Introduction to Keck Interferometer

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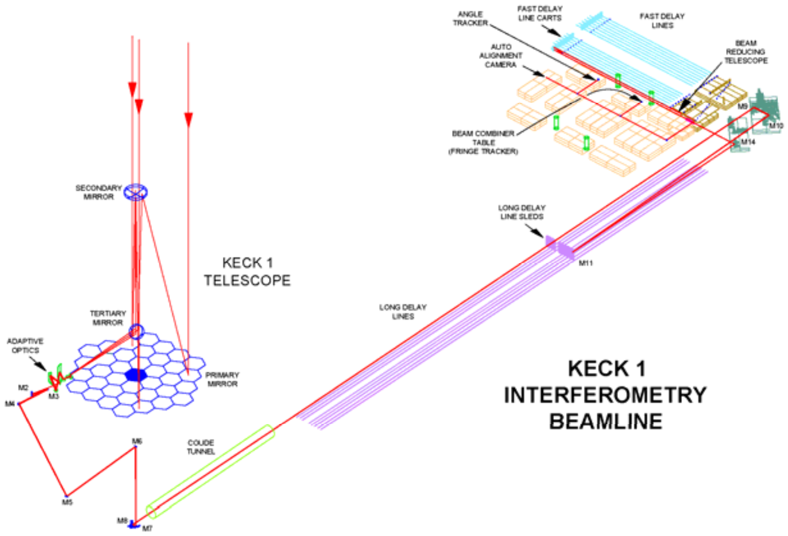
(with contributions from KI team)

Presentation sequence

1. Introduction
2. Current observing capabilities
3. Planning observations
4. Recent V^2 science results
5. Basics of Keck Interferometer
    - V^2, V^2–SPR & Nuller modes
6. Instrument overview (if time permits)
7. Future plans

1. Introduction (slide 1 of 2)



- Keck Interferometer (KI) combines the two 10 m Keck telescopes as a long baseline interferometer
- KI is funded by NASA
- KI is yet another AO instrument at Keck
- High-order adaptive optics corrections on both telescopes are essential for KI

- Joint development among the Jet Propulsion Laboratory, the W. M. Keck Observatory, and NASA Exoplanet Science Institute (NExScI; formerly MSC)

1. Introduction (slide 2 of 2)

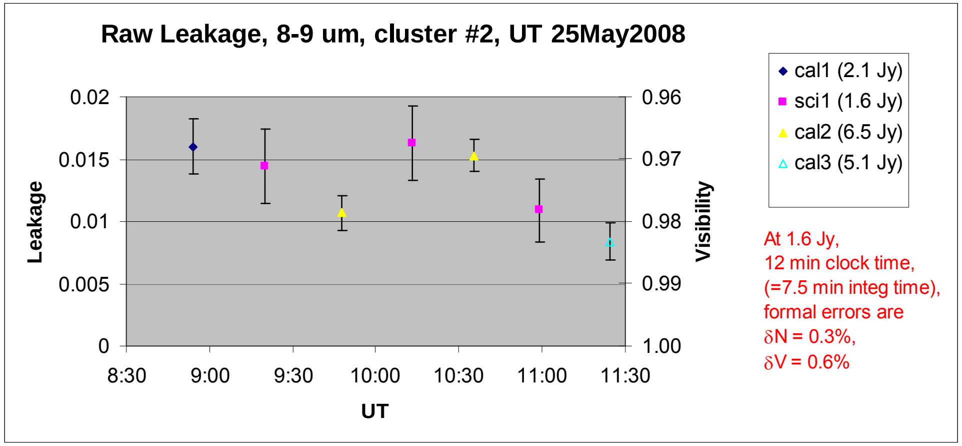
- KI operates in the near & mid-infrared wavelengths
- KI provides high spatial resolution information through fringe contrast measurements
- Resolution (λ/2B): ~ 2 mas at 1.65μm & 12 mas at 10μm
  - A factor of 17 finer resolution than that of single Keck telescope diffraction limit (along the direction of baseline for compact objects)
- KI fully supports service observing
- During last 2 years, we had 22 observing runs
  - 38 science nights (16.5 V^2 Science, 20.5 Nuller Science & 1 Ohana)
  - 28 engineering nights (3.5 for V^2, 24.5 for Nuller)
- Major developmental project at KI
  - ASTRA project funded by NSF
  - Led by W.M. Keck Observatory primarily to add dual-star and astrometry capabilities

2. Current Capabilities (1 of 6)

Spectral Capabilities

1. Nuller transitioned from Shared-risk to Science mode

- Nuller instrument cancels star light and enables detection of faint emissions from circumstellar environment
- Nuller Key Science Program (Exo-Zodiacal Dust Survey) is underway (2008A&B)
  - Three teams selected in Nov 2007
  - Started Key Science Program in Feb 2008
  - 5 runs completed (19.5 nights); 3 more remaining
- Team Keck Science nights
  - 1 night for Evolved stars & 1 night for YSO disks studies
- Nuller is available for science in 2009A & B
- Sensitivity: N flux > 2 Jy



Raw Leakage, 8-9 um, cluster #2, UT 25May2008

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

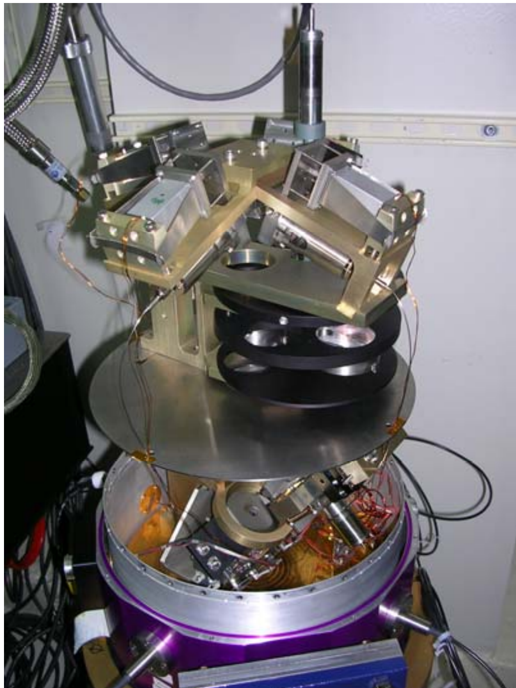
2. Current Capabilities (2 of 6)

2. Very Low & Low Dispersion Modes

- Standard visibility-square measurements at H (4 channels) & K bands (5, 10 or 42 channels)
- Current AO sensitivity for IF, R < 12
- Angle-tracking sensitivities, J & H < 10.5
- Fringe-tacking sensitivities, K' < 10.3 for 5 channels & K' < 7.6 for 42 pixels

3. Medium Dispersion Grism Mode (R ~ 1700) - Self-phase Referencing mode

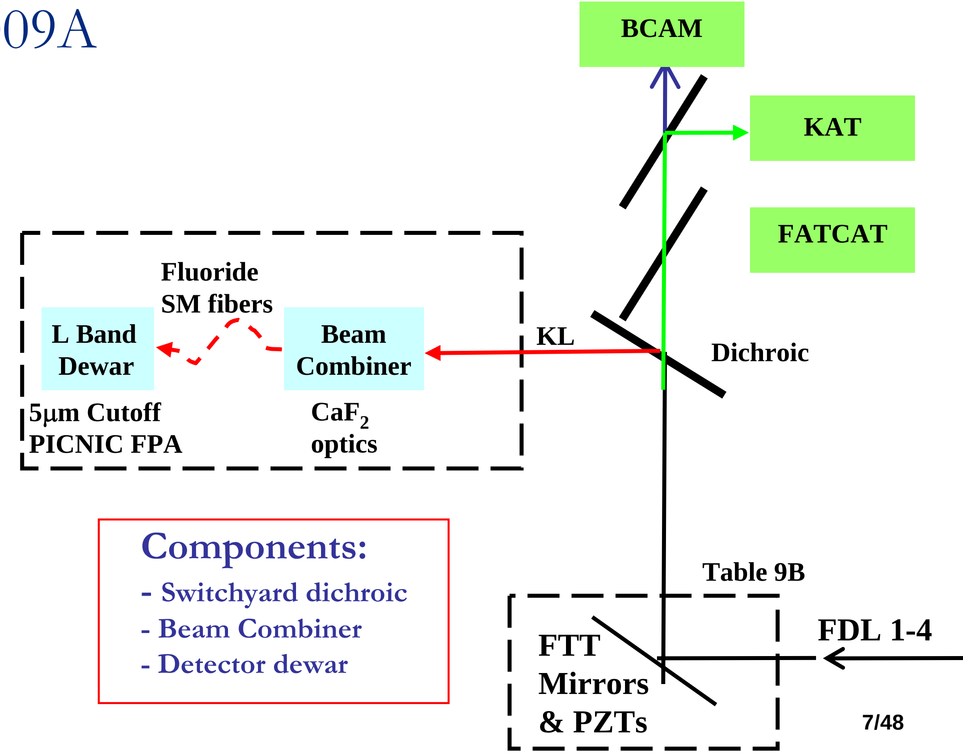
- Grism, 330 spectral channels in the K-band
- Spatially and spectrally resolved observations of hydrogen gas through Br γ emission line
- Available for shared-risk science in 2009A
- Angle-tracking sensitivity, H < 9
- Fringe-tracking sensitivity, K' < 7



2. Current Capabilities (3 of 6)

4. L-band (3.8μm) Science mode

- Uses a 5μm cutoff PICNIC FPA
- First light in April 2008
- Sensitivity, L ~ 6
- Available for shared-risk science in 2009A



Components:
- Switchyard dichroic
- Beam Combiner
- Detector dewar

2. Current Capabilities (4 of 6)

Improved Sensitivity

5. Improved sensitivity of Science camera for standard mode
   - Low noise and long integration (10 ms) clocks improved the K-band sensitivity for low resolution mode by ~ 1 magnitude
6. New angle tracking algorithm
   - Implemented a Gaussian algorithm and optimized the low-light level thresholds; ~ 1 magnitude sensitivity gain
7. Improved H-band angle tracking
   - H-band angle tracking capability is improved by ~4 magnitudes by upgrading switchyard dichroics.
8. Improved AO limiting magnitude for IF (R ~ 12; ~ 1.5 mag improvement)
   - Observatory funded AO/IF dichroic upgrade
   - New IF extraction beam-splitter

2. Current Capabilities (5 of 6)

KI Performance Summary

	KI Capabilities	Current performance	Prior to mid-2006
1	Nuller Science mode	N-band flux > 2 Jy	NA
2	Medium disp. mode; R~230	Science Mode	K ~ 7.6
3	L-band mode; R~60	L ~ 6	NA
4	SPR mode; R~1700	K ~ 7	NA
5	K5/H4 sensitivity	K = 10.3; H = 9	K = 9.2; H = 8.5
6	KAT sensitivity in J	J = 11.5	J = 10.5
7	KAT sensitivity in H	H ~ 11.5	H ~ 7.5
8	AO sensitivity limits for IF	R = 12	R = 10.5

- Currently advertised V2 and Nuller mode sensitivity limits on NExScI website

2. Current Capabilities (6 of 6)

Improved Operational Efficiency

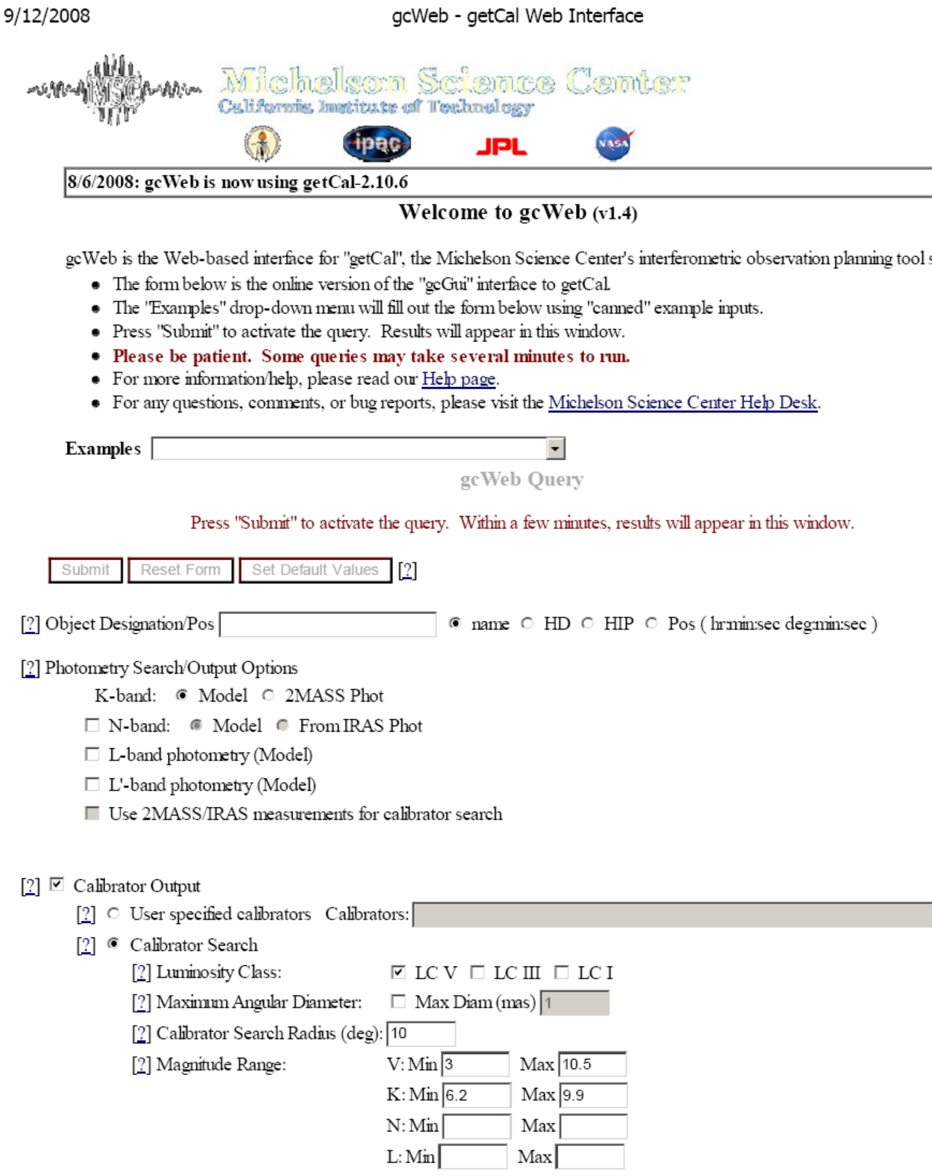
- The run preparations take less (~ 1/3rd) resources
  - Coude alignment is performed only once before each run (~ 66% gain in telescope & IF personnel resources)
  - Similar gain for basement alignments as well
  - Daytime summit run preparation takes one person (~ 50% gain)
- Gain in sky-time
  - Nuller nights ~ 23% gain
  - V^2 nights ~ 5% gain
- Several factors responsible for the improved efficiency, including
  - Well defined procedures for run preparation and run support
  - Careful scheduling of personnel & instrument resources
  - Automation and new operational tools
  - Documentation and staff training

3. Planning KI Observations: Planning Tool (slide 1 of 4)

- Target size consideration
  - Targets should be compact enough to exhibit fringes
  - For 85m baseline:
    - K-band measurements
      - Target size should be < 5 mas at 2μm
    - N-band Nuller measurements
      - Target size should be < 20 mas at 10μm & < 5 mas at 2μm
- (u,v) coverage
  - Observing targets at different hour angles provide fringe-contrast measurments at different spatial frequencies
    - Size measurement could be made from few data points
    - Binary studies would require a lot of data points

3. Planning KI Observations: Planning Tool (slide 2 of 4)

- NExScI planning tool: getCal
  - Web interface: gcWeb
  - Identifies potential visibility calibration sources
  - Models spectral energy distribution using archival (SIMBAD, 2MASS, IRAS) photometry
  - Computes observing accessibility and geometry
  - Enables easy creation of observing catalog for KI



9/12/2008 gcWeb - getCal Web Interface

8/6/2008: gcWeb is now using getCal-2.10.6

Welcome to gcWeb (v1.4)

gcWeb is the Web-based interface for "getCal", the Michelson Science Center's interferometric observation planning tool s

- The form below is the online version of the "gcGui" interface to getCal.
- The "Examples" drop-down menu will fill out the form below using "canned" example inputs.
- Press "Submit" to activate the query. Results will appear in this window.
- **Please be patient. Some queries may take several minutes to run.**
- For more information/help, please read our Help page.
- For any questions, comments, or bug reports, please visit the Michelson Science Center Help Desk.

