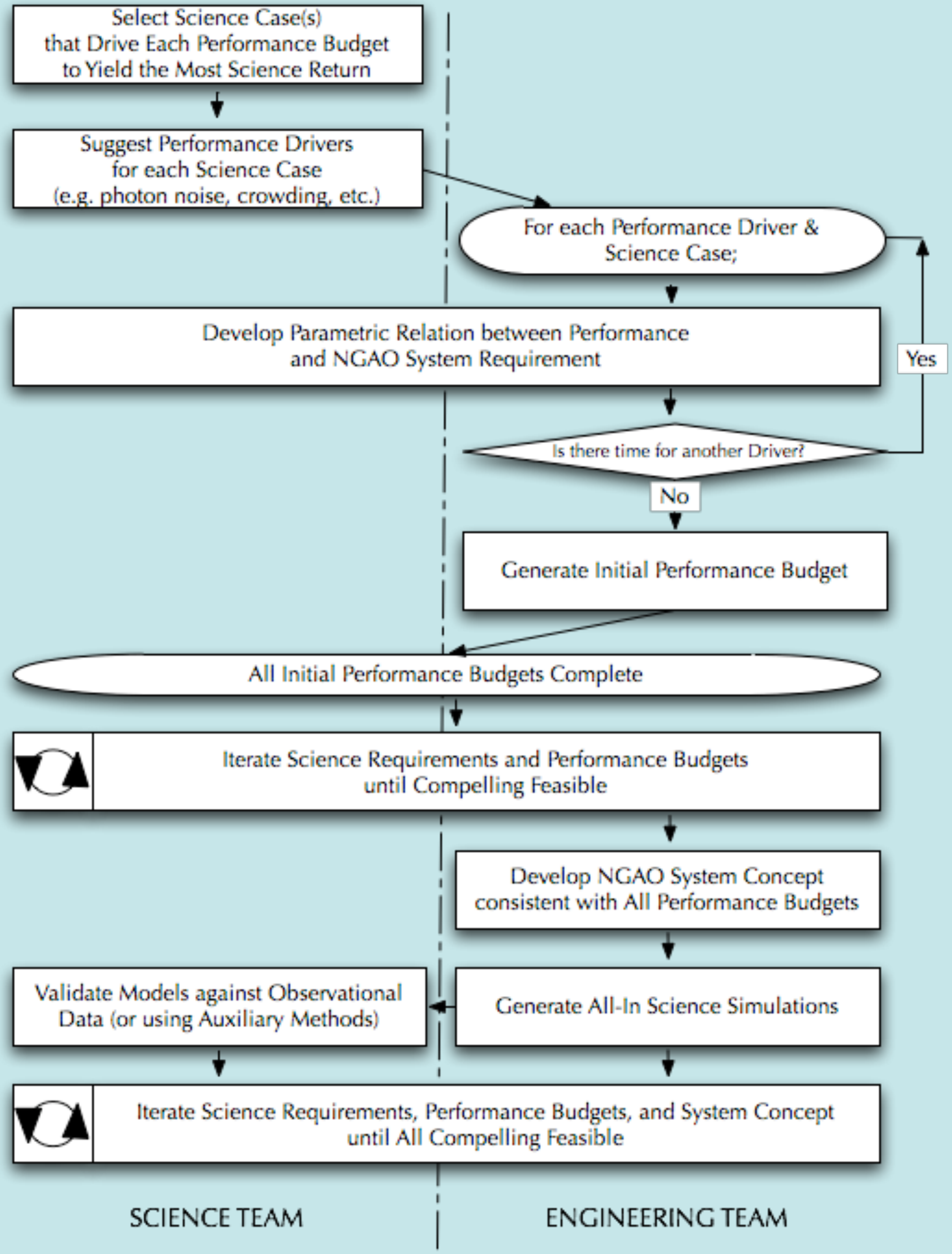
NGAO Performance Budget Development

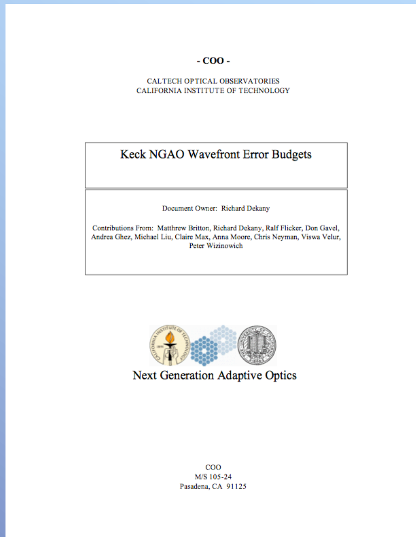
R. Dekany

A. Ghez, F. Marchis, C. Max, M. Liu, D. Gavel, R. Flicker, P. Wizinowich,
B. Cameron, J. Lu, M. Britton, Liu, B. Macintosh, C. Neyman, M. Ireland,
K. Olsen, A. Bouchez, D. Law, B. Bauman

