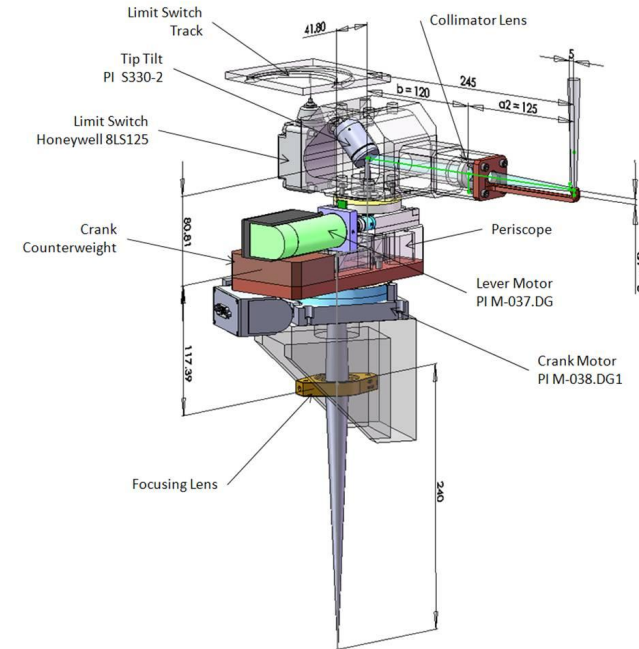
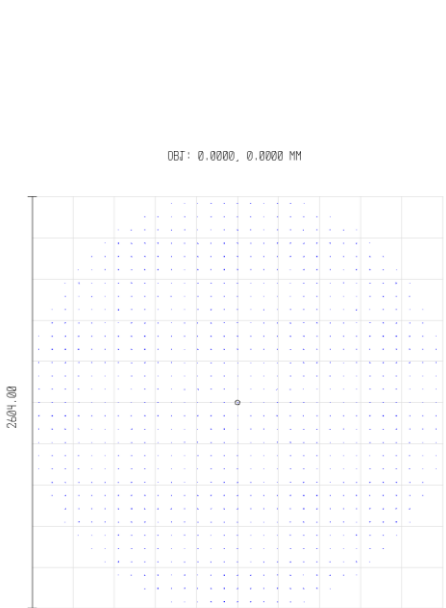
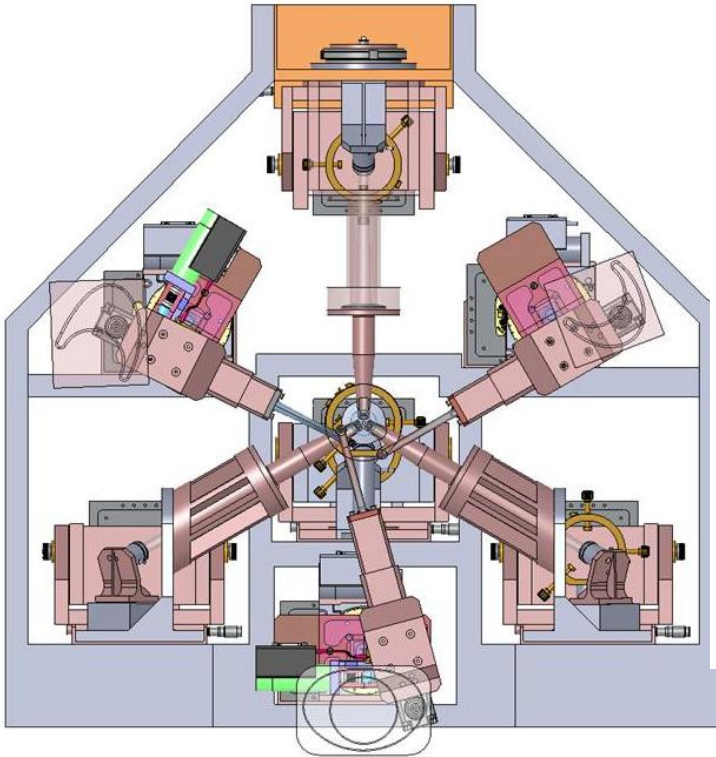
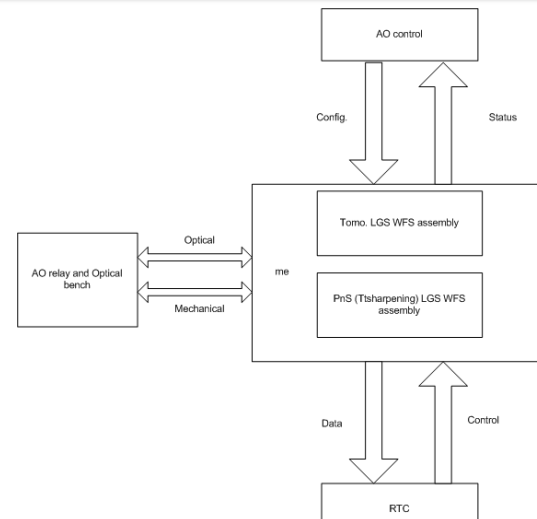
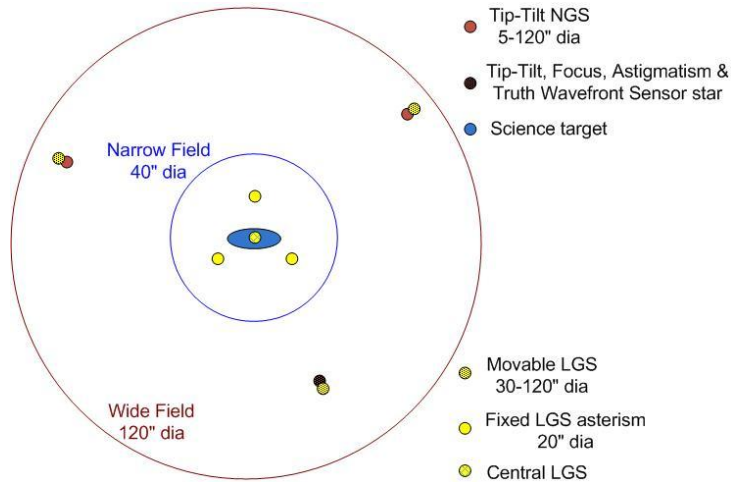


