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Keck Interferometer (KI) & ASTRA

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12 June 2008
VLTI Summer School, Keszthely

+some ASTRA slides from Jorg-Uwe Pott

Keck Interferometer

- Keck Interferometer links the two 10 m Keck telescopes
- NASA-funded joint development: JPL, Keck Obs., Caltech (MSC)
- NSF-funded upgrade, ASTRA, let by Keck Obs., to add dual-star capability

Keck Interferometer modes

- High sensitivity fringe visibility (V^2) measurements
  - Combines the AO-corrected beams
  - V^2 measurements in the near-IR
- Infrared nulling at 10 um
  - Nulling beam combiner to suppress central star
  - Measure zodiacal dust around nearby stars
- Dual-star capability via ASTRA

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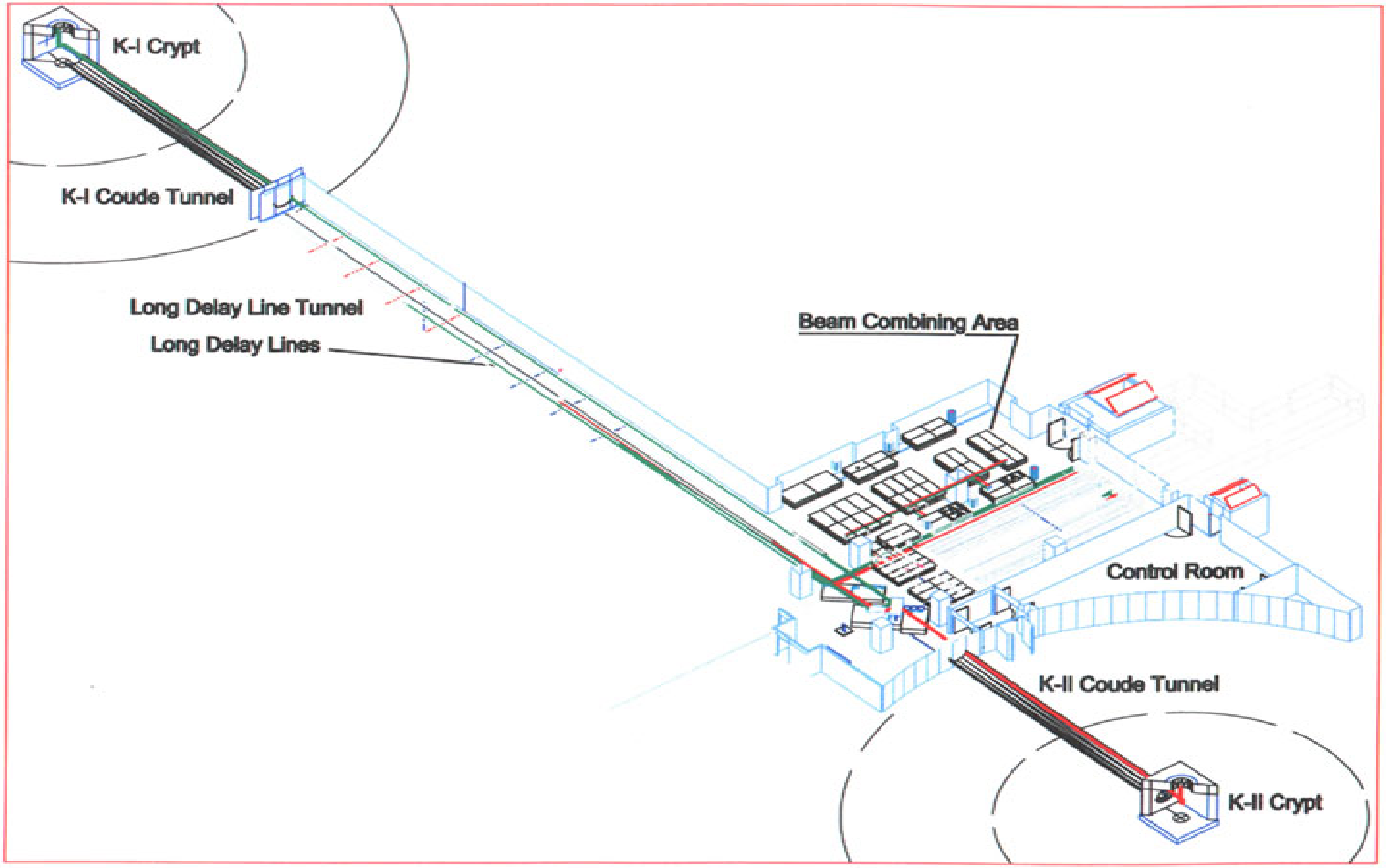
Configuration at the Summit



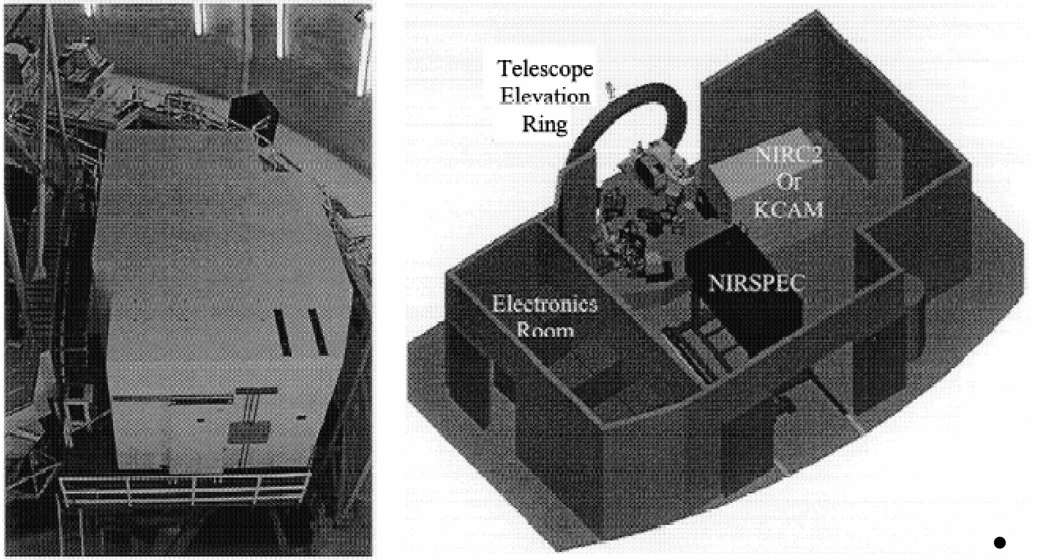
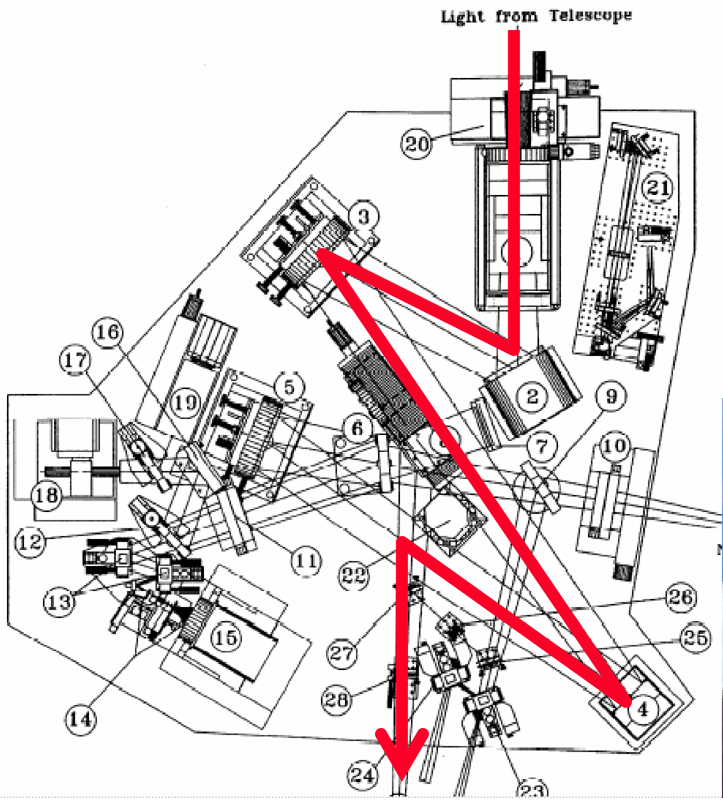


Figure 1. Left: The AO enclosure on the left Nasmyth platform of the Keck II telescope. Right: A schematic view of the AO enclosure with its roof removed.



Telescope & AO

- 10 m Keck telescopes
- High-order AO system
- Extract beam in collimated space on AO bench after deformable mirror
- 10 m aperture maps to 124 mm collimated beam
  - 80.4 : 1 demagnification

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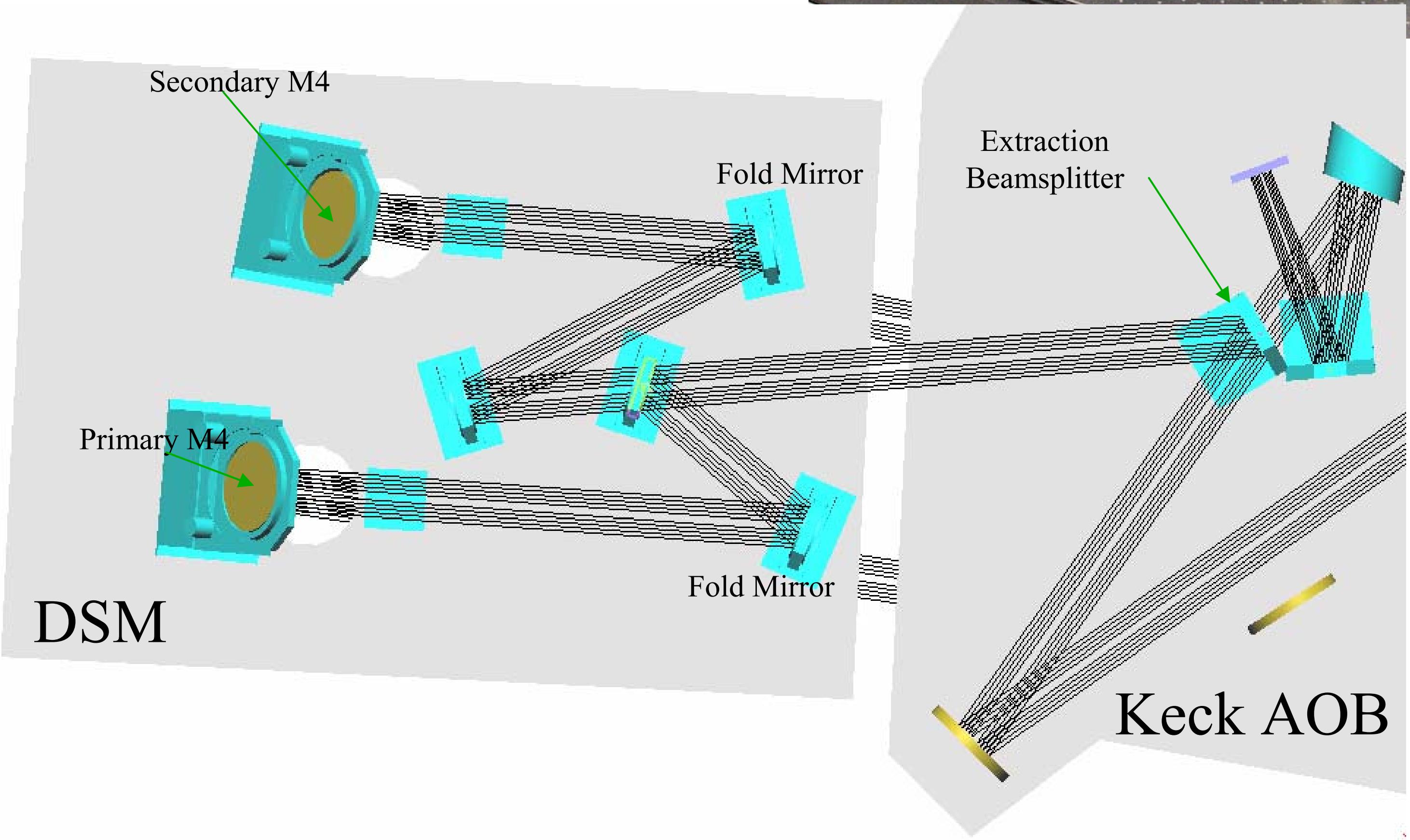
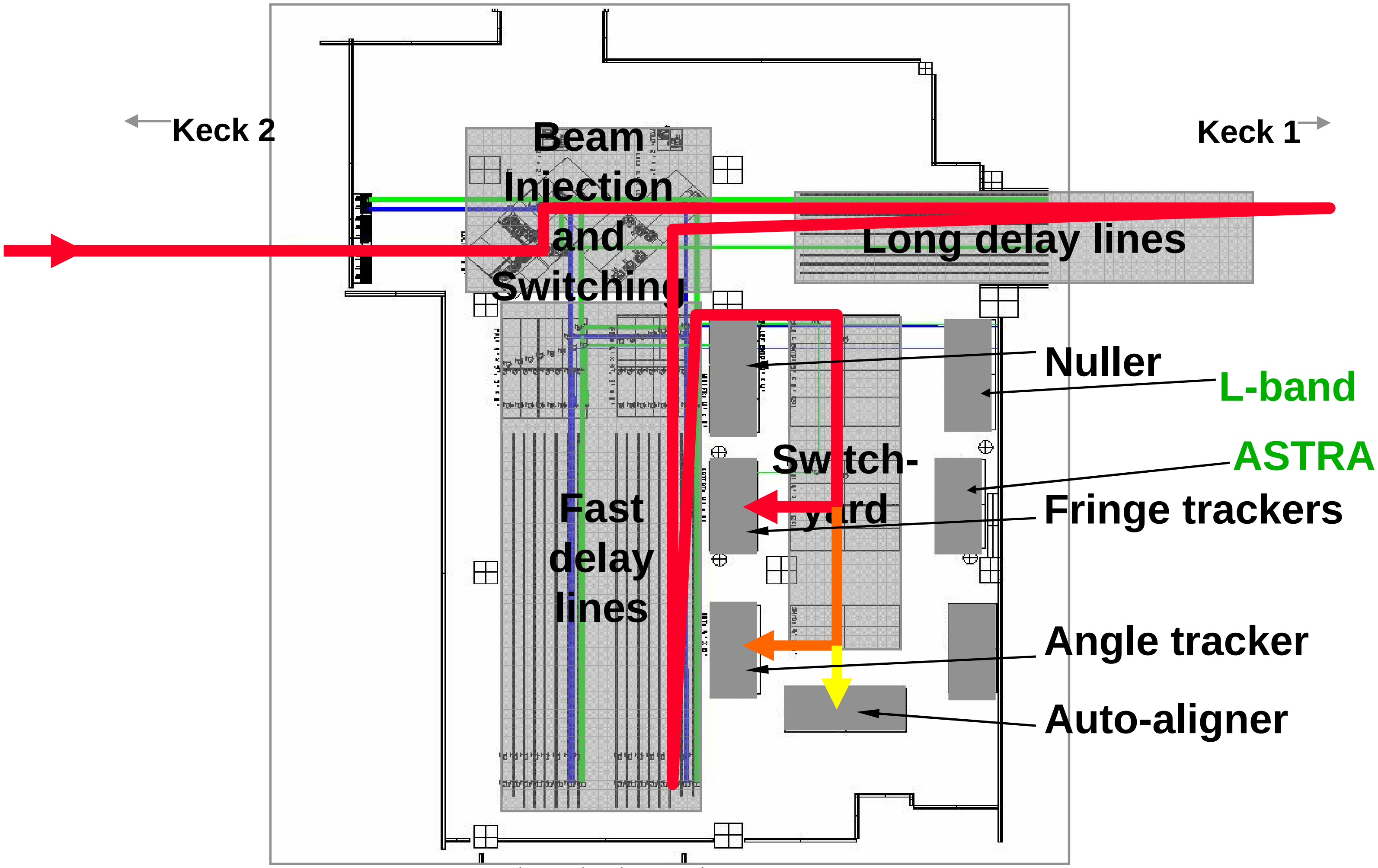
Dual star module