NGAO SD Phase: Science Requirements & Performance Budget Process



Error Budget Reports are being drafted



- COO -

CALTECH OPTICAL OBSERVATORIES
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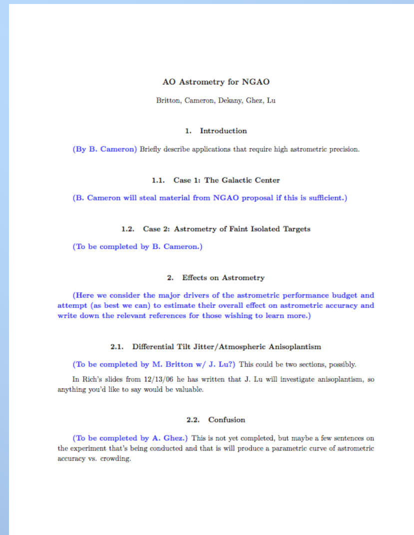
Keck NGAO Wavefront Error Budgets

Document Owner: Richard Dekany

Contributions From: Matthrew Britton, Richard Dekany, Ralf Flicker, Don Gavel, Andrea Ghez, Michael Liu, Claire Max, Anna Moore, Chris Neyman, Viswa Velur, Peter Wizinowich

Next Generation Adaptive Optics

COO
M/S 105-24
Pasadena, CA 91125



AO Astrometry for NGAO

Britton, Cameron, Dekany, Ghez, Lu

1. Introduction

(By B. Cameron) Briefly describe applications that require high astrometric precision.

1.1. Case 1: The Galactic Center

(B. Cameron will steal material from NGAO proposal if this is sufficient.)

1.2. Case 2: Astrometry of Faint Isolated Targets

(To be completed by B. Cameron.)

2. Effects on Astrometry

(Here we consider the major drivers of the astrometric performance budget and attempt (as best we can) to estimate their overall effect on astrometric accuracy and write down the relevant references for those wishing to learn more.)

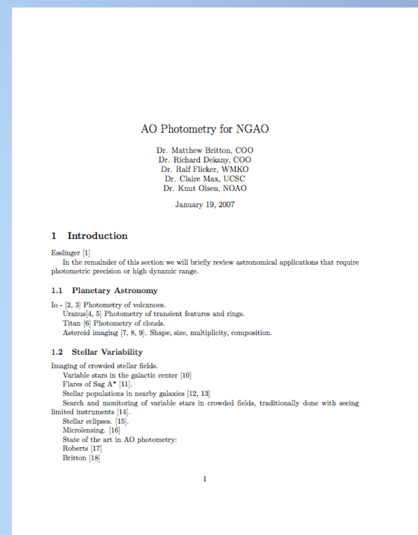
2.1. Differential Tilt Jitter/Atmospheric Anisoplantism

(To be completed by M. Britton w/ J. Lu?) This could be two sections, possibly.

In Rich's slides from 12/13/06 he has written that J. Lu will investigate anisoplantism, so anything you'd like to say would be valuable.

2.2. Confusion

(To be completed by A. Ghez.) This is not yet completed, but maybe a few sentences on the experiment that's being conducted and that is will produce a parametric curve of astrometric accuracy vs. crowding.



AO Photometry for NGAO

Dr. Matthew Britton, COO
Dr. Richard Dekany, COO
Dr. Ralf Flicker, WMKO
Dr. Claire Max, UCSC
Dr. Knut Olsen, NOAO

January 19, 2007

1 Introduction

Esslinger [1]
In the remainder of this section we will briefly review astronomical applications that require photometric precision or high dynamic range.

1.1 Planetary Astronomy

Io - [2, 3] Photometry of volcanoes.
Uranus[4, 5] Photometry of transient features and rings.
Titan [6] Photometry of clouds.
Asteroid imaging [7, 8, 9]. Shape, size, multiplicity, composition.

1.2 Stellar Variability

Imaging of crowded stellar fields.
Variable stars in the galactic center [10]
Flares of Sag A* [11].
Stellar populations in nearby galaxies [12, 13]
Search and monitoring of variable stars in crowded fields, traditionally done with seeing limited instruments [14].
Stellar eclipses. [15].
Microlensing. [16]
State of the art in AO photometry:
Roberts [17]
Britton [18]

1

NGAO Developing Science-based Performance Budgets

- Systems engineering will consider all of the following budgets
  - Wavefront error vs. sky coverage for 5-7 science cases
  - Photometric precision in crowded and sparse stellar fields
  - Astrometric accuracy at the GC and in sparse fields
  - High-contrast for diffuse debris disks and compact companions
  - Polarimetric precision for high-contrast observations
  - Transmission/background/SNR for several science cases
- Participants (respectively; <u>lead</u>)
    - Max, Ghez, Marchis, Liu & <u>Dekany</u>, Gavel, Flicker, Wizinowich
    - <u>Cameron</u>, Lu, Ghez, Britton, Max & Dekany
    - Liu, Macintosh, Dekany & <u>Flicker</u>, Neyman
    - <u>Ireland</u>
    - <u>Britton</u>, Olsen & Dekany, Flicker
    - <u>Bouchez</u>, Law & Dekany, Bauman

