.1) How we can operate without the camera. For how long?
2.8.2) Who will do what work
2.8.3) How to get the guider out, and in again, without removing the MIM?

2.9) Limitations & Catches
2.9.1) Offloading coma. Coma is caused by miscollimation of the optics, which can result from flexure of the telescope structure or mirror support. Coma can be corrected by tilting the secondary mirror. The WFS will be sensitive to coma, and thus it can be corrected by sending the appropriate commands to the hexapod. The major limitation to doing this in practice is that tilting the secondary mirror also affects the telescope pointing. If the tilt is done slowly, then the guider can keep up with it and the target can remain on the slit. However, there would need to be a way for the TCS to know how the pointing was changed so that the next target can be found.

2.10) Future capabilities
2.10.1) Mirror bender
2.10.2) Fast tip/tilt correction

3) Modes of Operation

Since the camera and reimaging optics are fixed, they are used for all modes of operation.

3.1) Target Acquisition

In this mode, using the guider will be the same as how the TOs currently use the acquisition TV camera. The guider is put into the center position, and filter (optional) is selected with the filter wheel. The pupil slicer is not used. The pupil viewing lens is not used. The sensitivity should be as good as the current system.

3.2) Off-axis Guiding

Again, this will be very similar to how the TOs currently use the off-axis guider. The guider is put to an off-axis position (selected by software to match the location of a guide star). The pupil slicer is not used. The pupil viewing lens is not used. The TOs can choose between using the TV camera or the CCD. The CCD may be desirable to be able to off-axis guide on fainter targets., as the sky background can be subtracted in DV.

3.3) Slow WFS

We will use the slow WFS during all observations. The operator chooses an off-axis guide star in Starcat, and moves the guider there, and tells the WFS to GO. After this point, the WFS control is automatic. The camera is set to readout at ~1 Hz (exposure time selected by software to match star brightness). The pupil slicer is selected from the filter wheel. The pupil viewing lens is not used. The software extracts the wavefront from the CCD image, and sends the corrections to the appropriate mechanism (hexapod for focus and coma, TCS for pointing) to close the WFS loop.

3.4) Tip-tilt

The CCD as been chosen to allow tip/tilt guiding in the future. The software will not be required to support this mode until we are able to do tip/tilt corrections.

3.5) Fast WFS

This mode will be for engineering by an engineer or support scientist. The telescope is pointed to a bright star. The guider is put into the center position, a sub-array is selected by the user and the camera is set to readout at ~1 kHz. The pupil slicer is selected from the filter wheel. The pupil viewing lens is not used. Data are taken by the CCD and written to disk for later analysis by the wavefront reconstruction software.

3.6) Science Imaging

This mode can be used by a science observer similar to MORIS, in cases where the instrument does not have its own visible light images (e.g. iSHELL, TEXES). The guider is put into the center position, the user selects a filter and exposure time. A filter is selected with the filter wheel. The pupil slicer is not used. The pupil viewing lens is not used. EM mode is not used. Data saved to disk, similar to MORIS images.

4 Example Use Cases

4.1 Regular observing a sidereal target, or a slow non-siderial target

For regular observing of an astrophysical target, the TO would use the video camera (much as they do now) to see the target (or nearby pointing star). Once on the target field, they would then choose an off-axis guide star, and see it in the video camera. They then push a button to enable wavefront control. The pick off-mirror then goes into the beam to send the light to the CCD, and the pupil slicer is put into the beam. The software automatically starts the CCD running, and selects and exposure time suitable for the star’s brightness. Since the instrument is guiding, the tip/tilt offsets are ignored, but the focus offsets are sent to the hexapod. If coma is detected, then that can also be offloaded to the hexapod.

4.2 Visitor instrument observing a sidereal target, or a slow non-siderial target

In this case, we assume that the visitor instrument doesn’t have its own guider. Same as above, but the tip/tilt offsets are sent to the TCS to guide the telescope

4.3 Day time observing

TO would use the video camera (much as they do now) to see the target (or nearby pointing star). They would pull out the POM to the stow position to let the instrument observe and start guiding. We would not try to do off-axis guiding or wavefront control since we won’t be able to see fainter off-axis guide stars in the day time.