- Slides in adjacent to AO system like other Nasmyth instruments
- Sends collimated beam into coude beam train



Beam Combining Lab Optical path



Interferometry basement

K1 in

K2 in

Long delay lines

Beam combiners

Fast delay lines

Switchyard

See virtual tour at planetquest.jpl.nasa.gov/Keck

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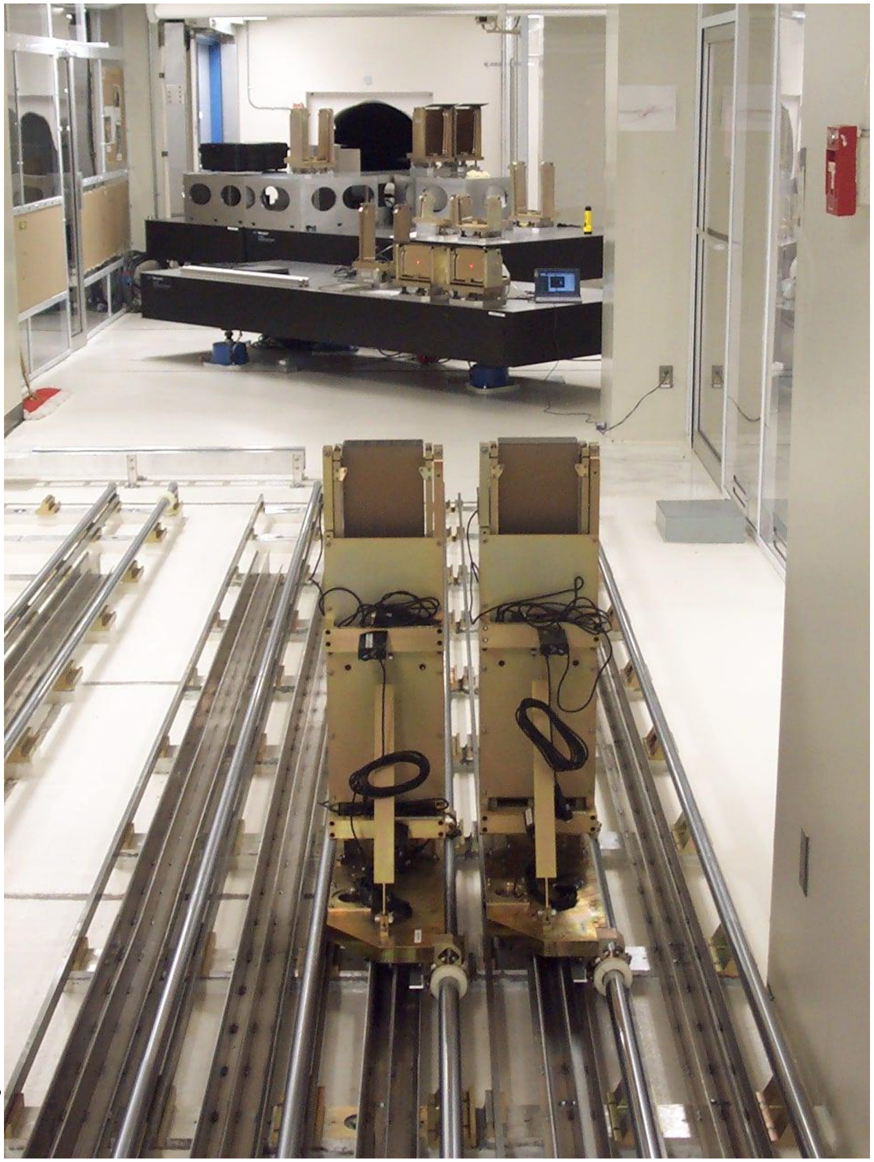
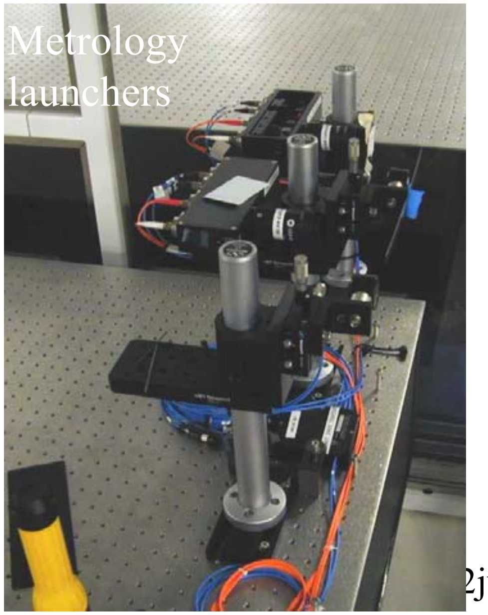
Long delay lines

- Installed in coude tunnel
- Provides coarse delay positioning (static during observation)
- Double-height mirror accommodates two beams for phase referencing



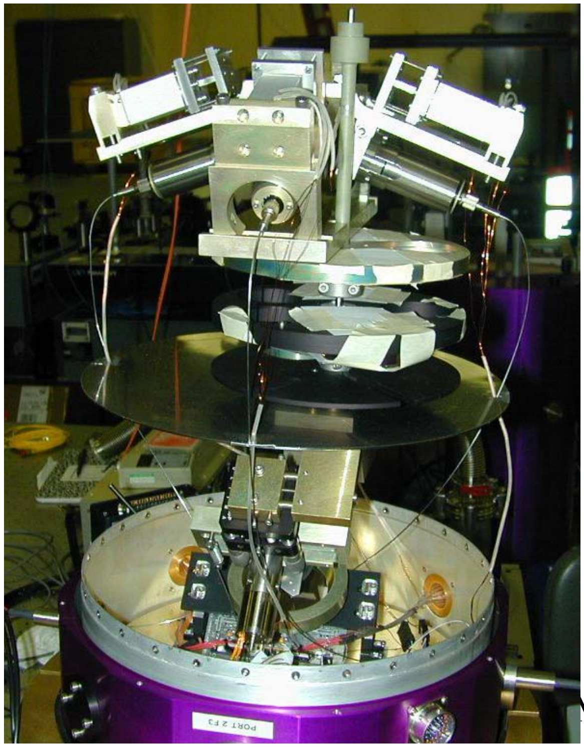
Fast delay lines

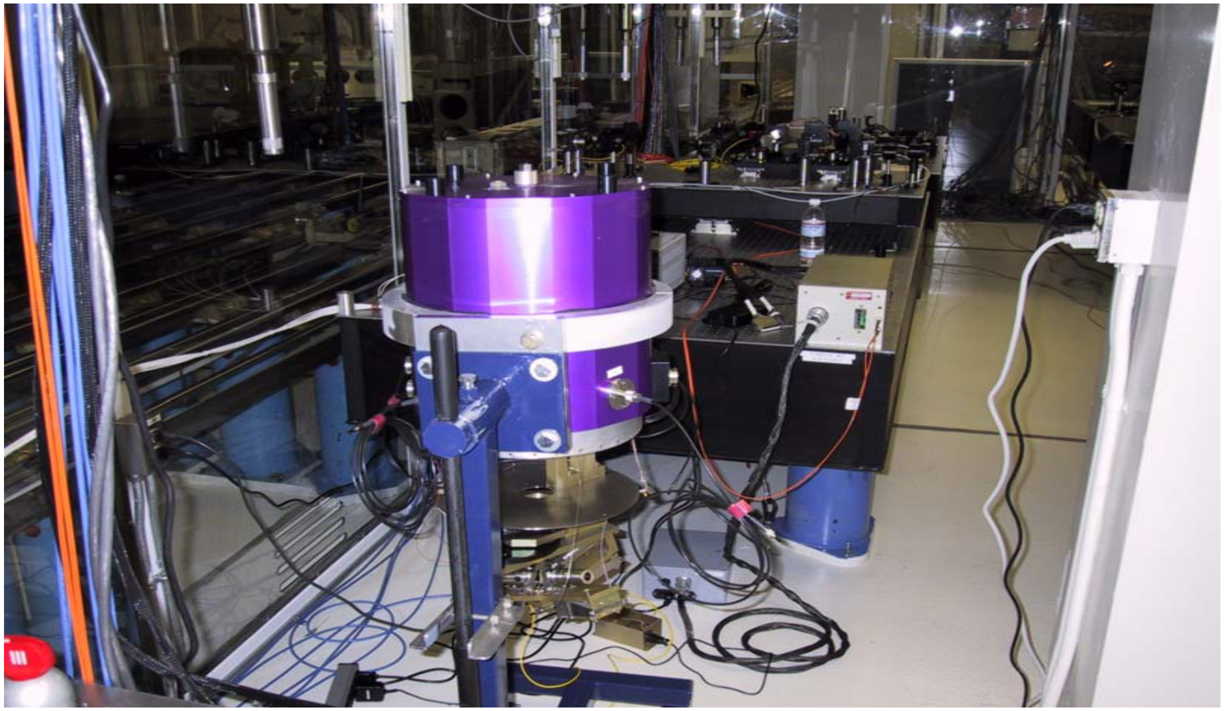
- 4-stage cat's-eye design
- Fiber-fed laser metrology
- Delay range +/- 15m
- High speed position and rate commanding



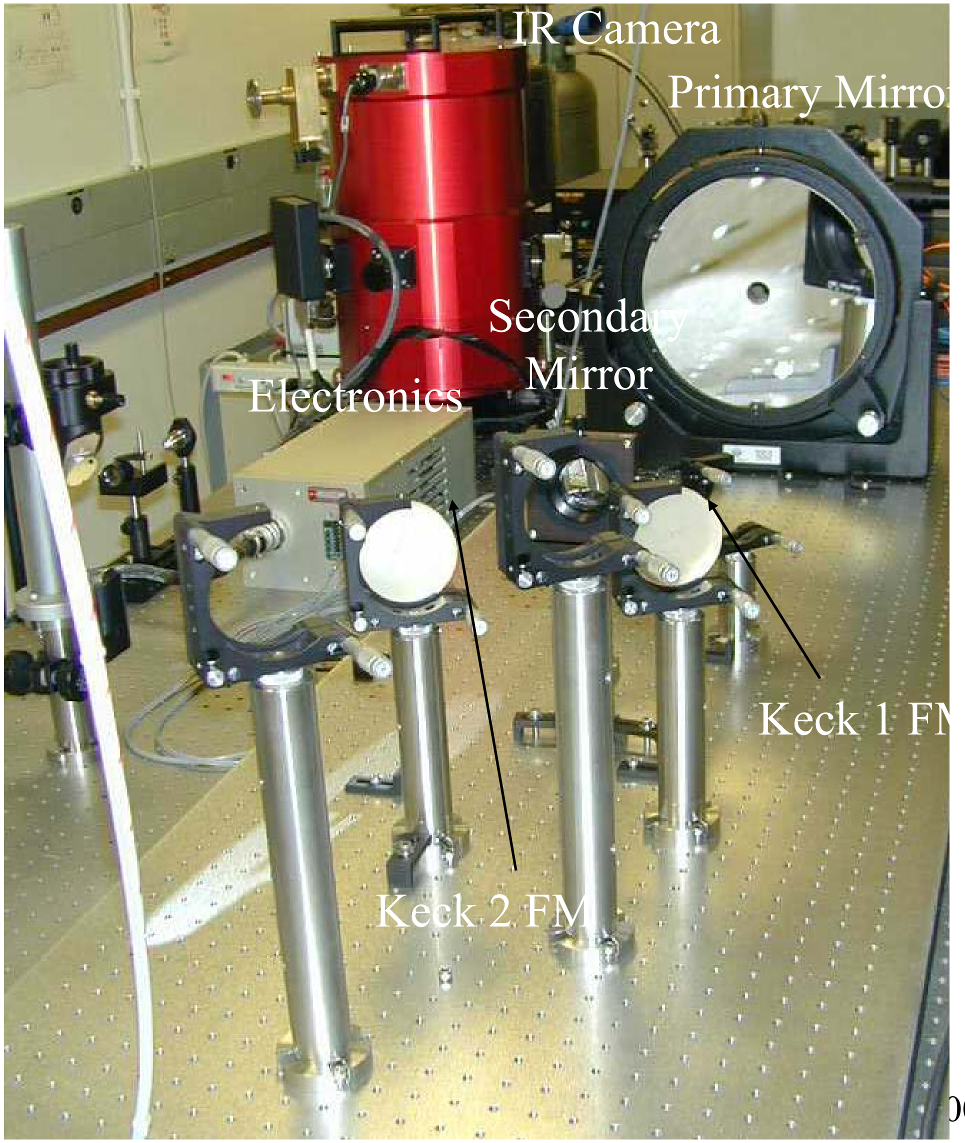
FATCAT (Fringe tracker)

- Free-space Michelson beam combination at H and K bands
- HAWAII array camera fed by single-mode fluoride fibers
- White-light and spectrometer channels; frame rates of 100-250 Hz
- Fringe tracking with coherent fringe demodulation, closed-loop to delay line