Performance Budget (PB) Integrated Product Team (IPT) common goals

- Produce a technical report
  - Describing the major PB drivers, including experimentally supportive information, quantitative background, and potential simulation results
- Produce a numerical engineering tool to support future design iterations
  - Emphasizing abstracted quantitative scaling laws and interdependencies (if unavoidable.)
    - Based upon Excel file template or utilizing existing tools
    - Traceable to, but independent of, any Monte Carlo simulation, covariance code, or similar machinery.
- Support science requirements development
  - Capturing the experience of the science team and reflecting quantitative underpinning to current limitations

PB IPT common assumptions

- Common model assumptions captured in performance budget spreadsheet template (to be posted to TWiki)
  - Telescope parameters
  - Photometric Band definitions
  - Atmospheric turbulence model
  - Meteorology model
  - Detector model

- Notional NGAO performance estimates from June ‘06 proposal
  - Estimates to be augmented and updated as part of the WFE PB IPT (due Jan 22, 2007)

Wavefront errror / Encircled energy IPT Status

(WBS 3.1.1.5 & 3.1.1.6)

Richard Dekany (IPT Lead)

Don Gavel, Ralf Flicker, Claire Max, Chris Neyman, Peter Wizinowich

Wavefront Error and Encircled Energy

- Science Cases
  - Maintain all cases from the June ‘06 NGAO proposal

- Key Drivers for initial budget
  - Uncertainty in tomographic reconstruction error
  - Uncertainty in sodium laser photoreturn from the mesosphere
    - Per delivered Watt, as a function of different pulse formats
    - Requires 50W class lasers to investigate non-linear optical pumping effects
  - Uncertainty in multi-NGS tilt tomography efficacy
    - Not included in original budget development
  - Uncertainty in tip/tilt control efficacy with large tip/tilt mirrors

WFE/EE Budget Recent Progess

- WFE Budget Spreadsheet
  - Measurement noise
    - Improved CCD noise vs. frame rate models (incl. CCID-56a)
    - Confirmed CCD dark current based on NGWFC measurements
    - Updated charge diffusion estimates based on vendor data
    - Improved SNR calculation to account for integrator in servo loop
    - Added telescope and optics emission to background model
    - Added z' as distinct photometry band
    - Improved fidelity of HgCdTe QE based on SNAP lab measurements
    - Implemented approx. variation in atm. trans. w/ wavelength (J,H,K)
    - Improved Rayleigh scatter model based on Palomar LGS measurements
    - Implemented choice of 4 star colors for guide star flux - typ. will use M stars for sky coverage
  - FA/Tomography error
    - Implemented tomography error model based on KAON 429
    - Added FA model for single laser tomography (backprojection) to condition degenerate asterism radius
  - Bandwidth error
    - Prepared new Greenwood wind velocity model - not yet adopted
  - Sky coverage calculations
    - Implemented detailed Spagna model (replacing approx. model)
    - Simplified selection between Spagna, Bachall, Parenti, and Allen models

Wavefront error budgets

- For observations of
  - TNO multiplicity
  - Galactic Center
  - Field galaxies
  - Io
  - Nearby AGN
  - Gravitational Lenses

- During requirements flowdown and initial design, all performance budgets will be used for rapid reevaluation of performance cost/benefit

Keck Wavefront Error Budget Summary

Band (microns)	V	R	I	J	**H**	K
λ (μm)	0.55	0.70	0.91	1.25	1.65	2.20
δλ (μm)	16%	31%	17%	30%	24%	22%
λ/D (mas)	11.3	14.4	18.8	25.8	34.0	45.4

High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	Strehl Ratios V	R	I	J	H	K
Atmospheric Fitting Error		55 nm	44 Subaps	0.67	0.78	0.87	0.93	0.96	0.98
Bandwidth Error		50 nm	74 Hz	0.72	0.81	0.89	0.94	0.96	0.98
High-order Measurement Error		58 nm	150 W	0.64	0.76	0.85	0.92	0.95	0.97
LGS Tomography Error		59 nm	5 beacon(s)	0.63	0.75	0.85	0.91	0.95	0.97
Asterism Deformation Error		22 nm	0.50 m LLT	0.94	0.96	0.98	0.99	0.99	1.00
Multispectral Error		25 nm	30 zenith angle, H band	1.00	1.00	1.00	1.00	1.00	1.00
Scintillation Error		15 nm	0.37 Scint index, H-band	0.97	0.98	0.99	0.99	1.00	1.00
WFS Scintillation Error		10 nm	Alloc	0.99	0.99	1.00	1.00	1.00	1.00
	118 nm								
Uncorrectable Static Telescope Aberrations		43 nm	62 Acts	0.79	0.86	0.92	0.95	0.97	0.99
Uncorrectable Dynamic Telescope Aberrations		15 nm	Dekens Ph.D	0.97	0.98	0.99	0.99	1.00	1.00
Static WFS Zero-point Calibration Error		20 nm	Alloc	0.95	0.97	0.98	0.99	0.99	1.00
Dynamic WFS Zero-point Calibration Error		10 nm	Alloc	0.99	0.99	1.00	1.00	1.00	1.00
Go-to Control Errors		0 nm	Alloc	1.00	1.00	1.00	1.00	1.00	1.00
Residual Na Layer Focus Change		3 nm	30 m/s Na layer vel	1.00	1.00	1.00	1.00	1.00	1.00
DM Finite Stroke Error		16 nm	4.0 um P-P stroke	1.00	1.00	1.00	1.00	1.00	1.00
DM Hysteresis		13 nm	from TMT	0.98	0.99	0.99	1.00	1.00	1.00
High-Order Aliasing Error		18 nm	44 Subaps	0.96	0.97	0.98	0.99	1.00	1.00
DM Drive Digitization		4 nm	10 bits	1.00	1.00	1.00	1.00	1.00	1.00
Uncorrectable AO System Aberrations		20 nm	Alloc	0.95	0.97	0.98	0.99	0.99	1.00
Uncorrectable Instrument Aberrations		25 nm	Alloc	0.92	0.95	0.97	0.98	0.99	0.99
DM-to-lenslet Misregistration (all sources)		15 nm	Alloc	0.97	0.98	0.99	0.99	1.00	1.00
	68 nm								
Angular Anisoplanatism Error		0 nm	0 arcsec	1.00	1.00	1.00	1.00	1.00	1.00
Total High Order Wavefront Error		**136 nm**	**High Order Strehl**	0.10	0.24	0.43	0.64	0.77	0.86