Examples

gcWeb Query

Press "Submit" to activate the query. Within a few minutes, results will appear in this window.

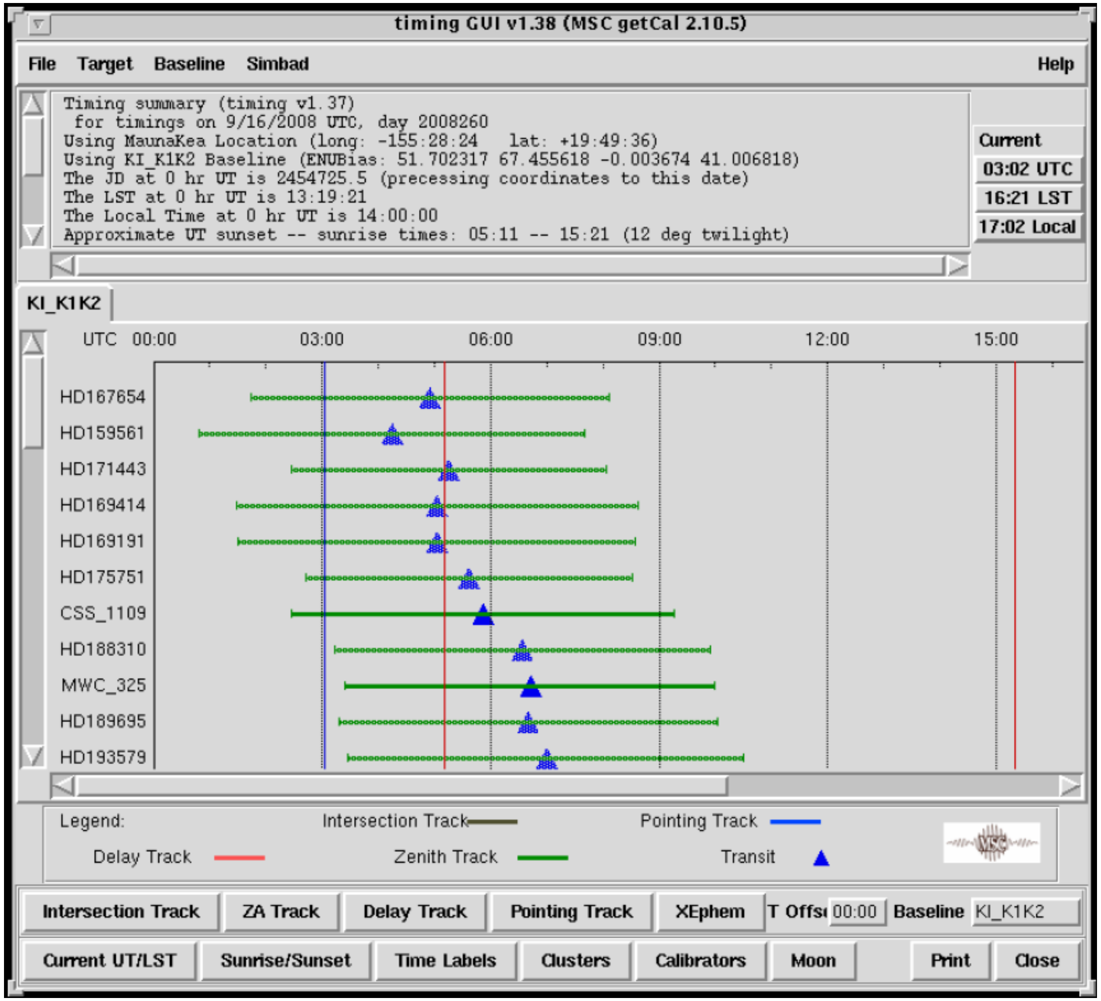
[?] Object Designation/Pos ● name ○ HD ○ HIP ○ Pos (hr:min:sec deg:min:sec)

[?] Photometry Search/Output Options
K-band: ● Model ○ 2MASS Phot
☐ N-band: ● Model ○ From IRAS Phot
☐ L-band photometry (Model)
☐ L'-band photometry (Model)
☐ Use 2MASS/IRAS measurements for calibrator search

[?] ☑ Calibrator Output
[?] ○ User specified calibrators Calibrators:
[?] ● Calibrator Search
[?] Luminosity Class: ☑ LC V ☐ LC III ☐ LC I
[?] Maximum Angular Diameter: ☐ Max Diam (mas) 1
[?] Calibrator Search Radius (deg): 10
[?] Magnitude Range: V: Min 3 Max 10.5
K: Min 6.2 Max 9.9
N: Min Max
L: Min Max

3. Planning KI Observations: Planning Tool (slide 3 of 4)

- NExScI Timing GUI
  - Timing GUI displays various tracks such as Delay Track, ZA track, Pointing Track, etc.
  - Very useful for optimizing observing in real-time



```
Timing summary (timing v1.37)
 for timings on 9/16/2008 UTC, day 2008260
Using MaunaKea Location (long: -155:28:24   lat: +19:49:36)
Using KI_K1K2 Baseline (ENUBias: 51.702317 67.455618 -0.003674 41.006818)
The JD at 0 hr UT is 2454725.5 (precessing coordinates to this date)
The LST at 0 hr UT is 13:19:21
The Local Time at 0 hr UT is 14:00:00
Approximate UT sunset -- sunrise times: 05:11 -- 15:21 (12 deg twilight)
```

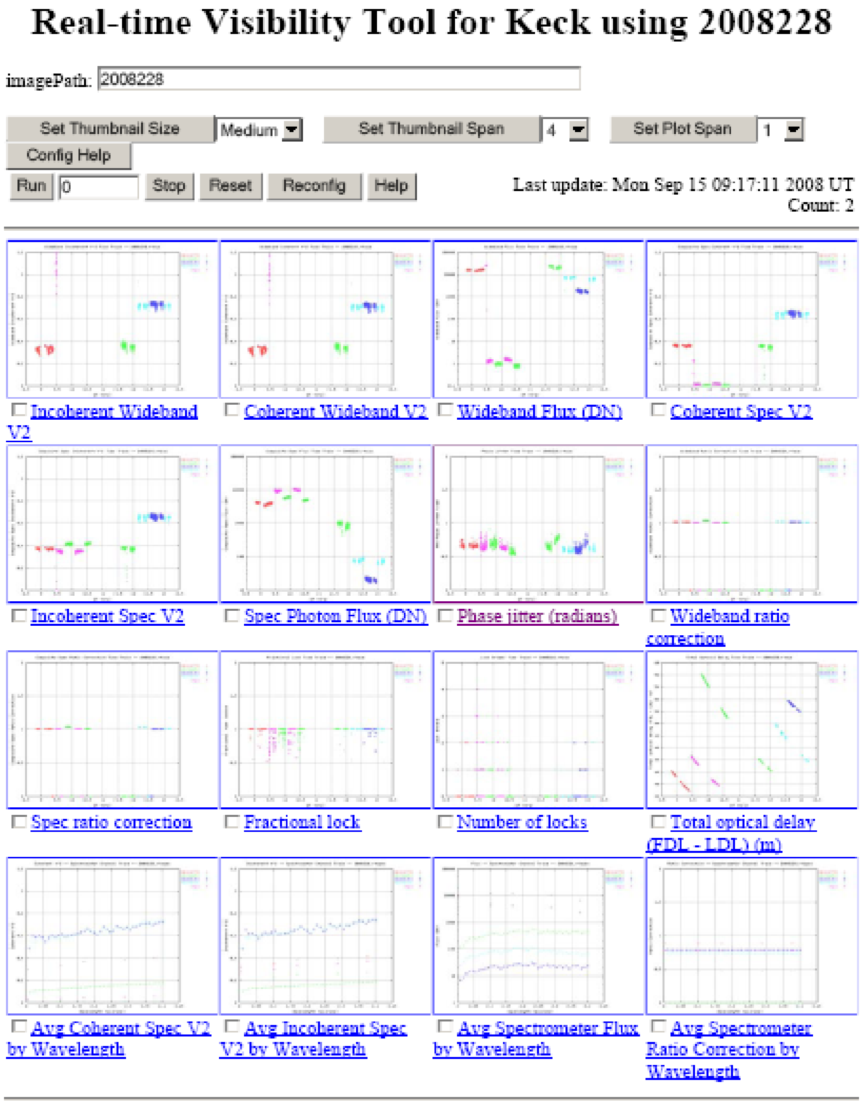
Current: 03:02 UTC, 16:21 LST, 17:02 Local

T Offs 00:00

Baseline KI_K1K2

3. Planning Observations: Near real-time visualization tool (slide 4 of 4)

- NExScI visualization tool
  - rtKvis produces near real-time Level 1 data: visibility amplitude, jitter, ratios etc.
  - Enable monitoring of the overall performance of the interferometer



Real-time Visibility Tool for Keck using 2008228

imagePath: 2008228

Set Thumbnail Size: Medium
Set Thumbnail Span: 4
Set Plot Span: 1

Run 0

Last update: Mon Sep 15 09:17:11 2008 UT
Count: 2

4. V^2 Science Results (Slide 1 of 9)

V^2 Science Highlights

- A total of 18 refereed publications
- Since 2007: 6 refereed publications + 1 submitted paper
  - Spatially resolving inner YSO disks (3 papers)
  - PMS stellar masses & evolutionary models (3 papers)
  - Circumstellar environment of evolved stars (1 paper)

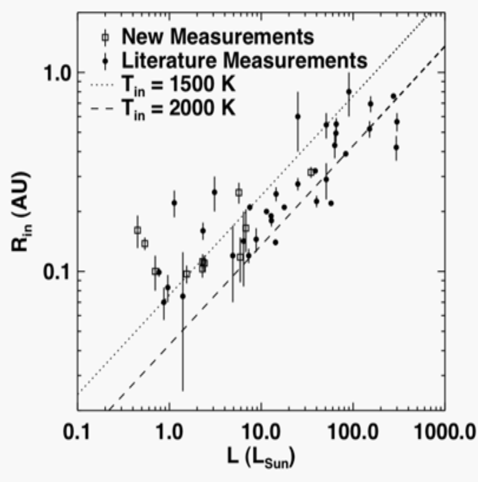
V^2 Observing efficiency

- 62% of the sky time used for science
- Lost the rest for weather and instrument problems
  - ~ 26% for bad weather
  - ~ 4% for Telescope/Adaptive Optics problems
  - ~ 7% for Interferometer instrument problems
    - ~ 2% if we exclude one night which had a major h/w failure

4. V^2 Science Results (Slide 2 of 9)

Resolving YSO inner disks

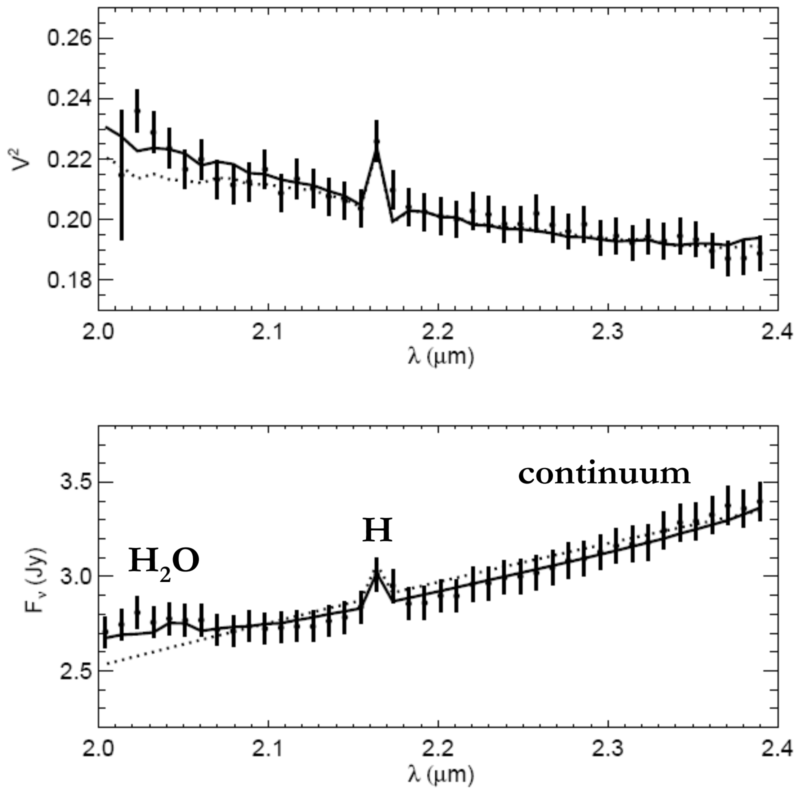
- Protoplanetary disk studies at high angular resolution could provide insight into how planets form
- Study of the inner most regions may reveal the mechanism responsible for accretion through the disk onto the star
- T Tauri stars with luminosities > 10 L_{Sun} agree with predictions from puffed-up inner disk model
- At lower luminosities, the measured inner ring radii is larger than the model values.
  - Stellar magnetosphere may truncate the dusty inner disk (Eisner 2007)
- At high luminosities, some measured NIR sizes are smaller than dust sublimation radius.
  - Shielding of dust wall by UV gas opacity (Monnier & Millan-Gabet 2002)
  - "standard" flat disk (Eisner 2004)



Eisner et al. 2007

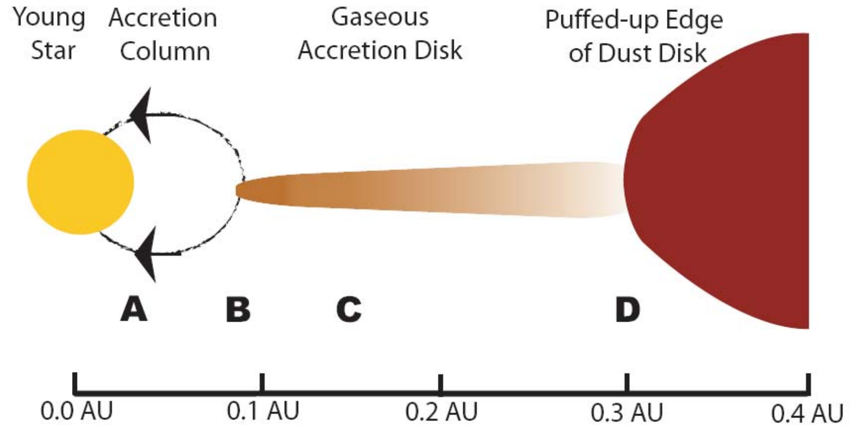
4. V^2 Science Results (Slide 3 of 9)

Water Vapor and Hydrogen in the Terrestrial Planet Forming Region of a Protoplanetary Disk



Measured V^2 and fluxes, compared to the predictions of simple physical models
- J A Eisner, Nature, 31 May, 2007

- Detected compact water & hydrogen gas around MWC 480
- The hydrogen gas appears to trace accretion onto the central star.
- The large amounts of water in the habitable zone may contribute to the formation of habitable planets.