# NGAO Laser Guide Star wavefront sensor Optical Design

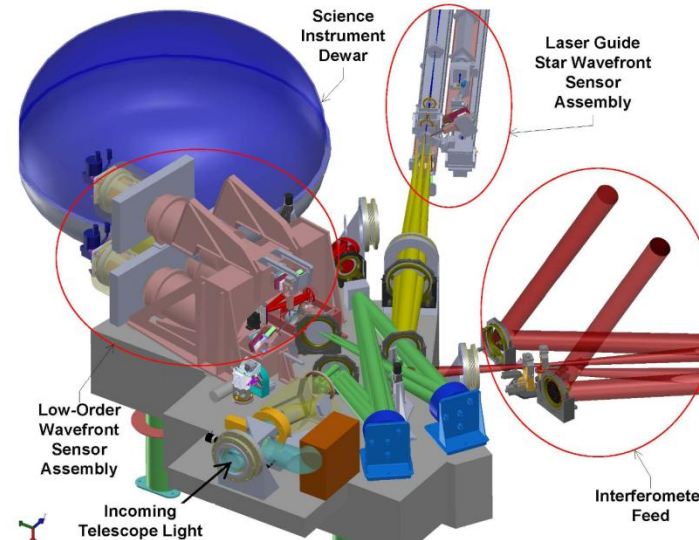


## PD Phase LGS WFS Mini-Review

# Introduction

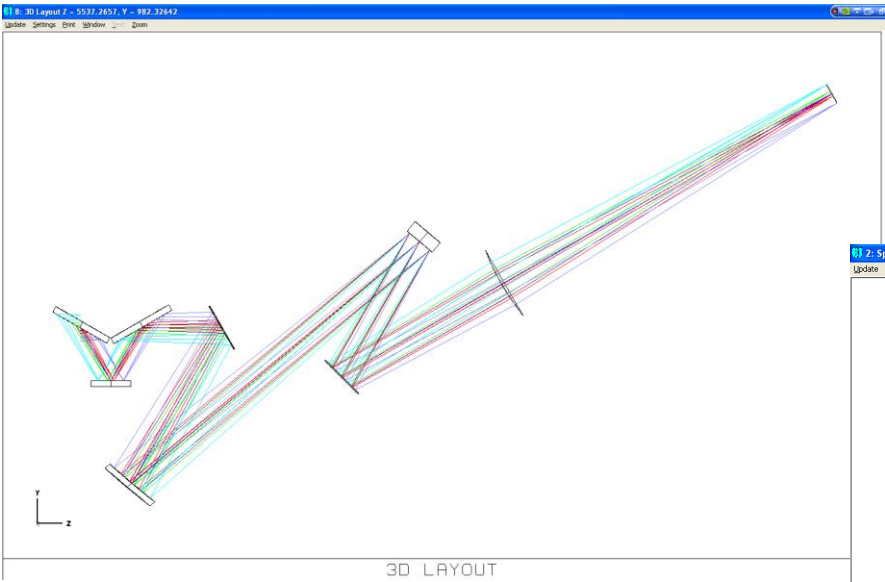


- Top left – NGAO LGS beacon geometry on sky showing 4 fixed laser beacons and 3 movable beacons.
- Top right – NGAO LGSWFS context diagram indication control, data and other interfaces with other NGAO sub-systems.
- Bottom right – 3D model of NGAO showing the position of the LGSWFS relative to the other components.

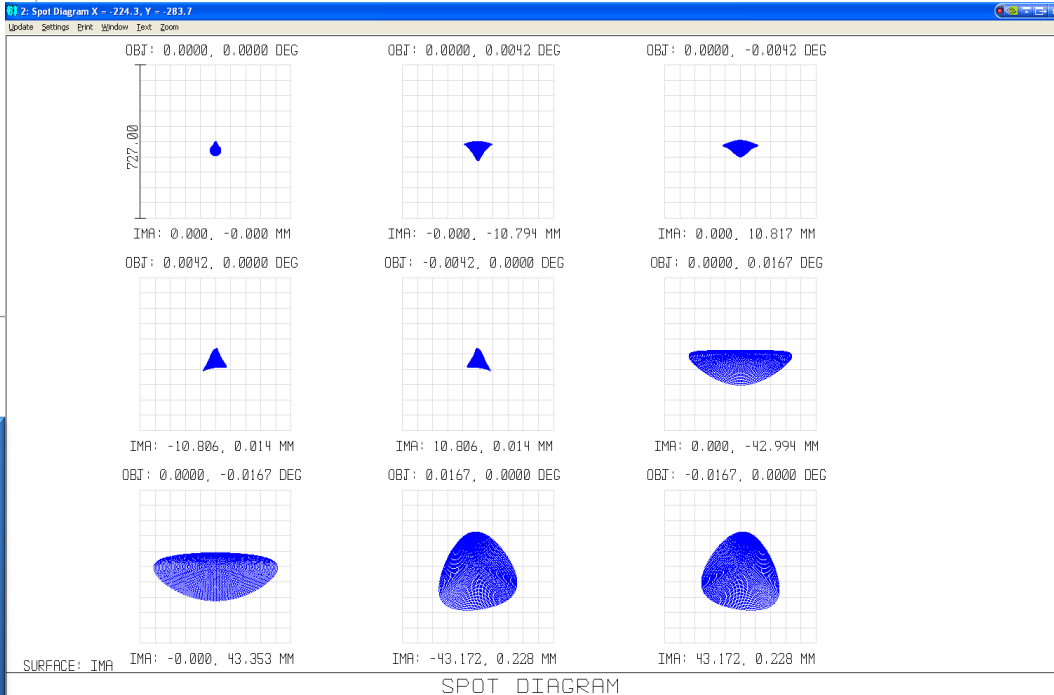


# Keck NGAO optical relay

Left – NGAO LGS beam path starting from the K mirror and ending at the LGS WFS pick off plane.



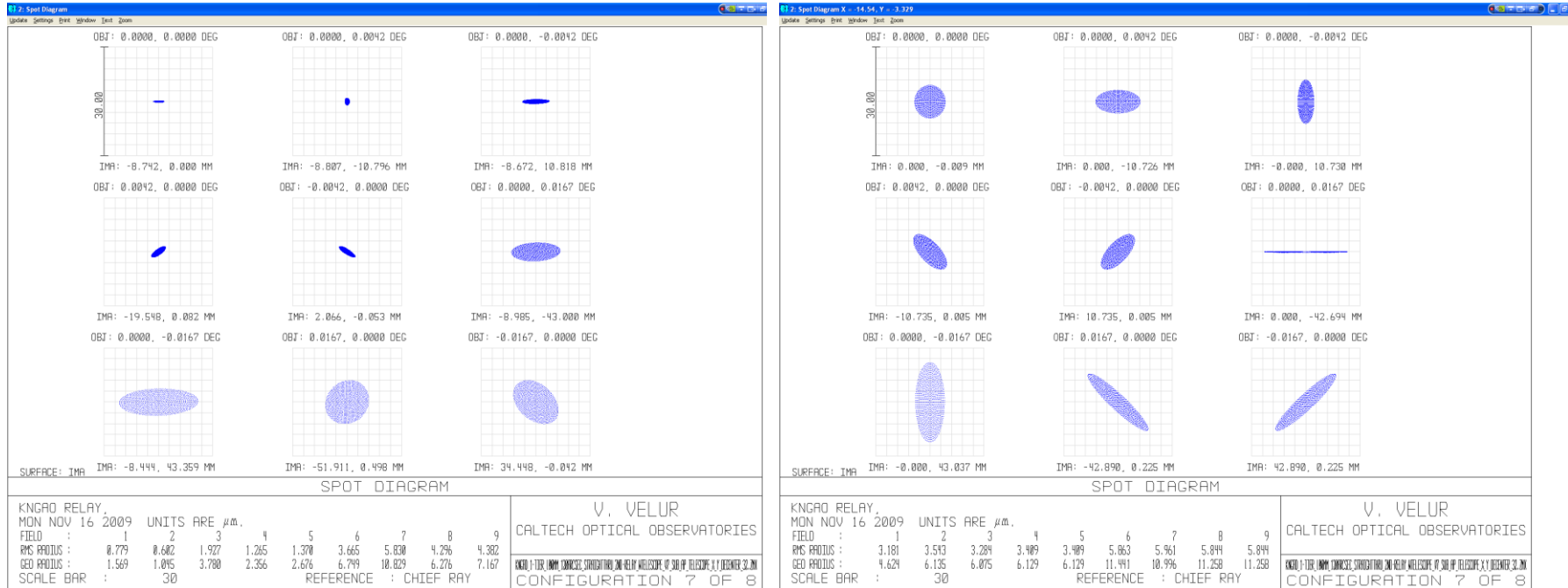
Right – Spot diagram resulting from NGAO relay with the sodium layer distance from telescope aperture being 90 km. One can see RMS spot sizes of 20-45  $\mu\text{m}$  for the Fixed asterism and 134-160  $\mu\text{m}$  at the Patrolling WFS pick off plane. For reference the scale next to the first field point corresponds to an arcsec.