4.4 Fast Non-Siderial Target

These objects would most likely be observed with SpeX/MORIS. These move too fast for an off-axis guide star to be in the guider’s field of view for any meaningful amount of time. Wavefront control would need to be done on the science target with MORIS itself. We will insert a roof prism into the MORIS filter wheel that will split the image into two spots. Defocus will change the separation between the two spots, which will tell the focuser which way to go. Note that this technique can be used for any target that can be seen in visible light and is a point source.

For these objects, the TO would use the video camera to acquire the target, then pull it out to let MORIS do the guiding and wavefront control.

Table 2: Summary of Observing Modes

Mode	User	Camera	Filter	Frame Rate	POM location	Correction To:	Correction Made:	
Target Acquisition	TO	TV	Any	6 Hz	Center	None	Pointing	
Off-Axis Guiding	TO	TV or CCD	Any	6 Hz or less	Off-axis	TCS	Pointing	
Off-Axis Wavefront Sensing (slow)	TO	CCD	Pupil slicer	< 1 Hz	Off-axis	TCS, hexapod	Pointing, Focus, Collimation	
Off-Axis tip/tilt (fast)	TO	CCD	Pupil slicer	> 10 Hz	Off-axis	TCS, hexapod	Pointing (fast) Focus (slow), Collimation (slow)	
Fast WFS	Engineering	CCD	Pupil slicer	~100 Hz with subarray	Center	None	None	
Science imaging	Observer	CCD	Any	< 1 Hz	Center	None	None	

Table 3: Observing Modes with iXon Ultra 888 and Apogee optics

Mode	Filter Wheel	Pupil Lens	Frame Size	Binning	Frame Rate (Hz)	Amp	EM gain	Limiting Magnitude (S/N=10)
Off-axis guiding	filter	out	full	3x3	1	1 MHz	off	18.5 @ g+r
Off-axis WFS	prism array	out	full	3x3	1	1 MHz	off	16.1 @ g+r
Engineering WFS	prism array	out	180x180 subarray	3x3	290	30 MHz EM	off	6.7 @ g+r

Pupil Imaging	filter	in	full	3x3	1	1 MHz EM	off	N/A
Science Imaging	filter	out	full	3x3	1	100 kHz	off	17.7 @ r

Table 3: iXon Ultra 897 with Collins optics

Mode	Filter Wheel	Pupil Lens	Frame Size	Bin	Frame Rate (Hz)	Amp	EM gain	Limiting Magnitude (S/N=10)
Off-axis guiding	filter	out	full	1x1	1	1 MHz EM	off/on	18.7 @ g+r 20.0 w/ EM
Off-axis WFS	prism array	out	full	1x1	1	1 MHz EM	off/on	16.5 @ g+r 17.7 w/ EM
Engineering WFS	prism array	out	64x64 subarray	1x1	397	17 MHz EM	off	8.0 @ g+r
Pupil Imaging	filter	in	full	1x1	1	1 MHz	off	N/A
Science Imaging	filter	out	full	1x1	1	1 MHz	off	18.8 @ r

4.5) Closing the Loop: Integrating the WFS With Other Mechanisms

The WFS is only one part of a larger system, to allow closed loop control of image aberrations such as defocus, coma, and astigmatism. The WFS software will need to be able to talk to these other mechanisms to close the loop.

4.5.1) Guiding offsets

Off load guiding offsets to TCS, as we currently do.

4.5.2) Focus

Off load focus offsets to focus mechanism. Compatible with chopper focus mechanism and hexapod. We'll model the focal plane curvature, so the software will know how much defocus to expect depending on the field position of the guide star.

4.5.3) Coma

Off load coma to secondary mirror tilt. This will affect the telescope pointing, so this mirror tilt must be with a compensating telescope pointing offset. Compatible with chopper focus mechanism and hexapod. Off-load should be done only during time between observations, so that we don't cause an image jump during an observation. We'll model the off-axis coma, so the software will know how much coma to expect depending on the field position of the guide star.

4.5.4) Astigmatism

Off load astigmatism offsets to (future) mirror bender. We'll model the off-axis astigmatism, so the software will know how much astigmatism to expect depending on the field position of the guide star.

4.5.5) Tip-tilt

Off load fast tip-tilt offsets to (future) tip-tilt stage on hexapod.