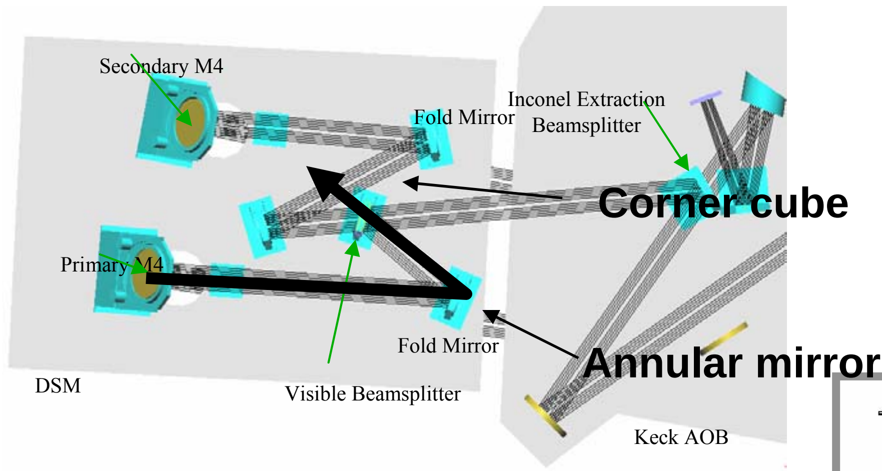
Angle tracker



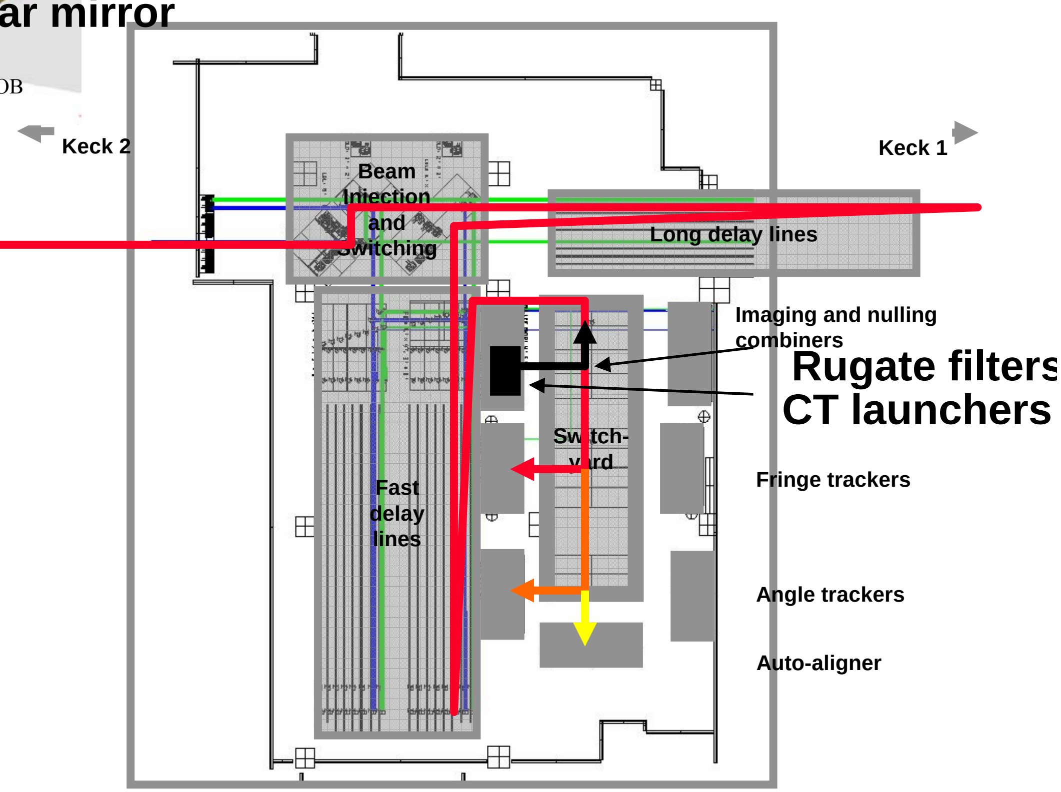
- H and J band angle tracking
- DCR corrector for good sky coverage
- Images from two Kecks multiplexed onto one quadrant of HAWAII array
- 80 Hz readout
- High-speed updates to local tip/tilt mirror
- Low-speed off-loads to AO system

Internal pathlength (CT) metrology

[this is the original system; I'll describe the newer system later]



- Adds laser metrology of (almost) entire optical path, not just FDL
- Measured position error combined with local FDL metrology to control FDL position



V2 status

- Has been available to the Keck (Caltech, UC, NASA, UH, NOAO) community since 2004
- Sensitivity numbers updated: March 6, 2008 (see msc.caltech.edu)
  - AO (adaptive optics) sensitivity:
    - » R < 12 (somewhat dependent on source color, less sensitive than AO alone due to the dichroic which sends light to interferometer)
  - Angle tracking:
    - » 80 Hz: 5.0 < J < 10.5 [this has recently been improved ~1 mag]
  - Fringe tracking:
    - » Low resolution modes (5 pixels across K')
      - 200 Hz: 6.2 < K' < 9.9
      - 100 Hz: 6.6 < K' < 10.3
    - » Medium resolution mode (42 pixels across K')
      - 200 Hz: 3.5 < K' < 7.2
      - 100 Hz: 3.9 < K' < 7.6

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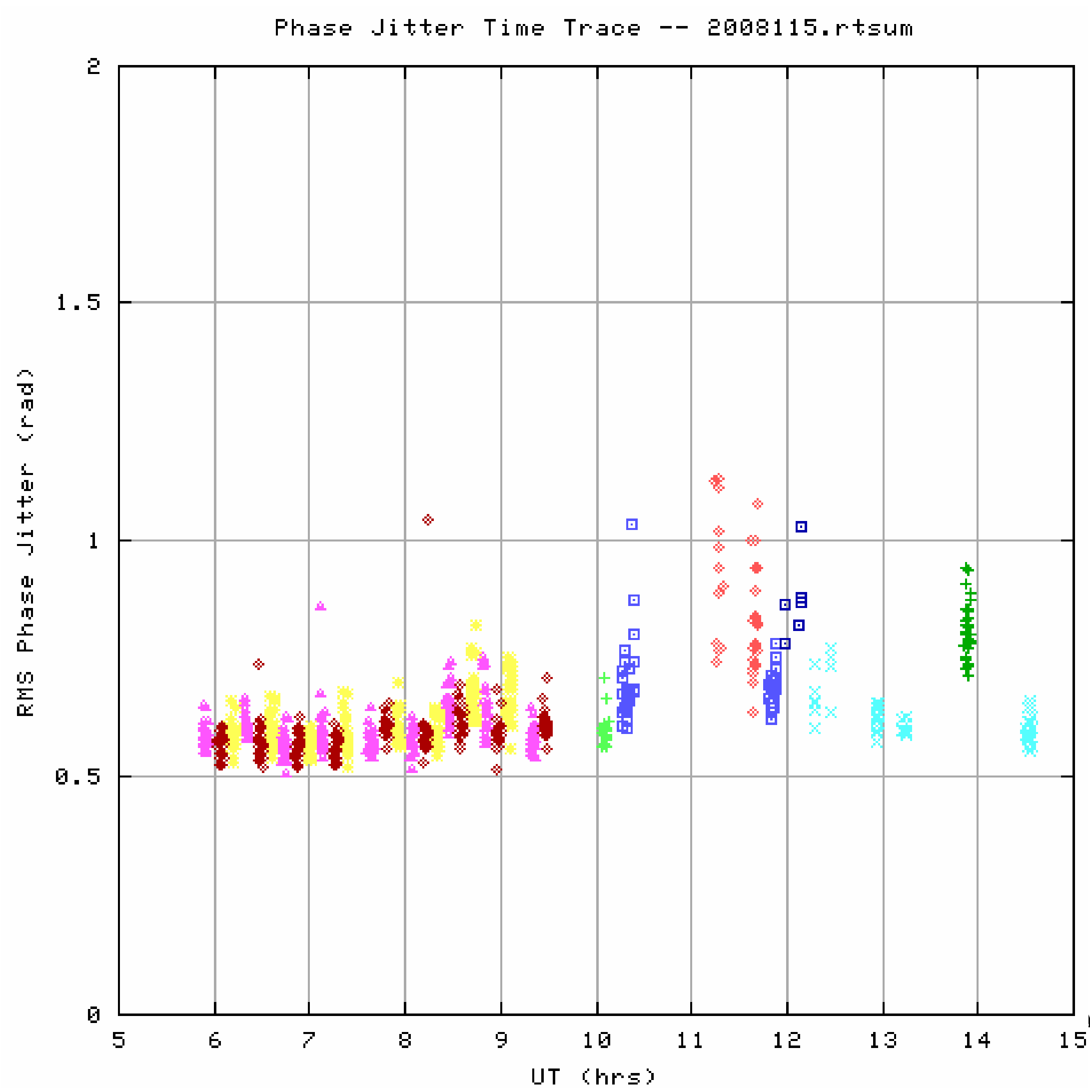
Some metrics: phase jitter



- This is the first difference of adjacent 5 ms points
- It's a quadrature sum of a vibration noise floor, ~0.5 rads, and atmospheric seeing

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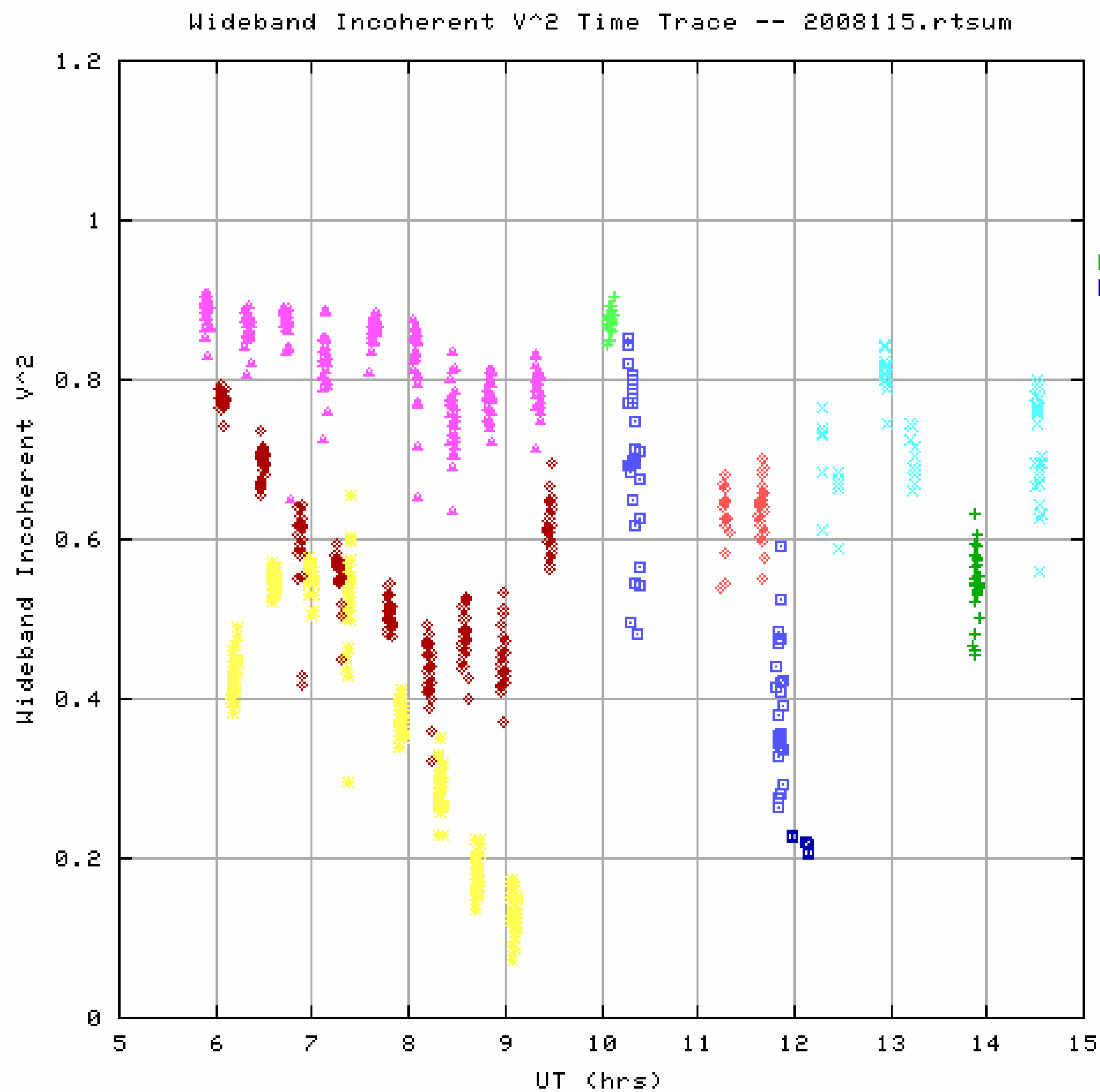
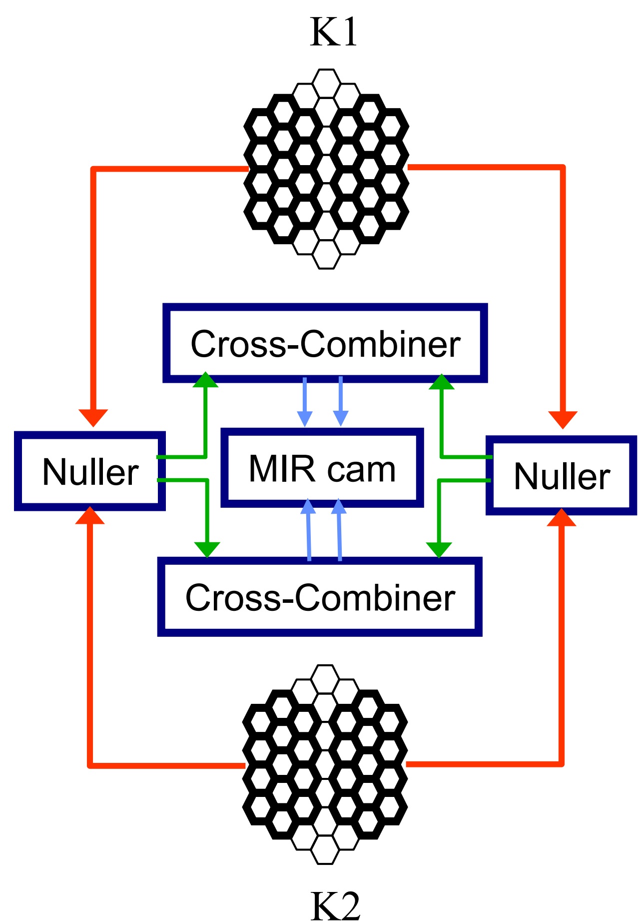
Metric: V^2 vs. time



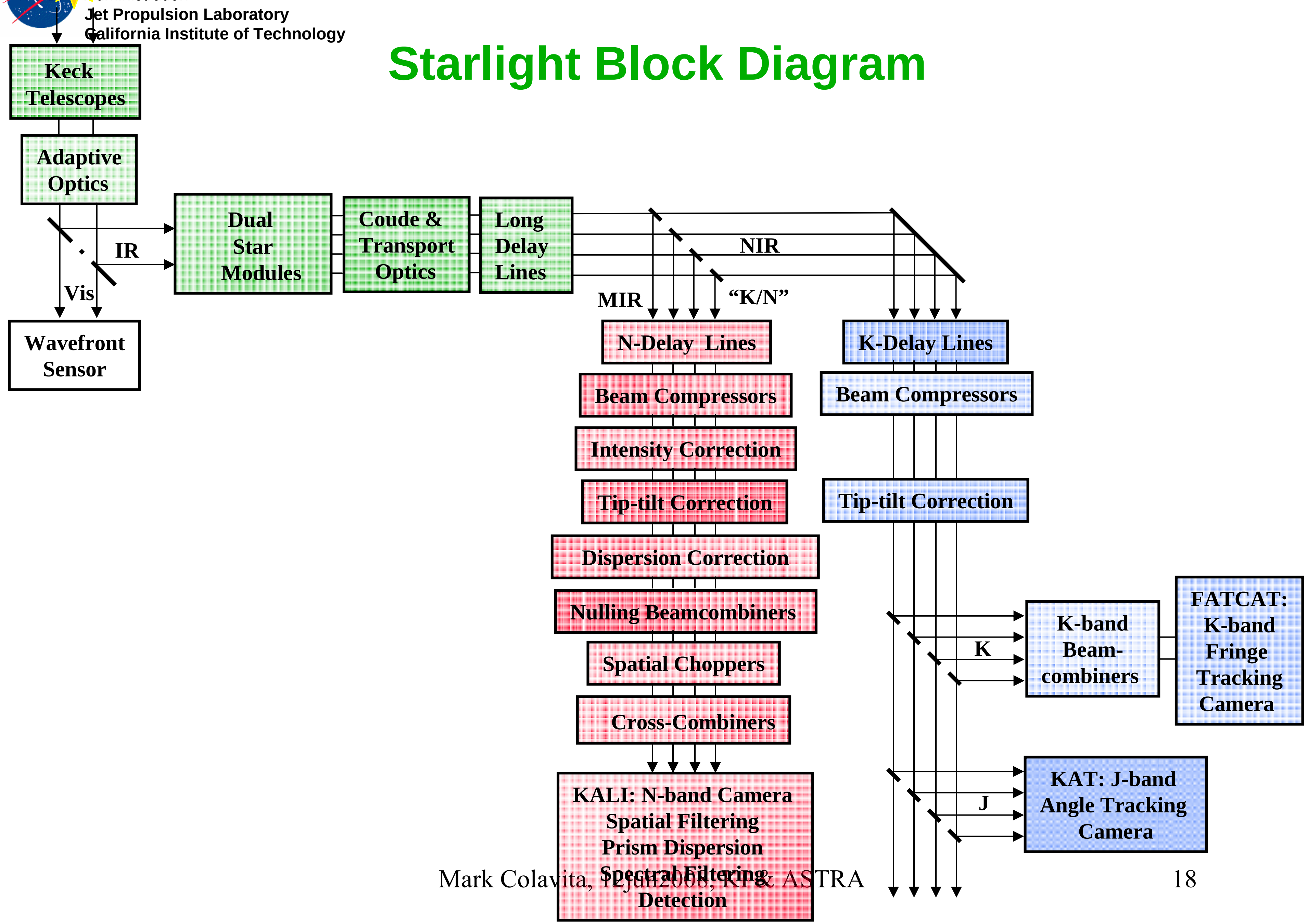
- This plot is of broadband visibility vs. time
- You can see clearly the signature of two binaries observed in the first-half-night program