Tip/Tilt Errors	Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios V	R	I	J	H	K
Tilt Measurement Error (one-axis):	2.93 mas	36 nm	19.1 mag (mV)	0.75	0.83	0.89	0.94	0.96	0.98
Tilt Bandwidth Error (one-axis)	2.63 mas	32 nm	14.7 Hz	0.79	0.86	0.91	0.95	0.97	0.98
Tilt Anisoplanatism Error (one-axis)	4.09 mas	50 nm	27.4 arcsec	0.61	0.72	0.81	0.89	0.93	0.96
Residual Centroid Anisoplanatism	1.99 mas	24 nm	Alloc (5x comp.)	0.87	0.91	0.95	0.97	0.98	0.99
Residual Atmospheric Dispersion	1.06 mas	13 nm	Alloc (20x compens.)	0.39	0.44	0.84	0.96	1.00	1.00
Science Instrument Mechanical Drift	0.50 mas	6 nm	Alloc (0.2 mas)	0.99	1.00	1.00	1.00	1.00	1.00
Long Exposure Field Rotation Errors	0.50 mas	6 nm	Alloc (0.2 mas)	0.99	1.00	1.00	1.00	1.00	1.00
Residual Telescope Pointing Jitter (one-axis)	2.00 mas	24 nm	100mas @ 0.7Hz input	0.87	0.91	0.95	0.97	0.98	0.99
Total Tip/Tilt Error (one-axis)	**6.47 mas**	78 nm	**Tip/Tilt Strehl**	0.38	0.50	0.63	0.76	0.85	0.91

Total Effective Wavefront Error	**157 nm**	**Total Strehl**	**0.04**	**0.12**	**0.27**	**0.49**	**0.66**	**0.78**

Sky Coverage Galactic Lat. 30 deg

Corresponding Sky Coverage	**5.0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

r0	0.165 m	at this zenith	Wind Speed	13.67 m/s	Zenith Angle	30 deg			
Theta0_eff	1.98 arcsec	at this zenith	Outer Scale	75 m	HO WFS Rate	1114 Hz	SH	using	CCD
Sodium Abund.	4×10^9	atoms/cm^2	LGS Ast. Rad.	0.08 arcmin	HO WFS Noise	1.7 e- rms			
					HOWFS anti-aliasing	NO			
Science Target:	SCAO				LO WFS rate	220 Hz	SH	using	SNAP
LOWFS Star(s):	MOAO	2 TT star(s) &		0 TTFA star(s)	LO WFS Noise	4.5 e- rms			

Example for LGS observation of TNO using two galactic M-dwarfs as tip/tilt stars

WFE/EE Budget Next Priorities

- WFE Budget Spreadsheet
  - Telescope errors
    - Need to update dynamical telescope error model based on Flicker et al. trade study
  - Measurement noise
    - Need to update sodium laser return vs. pulse format using on-sky measurements
    - Need model of effect of fratricide (from Monte Carlo sims)
    - Need to include saturation in LGS return models
    - Need to consider uncorrected halo light in LOWFS, particularly for low LOWFS Strehl
    - Need to clarify when/how Slow WFS light is taken away for focus sensing (choice of TT, TTFA, 3x3, or HO WFS for focus measurement)
    - Need to implement simple bright time sky model (vs. lunar phase).
  - FA/Tomography error
    - Need to consider generalized anisoplanatism
    - Need to implement simple comparison between SCAO, MOAO, and MCAO
  - Multispectral error
    - Need to consider multispectral contribution to tip/tilt error
- EE Budget Spreadsheet
  - Need to review new EE budget tool; eventually to integrate into WFE spreadsheet.