5) Software

The amount of software that will be needed to optimize the usefulness of the WFS must not be under estimated. I expect that the software will constitute the majority of the work for the new guider/WFS. If the WFS system is too difficult to use, then the TOs won't use it. In my conversation with some of the TOs, they objected to having to find an off-axis guide star for each target. To make sure the WFS gets used on each target, much of the off-axis star acquisition and camera control should be automated.

Things software will need to do

- 5.1) Display data (DV or similar) live from the CCD, so that the TO can monitor the WFS operation. The data also need to be made available to the wavefront control software.
- 5.2) Save the WFS CCD images for analysis (extracting wavefront data)
- 5.3) Save wavefront data to an archive, for possible future analysis (optional)
- 5.4) Control CCD and video camera functions and filter wheel position.
- 5.5) Guide on off-axis guide stars (similar to current Smokey), including non-siderial targets. Accommodate telescope nodding. Accommodate chopping?
- 5.6) Automatic wavefront sensing (All of this happens when the TO hits 'go')
  - 5.6.1) Select most appropriate guide star. Move POM there (optional)
  - 5.6.2) Choose appropriate exposure time, based on star brightness. TO can over-ride in case of clouds. Start taking data. Save images to disk
  - 5.6.3) Grab latest image. Identify star image, extract PSF centroids
  - 5.6.4) Extract slopes, convert to Zernike modes. The wavefront reconstruction algorithm will come from Mark Chun's GLAO project.
  - 5.6.5) Send corrections to TCS or hexapod, close loop
- 5.7) Protect the system. Open the loop if S/N drops too low, or the star is lost. Automatically default to open loop tracking and focus control.

6) Mechanical

We will also need to mount the new CCD, the pupil lens in a flip mount, and the new POM actuators. The CCD will be on a one-axis translation stage for focusing. Due to the larger and heavier camera, we will likely need to get a larger stage that is rated for more weight.

We will use the existing POM assembly and arm, which should be a simple bolt-on to the new guider box. The Apogee optics should be able to be used in their existing mounts.

7) What's This Going to Cost??

7.1) Money

- 7.1.1) iXon 888 CCD was quoted at $50k, and this money is in the current contract. We may consider a less expensive non-EM CCD.
- 7.1.2) Pupil lens and flip-in lens mount , ~$750
- 7.1.3) New guider box: Fabrication
- 7.1.4) Filter wheel: ~$1200
- 7.1.5) Pupil prism array: $4400 (don't remember where that comes from)
- 7.1.6) Focus stage for CCD: ~$8000 (Newport GTS150)
- 7.1.6) Focus stage for video camera:
- 7.1.7) POM tip/tilt stage: $2000
- 7.1.8) Video camera: $1800
- 7.1.9) In/Out Mirror stage: $1275-3800

7.2) Things we'll reuse:

- 7.2.1) Apogee lenses and lens mounts
- 7.2.2) POM and that whole POM arm
- 7.2.3) Existing filters
- 7.2.4) XY Table

Total cost: $ 70 K

6.2) Man power

6.1.2) Optical design

Since the first lens and reimaging lenses will be reused, that optical design is done. A suitable lens for the pupil viewing mode will need to be found, and the pupil prism array will need to be designed.

Done by MC.

Estimated hours:

6.1.3) Mechanical design

A new guider box will need to be designed, with appropriate holes to mount the filter wheel, lenses, CCD, etc. The design can (and probably should) be based on the existing off-axis guider box.

Done by MB.

Estimated hours:

6.1.4) Software development

See section 5 for a description of software requirements. Done by TD.

Estimated hours:

6.1.5) Machining

Fabricating the new guider box, and any ancillary mounting hardware inside.
Done by machine shop.
Estimated hours:

6.1.6) Electrical

Run cables, mount power supplies, etc. for filter wheel, pupil lens, and CCD.
Done by MK.
Estimated hours:

6.1.6) Assembly and testing

Assemble new guider box in the lab, test filter wheel, pupil lens, camera operations.
Done my MC, TD.
Estimated hours:

Total man hours:

Appendix

A1) System Requirements (Text)

Introduction

The image quality error budget shows that the IRTF, under typical observing conditions, is not seeing limited. This conclusion is supported by experience supporting observers using IRTF. Defocus is the strongest and most common error, caused by changes in temperature and telescope pointing. Flexure also causes changes in the collimation and primary mirror figure, inducing coma and astigmatism, respectively. A focus model will remove the bulk of the focus term. Despite this, residual defocus, coma, and astigmatism will continue to compromise the IRTF's image quality. A wavefront sensor (WFS) is required to measure the residual wavefront errors in real time and send corrections to compensate for those aberrations.