Nuller Concept

- Two problems
  - Bright star
  - Bright background
- Approach
  - Null star on two 85-m baselines
    - » Improves detectability of surrounding emission
  - Coherently demodulate nulled outputs
    - » Interferometric chopping to measure the nulled signal in a large background



Starlight Block Diagram



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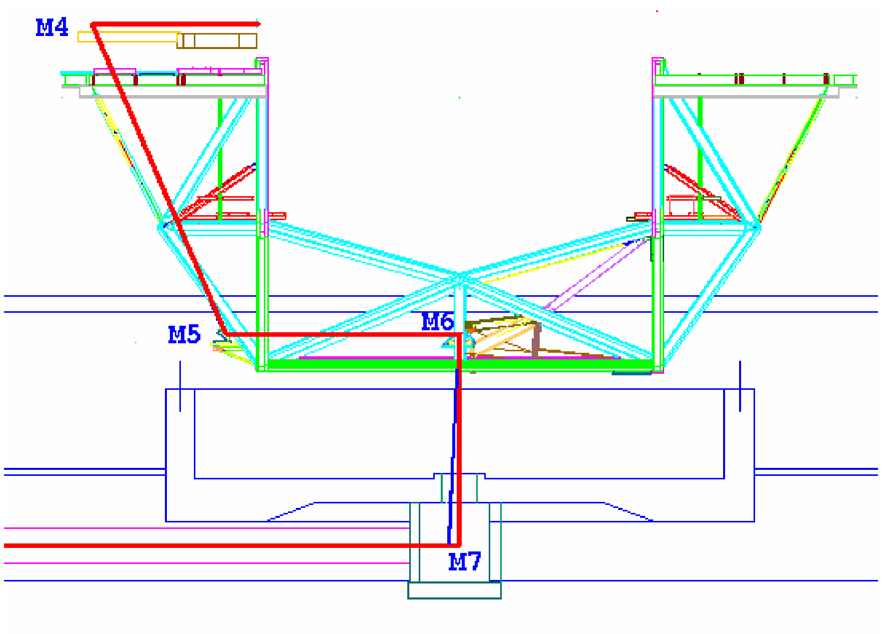
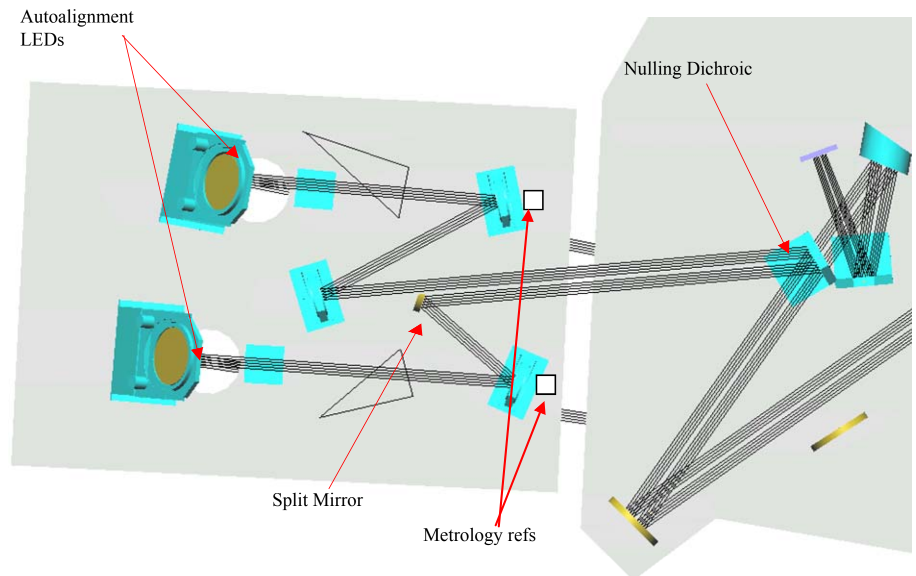
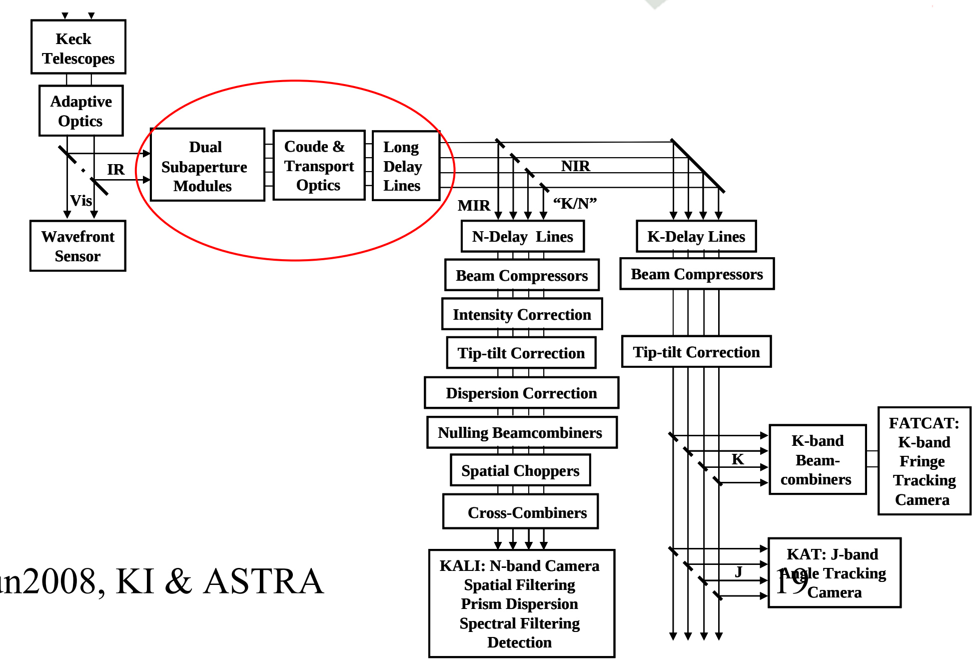
DSM & coude





- Left-right pupil split at DSM
  - "Primary" beam down passive coude
  - "Secondary" beam down active coude – M6 and M7 track azimuth
- Metrology end-points on DSM behind visible transmissive dichroics
- All 45 deg reflections bare gold



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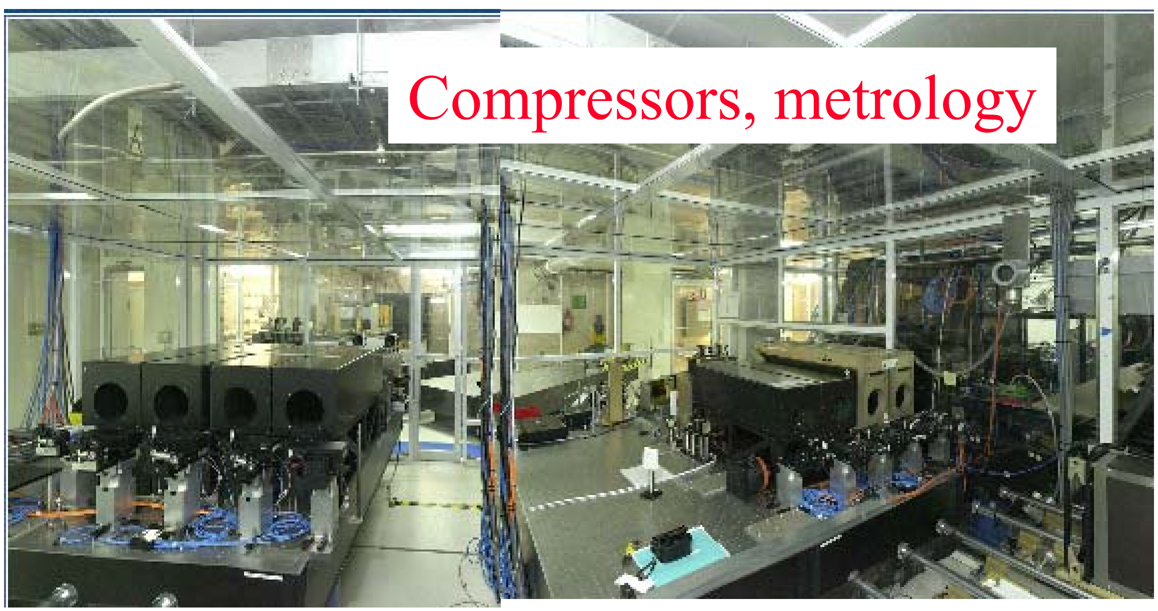
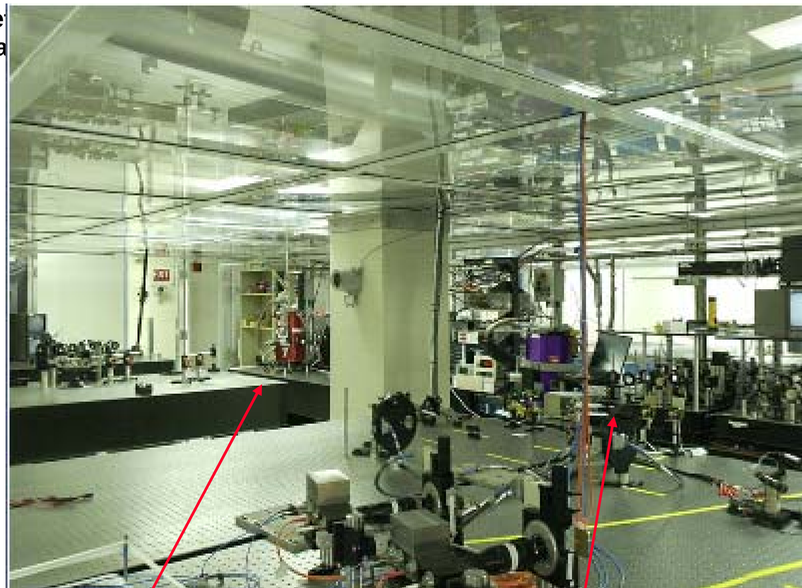
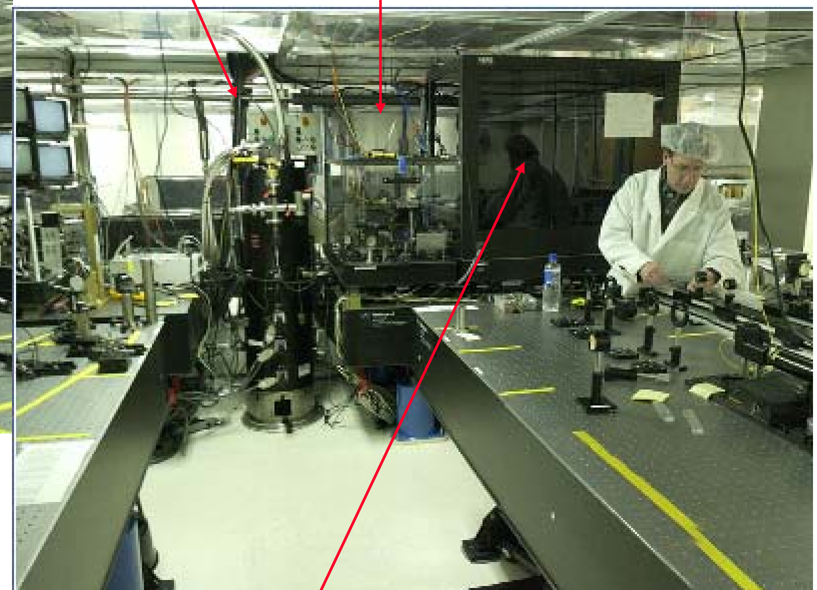
Fast delay line area