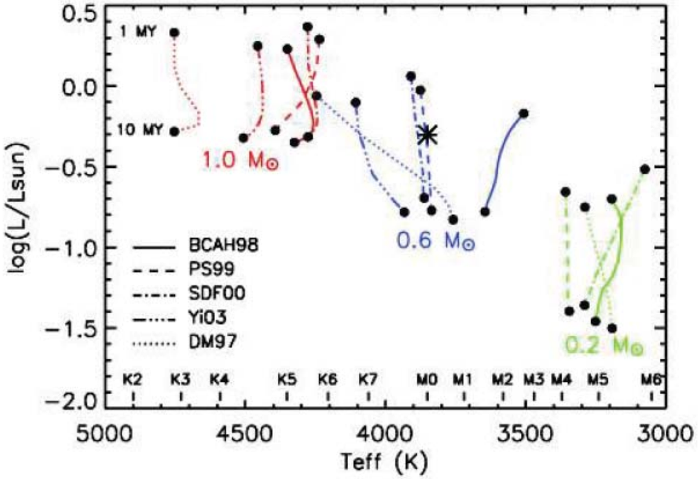


The environment within 1 AU of the young star MWC 480.
- J A Eisner, Nature, 31 May, 2007

4. V^2 Science Results (Slide 4 of 9)

Masses of Pre-Main Sequence Stars

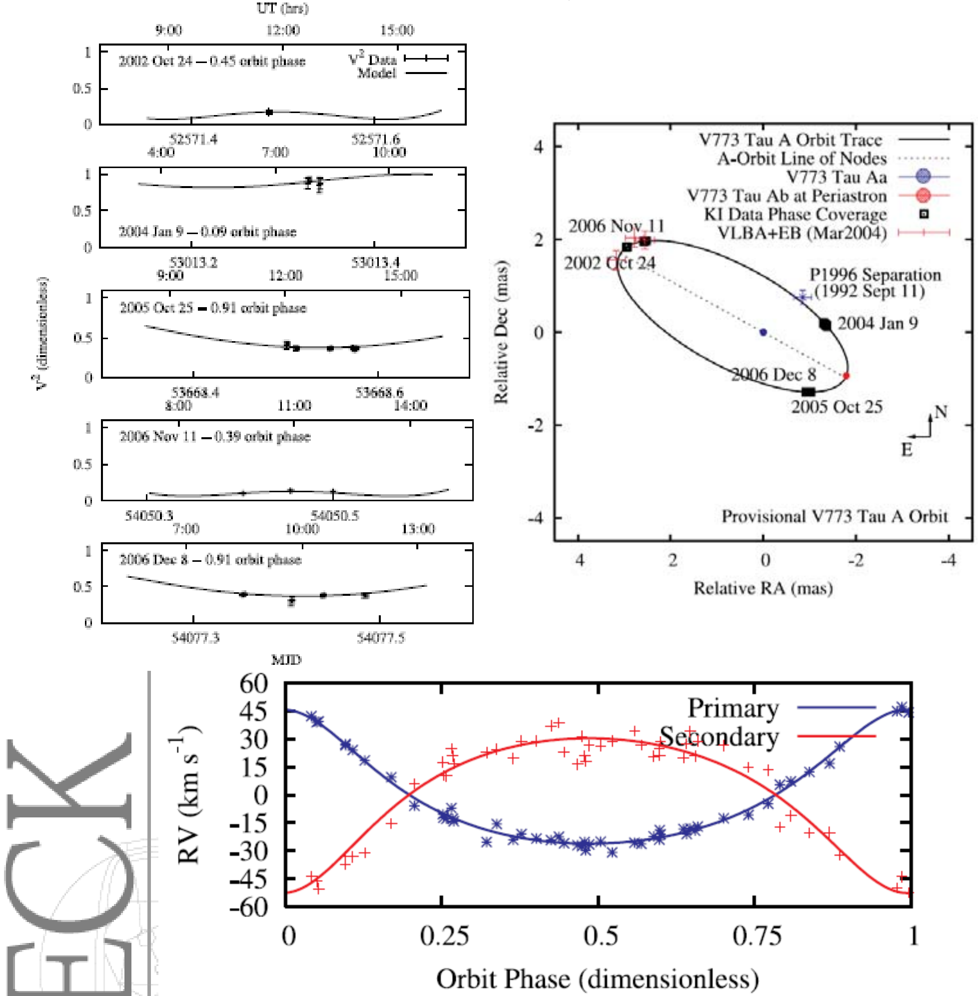
- The mass of a star determines how a star evolves throughout its lifetime
- Accurate masses and ages are needed for understanding a region's star formation history and IMF.



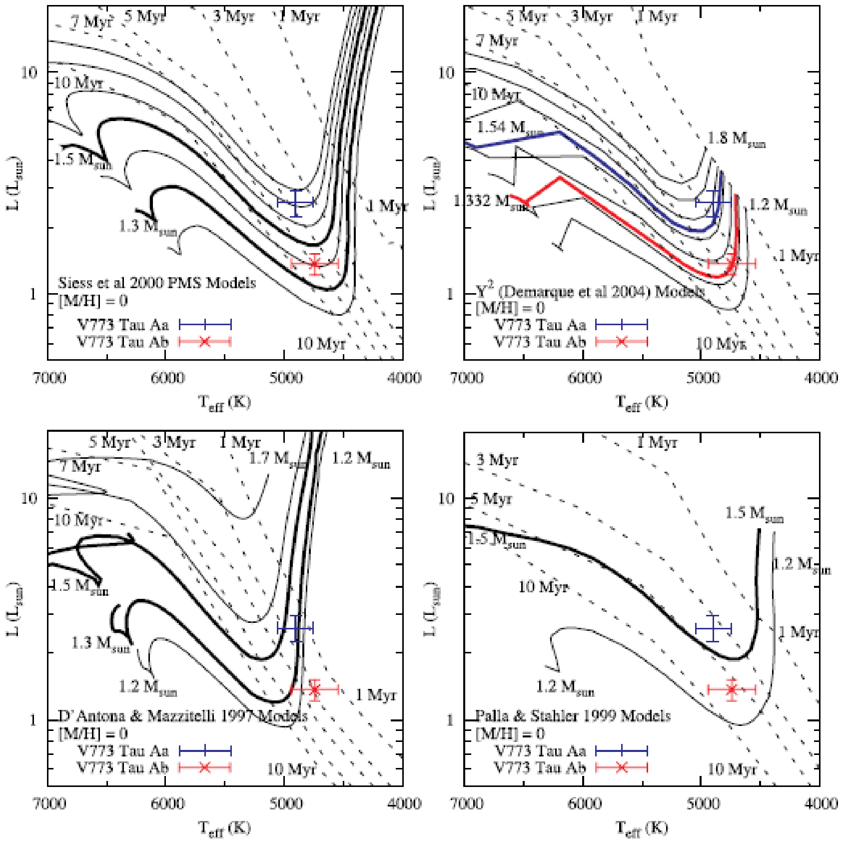
- Masses and ages of PMS stars are commonly determined from a star's location in the HR-diagram
- Different sets of evolutionary tracks yield discrepant results, particularly for $M_* < 1\ M_{sun}$
- High precision dynamical masses are required to calibrate the evolutionary tracks
- In combination with RV measurements, astrometric orbit yields physical orbit & individual masses

4. V^2 Science Results (Slide 5 of 9)

Orbit of the PMS Binary V773 Tau A



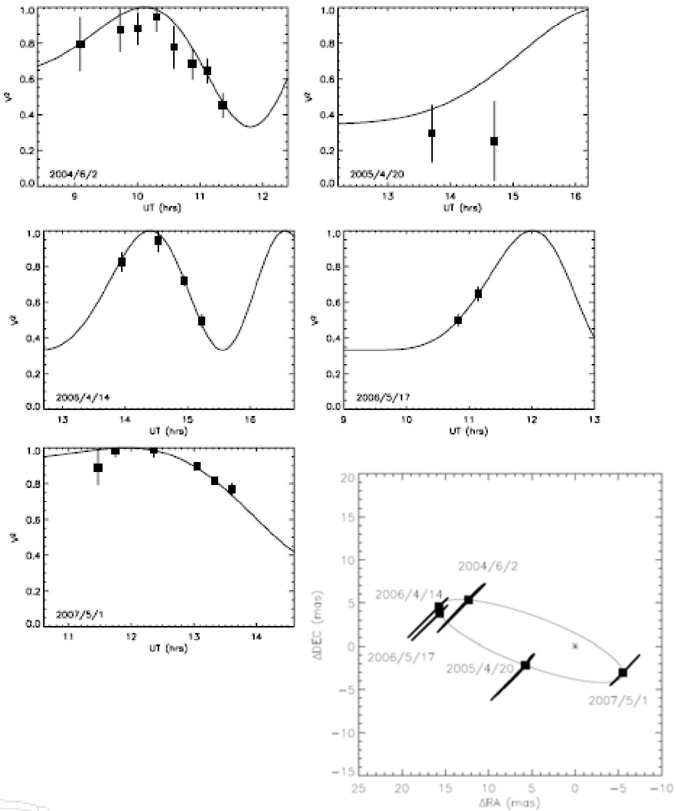
Orbit of V773 Tau A as derived by Hybrid solution - A. Boden et al., 2007, ApJ, 670, 1214



V773 Tau A components compared to PMS models - A. Boden et al., 2007, ApJ, 670, 1214

4. V^2 Science Results (Slide 6 of 9)

Orbit of the Young Binary Haro 1-14c



Best-fit orbit for Haro 1-14c. The large squares indicate the orbital position at the epochs of the KI observations.
- G. H. Schaefer et al., 2008

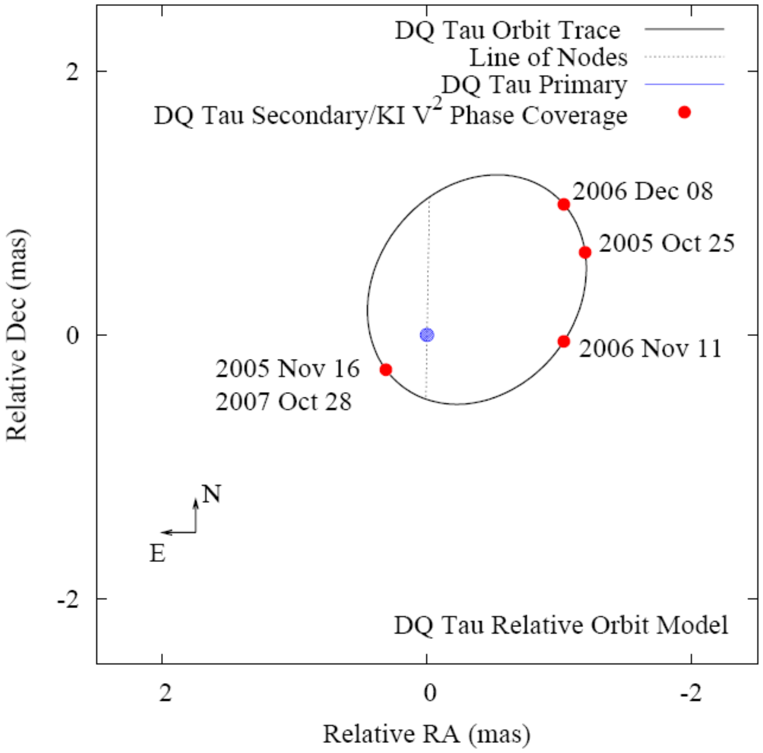
- Simultaneous orbit fit to KI visibilities and spectroscopic RV data

Parameter	Value
$M_1(M_\odot)$	$0.961^{+0.265}_{-0.083}$
$M_2(M_\odot)$	$0.326^{+0.092}_{-0.023}$
d (pc)	$111.^{+19}_{-18}$

- Based on comparison with evolutionary tracks, the age of Hara 1-14c is estimated to be 3-4 Myr
- With continued KI measurements to improve the orbit, the Haro 1-14c binary would provide useful constrains on calibrating PMS evolutionary tracks

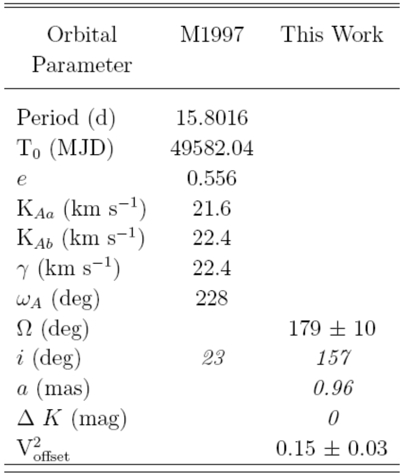
4. V^2 Science Results (Slide 7 of 9)

Orbit of the PMS Binary DQ Tau



Relative Visual Orbit of DQ Tau.
- A. Boden et al., 2008, ApJ (submitted)

- Partially resolved by KI
  - Ω & the sense of rotation on the sky
- Compact excess source ~ 0.2 AU
  - Dynamical clearing expected in such a binary system is not completely successful in dispersing the material



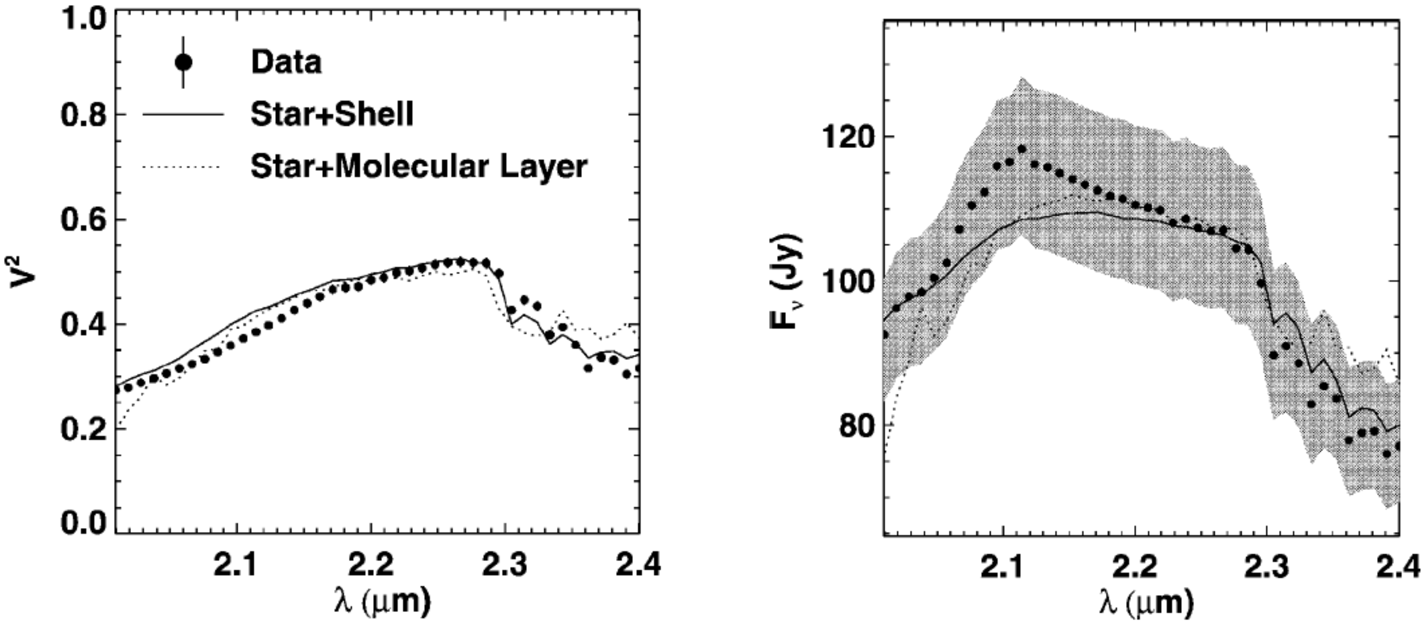
Orbital Parameter	M1997	This Work
Period (d)	15.8016	
T_0 (MJD)	49582.04	
e	0.556	
K_{Aa} (km s^{-1})	21.6	
K_{Ab} (km s^{-1})	22.4	
γ (km s^{-1})	22.4	
ω_A (deg)	228	
Ω (deg)		179 ± 10
i (deg)	*23*	*157*
a (mas)		*0.96*
ΔK (mag)		*0*
V^2_{offset}		0.15 ± 0.03

Orbital Parameters for DQ Tau.
- A. Boden et al., 2008, ApJ (submitted)

4. V^2 Science Results (Slide 8 of 9)

Stellar and molecular Radii of the Mira star R Vir

- Size changes significantly w/ wavelength in 2 – 2.4 μm region
- Photospheric size uncontaminated by molecular layer (R ~ 230)
- Molecular layers are roughly 2 R_*