Goal: To control tip/tilt, focus, astigmatism, and coma aberrations originating within the telescope so that the telescope is always seeing limited. A secondary goal is to serve as a diagnostic or maintence tool to address image quality issues.

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Optics
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Requirement Origin

Typical Mauna Kea seeing is 0.35 to 0.4" at K, which corresponds to a RMS WFE of 0.46 microns. Tip/tilt, focus, astigmatism, and coma should be controlled so that the telescope's RMS WFE is less than 0.2 microns. Since RMS errors RSS together well, each aberration should be kept under RMS=0.1 microns.

Requirements

- Tip/Tilt: Spot motion should be measured to a precision of less than 0.1 arcseconds, or 0.05mm on the IRTF focal plane

- Focus: RMS error of 0.1 microns corresponds to a focal plane motion of 4.6mm (secondary mirror motion of 0.02 mm), and a P-V error of 0.160 waves (0.35 microns)
- Astigmatism: RMS error of 0.1 microns corresponds to P-V error of 0.211 waves (0.46 microns).
- Coma: RMS error of 0.1 microns corresponds to P-V error of 0.231 waves (0.51 microns). This can be corrected with a 0.4 degree secondary mirror tilt.

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Hardware
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- Pick-off mirror:
  - Requirement Origin: The mirror on the XY stage that diverts light to the Apogee is really slow. Needs to be faster if we're going to be switching between guide camera and WFS. The POM can't move much perpendicular to the guide boxes. Will need a mechanism to put a star that is not in the middle of the guide region into the FOV of them WFS.
    ** Solution: Put image slicer in the pupil plane. Put image slicer into filter wheel, change to a Geneva mechanism to better location repeatability. Locate filters at the pupil, and incorporate the pupil stop into the filters (stack mask w/ filter if mechanism is repeatable enough). Copy iShell filter wheel design
  - Requirement: The time to switch from the guider to WFS should be reduced to NNN seconds. Mechanism needs to hold a mirror at least 1.3" diameter.
    ** Solution:
      A) Use a flipper mechanism to flip mirror in/out. Examples: Newport 8893-K (cost $1100), Thorlabs MFF001
      B) Use a faster linear motion stage. Examples: Newport XMS50 (size 2"x5"x5", cost $7000)
      C) Put image slicer in filter wheel. Have 1 camera only in guider. Switch from guider mode to WFS mode by changing filter wheel
  - Requirement: The WFS detector will need a wide enough field of view to see the whole guide region. Apogee FOV ~ 12.5 mm across. Andor iXon3 897 detector size = 8.2 mm across (512x512, 16um pixels). TV camera FOV ~ 5.7 mm across. Andor iXon 888 detector is 13.3 mm across (1024 x 13um pixels)

- Sensitivity
    Requirement Origin: The WFS need to be able to guide and track aberrations with full sky coverage near the galactic poles
    Requirement: To have full sky coverage, the WFS needs to be sensitive to V=16 magnitude stars w/ 1s exposure time.
    ** Solution: W/ 3x3 spot array, we get S/N=19 @ R in 1 second, S/N=44 in 5 sec.

- Time resolution
    Requirement Origin:
      1) Guider: The WFS needs to be fast enough to guide the telescope (1 Hz)
      2) Acquisition: "Live" image from camera @ video rate
      3) Tip/tilt: Take images at ~100 Hz frame rate of subarray of spots

4) Engineering WFS: NxN pixel subarray readout @ 1kHz
** Solution: iXon 888 camera
1) Guider: Can do 24 Hz full frame rate, so 1 Hz is no problem
2) Acquisition: Can do 24 Hz full frame rate. Need to be able to display image that fast w/ minimal lag
3) Engineering WFS: 16x16 (actually 64x64 binned 4x4) pixel subarray readout @ 1.9kHz

- Camera Focus
Requirement Origin: Be able to focus for all instruments
Requirement: Need to be able to move the camera by X mm