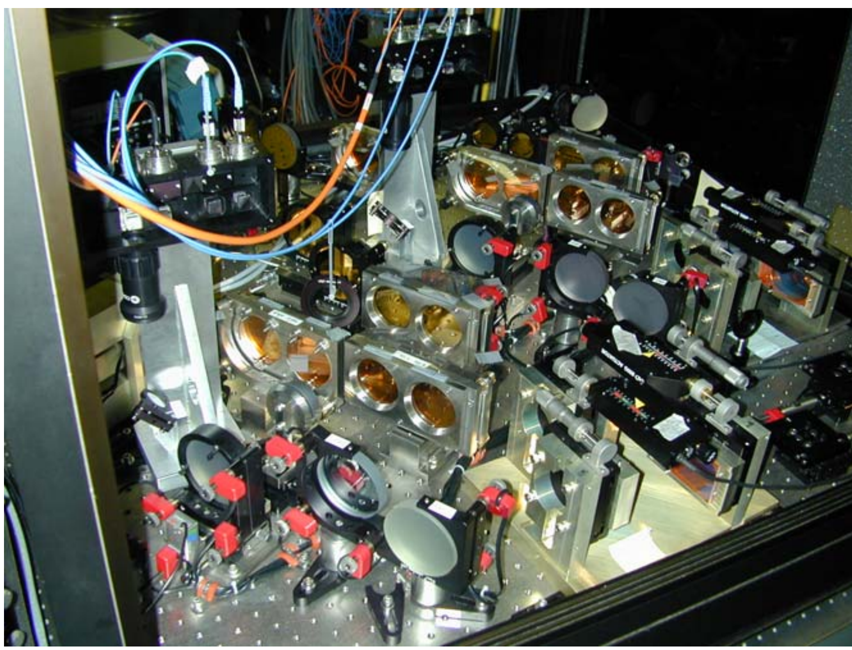
KALI

Nuller
Stimulus



KAT

FATCAT



Nuller
Breadboard

Beam combiner area

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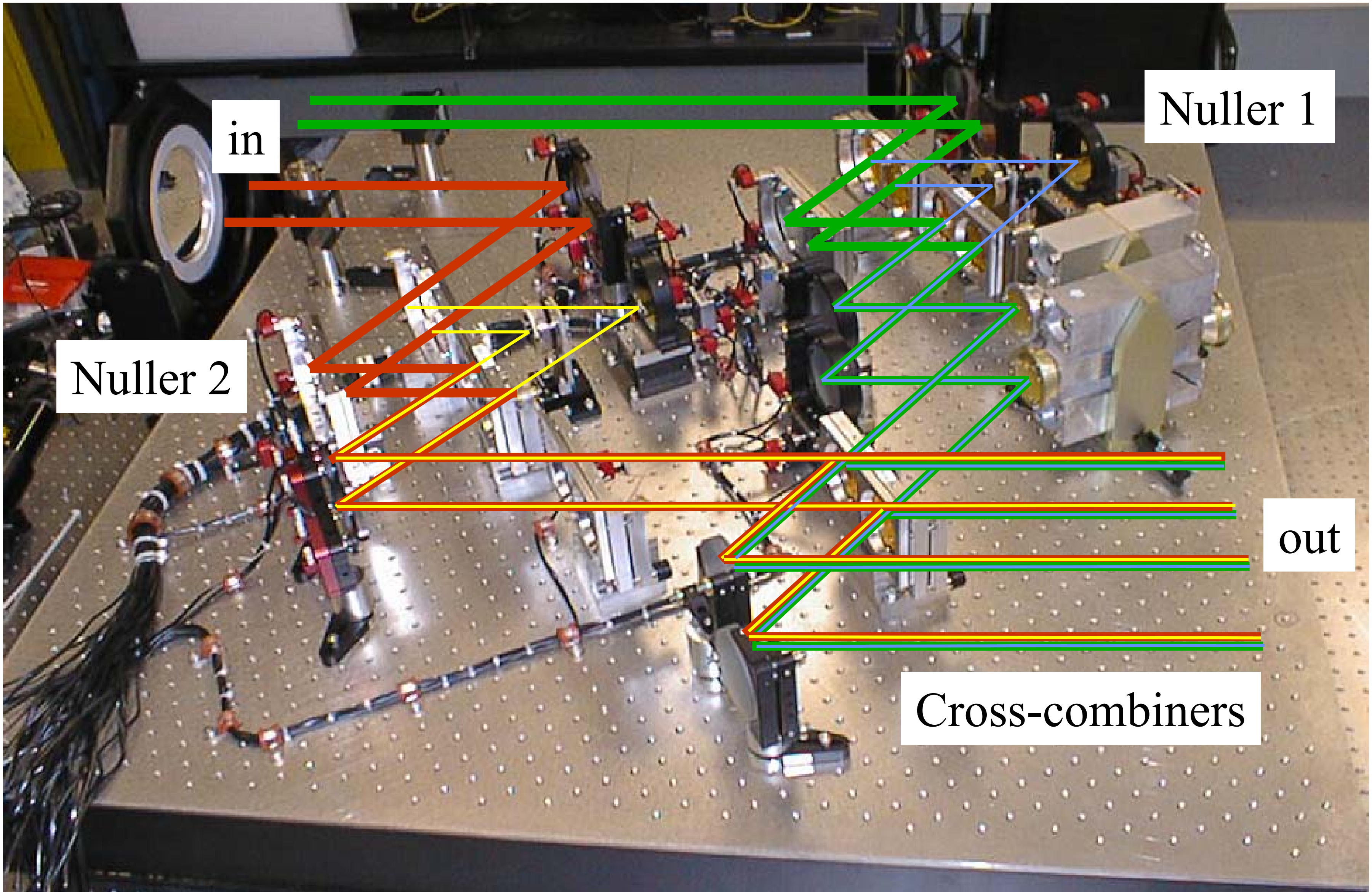
Keck nulling beam combiner
2 nullers & 2 cross-combiners



Observing scenario

Visibility

- Measure science target with interleaved calibrators
- From calibrators, compute "system visibility"
- Calibrated Visibility is $V^2_{science} / V^2_{system}$
  - Accuracy of this quantity is key performance metric

Nulling

- Measure science target with interleaved calibrators
- From calibrators, compute system leakage = 1 / Null Depth
- Calibrated Leakage is $L_{science} - L_{system}$
  - Accuracy of this quantity is key performance metric

Everything degrades the null

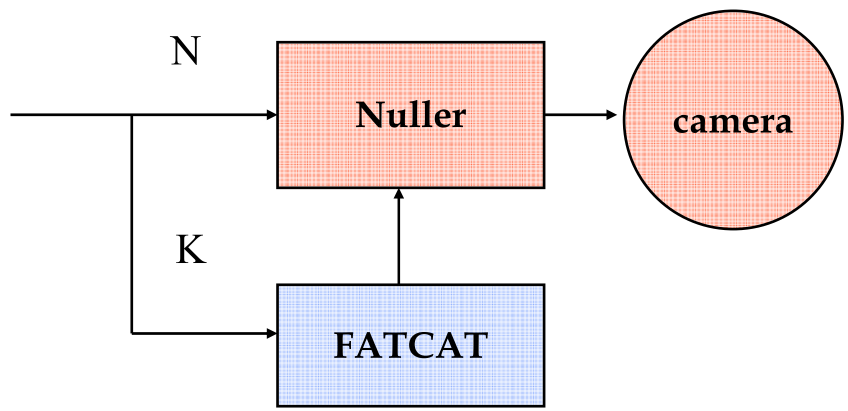
error budget terms for 1% leakage

1	**Differential OPD (windowed)**	$L = \frac{1}{4}\sigma^2_{\phi1-\phi2}$		300	(nm rms)
2	**Intensity balance**	$L = \frac{1}{4}[1-4I_1I_2/(I_1+I_2)^2\}$		50.0%	Δ, relative I difference btwn arms (%)
3	**Intensity fluctuations**	$L = 1/8\ \sigma^2_{Ii}$		28.0%	σ_{Ii}, total I rms each arm (%)
4	**Pure image rotation**	$L = \frac{1}{4}\theta^2$		12	θ, rotation (deg)
7a	**Static tilt with diff-limited det. Pinhole**	$L \cong 0.4\ (tp)^2$		0.160	t, total vector tilt *difference (waves)*
7b	**Dynamic tilt w/ diff-limited det. pinhole**	$L \cong 0.4\ (tp)^2$		0.160	t, total vector tilt difference (waves)
7e	**Ordinary shear with diff-limited det. pinhole**	$L \sim 0.4\ s'^2$		0.160	s', relative shear (frac of beam diameter)
8	**Focus + astigX,Y w/ diff-limited det. pinhole**	$L \cong 3\ w^2$		0.058	w, total rms phase difference in those modes (waves)
9	**Coma (4 terms) w/ diff-limited det. pinhole**	$L \cong 0.8\ w^2$		0.110	w, total rms phase difference in those modes (waves)
14b	**Amplitude curvature across pupil**	$L = (1/48)*(\Delta)^2$		0.700	Δ, peak I mismatch (%)
5	**Pure s-p phase shift**	$L = 1/16\ \phi^2$		23	ϕ (deg)

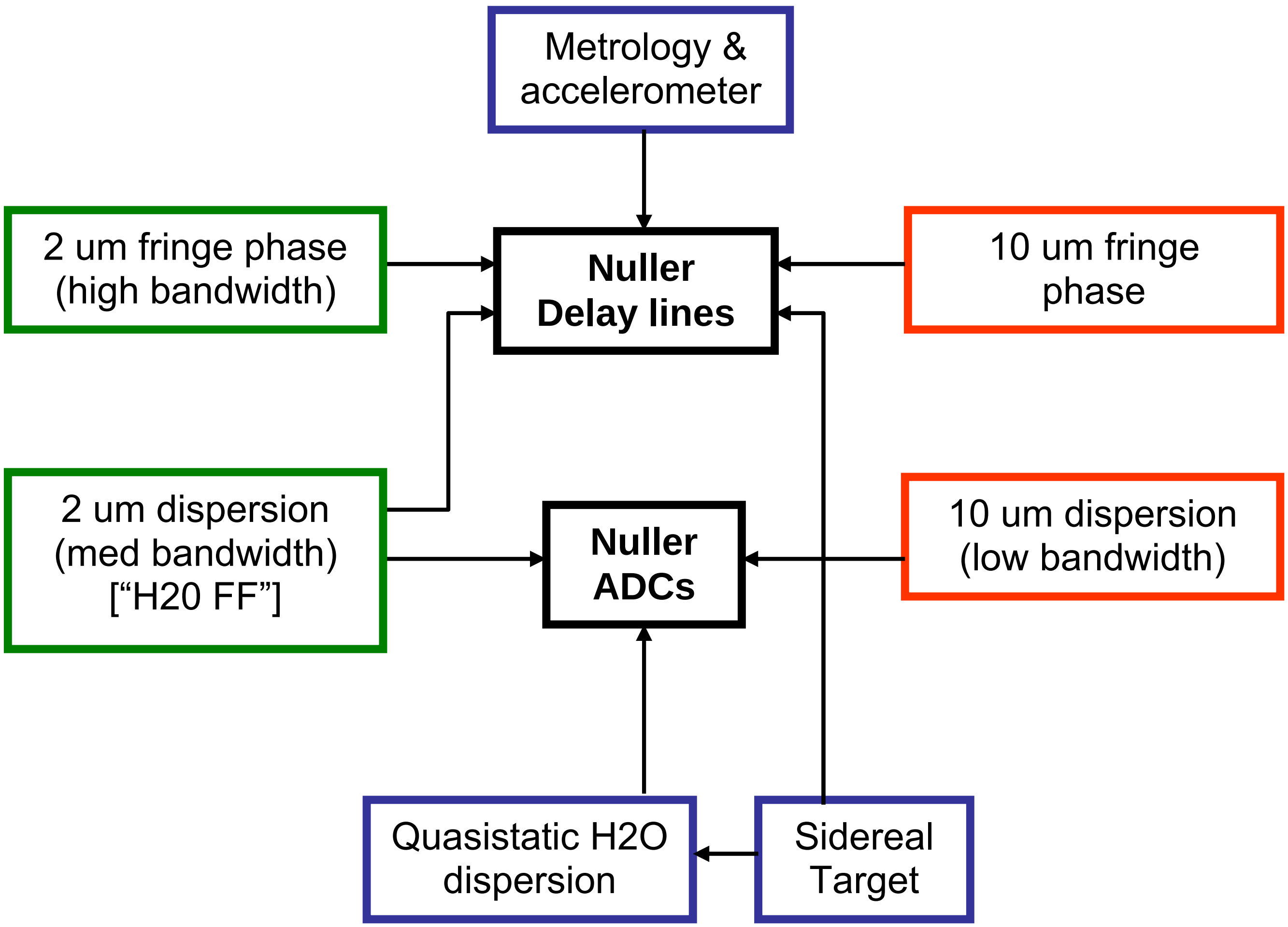
Dealing with the error budget

- Symmetry
  - Nuller beam combiner design
  - Beamtrain
    - Coatings, rotation, etc.
- Spatial filtering
  - Camera has a 1.4 λ / D pinhole
- Pointing and shear
  - Flux peak on bright star for each observing block
  - Shear adjustment each star using boresight laser
- Cophasing
  - 300 nm rms needed for 1% leakage
  - Atmosphere moves 300 nm in 10 ms
  - 10 um sources don't have enough SNR in 10 ms for compensation
    - Use 2 um system for fast tracking
    - Use 10 um system for slow tracking

Cophasing concept



A bit more detail



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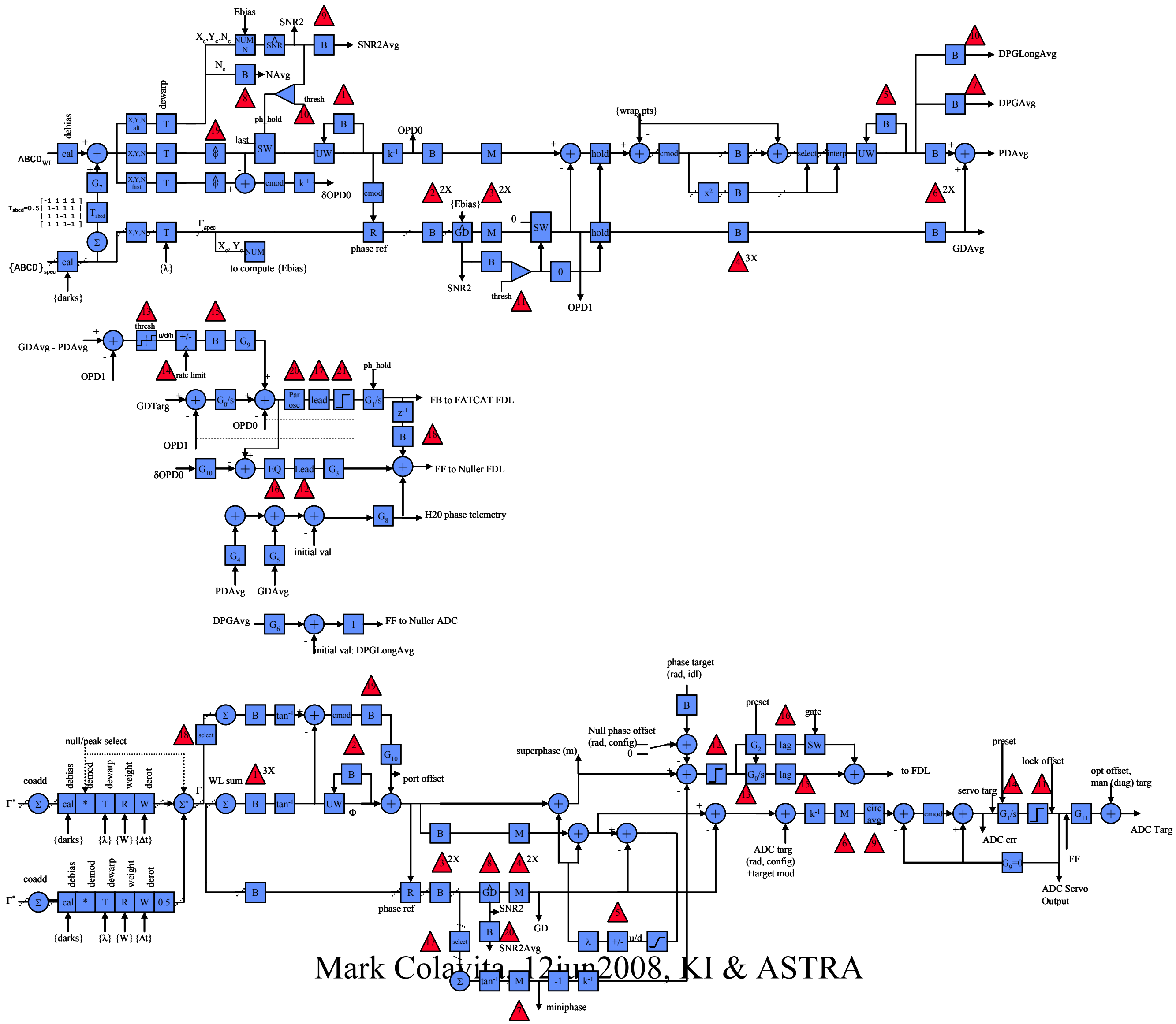
Cophasing implementation



Cophasing

- We rely upon the 2 um fringe tracker to stabilize the nuller fringe
- The total rms requirement makes this a challenge
  - The effective IF Greenwood frequency for median conditions is about 10.5 Hz
    - » In principal a 10-15 Hz fringe tracker bandwidth should do the trick
  - In practice, more rejection is needed
- Use feedback control for the Fringe Tracker
- Use feedforward control to the Nuller