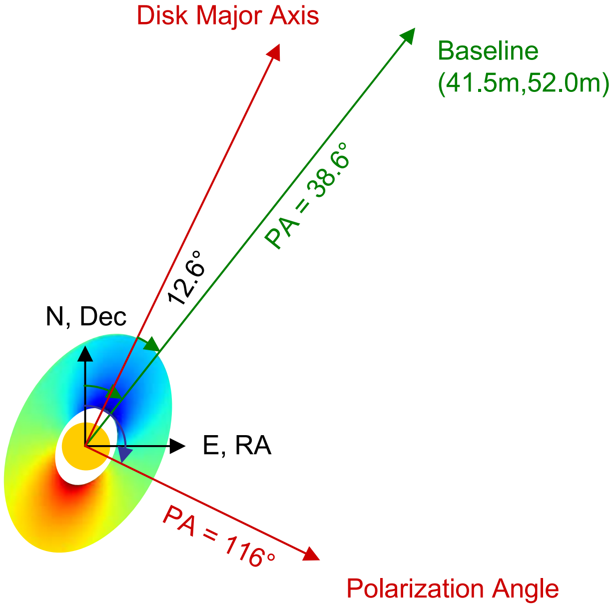


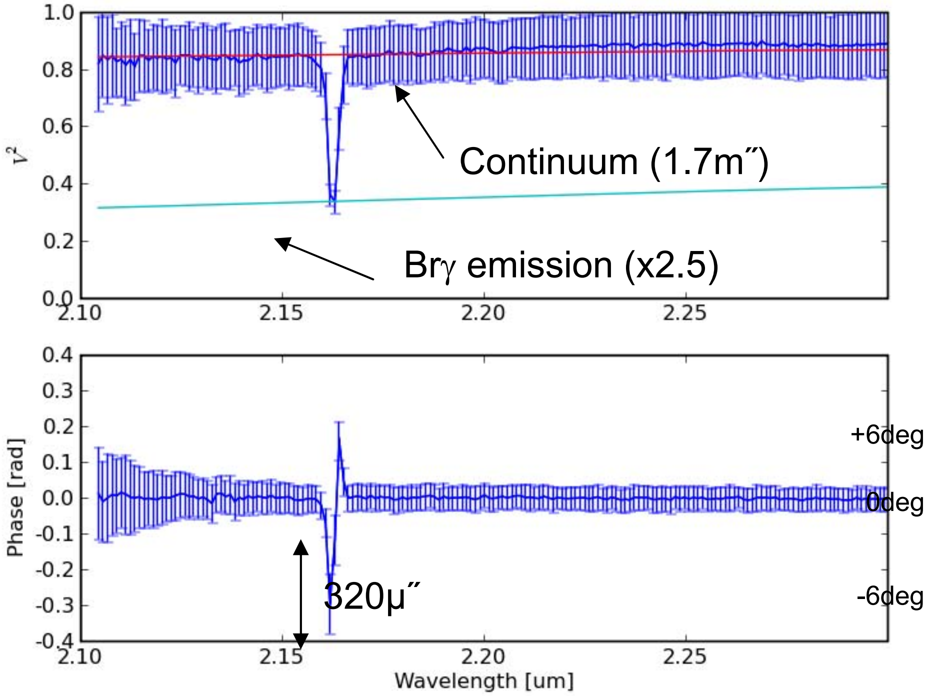
Observed and fluxes V2 plotted with the predictions of the best-fit models.
- J A Eisner et al. 2007, ApJL, 654, 77

4. V^2 Science Results (Slide 9 of 9)

Self Phase Referencing - an illustration on a Be star

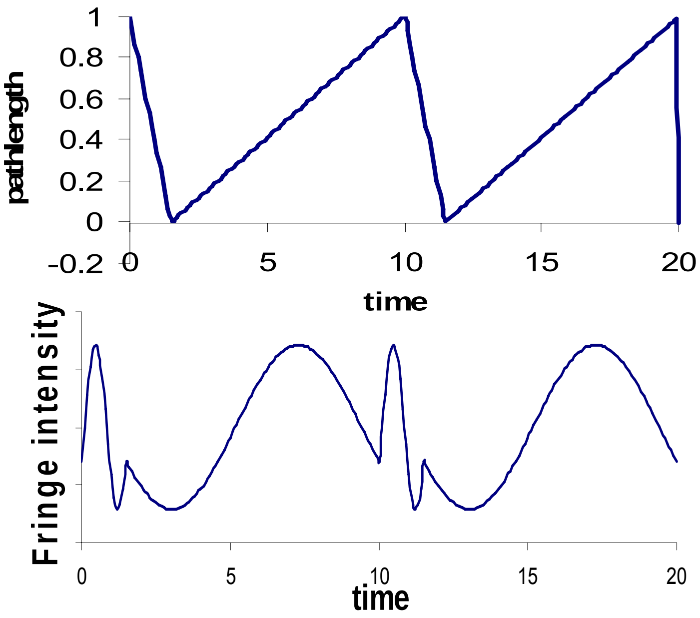
- An illustration on a Be star
  - Doppler broadened Brγ emission line
  - Disk major axis aligned with baseline as deduced from polarization angle measurements from the literature
  - Differential phase signature

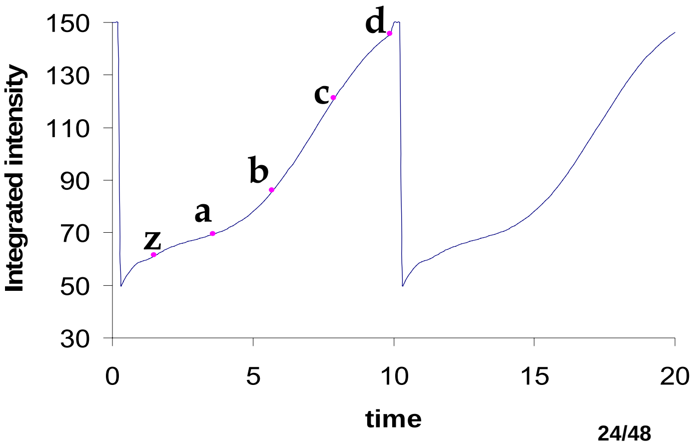




5. V^2 Basics: Fringe measurement (slide 1 of 5)

- Five synchronized reads are made while delay line scans over one wavelength
  - One reset (z), followed by four non-destructive reads (a, b, c, d) spaced at $\lambda/4$ intervals as detector integrates up
  - Fluxes per quarter-wave bins just A = a –z, B = b – a, etc.
- Reads are combined to compute the fringe quadratures, and a measure of correlated and total flux
  - Cosine quadrature X = A - C
  - Sine quadrature Y = B - D
  - Total flux N = A + B + C + D
  - NUM (square of correlated flux) = $X^2 + Y^2$
- Reads made for
  - White-light pixel ("wide-band"); 1st beamsplitter output
  - Spectrometer pixels ("narrow band"); 2nd beamsplitter output; 4, 5, 42 or 330 spectrometer pixels across K band





5. V^2 Basics: Fringe measurement (slide 2 of 5)

- Fringe parameter estimation
  - Phase $\phi = \arctan(Y/X)$
  - Visibility $V^2 = (\pi^2/2)$ NUM / N^2
  - SNR2 (squared signal to noise ratio)
    - Optimal: SNR2 $\propto$ NUM / (N + bias)
    - Scintillation-invariant: SNR2' $\propto$ NUM' / (N + bias)
      - » NUM' uses a different computation of X and Y to rejects false signal due to scintillation
- Fringe parameter estimation is performed in two regimes
  - Real time, to provide fringe tracking
  - Post processing, to produce science data
- Both use the same basic algorithms, post processing is more rigorous and does more calibration

5. V^2 Basics: Detector bias corrections (slide 3 of 5)

- Fringe parameters need to be bias corrected
- Bias corrections

1. Background calibration
    - Measured from mean of reads on dark sky; removed from N
2. Detector reset tail, i.e., quadrature offset
    - Measured from mean of reads on dark sky; Removed from X, Y
3. Read noise
    - Measured from variance of reads on dark sky; Removed from NUM
4. Photon counting bias
    - Detector gain computed based on noise change with white-light source flux; Removed from NUM based on average flux during interval and detector gain

- Quantities are also “dewarped” based on ratio between exact wavelength and scan length

5. V^2 Basics: Additional calibrations (slide 4 of 5)

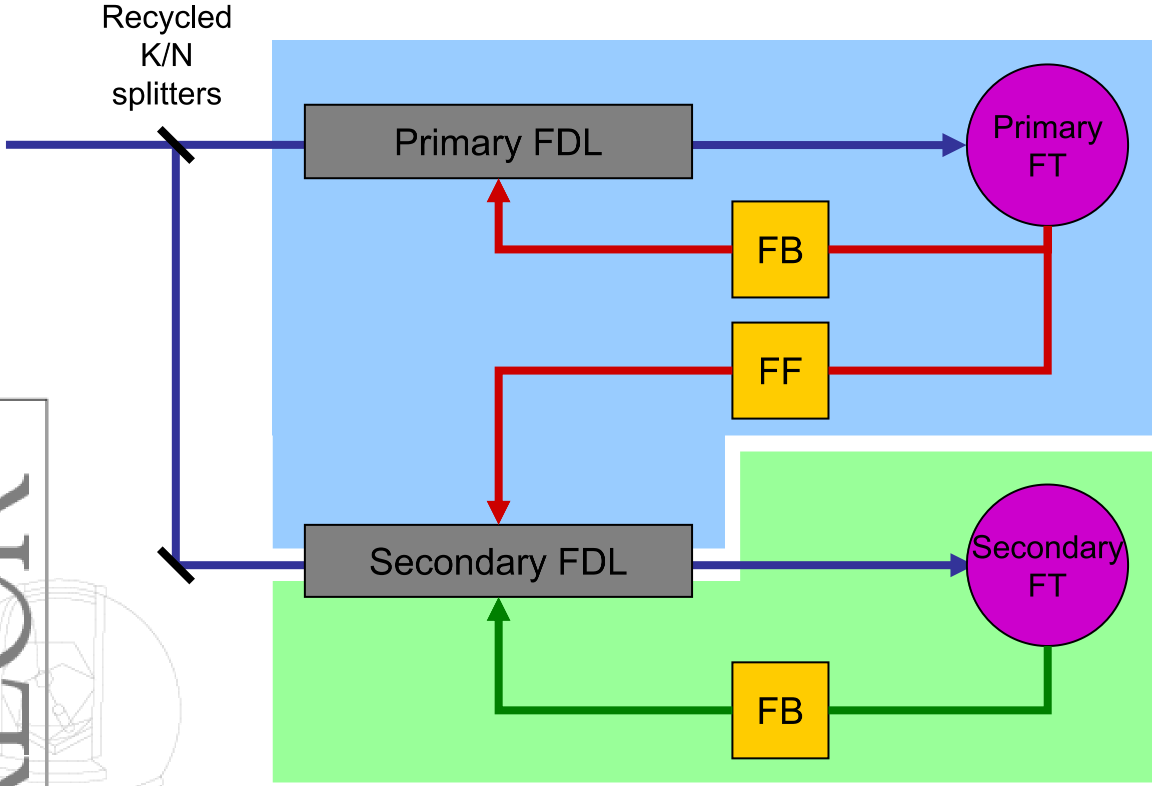
- Post processing does the following additional calibrations

1. Correction for intensity imbalance
   - Intensity imbalance reduces the mean V^2 by the factor $1 – 4\, I_1\, I_2 / (I_1+I_2)^2$, where I_1 and I_2 are the average single-aperture fluxes
2. Non-unity (system fringe contrast) measurements
   - After detector calibrations & amplitude calibrations, fringe-contrast remains non-unity even for a point source.
   - Reasons:
     - Temporal blurring due to atmospheric seeing and vibration
     - Static effects: image rotation, polarization rotation, etc.
   - Calibrator stars of known sizes are used to determine system fringe contrast for a given observing condition

- To first order, calibrated visibility is science visibility normalized by calibrator visibility, after accounting for calibrator size

5. V^2 Basics: SPR Concept (slide 5 of 5)

- Dedicated cameras for fringe-tracking and science integration
- Enabling long integration on science camera
- Fringe tracker limits the sensitivity of this mode
    - High spectral resolution of bright science targets

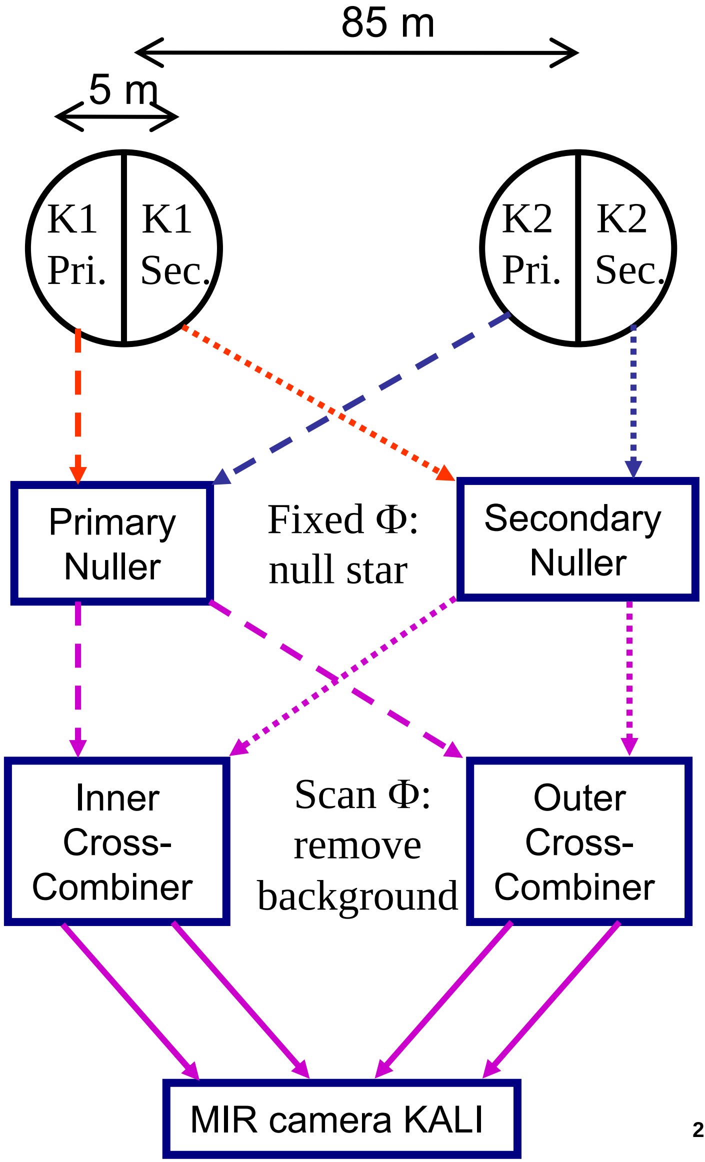


- Fast Servo
- Closed loop feed-back
- Open loop feed-forward

- Slow Servo
- Limited feed-back
- Long integration times
- High Spectral Resolution

5. Nuller Basics: Concept (slide 1 of 8)

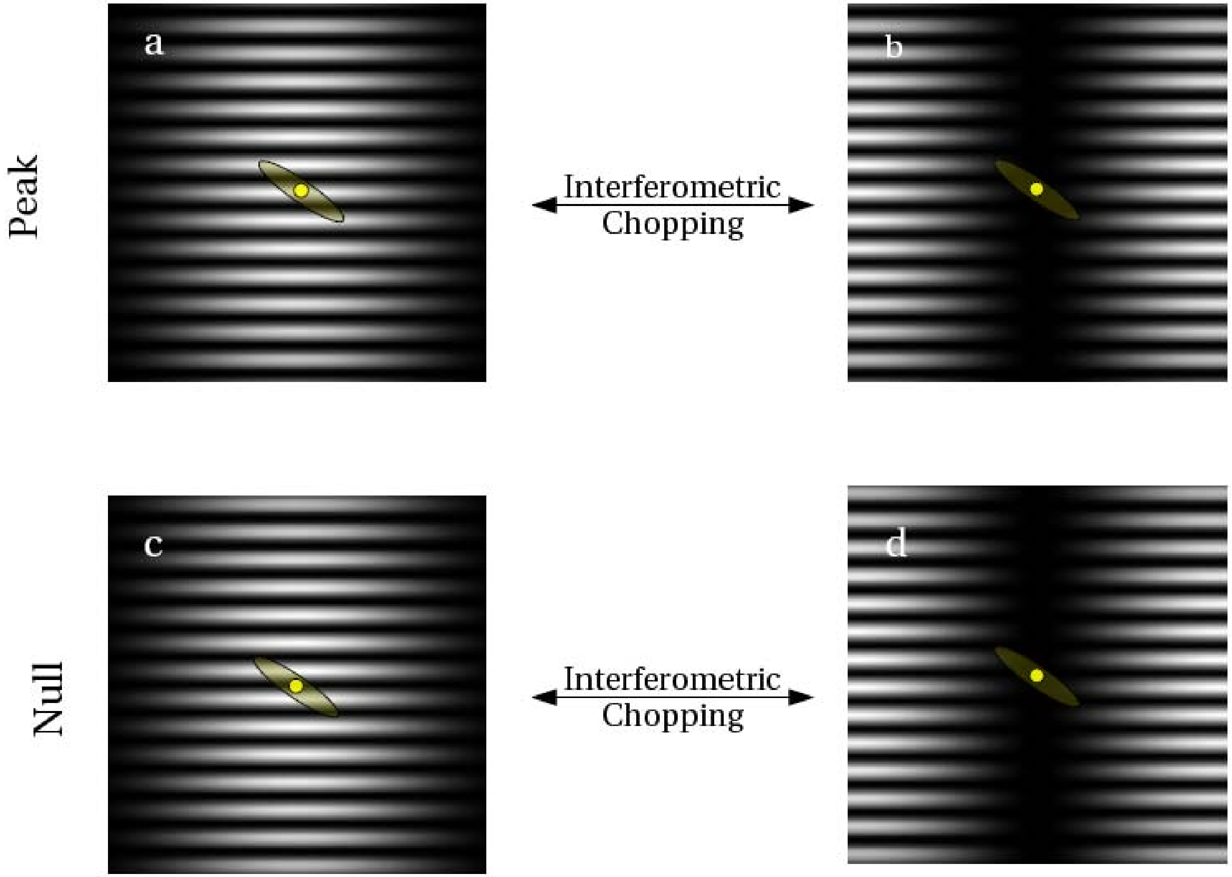
- Measures the faint emission from Exo-zodiacal dust
- Two extraneous signals
  - Strong light from central star
  - Strong 10 μm background
- Need to remove both
  - Null the star with interferometers on the long 85-m baselines
  - Combine these outputs in a second interferometer: the cross combiner
  - Scan the cross fringe on the short 4-m baseline to detect the signal in the presence of background