KNGAO RELAY									
FRI NOV 13 2009									
UNITS ARE $\mu\text{m}$ .									
FIELD :	1	2	3	4	5	6	7	8	9
RMS RADIUS :	25.581	43.637	44.980	41.618	41.618	135.117	159.096	134.170	134.170
GE0 RADIUS :	66.807	91.816	86.718	101.159	101.159	247.390	297.268	238.724	238.724
SCALE BAR :	727								

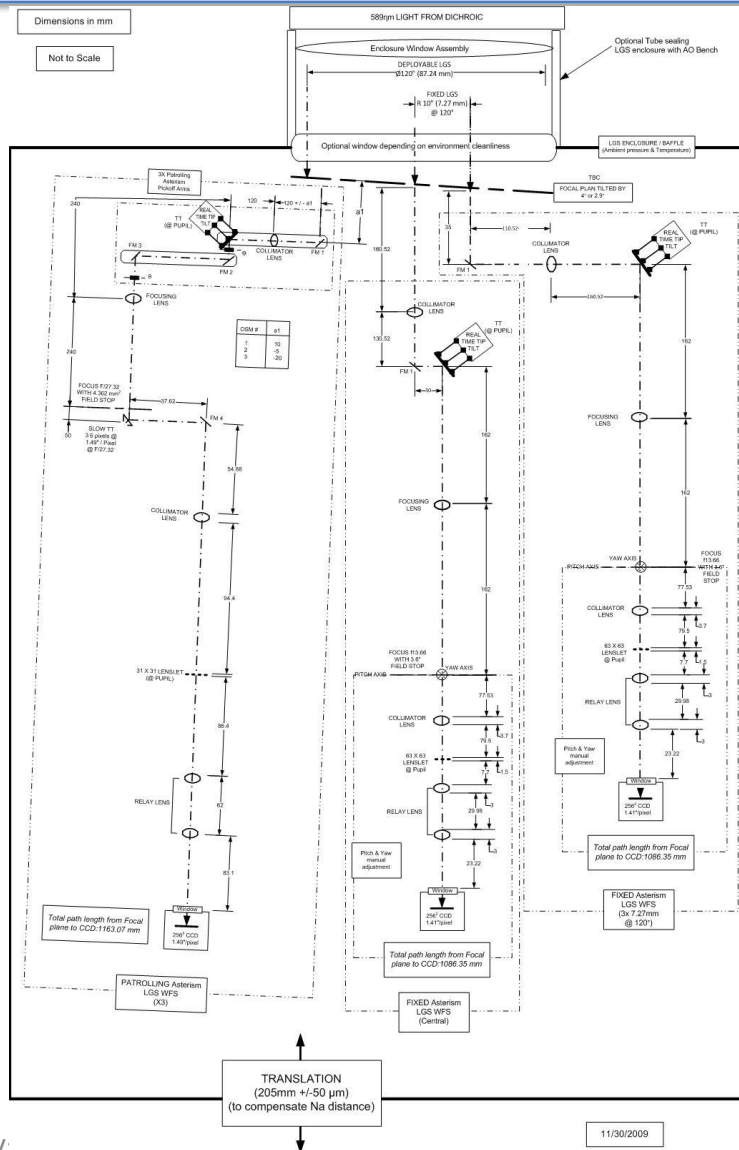
V. VELUR  
CALTECH OPTICAL OBSERVATORIES  
KNGAO\_1-TIER\_100MM\_120ARCSEC\_STRAIGHTTHRU\_2ND-RELAY\_WTELESCOPE\_V7.ZMX  
CONFIGURATION 3 OF 3

# Sub-aperture level aberrations or how I learned to stop worrying about the LGS spots produced by the AO relay



	On-sky field point	Full-beam RMS spot size radii (from Zemax)	Corresponding Full-beam FWHM	LGS WFS Subaperture RMS spot size radii (from Zemax)	Corresponding LGS WFS Subaperture FWHM
Fixed Laser Asterism WFS	10 arcsec	26 to 45 $\mu$ m	83 to 147 mas	negligible	negligible
Patrolling Laser Asterism WFS	60 arcsec	130 to 150 $\mu$ m	425 to 491 mas	< 6 $\mu$ m	< 20 mas

# To tilt or not to tilt?



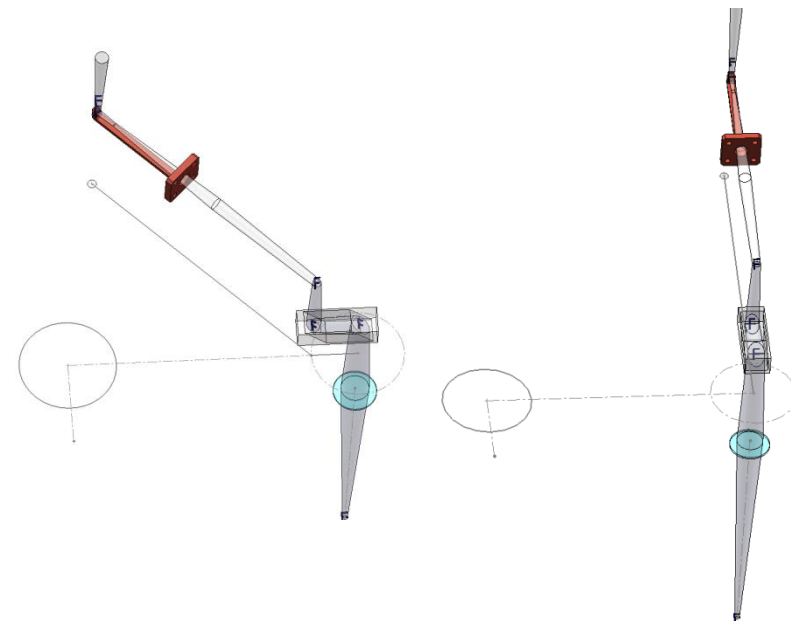
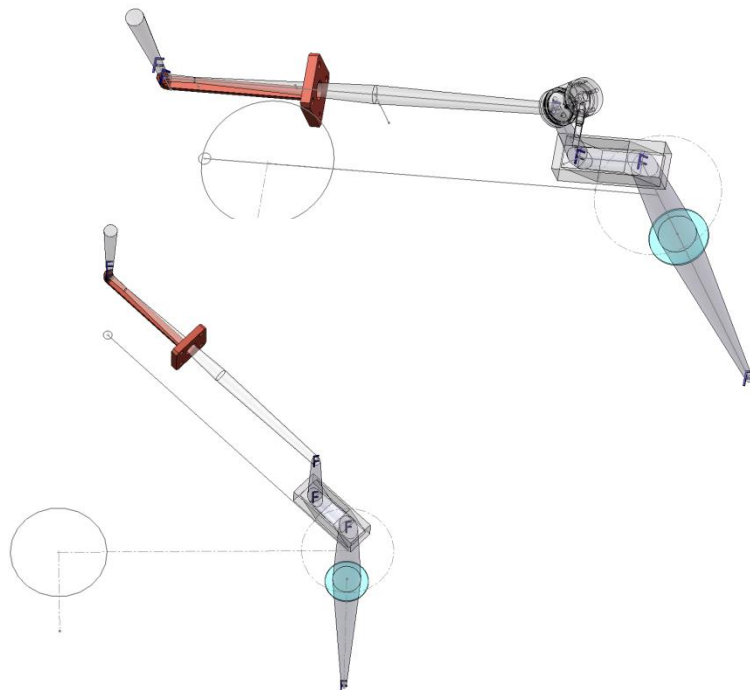
Based on KAON 685 (NGAO optical relay design) and personal communication with Reni, it was realized that the LGS focal plane delivered by the AO system is tilted. Moreover the tilt varies with change in object (sodium layer) distance.