** Solution: Put the camera on a translation stage
May be able to reuse existing Apogee stage

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Software
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- Catalogs:
Requirement Origin: The starcat map of guide stars can be unreliable. It shows stars on the map that are not there, and TOs that they can find stars that are not shown on the map. The scaling can be wrong, or flipped (mirror image), etc. Bobby is in charge of catalogs, so he should be consulted to find the best solution.
Requirement: The catalog needs to be accurate so that the TO can reliably find a guide star of a known visual magnitude

- Beam-swiching:
Requirement Origin: The telescope often nods/dithers/beam-switches during observations.
Requirement: The WFS needs to be able to continue to guide the telescope and track aberrations during observations when the telescope is beam-switching or dithering, such as when the star is being nodded along the slit in SpeX. The WFS does not need to guide or track aberrations during the beam switch itself.

- Chopping:
Requirement Origin: The telescope is occasionally used with the secondary mirror chopping.
Requirement: The WFS needs to be able to continue to guide the telescope and track aberrations during observations when the telescope secondary mirror is chopping.

- Guiding
Requirement Origin: Sometimes the WFS will do the guiding, and other times the instrument's own guider will guide the telescope
Requirements:
- Guiding w/ WFS: The instrument needs to be able to guide, and track focus, coma, and astigmatism

- Instrument guiding: The WFS needs to be able to track focus, coma, and astigmatism, but NOT guide when the instrument itself if guiding.

- Non-siderial guiding
  Requirement Origin: IRTF often observes non-siderial targets
  Requirement: The WFS needs to be able to track a non-siderial target, in particular perpendicular to the guide region for a while. We currently move the guidebox to follow the moving guide star since there isn't much room to move the POM. We can do this in WFS mode, but instead of one star we'll be following 3x3 grid of spots

- Instrument specific offsets
  Requirement Origin: Each instrument has its own pointing, focus, and collimation shifts.
  Requirements:
  - Pointing offset: Need to be able to take into account the different pointings for different instruments, and the change in pointing as the rotator in SpeX is moved
  - Focus offset: Need to be able to take into account the different focus for different instruments
  - Collimation offset: Need to be able to take into account the different collimations for different instruments

- Off-axis aberrations
  Requirement Origin: The focus, astigmatism, and coma increases with distance from the center of the field of view.
  Requirements: We will use Zemax to model how these aberrations change vs. direction and distance of the guide star from the science field center. The software needs take the difference between the measured aberrations and the model aberrations.
  Note: Over the 64 arcsecond field of view in the Apogee zemax file, the guider optics are very diffraction limited, so we don't need to worry about the off-axis aberrations of the guider optics themselves.

- Image processing
  Requirement Origin: The magnitude limit of the WFS is affected by dark current and detector flat field.
  Requirements: For each WFS image, a dark should be subtracted, then the result should be divided by a flat image. The dark and flats would have been taken during engineering time.

- Auto-exposure
  Requirement Origin: The WFS should be designed for consistent performance and to minimize added work load for the TO.
  Requirements: The software should take into account the brightness of the guide star (from the catalog), set an exposure time, take images and automatically adjust the exposure time to have good s/n observations within a reasonable amount of time. Software should check counts (especially in EM mode) and adjust exposure time

accordingly as observations continue (for example, if clouds come then it'll take longer exposures)

- Centroiding
  Requirement Origin: The WFS should be designed for consistent performance and to minimize added work load for the TO.
  Requirements: The software should automatically:
  - Find the spots, choose a sub-array window, and start taking exposures
  - Extract the centroids
  - Identify which spot corresponds to which subaperture, and thus calculate the local wavefront tilt

- Averaging/Filtering
  Requirement Origin: Seeing or bad data will compromise the guiding and aberration tracking.
  Requirements:
  - For guiding and aberration tracking, we need to have a moving average, to smooth out seeing effects. The user should be able to set the duration of the averaging window.
  - A bad number filter is necessary to throw out wavefront measurements that differ strongly than measurements taken immediately prior. Such bad measurements could be caused by an image being taken during a beam switch, or a spot being near a bad pixel.