5. Nuller Basics: Concept (slide 2 of 8)

Null Measurement: Chopping between four fringe states

Fringe patterns on the sky, with a realistic star+disk system to scale



Peak

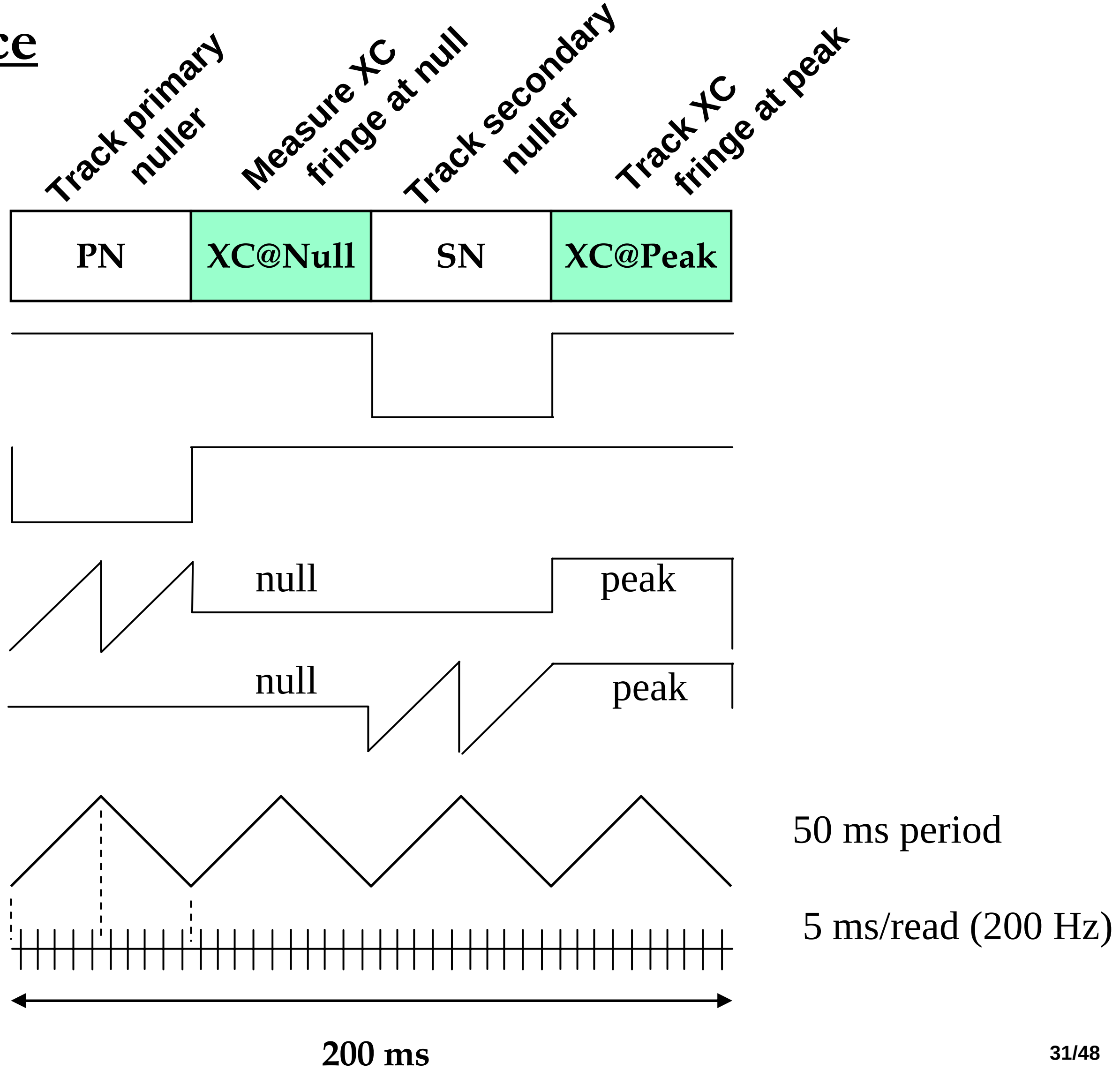
Interferometric Chopping

Null

Interferometric Chopping

5. Nuller Basics: Null measurements (slide 3 of 8)

Gated mode sequence



Primary nuller spatial chop

Secondary nuller spatial chop

Primary nuller OPD

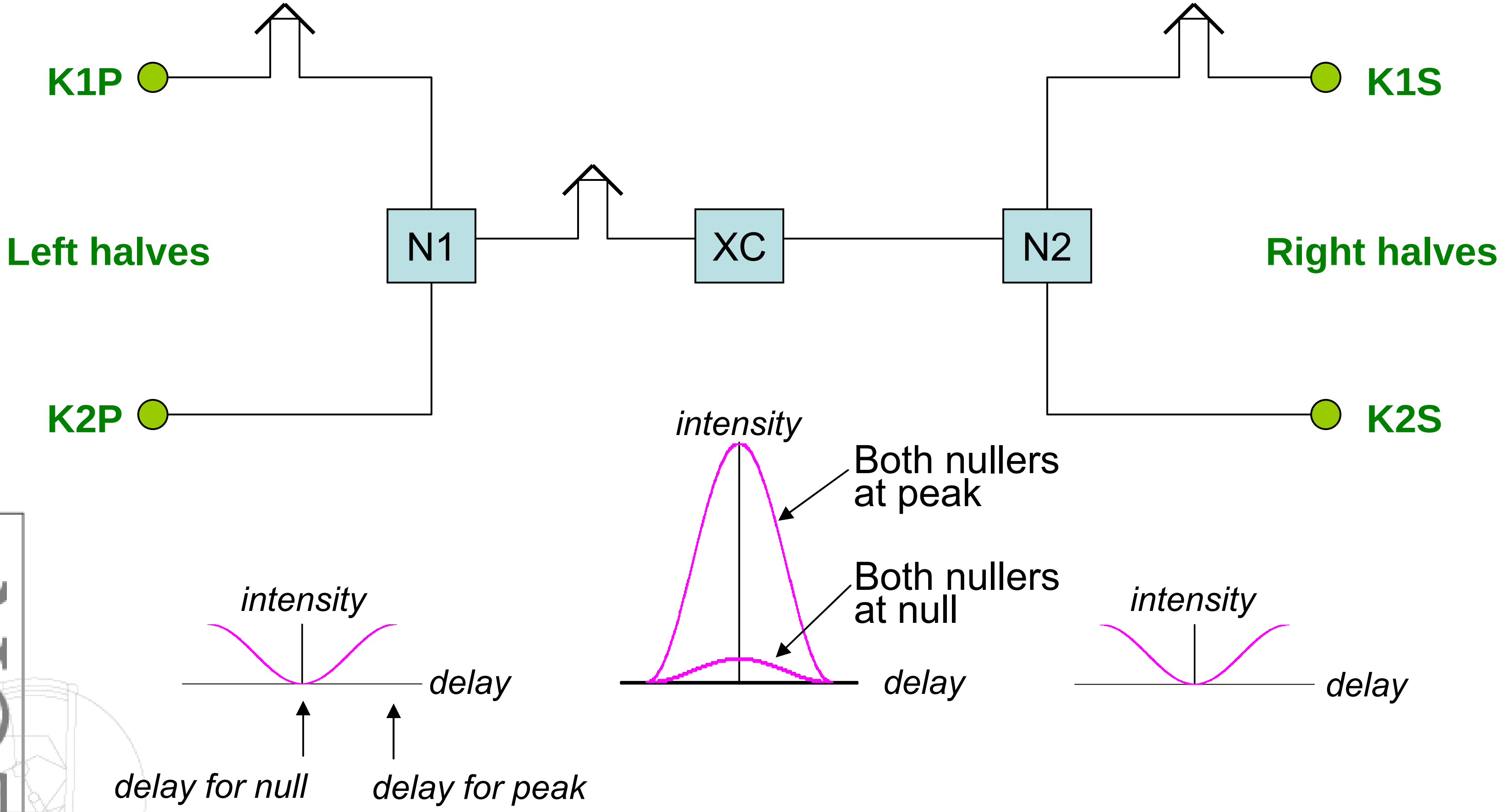
Secondary nuller OPD

Cross-combiner OPD dither
(5 KALI reads/segment)

KALI reads: 5/XC ramp

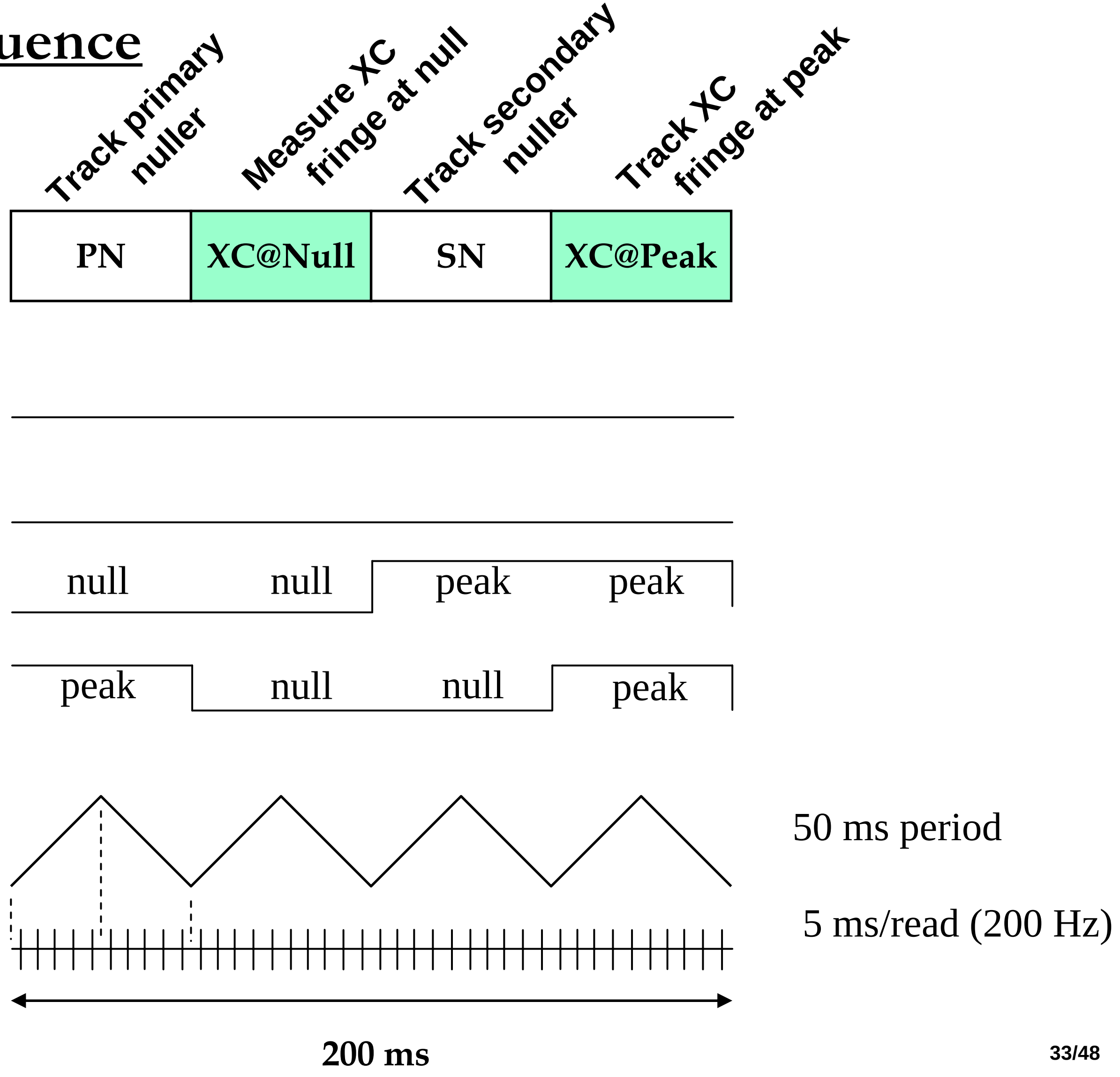
5. Nuller Basics: Null measurements (slide 4 of 8)

Dual-nuller architecture and signals



5. Nuller Basics: Null measurements (slide 5 of 8)

Null-peak mode sequence



Track primary nuller

Measure XC fringe at null

Track secondary nuller

Track XC fringe at peak

PN	XC@Null	SN	XC@Peak

Primary nuller spatial chop

Secondary nuller spatial chop

Primary nuller OPD: null, null, peak, peak

Secondary nuller OPD: peak, null, null, peak

Cross-combiner OPD dither (5 KALI reads/segment)

50 ms period

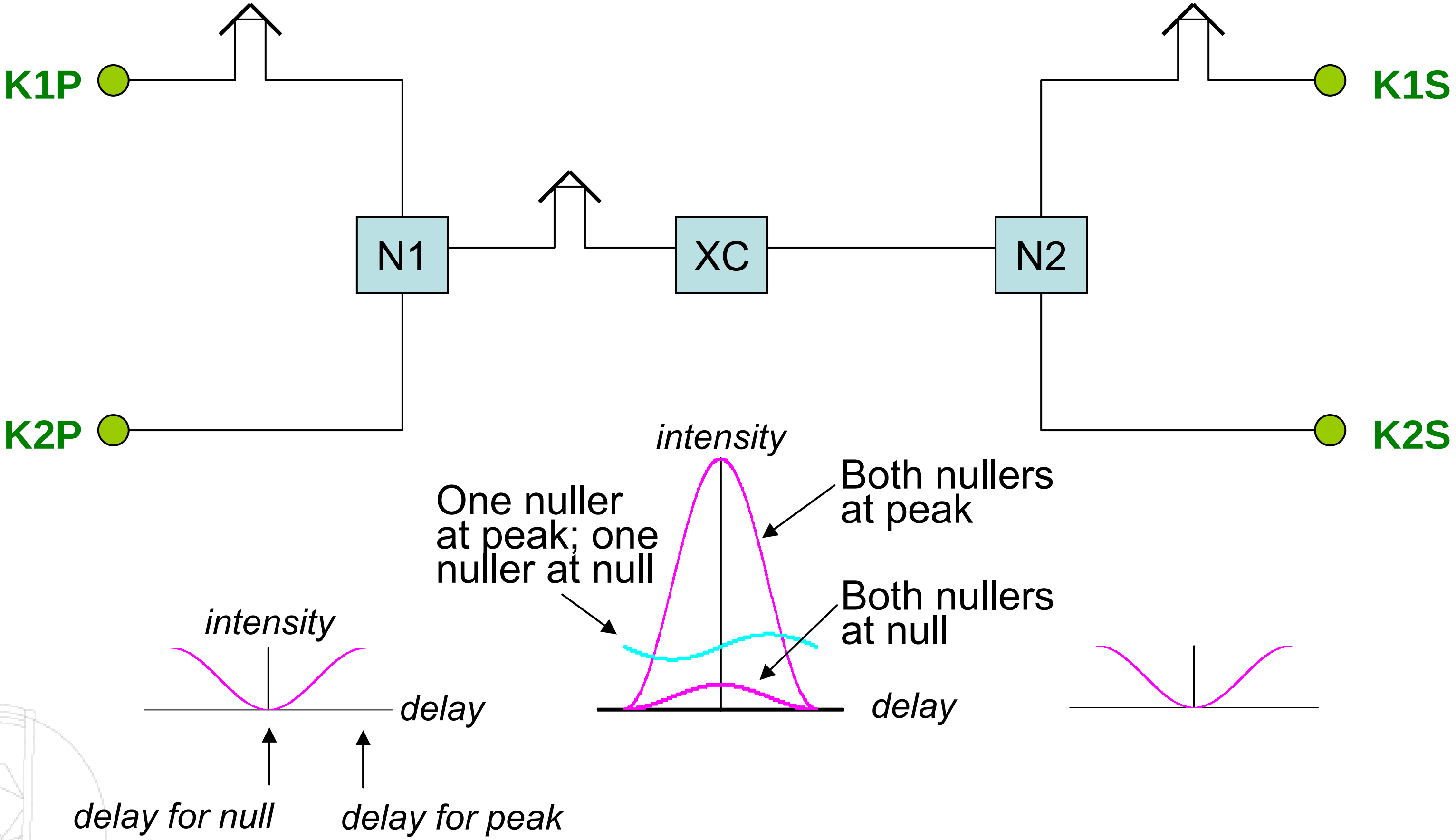
KALI reads: 5/XC ramp

5 ms/read (200 Hz)