The spots in the previous slide were generated using Version 7 of the NGAO optical design without inducing a tilt at the LGS focal plane. Though the aberrations introduced at the sub-aperture level is small, it may be possible to decrease the input WFE to the LGSWFS. Both the effect of the tilt and the use of an alternate LGS light focusing lens will be explored with Reni. Both the new focusing lens (also a two element window?) and the tilted WFS assembly come at a cost (value TBD). The tilt may need us to either choose an optimal plane to tilt the WFS channels to pick off from or use individual focus stages for the Patrolling WFS's.



## Why theta-phi pick-offs?

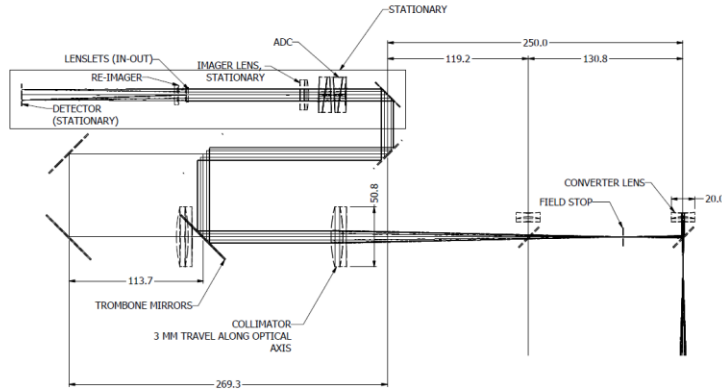
Theta-phi pick-offs as compared to a r-theta pick-off don't need a translation to compensate for the change in field position and at the same time they don't need a de-rotation. Though this needs to be prototyped, it is a lot simpler than the HIA r-theta mechanism.



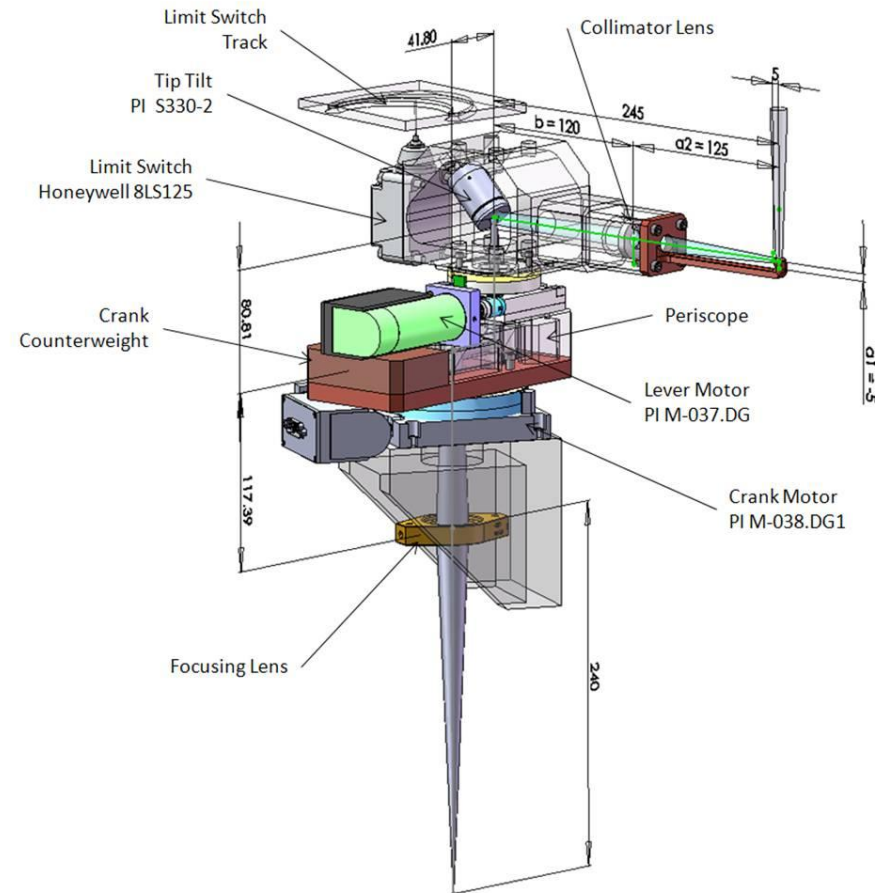
More info. :

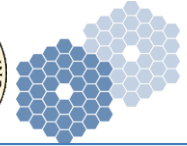
[http://www.oir.caltech.edu/twiki\\_oir/pub/Keck/N\\_GAO/WFS/OSM\\_De-rotation.ppt](http://www.oir.caltech.edu/twiki_oir/pub/Keck/N_GAO/WFS/OSM_De-rotation.ppt)

# Why theta-phi pick-offs?



Though this pick-off needs to be prototyped, it is a lot simpler than the HIA r-theta mechanism (HIA mechanism also needs to be prototyped). All motion control components are commercial in the theta-phi pick off.





## Shack Hartmann design maths

1. Hardy's 'p' parameter choice (based on spot size at the detector)
2. Stabilization TT Mirror Specification
3. Evaluation of Differential Focus & Impact of Single LGS WFS Focus Stage
  1. change in radius of curvature (RoC) of the LGS focal plane with change in distance to the sodium layer
  2. Finite size of LGS asterism on-sky
4. LGS WFS Relay Optical Aberration Specification