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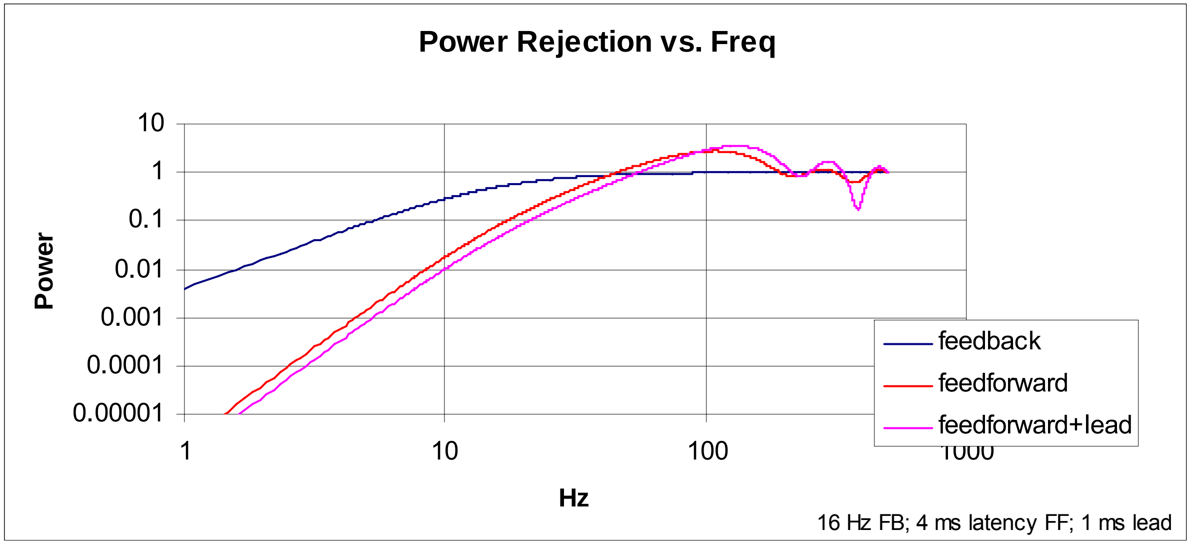
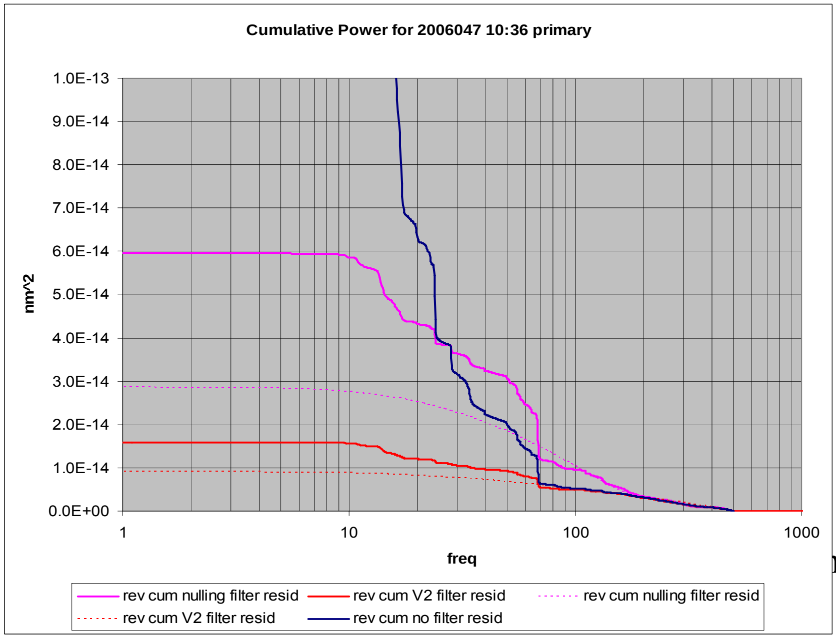
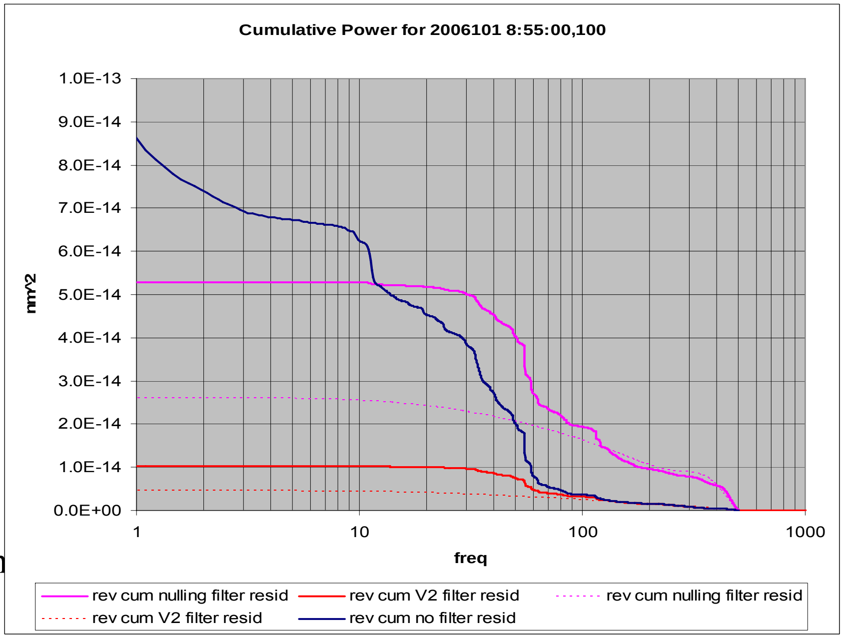
Cophasing performance



Minimizing latency
- Overlapped ZABCD
- Optimized IPC
- Compensation

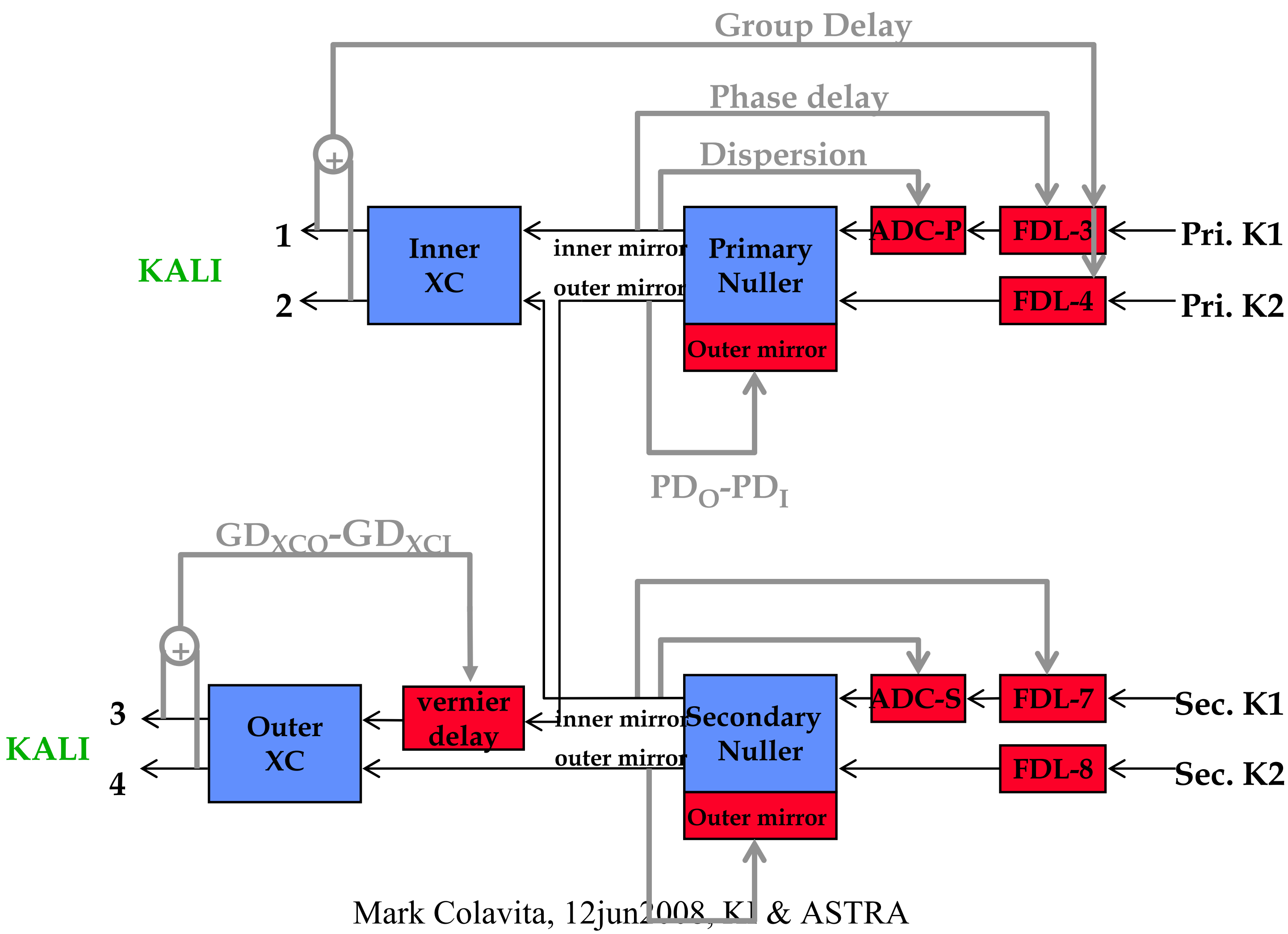




Laser metrology and accelerometers

- External metrology
  - Measures common mode pathlengths from basement to telescope – 4 systems
    - » Launched off-axis at exit of delay lines to corner cubes behind dichroic mirrors on DSMs (replacing annular mirror shown on earlier slide) – this one for vibration control
- Internal metrology
  - Measures non-common-mode pathlengths from fringe tracker and nuller to wavelength split – 4 differential systems
    - » Launched from behind starlight beamsplitters to exit of delay lines; this one for systematic error control (typically not used, as nuller control bandwidth has proved suitable)
- Delay line metrology
  - Local delay line servo control – 8 systems – allows accurate command following
- Telescope accelerometers – 15 per telescope
  - Acceleration converted to position; composite signal sent to FDLs to cancel telescope vibrations
- All systems implemented transparently to the fringe tracker and nuller

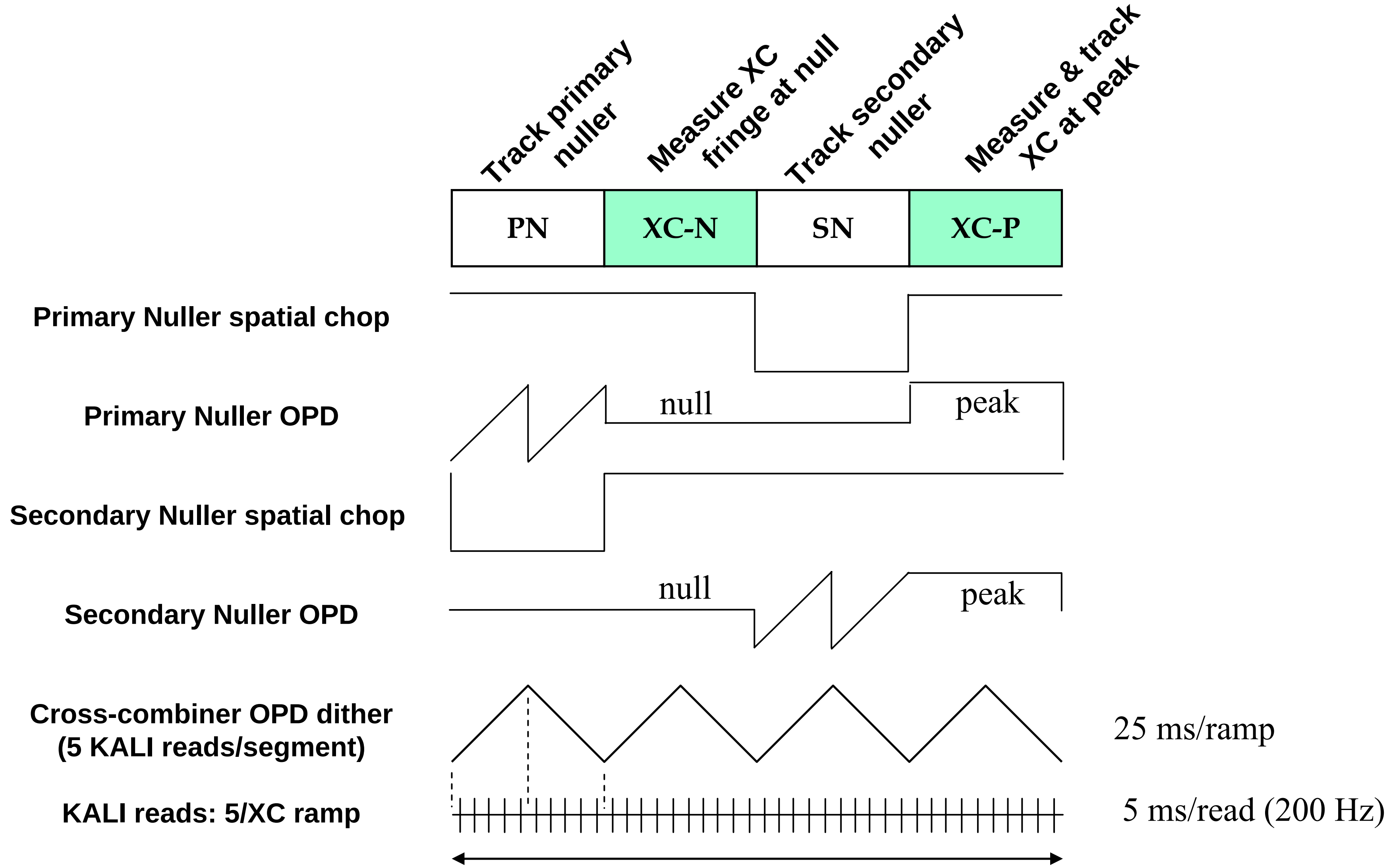
10 um starlight control loops



Multiplexing

- Laser metrology + 2 um fringe tracking + 10 um fringe tracking all simultaneous via WDM (wavelength division multiplexing)
  - Nuller is more problematic
    - » 1 wavelength, 1 camera: 3 beam combiners
- A second issue – total flux calibration
  - V^2
    - » Measure fringe power N^2V^2
    - » Measure total flux N
    - » Compute normalized V^2
  - Nulling
    - » Measure coherent "null" power NL with both MMZs at Null
      - How to get N?
    - » Best approach for us is to measure coherent "peak" power with both MMZs at peak
- Leads to time-multiplexed sequence

Null measurement sequence "gated mode"



40 KALI reads per null measurement cycle

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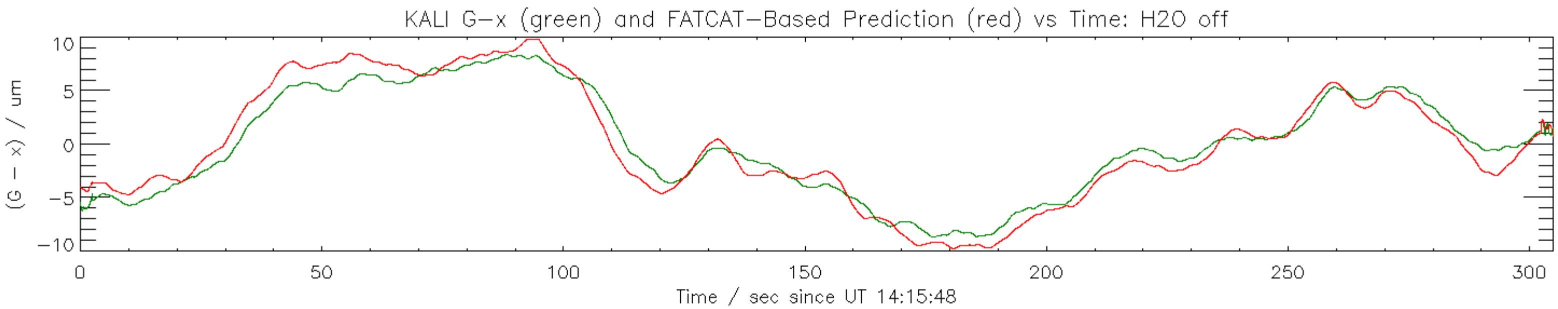
Cophasing and water vapor