200 ms

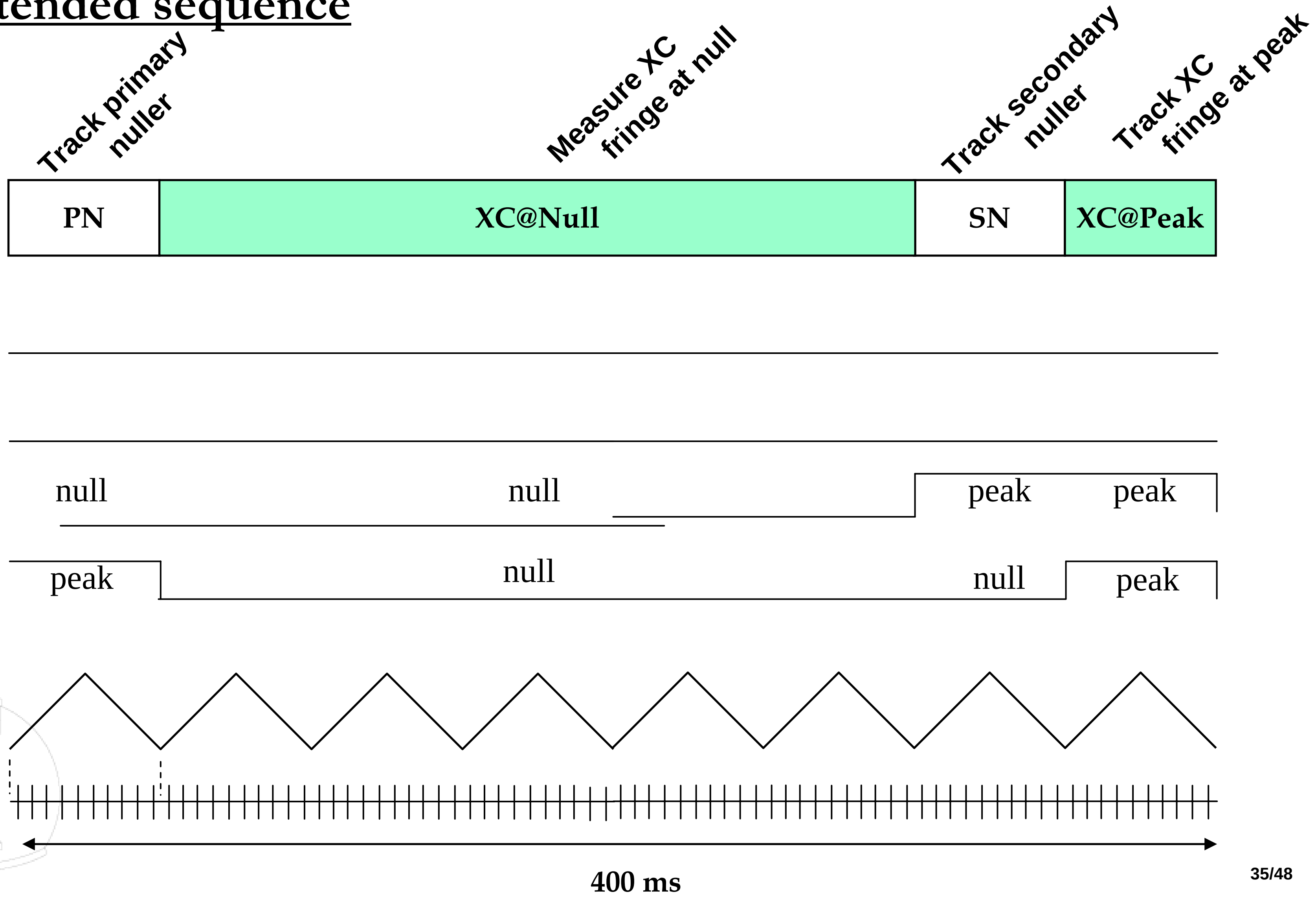
5. Nuller Basics: Null measurements (slide 6 of 8)

Null-peak mode



5. Nuller Basics: Null measurements (slide 7 of 8)

Extended sequence



Track primary nuller
Measure XC fringe at null
Track secondary nuller
Track XC fringe at peak

PN
XC@Null
SN
XC@Peak

null
null
peak
peak

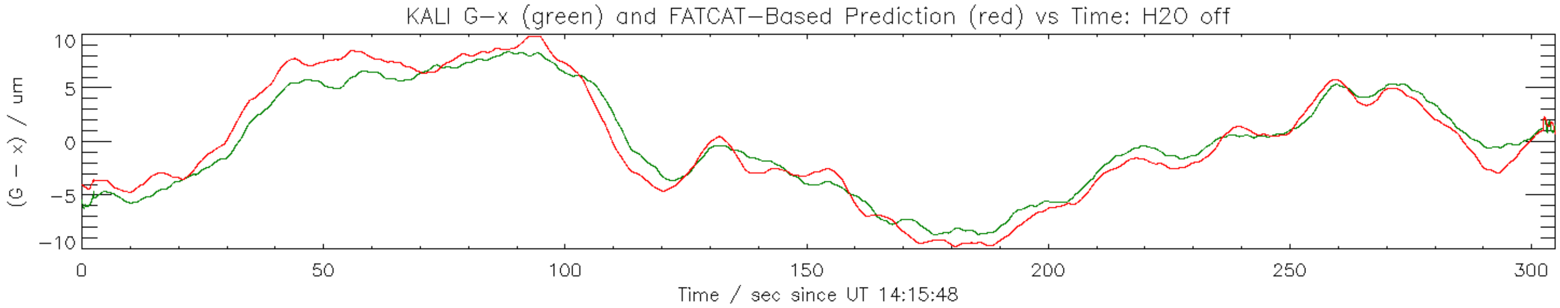
peak
null
null
peak

400 ms

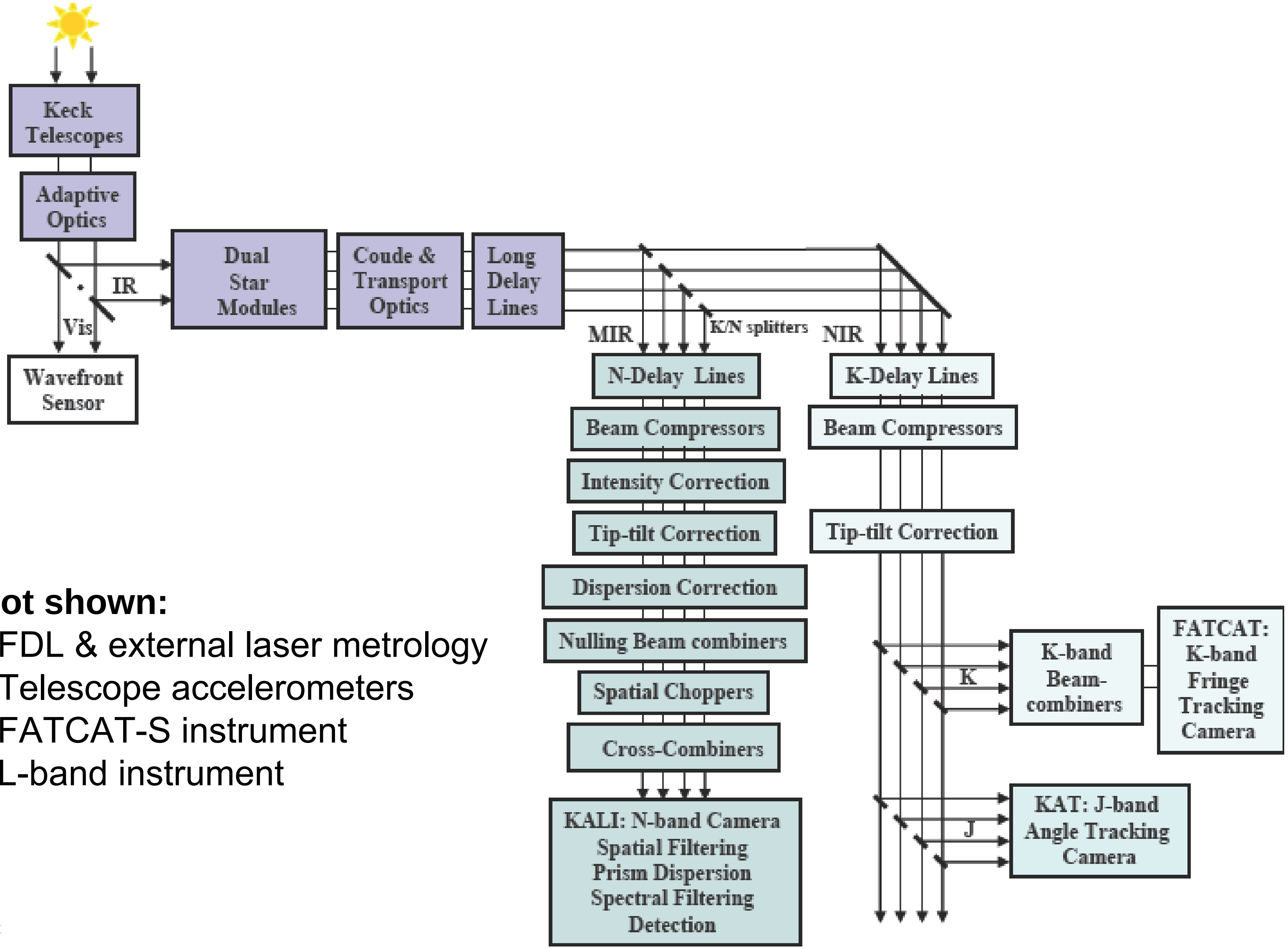
5. Nuller Basics: Null measurements (slide 8 of 8)

Co-phasing and water vapor dispersion corrections

- Feed-forward to Nuller FDLs
  - Nuller FDLs are phase-referenced with 2μm fringe measurements
- Feed-forward to Nuller ADCs
  - Water vapor seeing, while smaller in amplitude, is not achromatic
    - At 2 μm, it contributes ~1/20 total OPD
    - At 10 μm, it contributes ~1/7 total OPD
  - Dispersion due to water vapor seeing is estimated from 2μm fringe data and extrapolated to 10 μm wavelength region.
  - Dry air seeing predominates in the optical, and is relatively achromatic
- Data matches theory well



6. Instrumental Overview: Schematic diagram (slide 1 of 11)


Keck Telescopes

Adaptive Optics

IR

Vis

Wavefront Sensor

Dual Star Modules

Coude & Transport Optics

Long Delay Lines

MIR

K/N splitters

NIR

N-Delay Lines

Beam Compressors

Intensity Correction

Tip-tilt Correction

Dispersion Correction

Nulling Beam combiners

Spatial Choppers

Cross-Combiners

KALI: N-band Camera
Spatial Filtering
Prism Dispersion
Spectral Filtering
Detection

K-Delay Lines

Beam Compressors

Tip-tilt Correction

K

K-band Beam-combiners

FATCAT: K-band Fringe Tracking Camera

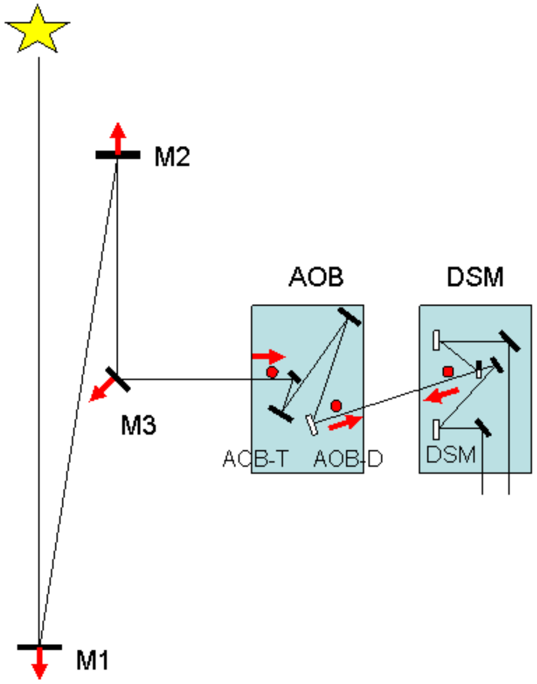
J

KAT: J-band Angle Tracking Camera

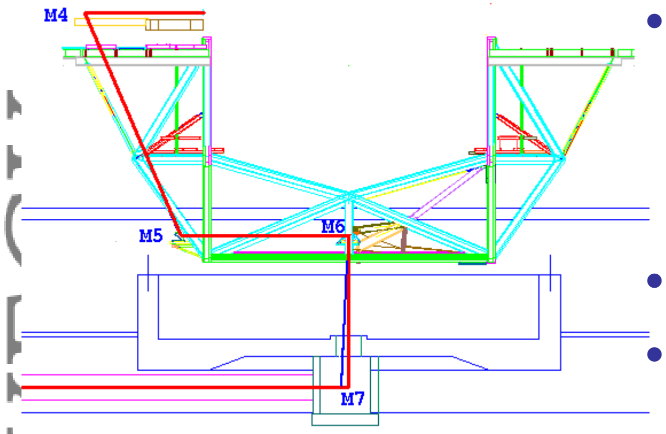
Not shown:

- FDL & external laser metrology
- Telescope accelerometers
- FATCAT-S instrument
- L-band instrument

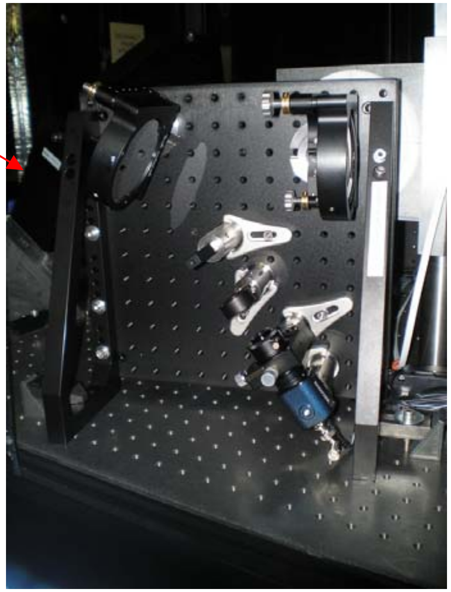
6. Instrumental Overview: DSM & Coude & Transport optics (slide 2 of 11)



- Slides in adjacent to AO system like other Nasmyth instruments
- Left-right pupil split at DSM (for Nulling mode)
  - “Primary” beam down passive coude
  - “Secondary” beam down active coude – M6 and M7 track azimuth
- For V2 use, DSM serves as a beam relay using only the full-aperture primary beam
- Metrology end-points on DSM behind visible transmissive dichroics
- Shear sensors on DSM

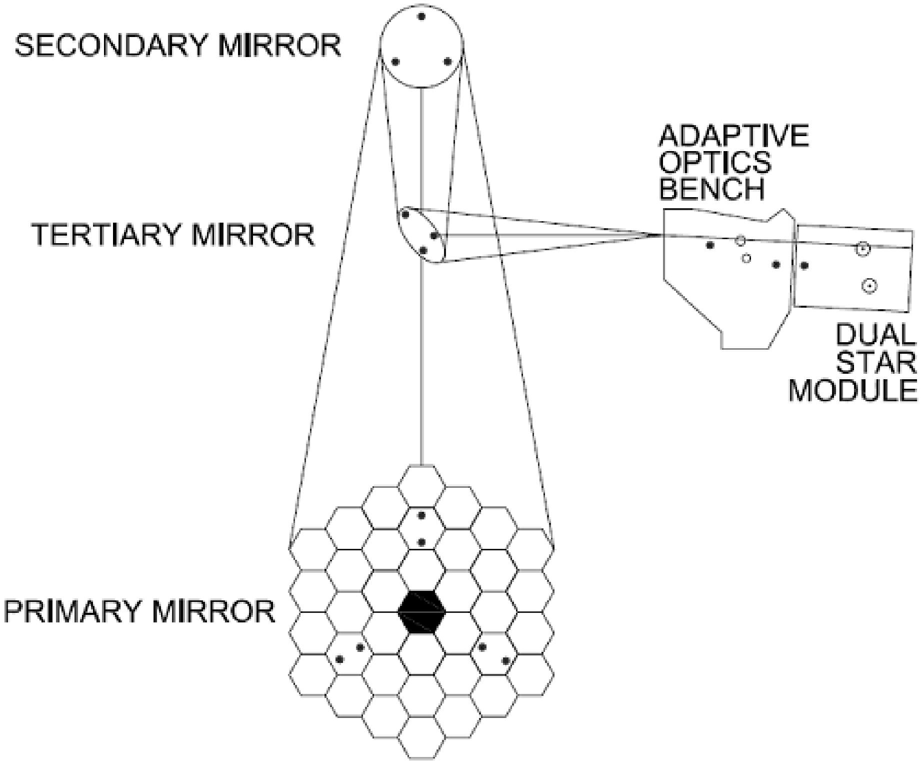


- Transport from DSM via coude beam train to crypt at base of telescope
  - Window seals crypt
- Transport to long delay line
- Transport from long delay line to fast delay line