# Shack-Hartmann design parameters – LGS spot size and $p$ parameter

## Fixed LGSWFS

## Patrolling LGSWFS

Laser Guide Star Size Calculation		Laser Guide Star Size Calculation	
<b>Finite Object Size</b>		<b>Finite Object Size</b>	
Intrinsic guide star diameter	0.00 arcsec	Intrinsic guide star diameter	0.00 arcsec
<b>Uplink formation of the beacon(s)</b>		<b>Uplink formation of the beacon(s)</b>	
Perfect Uplink AO?	NO	Perfect Uplink AO?	NO
Inherent aberrations in the uplink beam:	0.90 arcsec	Inherent aberrations in the uplink beam:	0.90 arcsec
Beam movement contribution to uplink	0.27 arcsec	Beam movement contribution to uplink	0.27 arcsec
Residual seeing contribution to uplink	0.47 arcsec	Residual seeing contribution to uplink	0.47 arcsec
Diameter of point source laser at Na layer:	1.02 arcsec	Diameter of point source laser at Na layer:	1.02 arcsec
<b>Seeing</b>		<b>Seeing</b>	
Natural seeing FWHM at GS wavelength	0.46 arcsec	Natural seeing FWHM at GS wavelength	0.46 arcsec
Subaperture Tip/Tilt corrected FWHM		Subaperture Tip/Tilt corrected FWHM	0.39 arcsec
AO-compensated FWHM		AO-compensated FWHM	0.06 arcsec
Contribution due to seeing		Contribution due to seeing	0.39 arcsec
<b>Elongation</b>		<b>Elongation</b>	
Distance from LLT to telescope axis:		Distance from LLT to telescope axis:	0.00 m
Use Max. Elongation?	N	Use Max. Elongation?	1.39 arcsec
Avg. Elongation		Avg. Elongation	0.93 arcsec
Contribution to FWHM due to elongation		Contribution to FWHM due to elongation	0.93 arcsec
<b>System Aberrations</b>		<b>System Aberrations</b>	
Aberrations in AO thru to WFS		Aberrations in AO thru to WFS	0.25 arcsec
<b>Atmospheric Dispersion</b>		<b>Atmospheric Dispersion</b>	
ADC in HOWFS?	N	ADC in HOWFS?	
RMS blurring due to atmospheric dispersion		RMS blurring due to atmospheric dispersion	0.000 arcsec
Total size of detected return beam:		Total size of detected return beam:	1.45 arcsec
<b>Sensing Approach</b>		<b>Sensing Approach</b>	
Pyramid WFS?	N	Pyramid WFS?	
<b>Charge Diffusion</b>		<b>Charge Diffusion</b>	
Charge Diffusion		Charge Diffusion	0.00 pixels
Contribution due to Charge Diffusion		Contribution due to Charge Diffusion	0.00 arcsec
<b>Subaperture Diffraction</b>		<b>Subaperture Diffraction</b>	
Lambda/d (for sensing)		Lambda/d (for sensing)	0.36 arcsec
<b>Spot size used for centroiding</b>	1.41 arcsec	<b>Spot size used for centroiding</b>	1.49 arcsec

Apparent spot size measurement at the detector due to various effects for the fixed tomographic LGS WFS spots (left) and that the apparent spot size at the detector of Patrolling WFS (TT sharpening) LGS WFS spots (right). Charge diffusion term is set to 0 here in order to make an optical estimate of FWHM, which is appropriate for determining the detector pixel scale. [The EBS models charge diffusion and so will the final system when transfer curve calibration is performed on the as-built system.]

Detector size per subaperture	Pixel Size/ spot size (p)	Useful tilt range +/- waves	Departure from linearity (waves)
2x2	1.0-1.5	0.5	0.024
2x2		1.0*	.13*
4x4	0.5	1.5	0.019
4x4	0.67	2	0.085
4x4	1	2.5	0.19

\* - nonlinear response

	Fixed	Patrolling
<b>P value</b>	0.5	1
<b>Capture range</b>	1.5*2 waves	2.5*2 waves
<b>lambda/d</b>	710 mas	355 mas
<b>Capture range</b>	2.13 arcsec	1.775 arcsec
<b>1d tilt (RMS)</b>	50 mas	100 mas

## Stabilization TT Mirror Specification

Pupil de-magnification at the TT mirror =  $10.949 \text{ m} / (12.5 \text{ mm} / 1000 \text{ mm/m}) = 875.92$

TT resolution on sky = 1 milliarcsec (say) [The RMS 1D tilt error is 95 milliarcsec]

Hence, TT mirror resolution =  $0.001 \text{ (arcsec)} * 875.92 = 0.875 \text{ arcsec} = 4.2 \text{ microradians}$

Capture need, say is, 0.5 arcsec (on sky angle) =  $0.5 * 875.92 \text{ ''} / 206265 \text{ (''/rad)} = 2.12 \text{ millirad}$

Based on the resolution and the capture range we choose the following mirror from Physik Instrumente's catalog:

<http://www.physikinstrumente.com/en/products/prspecs.php?sortnr=300700>

S-330.8SL has 10 mrad of tilt travel with 0.5 microrad (0.12 milliarcsec resolution on sky) open-loop resolution is the mirror of choice. The mirror has a resonance frequency of 1 kHz with a 1" diameter optic with 1/4" thickness.





# Evaluation of Differential Focus & Impact of Single LGS WFS Focus Stage

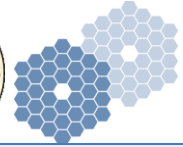
Cause 1 : change in radius of curvature (RoC) of the LGS focal plane with change in distance to the sodium layer

Dist. To Na layer	ROC of focal plane (mm)	focal plane size (mm)	Sag (um)	Delta sag (um)	Error (in waves) after splitting the difference
<b>PnS asterism</b>					
90 km	883.20	87.24	1077.82		
180 km	2064.00	87.24	460.98	<b>616.84</b>	0.5236
<b>Fixed LGS asterism</b>					
90 km	883.20	7.27	7.48		
180 km	2064.00	7.27	3.20	<b>4.28</b>	0.0036

Cause 2: Finite size of LGS asterism on-sky

Guide star asterism diameter	Defocus error due to geometry of the asterism (um), $x/2$	Error in waves (220 um corresponds to $\lambda/4$ depth of focus)
20	6.5	0.006 waves
120	68	0.077waves

These effects are deterministic and can be calibrated for.