Astrometric Accuracy IPT Status

(WBS 3.1.1.8)

Brian Cameron (IPT Lead)
Matthew Britton, Richard Dekany, Andrea Ghez, Jessica Lu

Astrometry IPT Summary

- Science cases
  - Astrometry of the Galactic Center
  - Astrometry of faint isolated targets

- Key Drivers for initial Budget
  - Atmospheric anisoplanatism
    - » Leaped to forefront (?) in absence of anisoplanatism calibration
    - » Jessica and Andrea to quantify
  - Atmospheric tilt anisoplanatism
    - » Matthew to parameterize
  - Imperfect knowledge of geometric distortions
    - » New distortion solution from Brian
  - Stellar Confusion
    - » Andrea to study via parametric simulations for differing WFE (provided by Chris) - TBC
  - SNR for isolated stars
    - » Brian to parameterize and confirm precision based on SNR and PSF FWHM
  - Differential atmospheric refraction (as well as achromatic refraction)
    - » Brian has considered limits to calibration (e.g. meteorological calibrations)

Differential Atmospheric Refraction

- Stars with different surface temperatures and/or different zenith angle separations suffer from changes in separation due to differential atmospheric refraction.
  - Can be as large as 12 mas @ zenith angle of 45 degrees, separation of 30” and ΔT ~ 5000 K

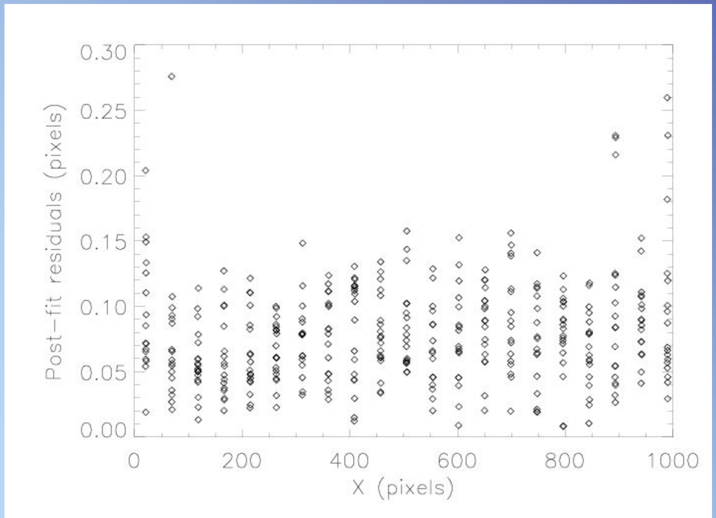
- Noise from correction:
  - Meteorological uncertainties (Table)
  - Atmospheric model uncertainties
    - Marginal (< 1uas) for reasonable temperature lapse rates, tropopause and stratosphere heights.

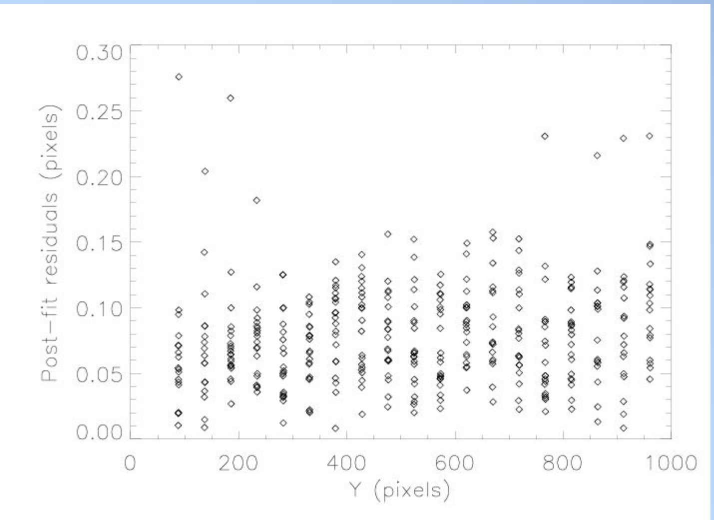
Parameter	Uncertainty	Noise (uas)
Ground Temp.	3 K	50
Pressure	8 mb	50
Zenith Angle	36”	10
Separation	30 mas	10
Relative Humidity	10%	<10
Relative Stellar Temp.	100-1700 K	10

Gubler & Tytler 1998

Geometric Distortion

- New distortion solution derived for NIRC2 with pin-hole mask
- < 0.1 pixel post-fit residuals in both wide and narrow cameras
  - ~800 uas in narrow camera
  - ~4 mas in wide camera
  - Can be averaged down by Sqrt(dither positions)
- Some structure in narrow camera solution residuals
  - higher order polynomial may reduce the scatter further.
- Further investigations underway
  - Filter effects
  - Time dependence





Narrow camera post-fit residuals

Photometric Precision IPT Status

(WBS 3.1.1.7)

Matt Britton (IPT Lead)

Richard Dekany, Ralf Flicker, Knut Olsen

Photometric Precision

- Science cases
  - Photometry in disks and bulges of high-z galaxies
  - Stellar populations in crowded fields
- Key Drivers for initial budget
  - Crowding
  - Sky background
  - Photon noise
- Both science cases are limited by imperfect knowledge of the system PSF
  - The IPT has divided the problem into two flavors
    - Determining the on-axis PSF
    - Determining the off-axis PSF

Sources of PSF Knowledge

	On-axis	Off-axis
Data-based ↕ Model-based	Direct measurement of isolated point source [e.g. de Pater] Calibration star PSF [many examples] ADI (Telescope Roll) [e.g. Marois] AO system telemetry [e.g. Veran]	Calibration star cluster PSF [e.g. Steinbring] Dedicated concurrent PSF camera [e.g. COO TMT IRMOS concept] Self-consistent solution of multiple sources [e.g. Christou, *StarFinder*] Auxiliary information from $C_n^2(h)$ [e.g. Britton]

Polarimetric Precision IPT Status

(WBS 3.1.1.9)

Mike Ireland (IPT Lead), Richard Dekany

Architecture and Technology Drivers for Polarimetry

- The key technology drivers for high-contrast imaging polarimetry are instrumental
  - Need rapid polarization modulation (e.g. with a Liquid-Crystal Variable Retarder)
  - Need simultaneous channels (e.g. by using a Wollaston prism).