- Dry air seeing predominates in the optical, and is relatively achromatic
- Water vapor seeing, while smaller in amplitude, is not
  - At 2 um, it contributes ~1/20 total OPD
  - At 10 um, it contributes ~1/7 total OPD
- However, at both bands it contributes essentially all of the dispersion
  - Can estimate water seeing at 2 um from GroupDelay – PhaseDelay, and extrapolate effect to10 um
- Data matches theory well
- Feedforward to Nuller ADC has proven essential for good 10 um group delay tracking
- Feedforward to Nuller FDL has recently been used routinely for fainter stars where limited nuller control bandwidth is available



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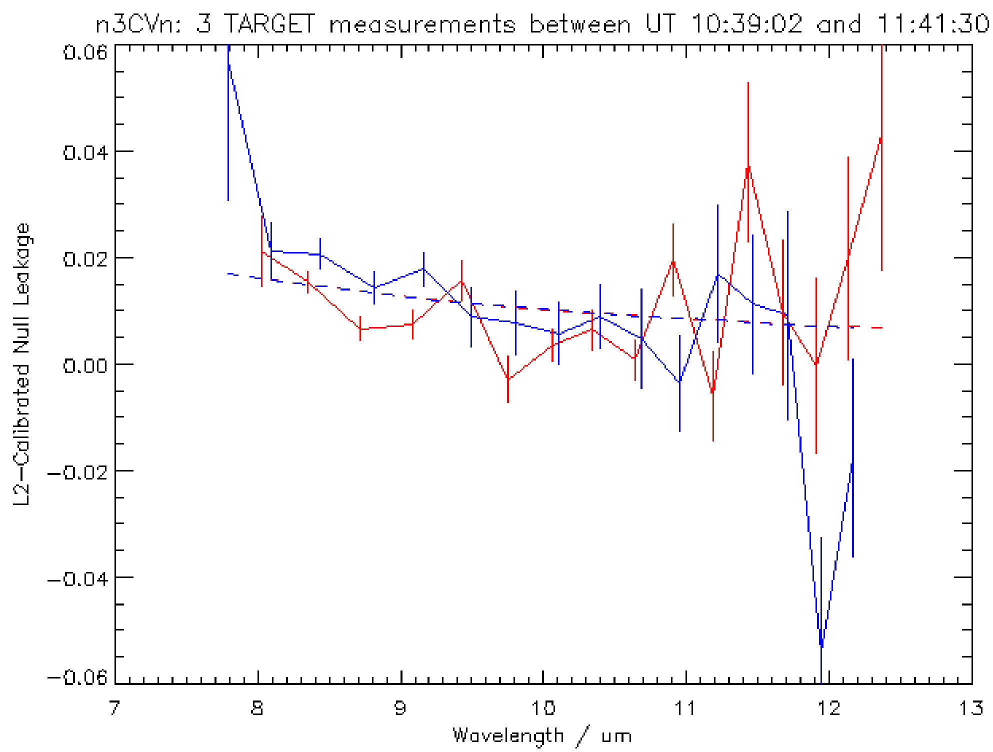
Null calibration

- Used two nearby similarly-sized stars
- Raw nulls not perfect, but calibration yields significant improvement
- Dashed curve is the expected stellar null



NASA Exo-zodiacal Dust Survey Key Science Program

- NASA is using the majority of its Keck time in 2008 to conduct a survey for exo-zodiacal dust around nearby stars
  - 32 nights from Feb 2008 to Jan 2009
- Teams were competitively selected to observe targets for future planet finding missions as well as known debris systems
  - Selected PI's: Phil Hinz (Univ. Arizona), Marc Kuchner (GSFC), Gene Serabyn (JPL)
  - 40 targets allocated
  - Progress to date (3 of 8 runs): 15 sources observed
- Data become public 18 months after observation

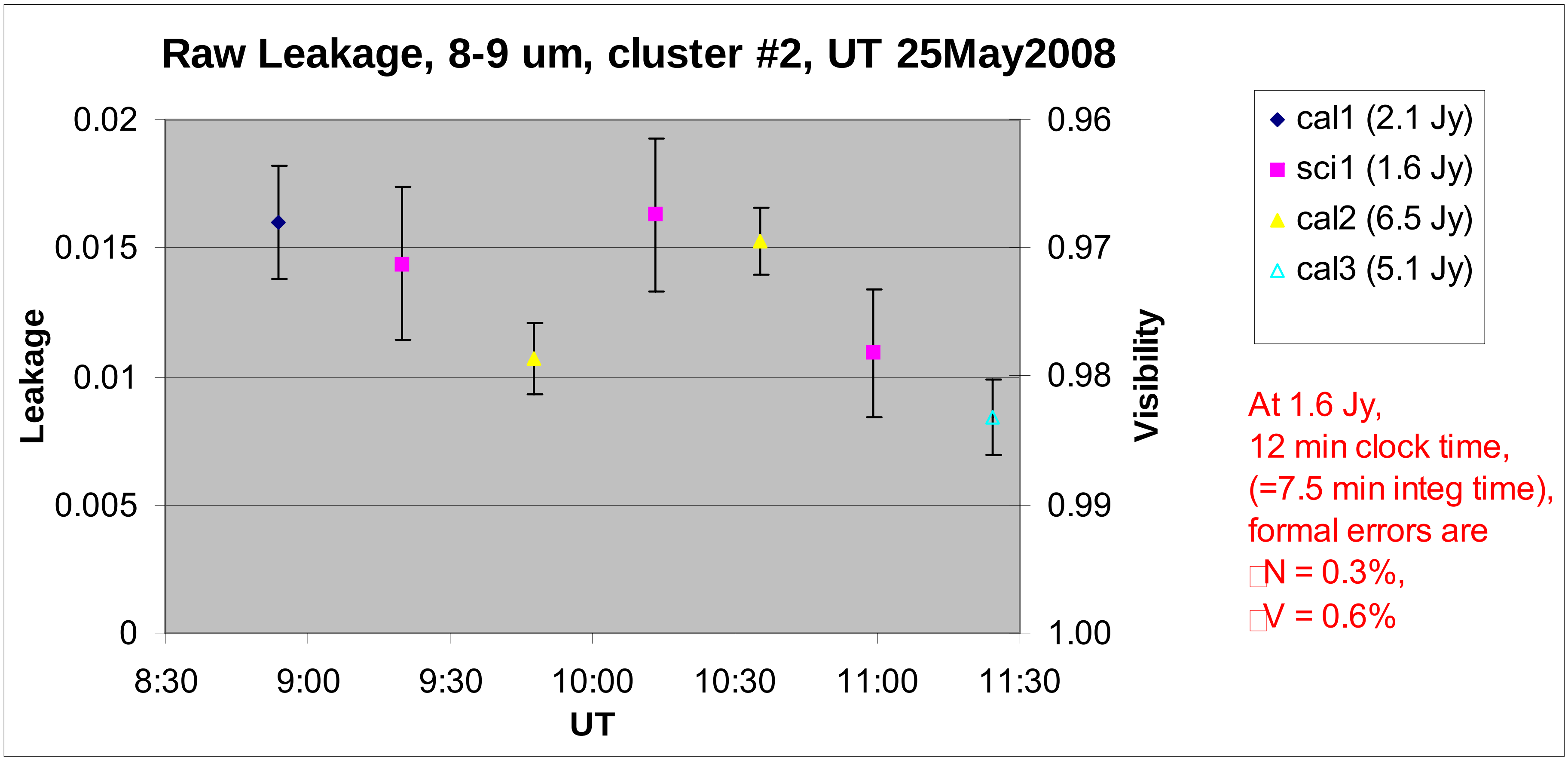
Current performance

- Current performance was measured in a series of validation tests on stars with a range of brightness which have no circumstellar material (to the best of our knowledge)
- From analysis of 21 observation sets (each comprising multiple target and calibrator scans over ~3 hrs)
  - KI achieves an external error of 0.25% rms null leakage uncertainty in a broadband 8 – 9 um channel
  - Equivalent to 100 zodi rms (where 1 zodi = flux ratio of $5x10^{-5}$) after accounting for transmission through the long-baseline fringe pattern
  - Systematic errors observed early in the validation process have been minimized by altering the adaptive optics rotator angle, more closely matching the target and calibrator fluxes, and including only the shorter wavelengths in the broadband average
- Demonstrated sensitivity to 1.6 Jy
  - For sources near the flux limit, the null leakage is computed only in the broadband channel
    - » Potential to go slightly fainter with longer integration times
  - For brighter sources, can use the 20 spectral channels

How do null depth and visibility relate?

- Visibility defined in terms of maximum and minimum fringe intensity as V = (Max-Min)/(Max+Min)
  - This is the classical Michelson definition
- Null leakage defined as: L = Min/Max
- So…
  - $V = (1-L)/(1+L)$
    or, for $L \ll 1$
  - $V \approx 1-2L$

Metric: Nuller performance



At 1.6 Jy,
12 min clock time,
(=7.5 min integ time),
formal errors are
□N = 0.3%,
□V = 0.6%

Science with Large-Aperture Infrared Interferometry

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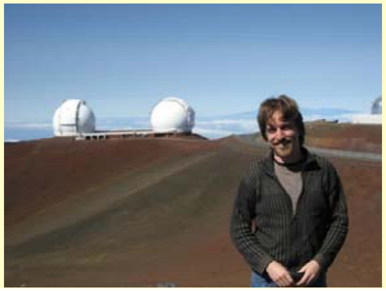
ASTRA: A new tool to study the Galactic center

Workshop: Astrometry and Imaging with the VLTI

Keszthely, Jun 4, 2008



Jörg-Uwe Pott

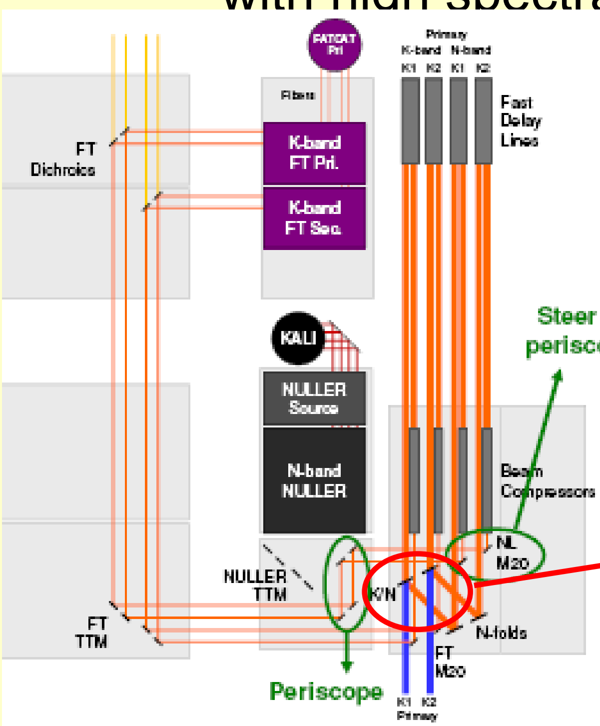
W. M. KECK OBSERVATORY

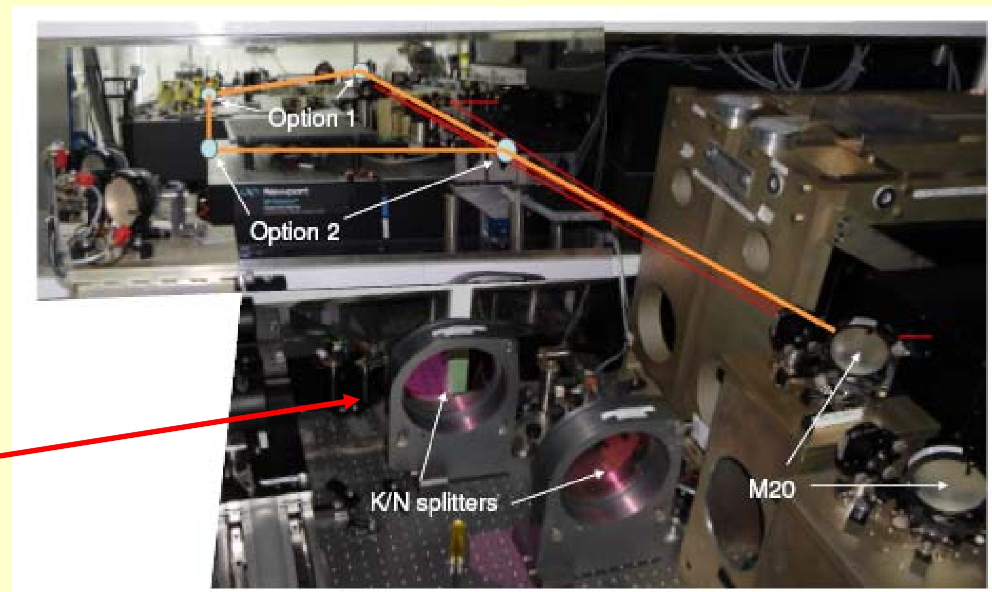
W.M. Keck Observatory
UCLA

UCLA

- Near future: Keck-IF ASTRA-
  ASTrometric and phase-**R**eferenced **A**stronomy
  - NSF-funded sensitivity and versatility upgrade
  - Pushing IF to K ~ 15 mag science with phase-referencing
  - Collaborators:
    - SA: J. Woillez, PI: P. Wizinowich and the IF-team at WMKO
    - M. Colavita, and the IF-team at JPL
    - R. Akeson, R. Millan-Gabet (MSC)
    - Core science team: PS: J. Graham, J. Eisner (UCB), A. Ghez (UCLA), L. Hillenbrand (Caltech), J. Monnier (UoMichigan)

- Keck-IF ASTRA – first step – Self-referencing
  - Atm. turbulence sets the coherence time -> correction loop of ~ 20 Hz at NIR needed -> input 10x faster -> limits sensitivity or spectral resolution
  - Solution: split the light, track fast on one half, and see the spectroscopic details of other half with 2nd slow fringe camera
  - It works and will be offered this fall to the community to do IF with high spectral resolution (R~1000) at K~8-9