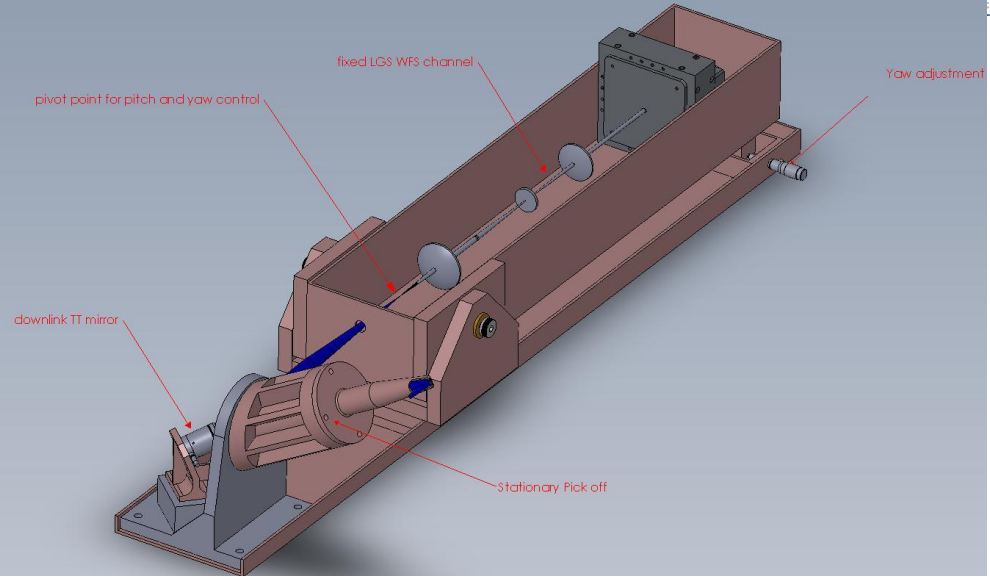
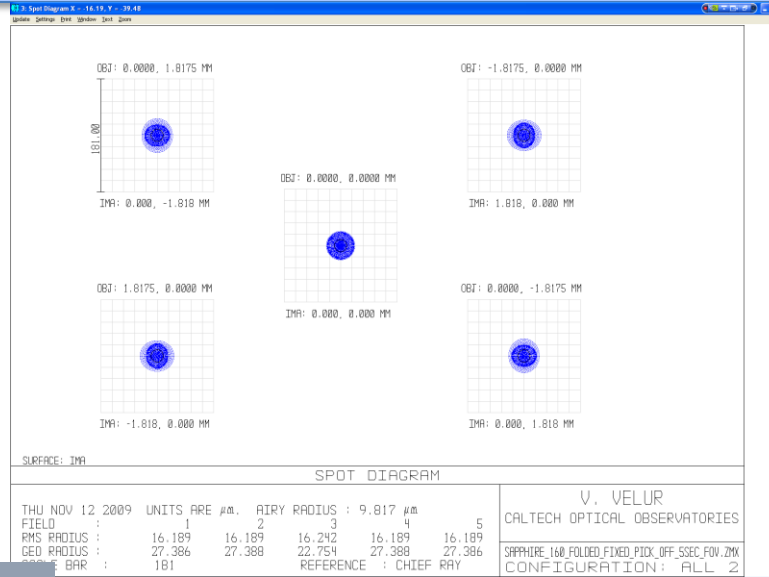
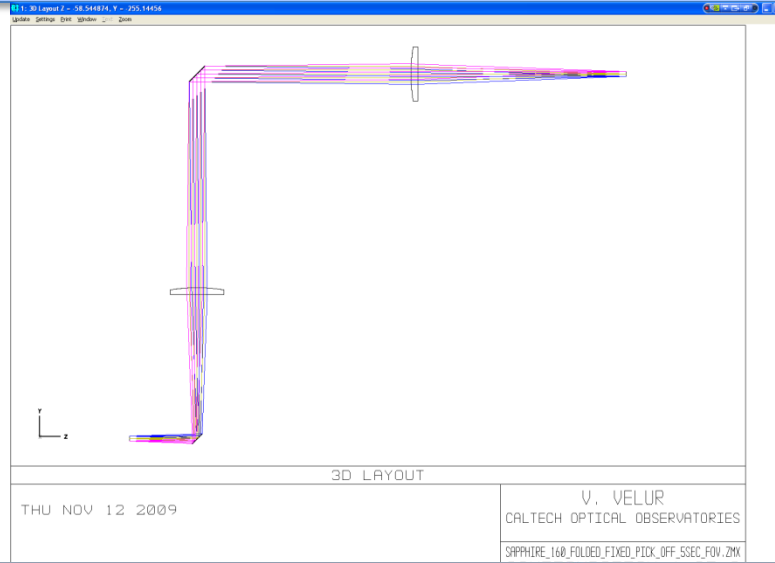


## LGS WFS Relay Optical Aberration and Field Stop Specification

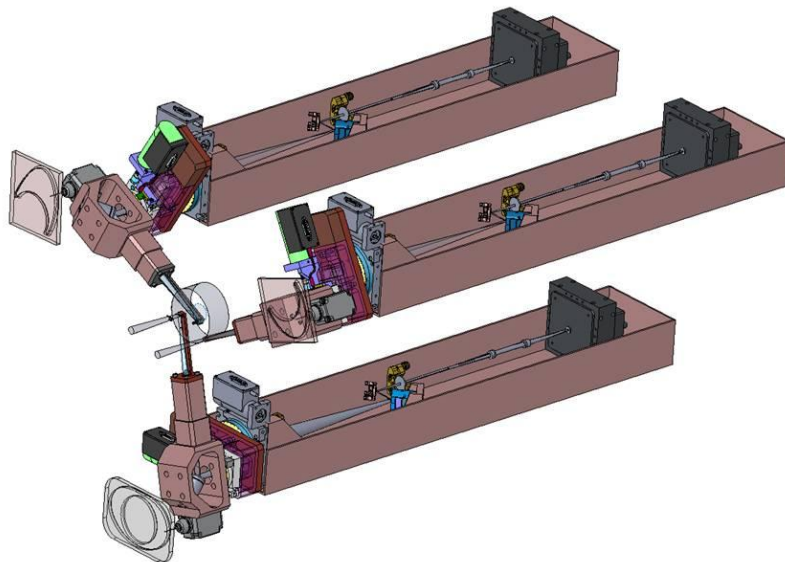
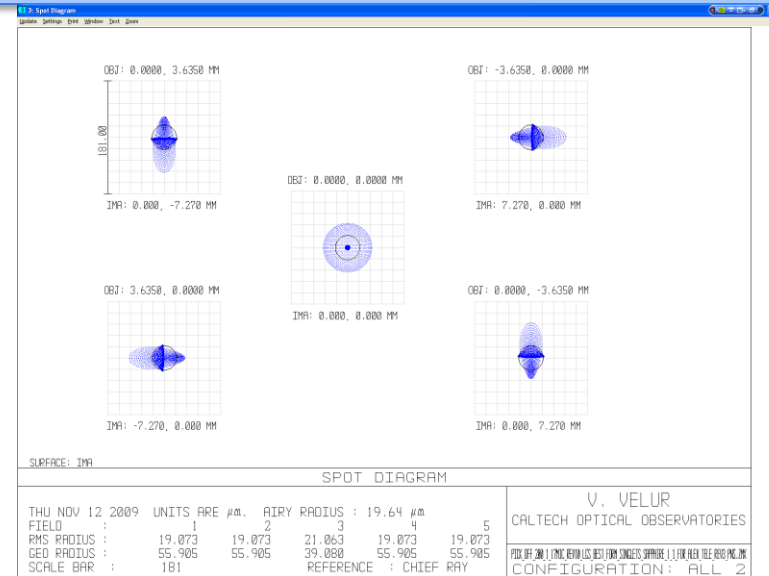
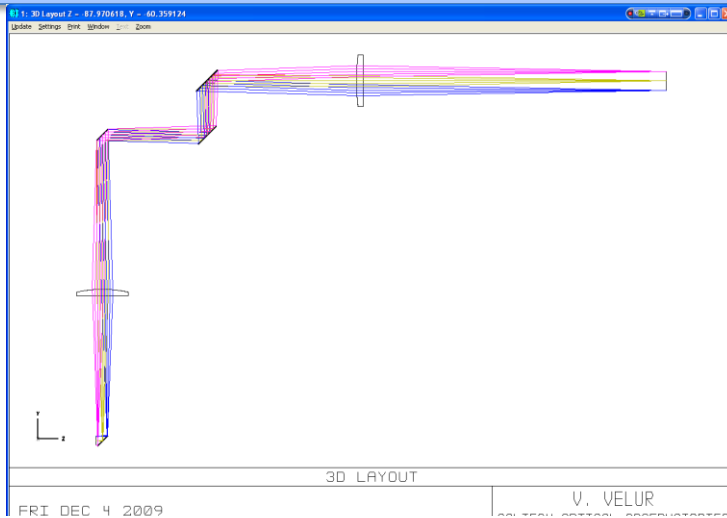
Spot size (RMS as indicated by Zemax) at the detector =  
Allocation (arcsec FWHM) / 2.355 (FWHM/RMS) \* 21  
(um/pixel) / 1.49 (arcsec/pixel) =  
 $0.25 / 2.355 * 21 / 1.49 = \sim 1.5 \text{ um}$

Field stop size = 2.8 arcsec (subaperture size of the fixed LGS asterism size). The field stop will be located after the pick-off, just before the collimator of the sensor. Is this OK?