- Imaging polarimetry is different from absolute polarimetry
  - It is OK to polarize the entire field (e.g. by a 60 degree AOI mirror in a collimated beam) and calibrate later.

- A Nasmyth focus is certainly possible if the instrument rotates (e.g. VLT http://www.eso.org/projects/vlt/unit-tel/nasmyth.html)

- A K-mirror in a converging beam likely kills any kind of precision polarimetry mode
  - PSF's will be different enough in orthogonal polarization states. A way around this is an LCVR placed before the K-mirror - but readily available LCVR's only go to 1.6” clear-aperture…

Polarimetric Performance Budget
(extracted from note by M. Ireland)

- Low-precision polarimetry
  - Extract all Stokes parameters, including Stokes I
  - Nominal fractional polarization 10%
    - Telescope polarization TBD
    - NGAO polarization TBD
  - Orthogonal polarization difference image should subtract away PSF artifacts by > 10x.
    - This will set a limit on difference aberrations between orthogonal polarizations.

- High-precision polarimetry
  - Extract Stokes Q, U, V, even with Stokes I not discerable due to speckle noise

High-Contrast IPT Status

(WBS 3.1.1.10 aka Companion Sensitivity)

~~Initial WFE budget and~~ status report

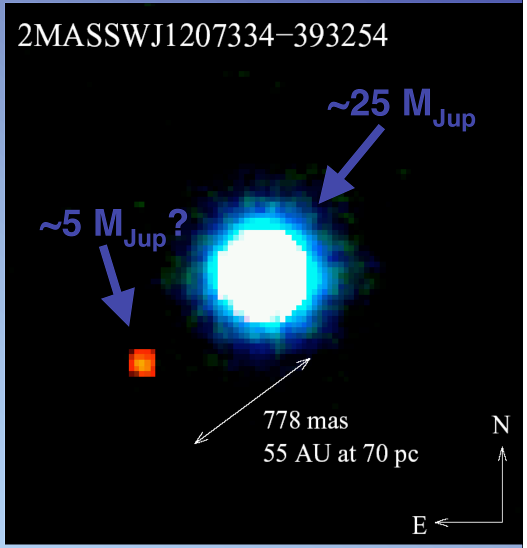
NGAO Team meeting #4, WMKO Kamuela HI, 1/22/2007

NGAO High-Contrast IPT

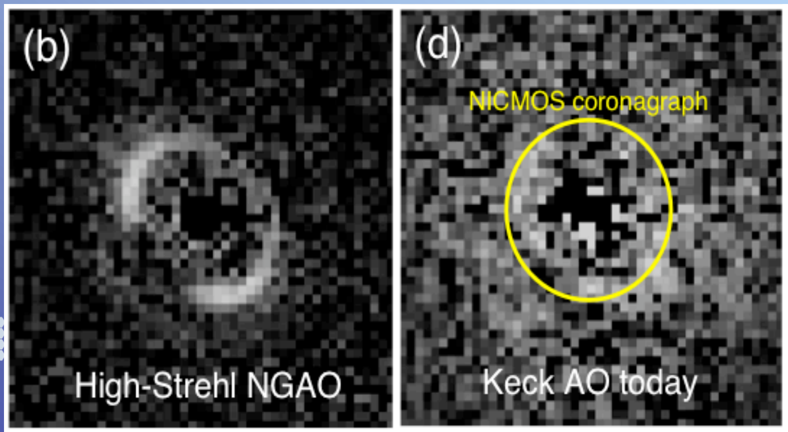
- Current participants:
  - Rich Dekany, Ralf Flicker, Mike Liu, Bruce Macintosh, Chris Neyman
- IPT meetings: Nov 06, Dec 06, Jan 07
- Goal of HC WFE budget (WBS 3.1.1.10):
  - *Development of a companion sensitivity performance budget, based on a strawman coronagraph approach meeting the science requirements. Develop a contrast-driven spatio-temporal wavefront error budget that includes not just AO performance but realistic values for static/internal effects, so that we can see what instrument design choices (e.g. optics quality) are important now*
- Time allocation: 240 hr
  - Chiefly efforts by Rich (lead), Mike (science) and Bruce (WFE tool) so far
  - Simulation work shifting to Ralf and Chris when spread sheet tool is ready
- Current status:
  - Primary analysis tool not in place yet (as of 1/21/07), but very soon!
  - Secondary simulation tools under development (partially done)
  - Science cases outlined (no changes since NGAO meeting #1)