- Control Loop
  Requirement Origin: The WFS should be designed for consistent performance and to minimize added work load for the TO.
  Requirements: The software should automatically:
  - Use the centroids to calculate aberration terms
  - Apply offsets to compensate for guiding, instrument specific offsets, or position of the guide star with respect to the field center
  - Minimize residual aberration terms in a closed loop
    - Tip/tilt errors should be used to control the pointing of the telescope.
    - Focus errors should be used to control the focuser to zero the focus term.
    - Coma errors should be used to control the secondary mirror collimation to zero the coma term. Adjusting collimation will change the pointing of the telescope, which should be corrected by the guiding loop.
    - Astigmatism errors should be used to control the primary mirror bender to zero the astigmatism term.
  - Freeze mode: Should be able to look at a nearby bright star, quickly measure wavefront and zero terms, then offset to target. Useful for targets where no visible light guidestar is available.

- Collimation Changing Pointing
  Requirement Origin: Changing collimation will change the telescope pointing.
  Requirements: The change in pointing should be taken into account so that the telescope points with the updated pointing, and not the pointing before the collimation loop was closed.

- Slow adjustment

Requirement Origin: Changes should not to stress components or make image jump. Control systems are written to command a change once an error has exceeded a limit, not as soon as an error is detected, to avoid a situation where changes are constantly being made.

Requirements:

- When a change to a mechanism is commanded, it should be implemented slowly, over several seconds, to prevent stress on mechanisms and to avoid image jumps. Use a gain factor, so that only a fraction of the correction is applied per correction loop.
- When a collimation change is commanded, the telescope pointing should also be adjusted to keep the star centered during the collimation change. We will calibrate the star motion vs. collimation change. Since the collimation change takes a few seconds, the guider should be able to keep up.

- Mirror bender control

Requirement Origin: Mirror bender should only induce an astigmatism mode, and not a tilt, trefoild, or higher order stuff.

Requirement: Monitor loads, make sure that opposing fingers have same load, and orthogonal fingers have opposite load.

- WFS Failure

Requirement Origin: The WFS may fail, or a guide star may not be available, or a guide star may be lost (clouds, telescope slew, etc.)

Requirements:

- When the WFS is not being used, the focus model runs to track focus changes. The focus and collimation should still be able to be changed by hand. The mirror bender should be set to a nominal 'zero force' state.
- If the guide signal is lost (for example, if clouds block the star, or the telescope is slewed before the WFS is turned off), then the guider should stop sending correction signals to mechanisms, or disable TCS interaction.

- Fail Safes

Requirement Origin: We don't want the wavefront control system to break anything on the telescope.

Requirements:

- Guiding
  - Limit guider offset to a certain range
- Focus
  - Limit focus change to a certain range above and below nominal focus setting
- Collimation
  - Limit collimation change to a certain range above and below nominal collimation setting
- Mirror Bender
  - Limit motor torque to a certain range above and below 0 force setting
  - Limit pressure measured by load cells to well below failure limit of mirror

- Install multiple load cells so that failure of one cell doesn't compromise fail safe
- Modify actuator so that a component mechanically fails well before reaching failure limit of mirror

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Glossary
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astigmatism: image aberration primarily caused by flexure of the primary mirror, resulting in an enlarged psf.
coma: image aberration primarily caused by misalignment of the primary and/or secondary mirror, resulting in an elongated 'comet' shaped psf.
focus: image abrerration caused by curvature of the wavefront, resulting in an enlarged psf. Primary cause of defocus is a spacing
error between the primary and secondary mirror.
POM: pick-off mirror, on the off-axis guider's XY stage
RMS: Root-mean-square
RSS: Root-sum-square
tip/tilt: image aberration caused by a tilt in the wavefront, resulting in image motion on the focal plane
WFE: wavefront error
WFS: wavefront sensor

Desirable Features
- WFS should be able to do the acquisition and guiding
- WFS should have as wide a field of view as possible for acquisition, or so that the WFS is less likely to loose the star.
- WFS should be sensitive to aberration modes up to and including spherical, since these higher order modes can alias into lower order modes
This would also help in using the WFS as a general diagnostic tool.