# Fixed LGS WFS Pick offs

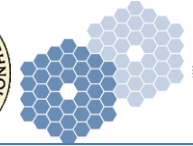


# Patrolling LGS WFS Pick offs



The pick-off planes are staggered so that all pick-offs can access all field points within the FoR





## Some comments that will change the design ☹️

- From the agreed upon drawings of the telescope pupil on the MEMS actuators should use 60 subapertures (not 63). Using these two numbers you get a lenslet pitch of 97.6  $\mu\text{m}$ .

*Don and I talked at a meeting at UCSC and agreed on 31 and 63 sub-apertures based on a Fried geometry for the 32x32 and 64x64 mirror. This supposed change is not reflected on in the requirements.*

- From the agreed upon drawings of the telescope pupil on the MEMS actuators should use 30 subapertures (not 31).

*Don and I talked at a meeting at UCSC and agreed on 31 and 63 sub-apertures based on a Fried geometry for the 32x32 and 64x64 mirror. Requirements say the same thing as our meeting. And to my best knowledge, the EBS has the 63 and 31 subapertures for the Fixed and Patrolling sensors. Wonder how the Systems Engg. Group didn't realize the change in architecture when the pupil mapping definition was changed! It certainly didn't make it into the WFS requirements.*

**•Nutation issue – should we design 60x60 subaperture sensor or even lesser as we can have a already available commercial (PN sensor) detector as a back-up for the 256x256 pixel CCID56?**

- Need to verify that optics work for 594 nm as well as 589 nm. For instance, the spots at the PNS cameras almost double in size at 594 nm. They're still only a few microns diameter, but this should be checked.

*Valid point - the requirements don't say that the performance must be the same at 589 and 594 nm; it just says that the sensor needs to operate between 589-594 nm. I'll re-optimize the PnS sensor design to include both wavelengths. We must also add the requirement on specifying performance specs over the 5 nm range.*

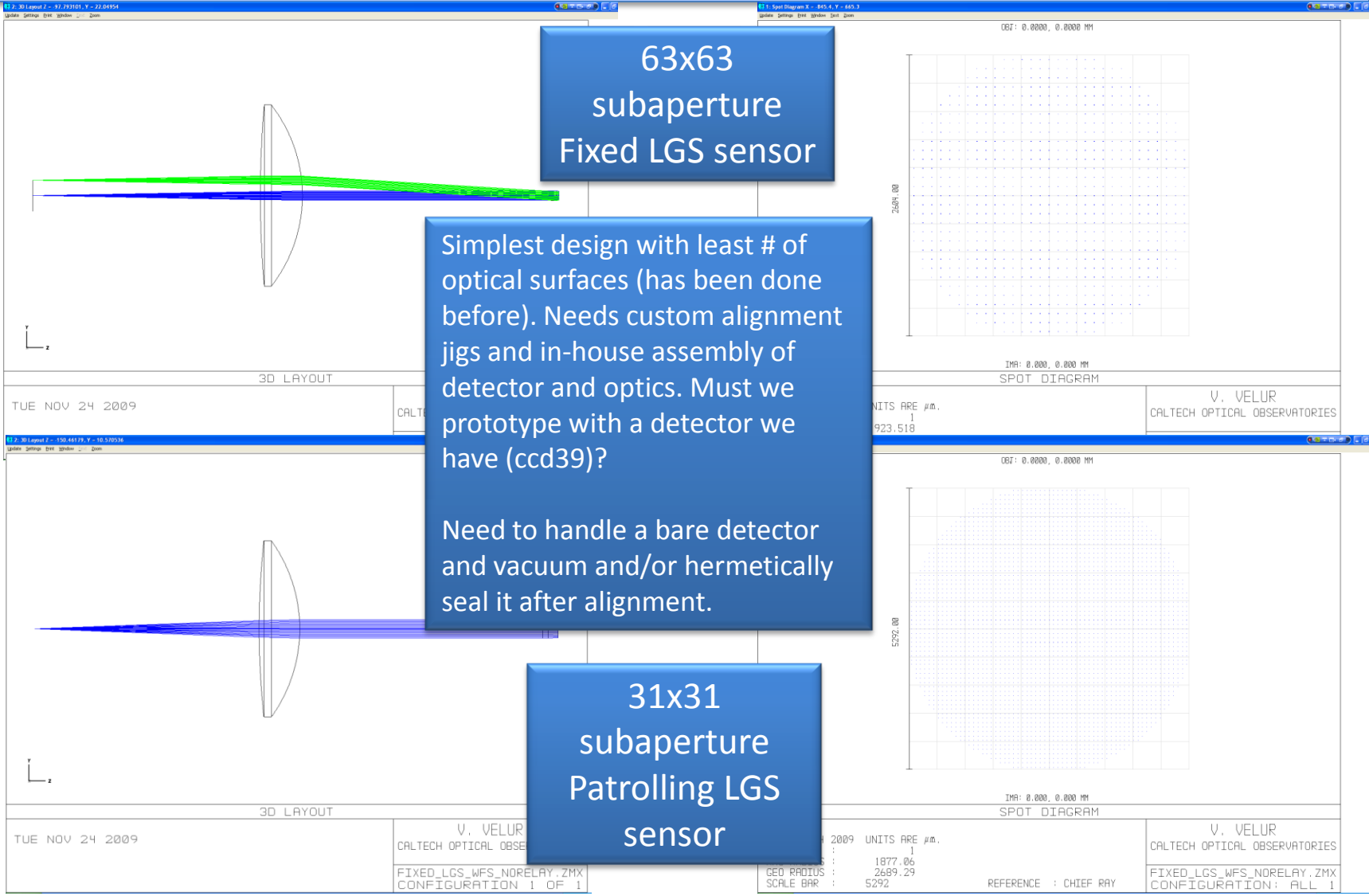
# LGS WFS (the dot-relay less design)