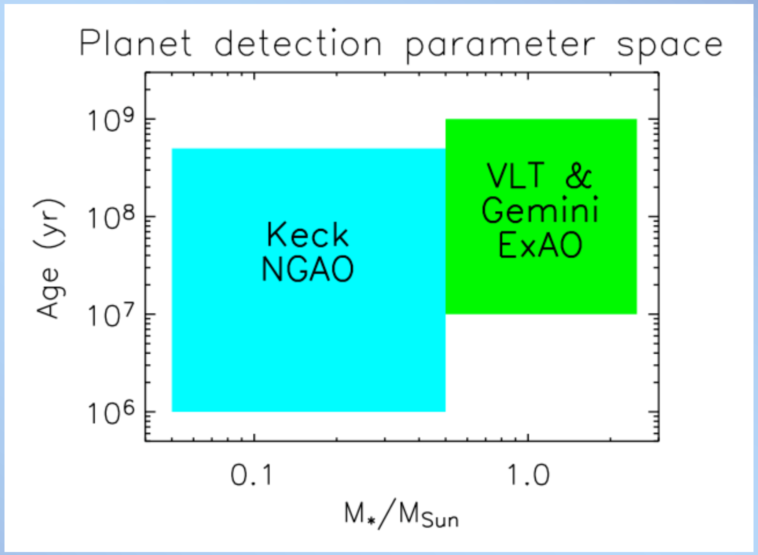
HC science case recap

- Principal NGAO high-contrast science cases:
  - Direct imaging and spectroscopy of
    - Planets around low-mass stars and brown dwarfs
    - Resolved debris disks and protostellar envelopes



- NGAO high-contrast selling points:
  - LGS tomography is the primary AO mode of interest
    - Large sky coverage
    - Fainter stars = many more targets + relaxed contrast requirements
    - Multi-band studies: optical & near-IR





(images from M. Liu ppt NGAO m1)

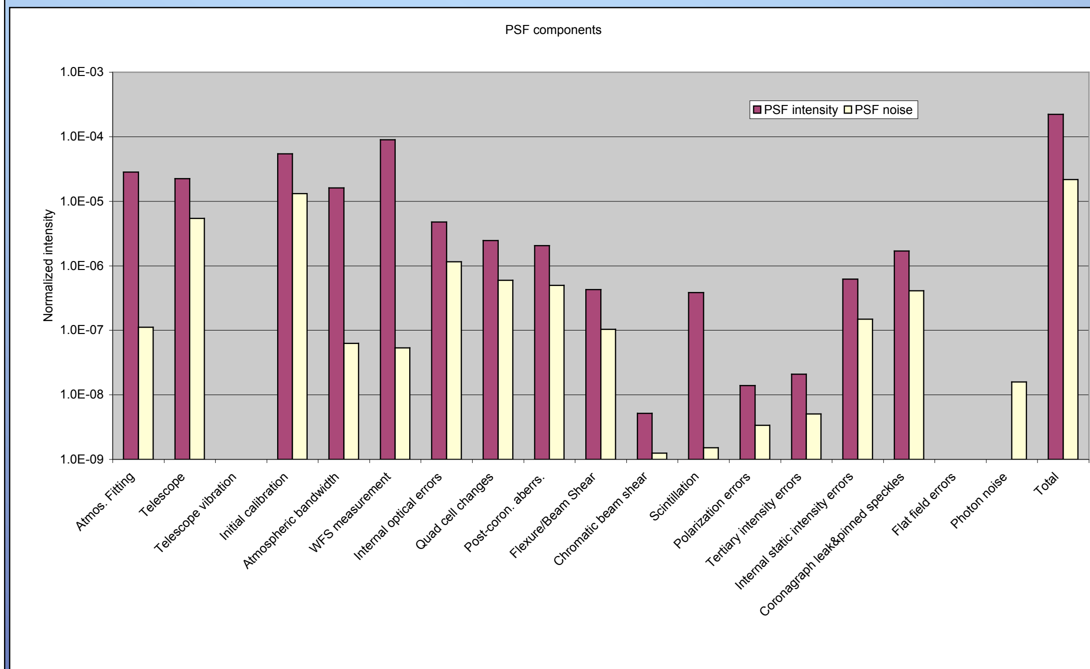
Contrast-driven WFE approach

- Well-developed modeling tools to a large extent available:
  1. Bruce Macintosh to provide NGAO version of GPI spread sheet tool
     - » Some LGS and telescope aberration effects not modeled initially
  2. Refined by input from numerical AO simulations with quasi-coronograph
     - » Ralf Flicker and Chris Neyman to run LAOS/YAO simulations to generate more accurate PSFs/PSDs for Keck/NGAO effects to be included in the spread sheet tool
     - » Quasi-coronograph (Blackman pupil) implemented in YAO
  3. Implement more realistic coronograph model in simulations, refine WFE budget

- Key drivers for performance budget
  - Calibration of non-common path aberrations and chromatic errors
  - Static and dynamic telescope aberrations
    - » New simulation model for dynamic errors now exists
  - Tomography errors
    - » Have estimate of spatial PSD now (needs to be refined)
  - LGS specific errors (Na-layer height and structure variability, tilt anisoplanatism, Rayleigh scatter, etc)
    - » Some low-order effects may be unimportant, but they need to be quantified to first order