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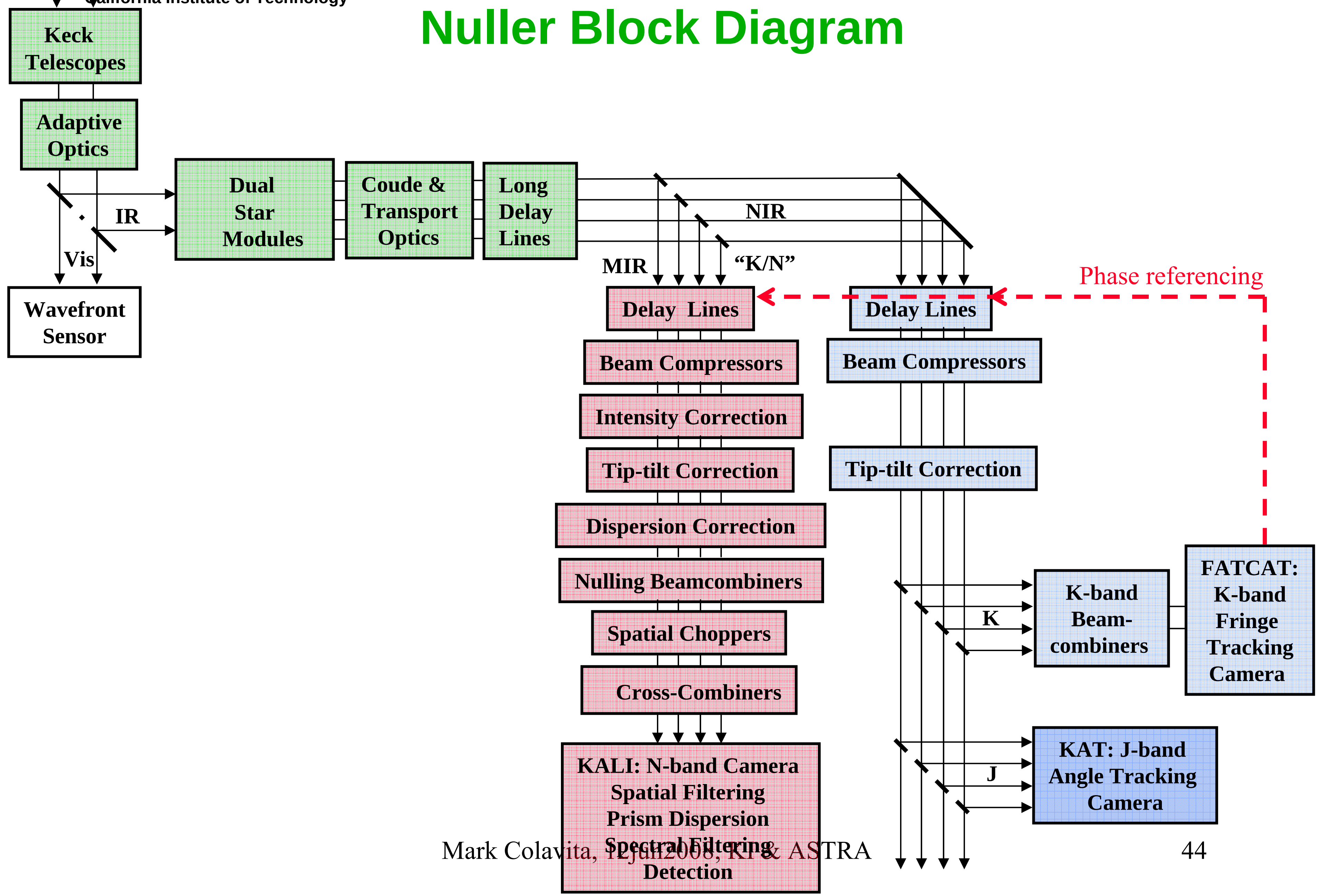
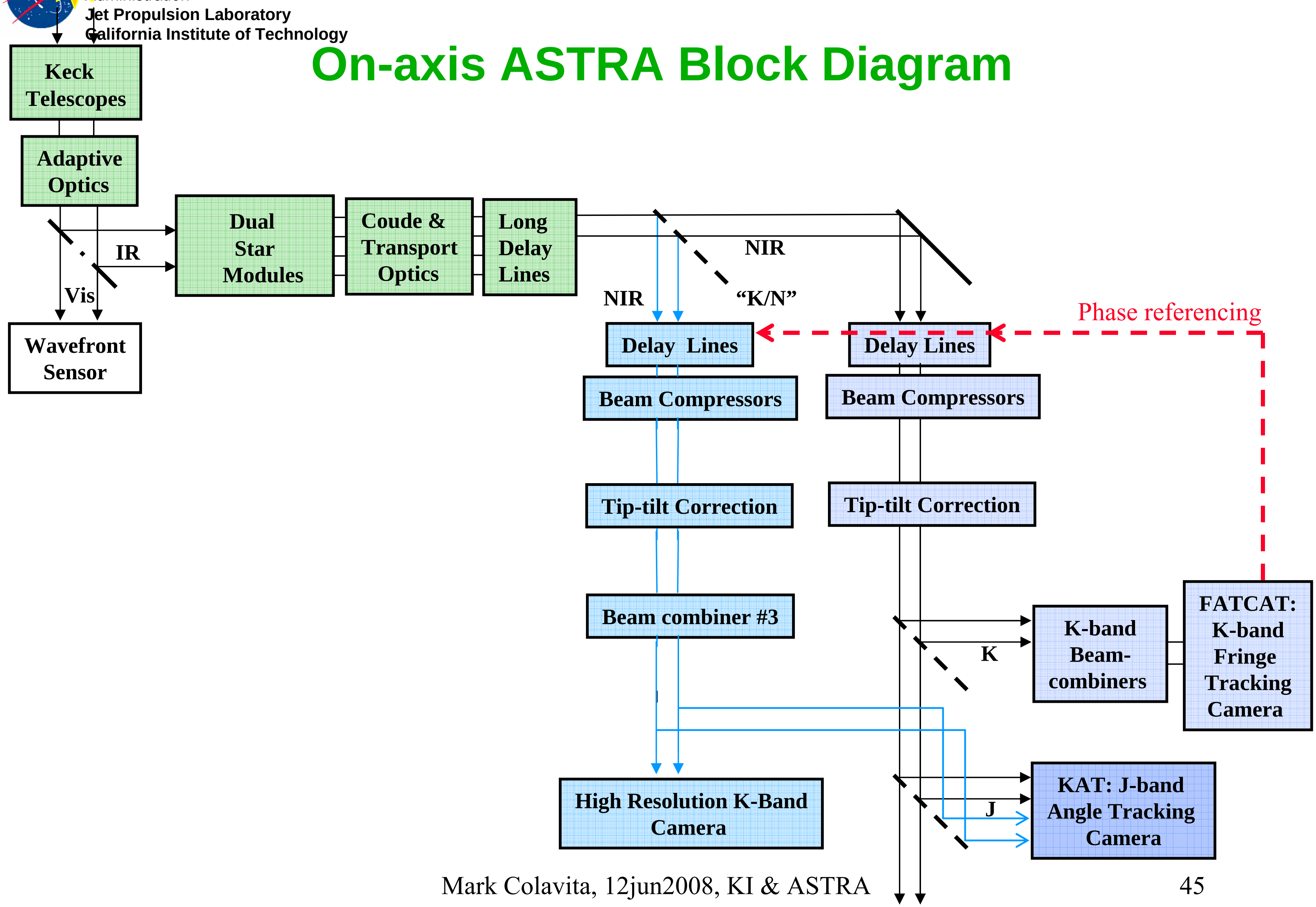
Nuller Block Diagram

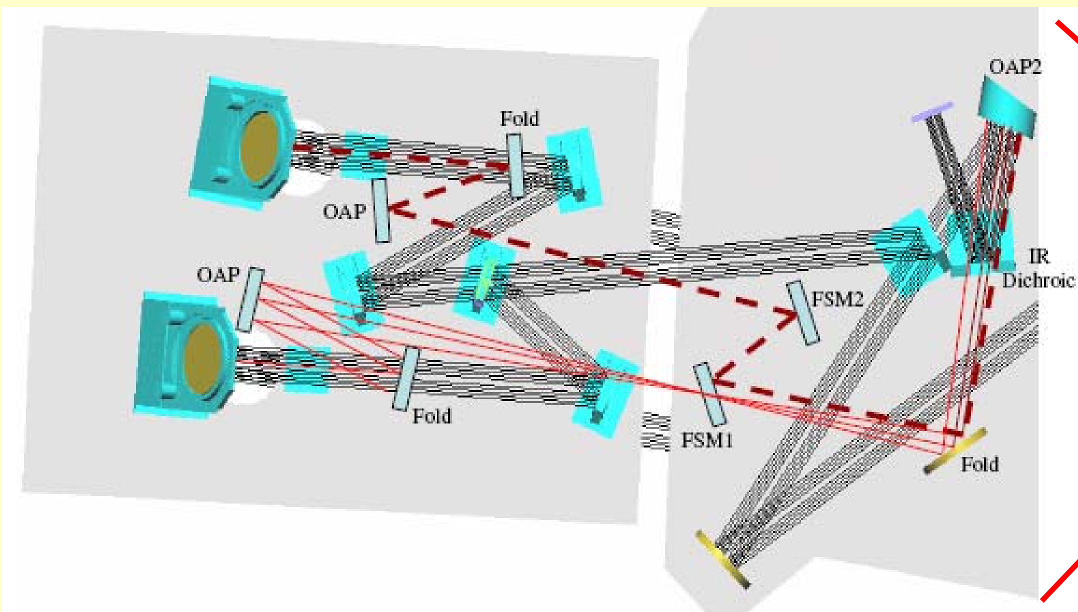


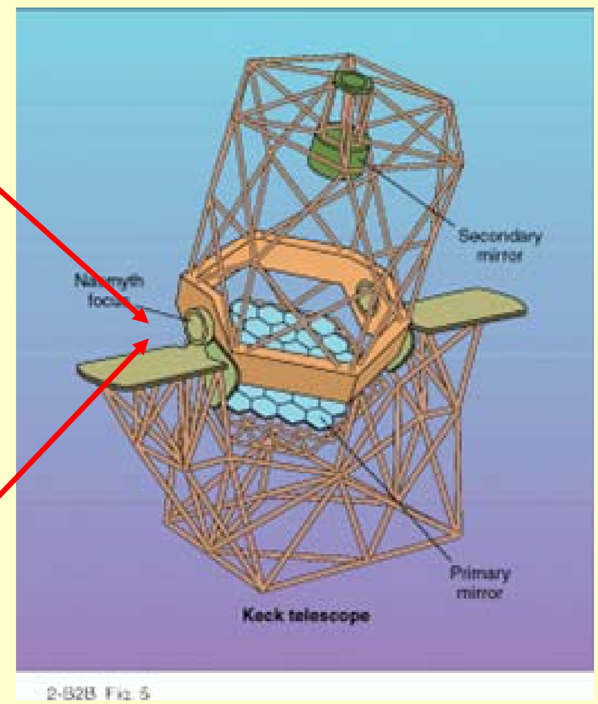
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

On-axis ASTRA Block Diagram



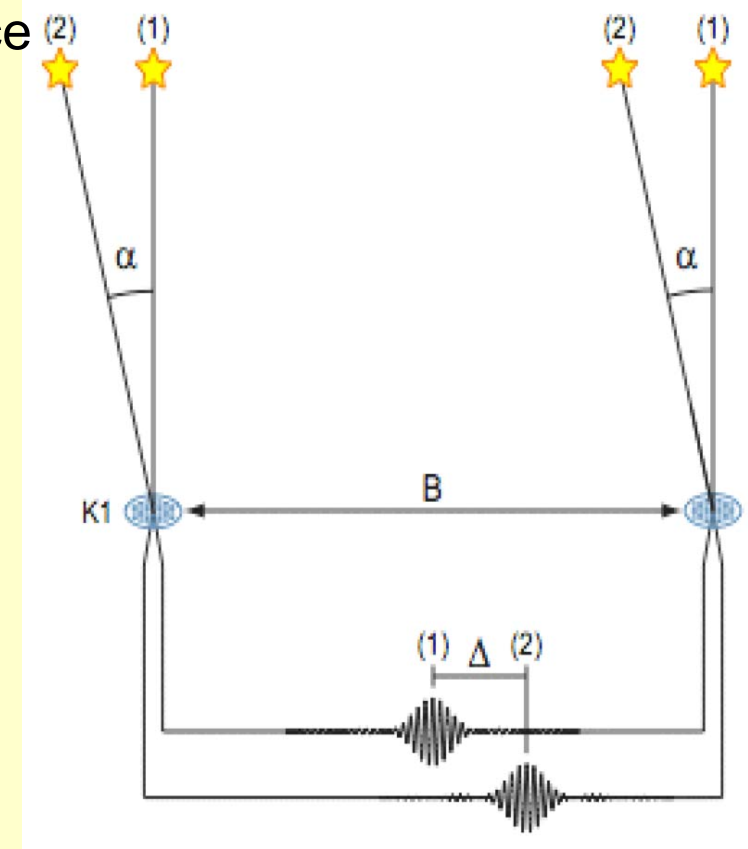
- Keck-IF ASTRA – second step - Off-axis phase-referencing
  A key technology is 'star separation'
  - Split the light already in the telescope foci to get maximum FOV
  - Apply the gain of a stabilized fringe and a second camera to another (faint or red) star in the iso-planatic patch
  - Never been done before with large apertures!



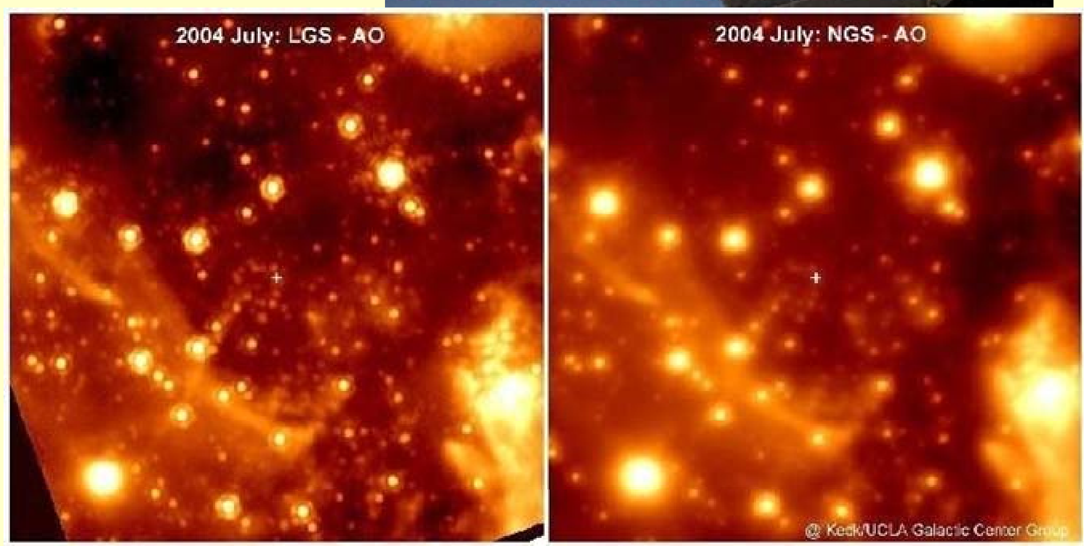


- Keck-IF ASTRA Future:
  Dual-star phase-referencing facilities will also enable:
  narrow angle precision astrometry down to ~50uas
  - IF-astrometry is orthogonal to imaging-like visibility-interferometry
  - Measure is the angular distance between two stars via intrinsic geometric-delay difference
  - Usually limited by atmosphere
  - 50µ" require control of delay to ~ 20nm and the baseline to ~ 150µm
  - Repeated measurement can reach even higher precision
  - Laser metrology needed to probe the complete internal path at the 20nm level of precision

-> talk by Colavita for some more KI-technology



- Keck-IF ASTRA for the GC: Key properties
  - 10m diameter of primaries
  - Visible AO will be replaced by two LaserGuideStars
  - Fringe tracking in K, and angle-tracking in H -> GC stars are very red
  - star-separator fully exploits the iso-pistonic angle of ~25” -> covers the complete central pc



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- planetquest.jpl.nasa.gov [follow Keck link]
- www.msc.caltech.edu [follow mission and instruments link]