63x63  
subaperture  
Fixed LGS sensor

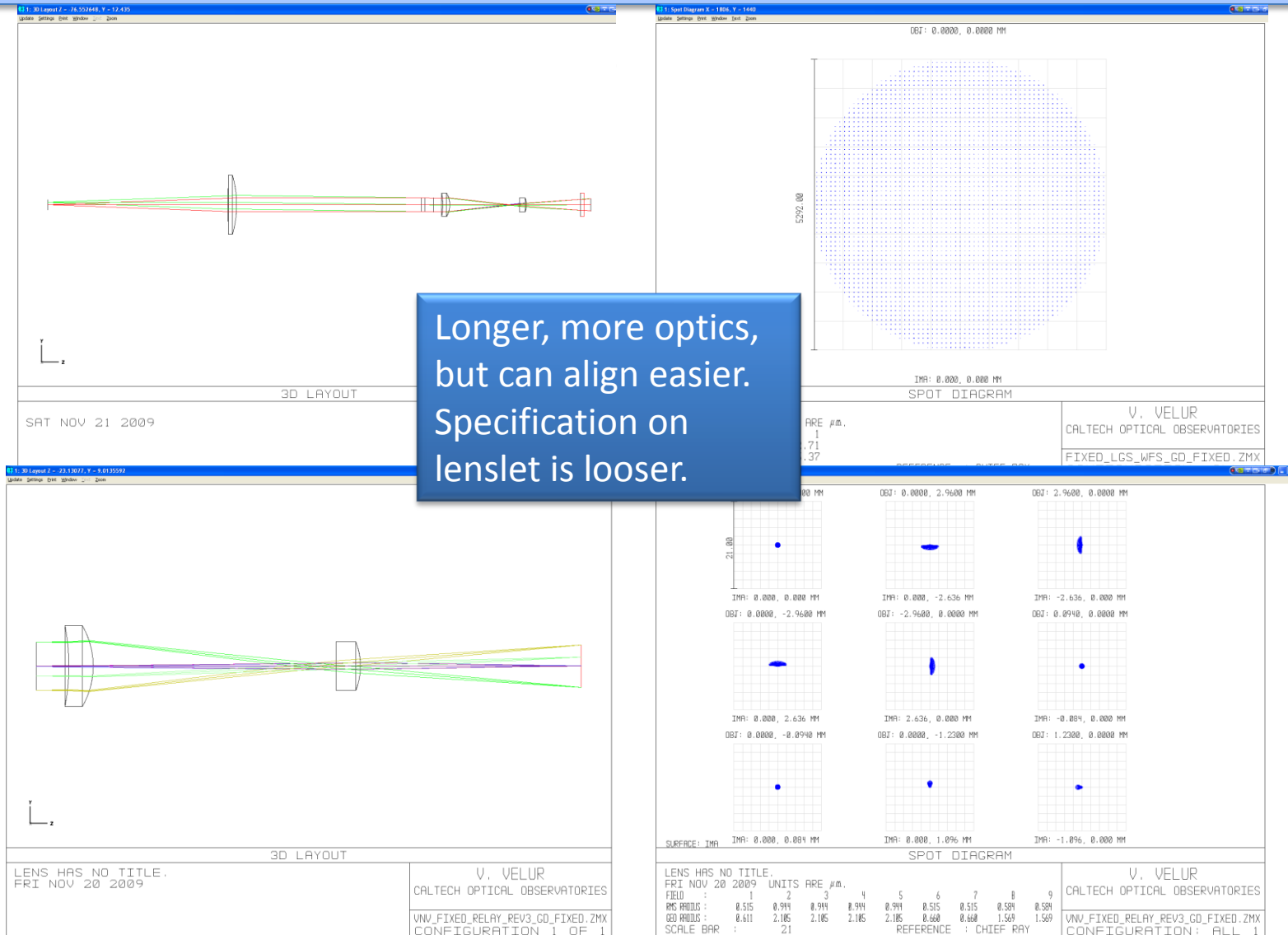
Simplest design with least # of optical surfaces (has been done before). Needs custom alignment jigs and in-house assembly of detector and optics. Must we prototype with a detector we have (ccd39)?

Need to handle a bare detector and vacuum and/or hermetically seal it after alignment.

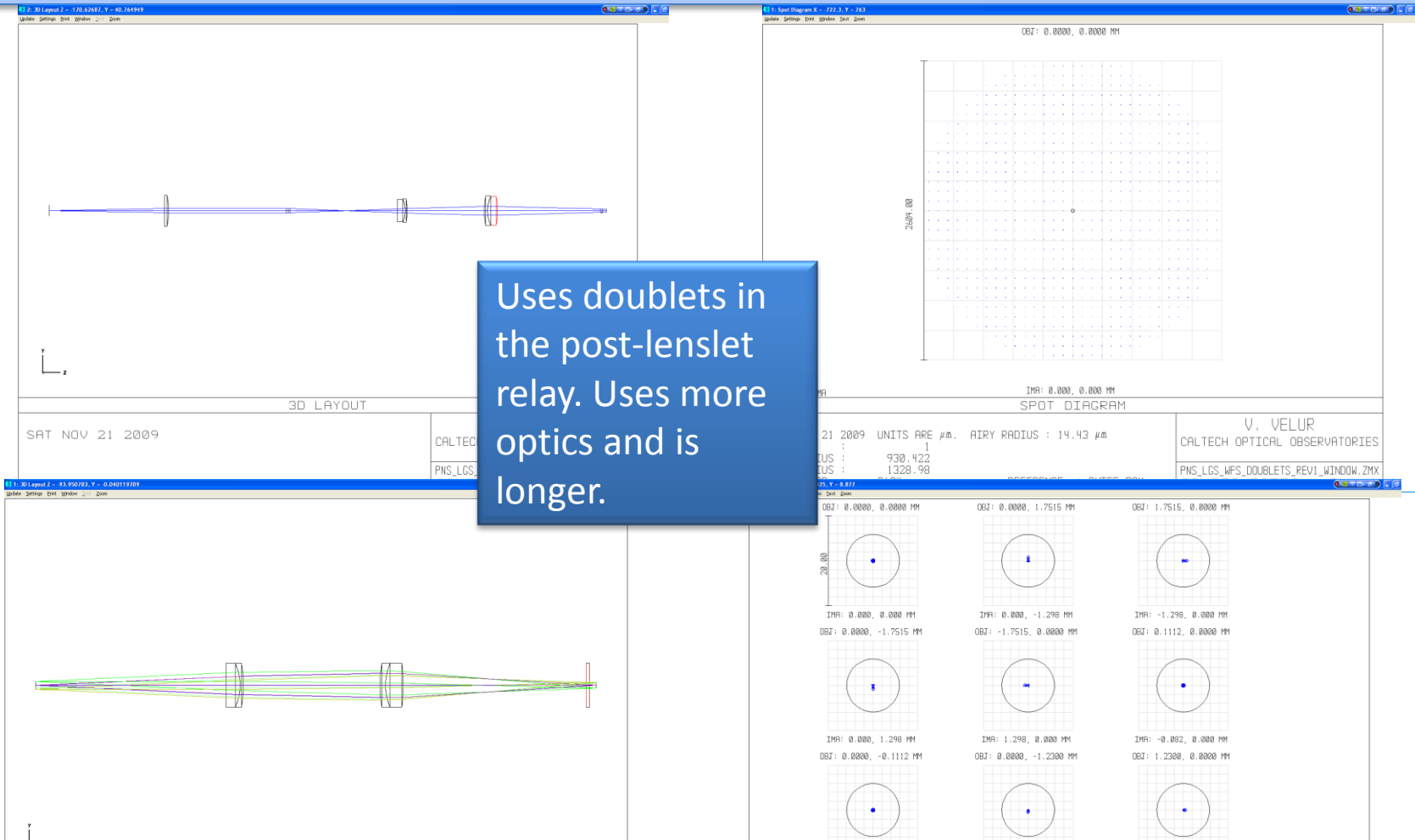
31x31  
subaperture  
Patrolling LGS  
sensor



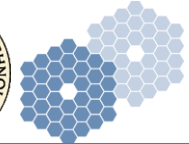
# Fixed LGS WFS design with relay



# Patrolling LGS WFS design with relay



Changing the design (due to change in NGAO optical design or change in specification) doesn't take too time. Probably 2 days to design and two more days to refine update mechanical design and document. But, it would be nice to finalize design ASAP.



## Outstanding Items to be completed by PDR:

1. Stray light (including Rayleigh scatter) analysis
2. LODM Pupil & lenslet registration scheme
3. Pupil aberrations at the lenslet.
4. Simplification of the Optical Design of sensors if possible.
5. Identifying what all needs to be prototyped in the next phase.
6. Try to redesign the plano-(parabolic) convex lens to try and provide less aberrated LGS spots at the LGS assembly input.
7. Cost reduction by finding more economical components.
8. Draft interface documents between the LGSWFS assembly and the various other sub-systems.
9. Detailed cost estimate revision, in support of the PD Phase NGAO Cost Book.