Initial WFE budget: under construction

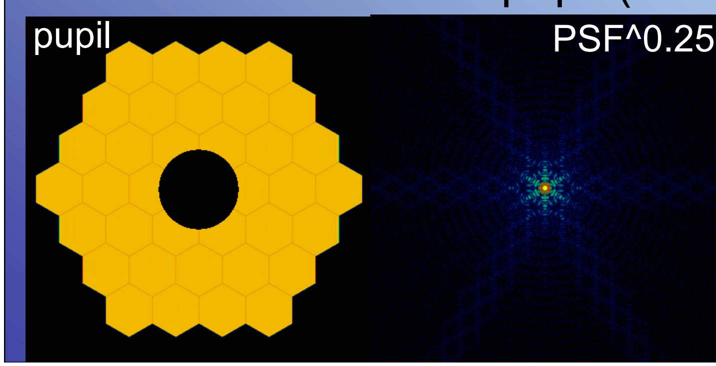
– When we get to the initial WFE budget, it may look something like this…

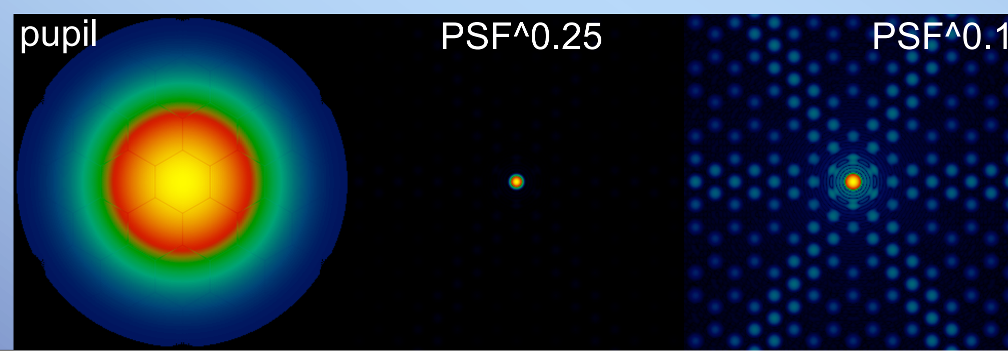


WFE source	low freq. (nm)	mid freq. (nm)	high freq. (nm)	all freq	PSF intensity 0.4 arc sec	Speckle noise 0.4 arc sec 3600 seconds
Atmos. Fitting	0.0	1.1	52.2	52.2	3.8E-08	7.4E-11
Telescope	0.1	0.1	8.2	8.2	9.9E-11	1.1E-11
Initial calibration	5.0	1.0	0.0	5.1	3.2E-08	3.5E-09
Atmospheric bandwidth	13.0	13.9	9.7	21.0	2.2E-06	4.2E-09
WFS measurement	0.0	31.8	0.0	31.8	3.2E-05	8.4E-09
Internal optical errors	0.0	0.0	12.4	12.4	1.7E-11	1.9E-12
Quad cell changes	0.3	0.2	0.0	0.4	1.1E-09	1.2E-10
Post-coron. aberrs.	8.9	3.6	1.9	9.7	2.9E-08	3.3E-09
Flexure/Beam Shear	0.0	0.6	0.0	0.0	1.1E-08	1.2E-09
Chromatic beam shear	0.0	0.0	0.0	0.1	3.9E-10	4.3E-11
Scintillation	10.0	0.5	1.0	10.1	5.1E-07	1.0E-09
Polarization errors	20.0	0.0	0.0	20.0	7.9E-09	8.8E-10
Tertiary intensity errors	0.0	0.0	0.0	0.0	1.9E-08	2.1E-09
Internal static intensity errors	0.0	0.0	0.0	0.0	1.3E-07	1.5E-08
Residual diffraction					1.7E-06	1.0E-20
Flat field errors					1.0E-20	3.7E-09
Photon noise						4.5E-09
Total	**27.8**	**34.9**	**55.2**	**71.0**	**3.7E-05**	**4.3E-08**
Strehl ratio @ *H* band				**0.93**		

Table 7: ExAOC contrast budget for a one-hour observation. PSF intensity and PSF noise are normalized with respect to the peak intensity of the coronagraphic PSF, so that a PSF noise of $4.3x10^{-8}$ would represent a 5-sigma detection of a companion with a contrast relative to its primary of $2.1x10^{-7}$.

– Blackman pupil (diffraction suppressor) implemented in YAO





Next steps

1. Initial WFE budget
2. Iterate once with numerically simulated PSFs

- Next level work:
  - More realistic coronograph models
    - » Standard Lyot, apodized Lyot
  - Understanding LGS specific effects on the contrast
    - » Will be hard to model everything, but what are the leading terms we should be worrying about?

- To be addressed in upcoming IPT discussions:
  - Where does the coronograph live? (AO, science instrument, between?)
    - » Does this matter for the modeling and WFE budget?
  - Imaging strategies, observing scenarios
    - » May relax WFE requirements (PSF subtraction, polarimetry, speckle suppression and differential imaging techniques, etc)