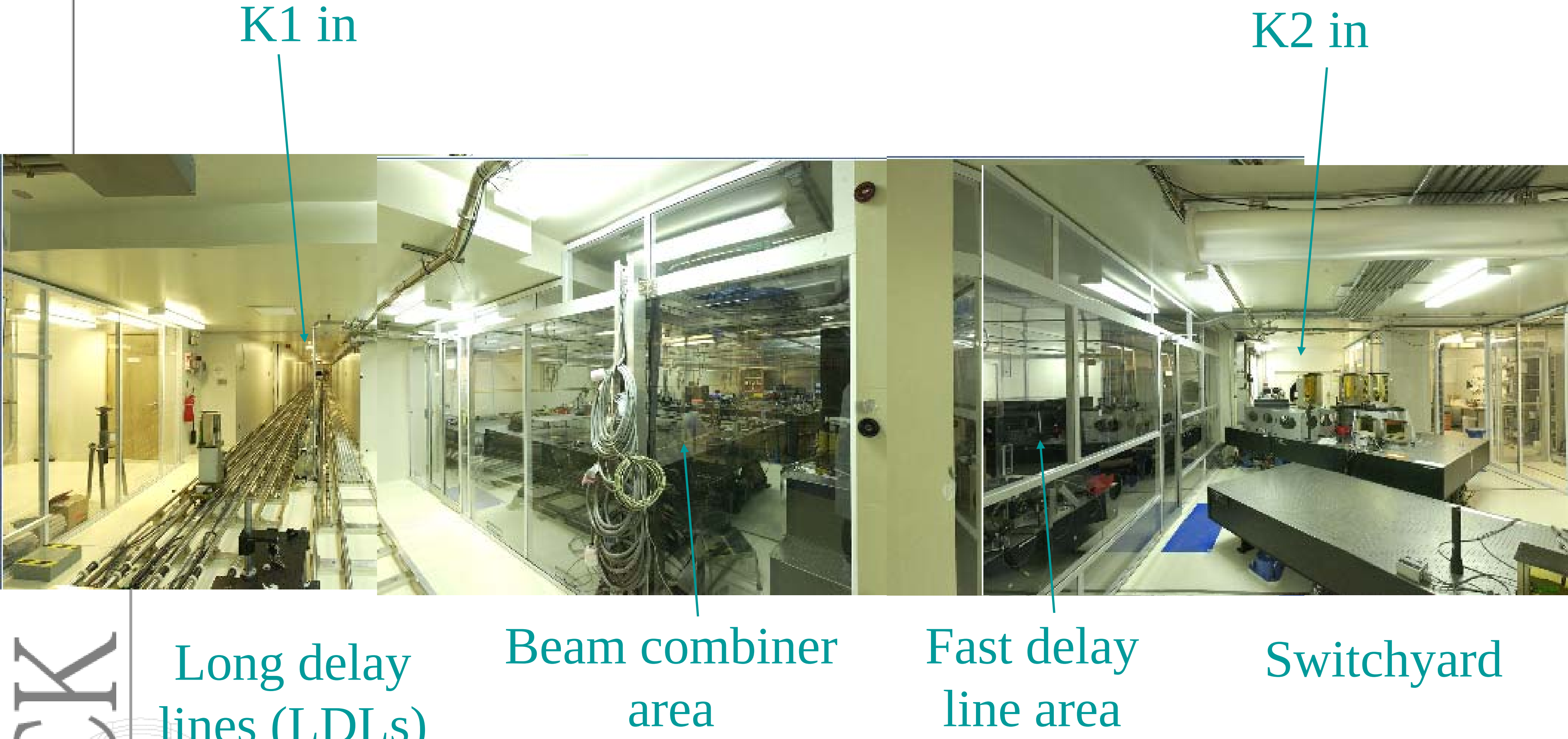


6. Instrumental Overview: Accelerometer feedforward system (slide 3 of 11)

- For each telescope
  - 6 accels installed on primary
  - 3 each on secondary, tertiary
  - 3 on AOB and DSM
- Signals combined to generate feedforward correction to FDL to cancel pathlength variation contributed by telescope
  - Generally a small effect for current frame rates



6. Instrumental Overview: Basement sub-systems (slide 4 of 11)

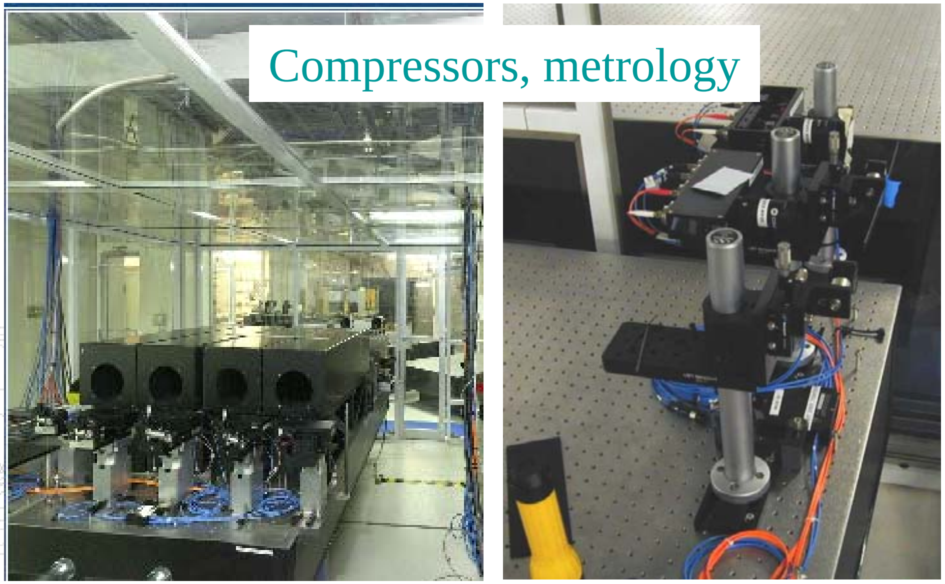


- LDLs Provide coarse delay positioning
  - Static within clusters

6. Instrumental Overview: Fast delay line & Beam compressor (slide 5 of 11)

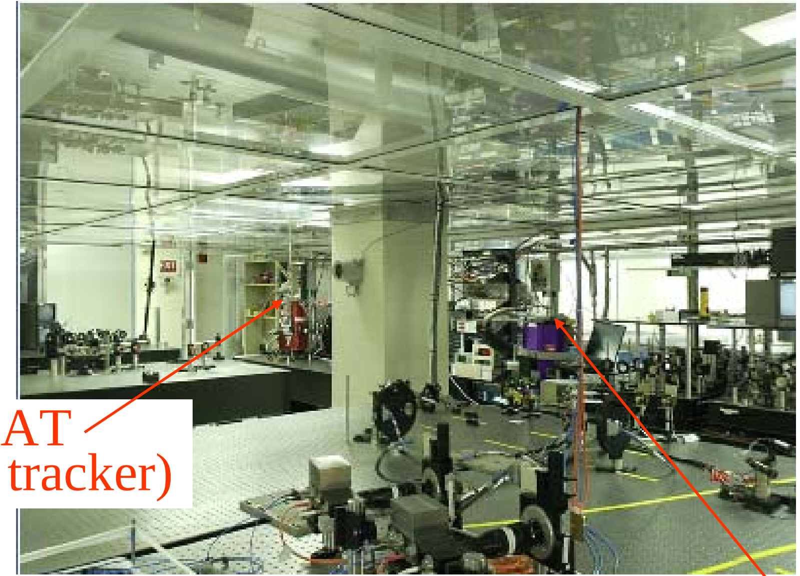
- 4-stage cat's-eye design
- Fiber-fed laser metrology
- Delay range +/- 15m
- High speed position and rate commanding


Fast delay lines

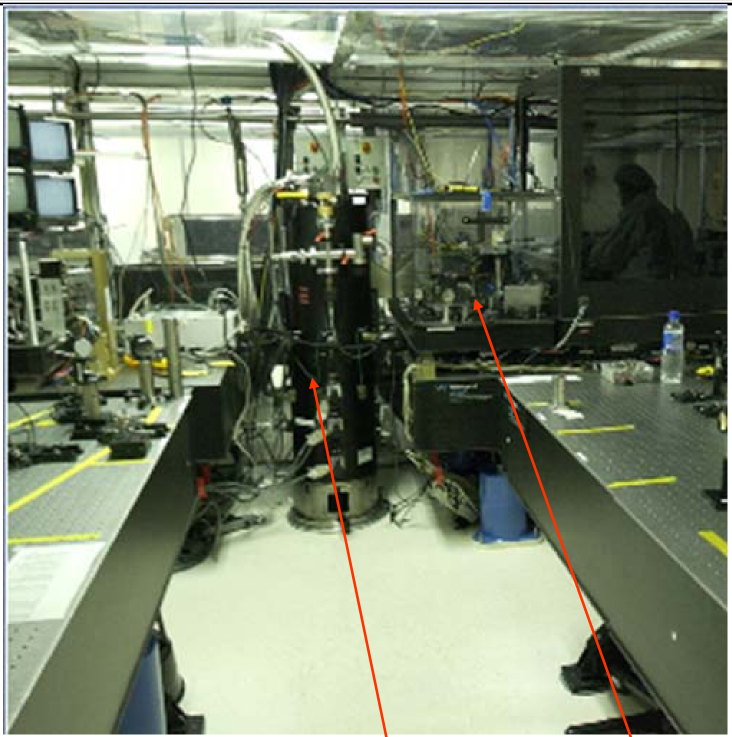

Compressors, metrology

- Beam compressors compresses beams from 4" to 1"
- FDL laser metrology measures the absolution position of FDL carts to track fringes

6. Instrumental Overview: Beam combiner Lab. (slide 6 of 11)



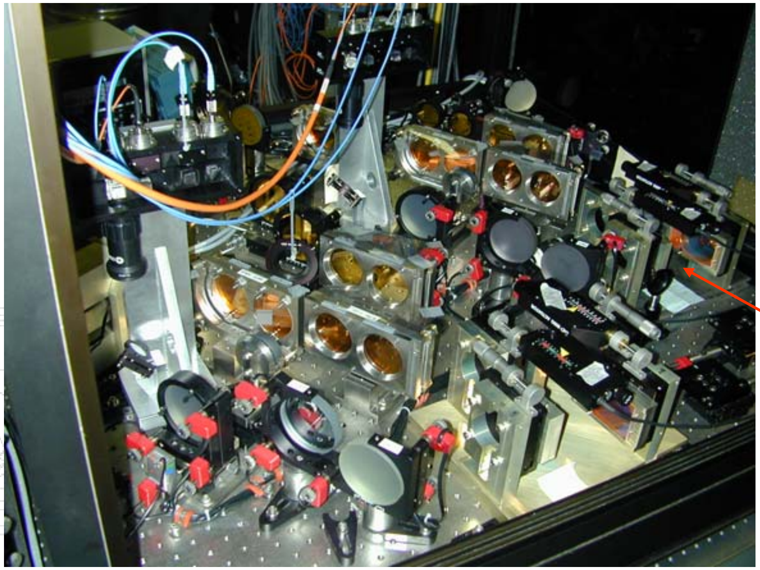
KAT
(angle tracker)



FATCAT
(fringe tracker)

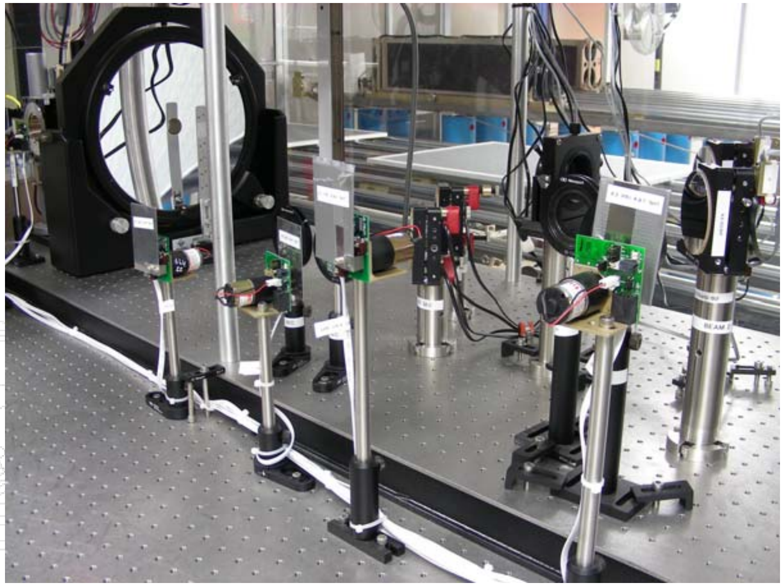
KALI

Nuller
Stimulus



Nuller
Breadboard

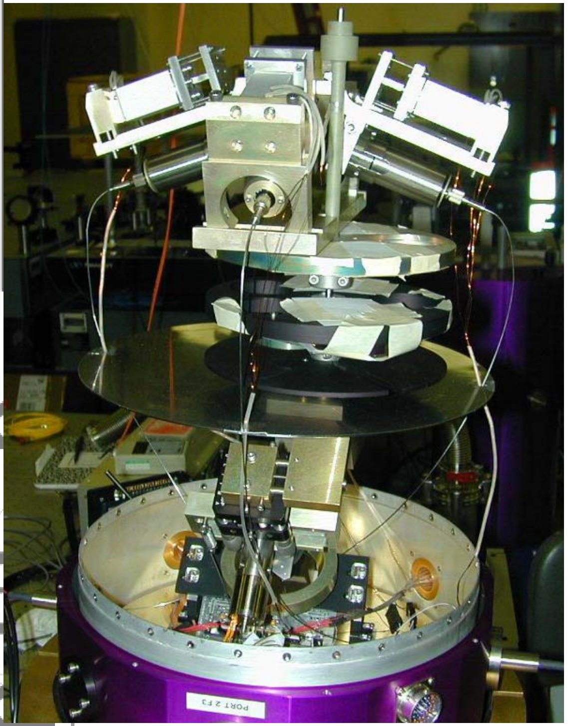
6. Instrumental Overview: Angle tracker (KAT) (slide 7 of 11)