Zemax notes
Focus: For 0.1 microns RMS of defocus, move focal plane by 4.6mm.
Currently, typical defocus is RMS=0.71 microns (0.32 waves). Move focal plane by 33 mm
Astigmatism: For 0.1 microns RMS of astigmatism, set zenike6 = 5e-5 in zemax
Currently, typical astig is RMS=0.52 microns (0.24 waves), set zenike6 = 2.5e-4 in zemax.
Coma: For 0.1 microns RMS of coma, set zernike7 or 8 = 5e-5 in zemax.
Currently, typical coma is RMS=0.35 microns (0.16 waves), set zernike7/8 to 2e-4.
Comment: If each aberration has a RMS amplitude of 0.1 microns, then the P-V error is 0.44 waves (0.97 microns)
This exceeds the Richey 1/4 criterion.
The pdf file irtf_half_error has half of the nominal focus, coma and astig.
The pdf file irtf_full_error has all of the nominal focus, coma and astig.

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Specs for Current Guider
****
Beam height above bench: ~ 124 mm = 4.9"
 - centers between fold mirrors = 6.415"
Apogee FOV ~ 12.5 mm across.
TV camera FOV ~ 5.7 mm across.
Andor iXon3 897 detector size = 8.2 mm across (512x512, 16um pixels)
 - Cost: $40K list price for Ultra, usb2 & camera link data port for direct access to data
  $36K for standard camera which is what we have
 - ~ 30 fps no binning, on frame transfer mode,
  Run to abort mode, just displays image
  No video output mode
  Andor has some software to help you show image, will skip frames if data is coming in faster that ~30 Hz
  Ultra has cameralink data port, may be able to go to a card that could convert to a video
  - Solar group (David Harringtron, Jeff Kuhn) has used this camera in a live video mode like an expensive video camera.
Andor iXon3 888 detector size = 13.3 mm across (1024x1024, 13um pixels)
 - Frame rate binned 2x2 ~ 17 Hz
 - Cost: $50K list price
  - often 15% off for universities

Camera/Optics Scenarios
A) iXon Ultra 897 w/ guider optics
 60" = 5.7 mm
 pixel scale: 0.17" / pixel
 field of view:
B) iXon 888 w/ Apogee optics
 60" = 12.5 mm
 pixel scale: 0.06" / pixel

3m = 95 mm
cable length = 320 mm = 10.1 m
long way = 450 mm = 14.2 m

****
Pupil Slicer
****
Diameter of pupil image: 15.0 mm

*** Pyramid prism ****
Focus-to-focus distance = 490 mm
Lens to focus distance = 245 mm
Focal length of reimaging lens = 122 mm

Focus to pupil plane = 160 mm
Lens to pupil plane = 85 mm
Apogee plate scale: 1' = 12.1 mm => 5.0"/mm
 ---> Spot separation should be about 3" = 0.6 mm
  13 um pixels -> plate scale is 0.065"/pixel.
   - Usually run array binned 3x3 to get 0.20"/pixel
  3x3 grid then requires 9"x9" subarray -> 45x45 pixels (after binning)
   iXon 888 camera can support this subarray @ ~1kHz
  Deflection of beam by each facet of wedge prism = 0.18 degrees
   - this deflects spot by 0.5 mm
Prism sources
 - deflection angle d ~ (n-1)a
  - for 30', deflection is 13.8' = 0.23 degrees
 - Alikor: http://www.alkor.net/wedges.html
  - 30' and 12' angles.
 - ISP optics: http://store.ispoptics.com/store/index.php?main_page=index&cPath=1_43_156_150
  - Note: uncertainty in wedge is half of the wedge angle!
 - rainbow optics
  http://www.rainbowoptics.com/products/windows/
  30' wedge window

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Pupil Viewer
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** Requirement: It'd be nice to have a pupil viewer mode, to check alignment of pupil on pupil stop
** Solution:
 A) 1" doublet lens on flipper mechanism
  - Motorized flipper mount:

http://www.newport.com/Motorized-Flipper-Optical-Mounts/955083/1033/info.aspx#tab_Specifications
   Cost: $865
  - 1" achromatic doublet: http://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=120
   Cost: $80

WFS Project Costs
- Andor CCD: $35 to $50 K
- Pyramid prism: $4400
- New Filter wheel: $10K
- Motorized flipper: $900
- Doublet pupil viewer lens: $100
- Front doublet:
- New guider box:

--> Total:

Cross roller table
Dover XYRB-1212
(508) 951-9643
Contact: Harry Packer
(508) 475-3443