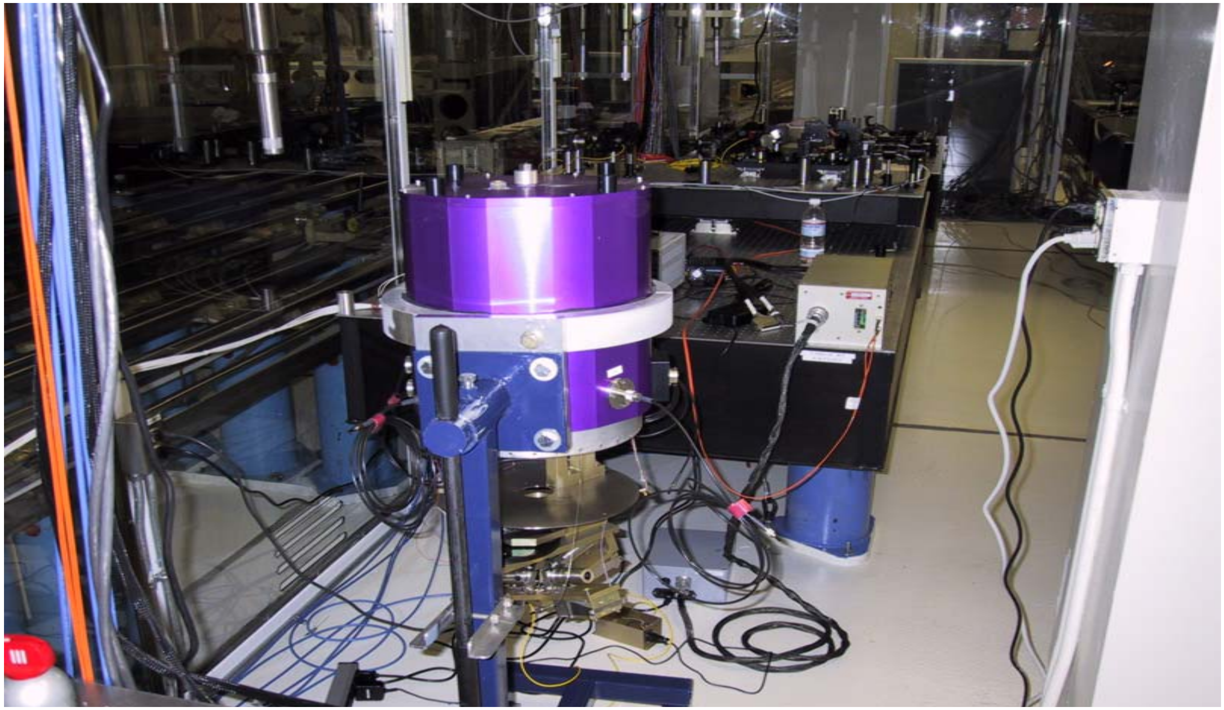


- J or H band angle tracking
  - J standard
- DCR corrector for refraction correction
- Images from two Kecks multiplexed onto one quadrant of HAWAII array
- 20-80 Hz readout
  - 80 Hz standard
- High-speed updates to local tip/tilt mirror
- Low-speed off-loads to AO systems & M7S mirrors
- Selected suppression of narrow-band angle vibration

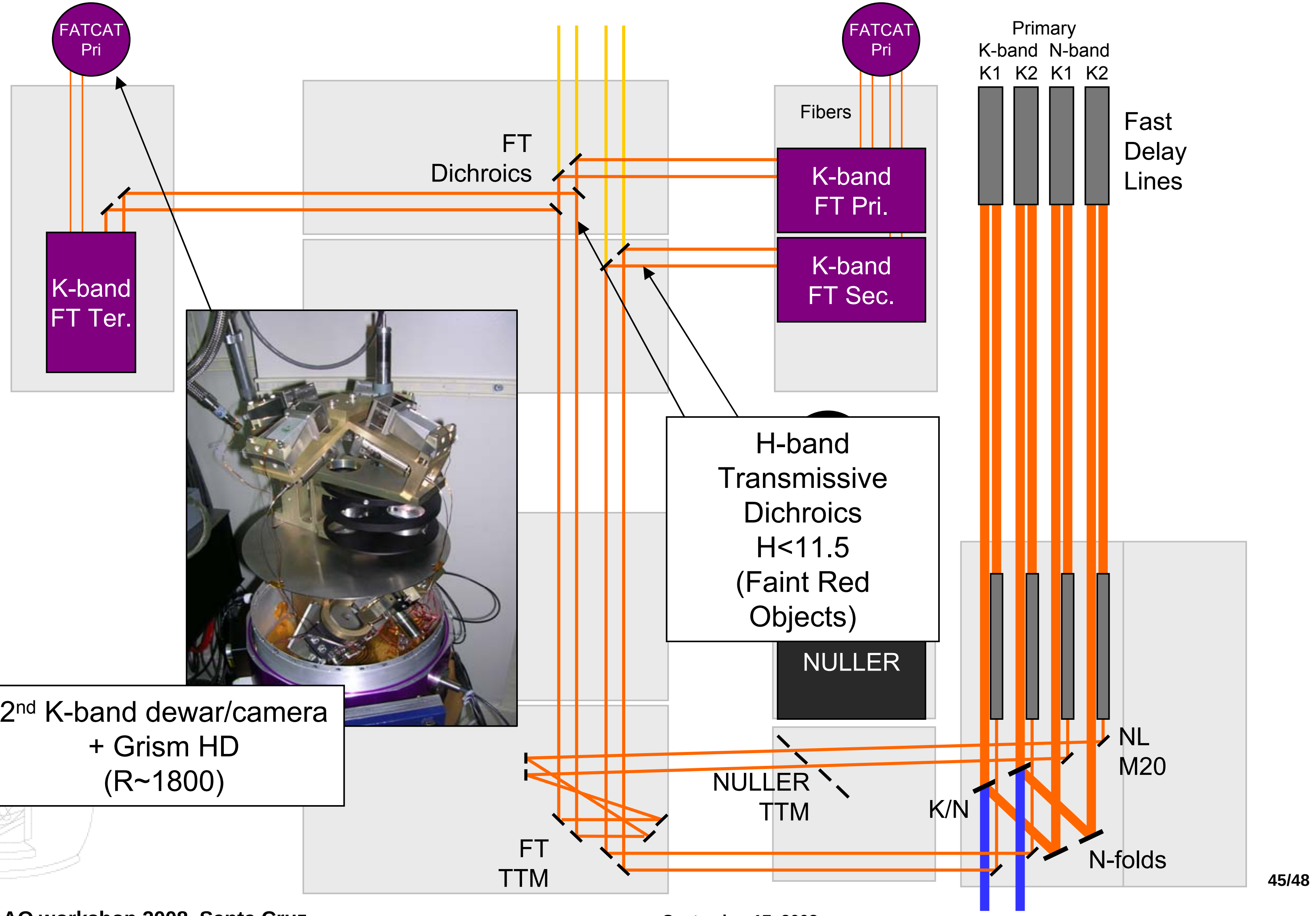
6. Instrumental Overview: Fringe tracker (FATCAT) (slide 8 of 11)

- Free-space Michelson beam combination at H and K bands
- HAWAII array camera fed by single-mode fluoride fibers
- White-light and spectrometer channels
  - Standard frame rate: 200 Hz (V2) and 250Hz (Nuller)
- Fringe tracking with coherent fringe demodulation, closed-loop to delay line





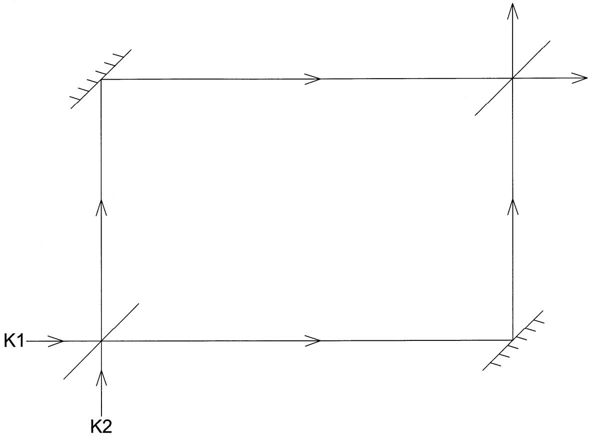
6. Instrumental Overview: SPR Optical Setup (slide 9 of 11)



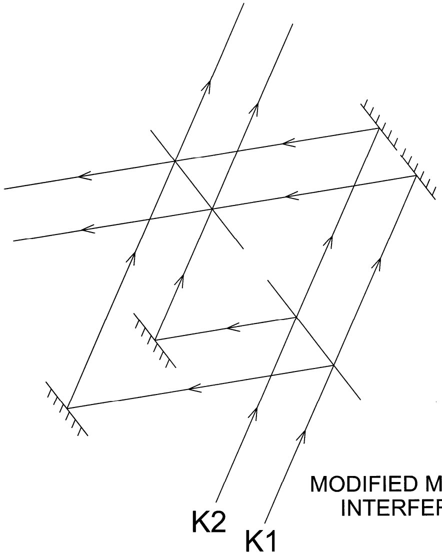
H-band Transmissive Dichroics H<11.5 (Faint Red Objects)

2nd K-band dewar/camera + Grism HD (R~1800)

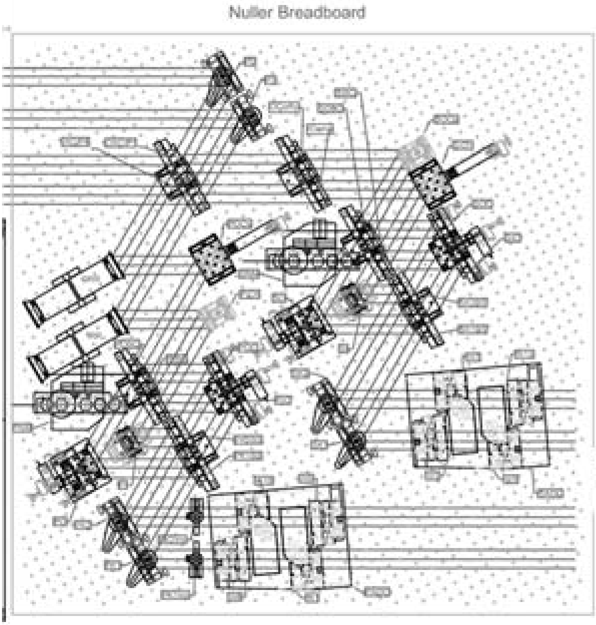
6. Instrumental Overview : Modified Mach-Zehnder Interferometer (MMZ) (slide 10 of 11)



MACH-ZEHNDER INTERFEROMETER

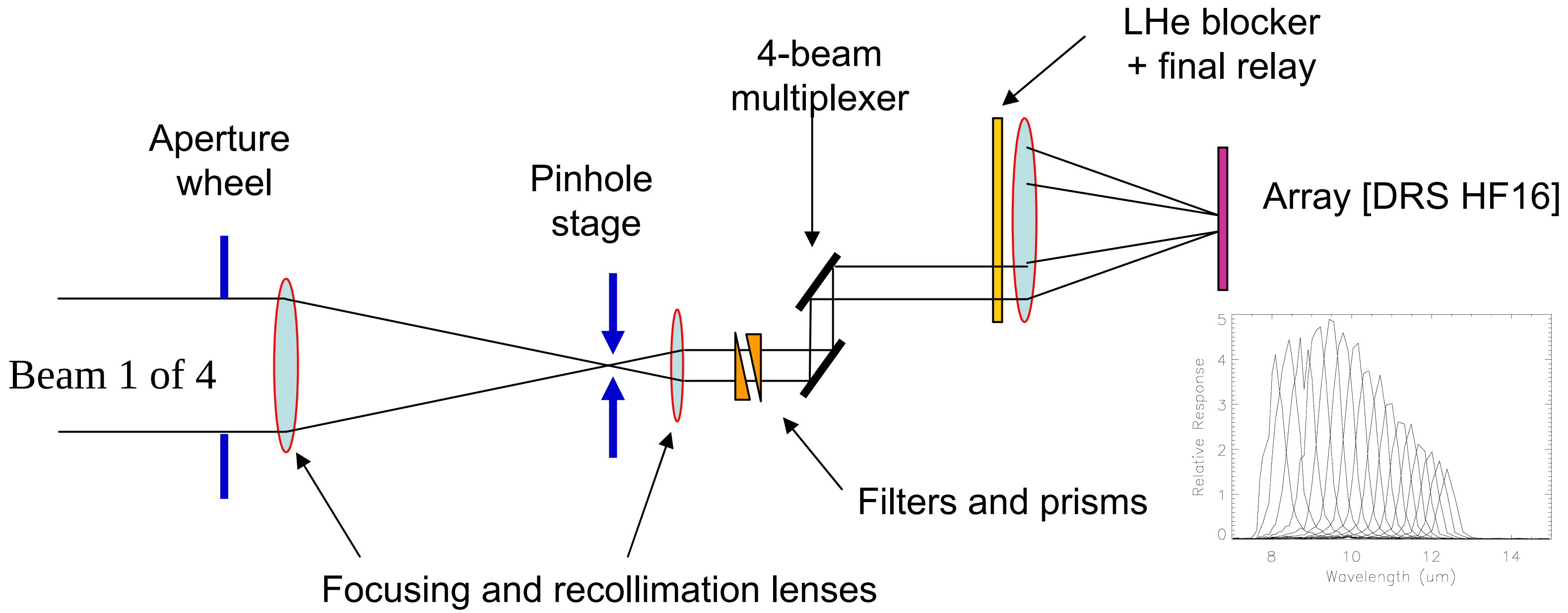


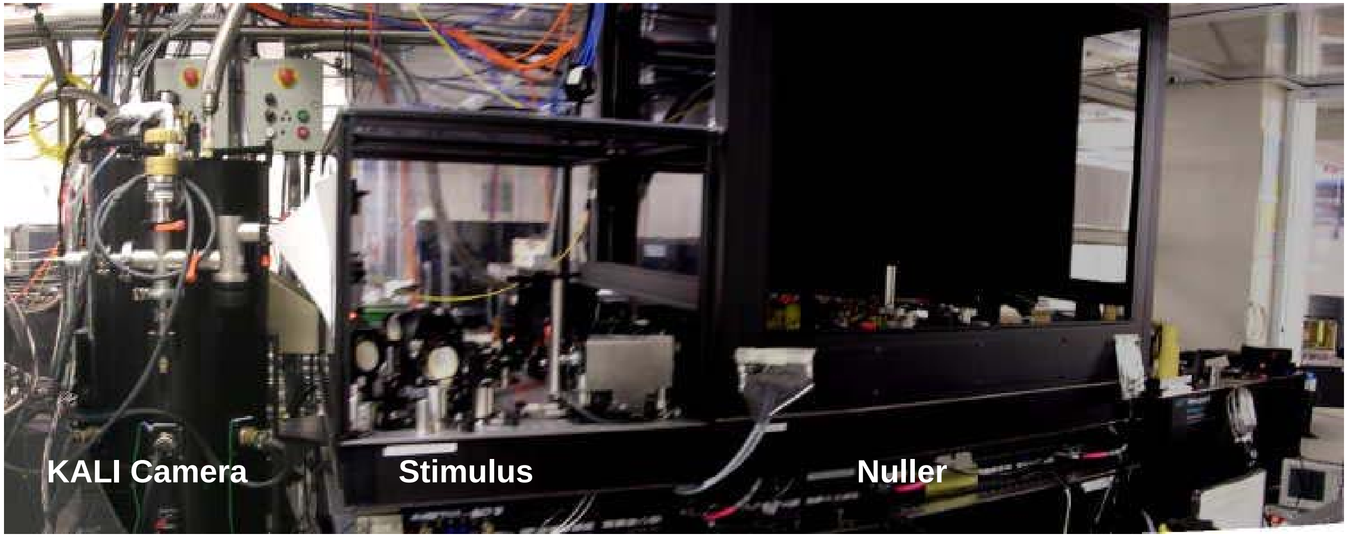
MODIFIED MACH-ZEHNDER INTERFEROMETER



P - Primary
S - Secondary
ADC - Atmospheric Dispersion Compensator
W# - ADC Wedge #
K1 - Keck 1
K2 - Keck 2
BS - Beam Splitter
I - Inner
O - Outer
C - Common
NM - Nuller Metrology
BC - Beam Combiner
Ch - Chopper
RR - Rapid Ramp
Comp - Compensator
XC - Cross Combiner
P# - Kali Port #

6. Instrumental Overview: Nuller 10 µm camera - KALI (slide 11 of 11)





7. Future plans (Slide 1 of 1)

ASTRA project

1 Self Phase Referencing

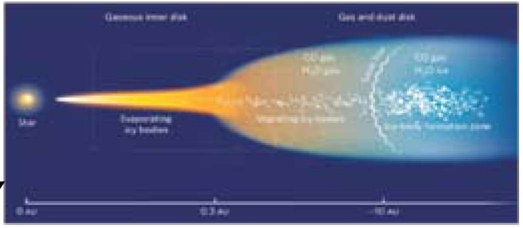
K<8 limit
R~1800

2 Dual Field Phase Referencing

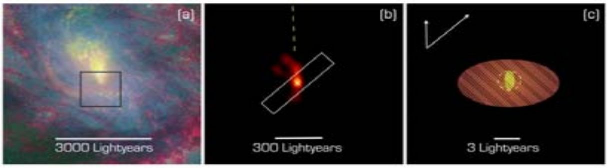
K<8.5 reference
K<15 science

3 Astrometry

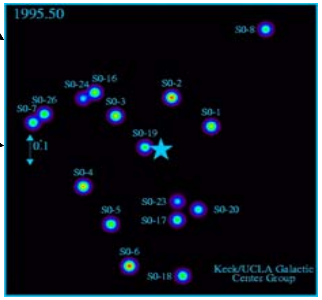
30μ˝ for
30˝ separation



Young Stellar Objects
Chemical Composition at R~1800



Active Galactic Nuclei
Chemical Composition
Increased Sample



Galactic Center
Stellar Population
BH mass
and GR effects

Exoplanets
Reflex Motion of
Multiple Planet Systems