Killers and Kabooms

Observing the Transient Universe
with Pan-STARRS

Pan-STARRS

Panoramic Survey Telescope and Rapid Response System

PS1 – PanSTARRS Telescope #1

Your

Name

Here

Pan-STARRS Telescope #1 - PS1 can survey the available sky (2 pi steradians, 20000 square degress) to 24th magnitudein 4 nights.

~ conservatively tens of Orphan Afterglows per year

The problem will be follow up observations.

Get ready.

Science Drivers

- Potentially Hazardous Objects - threat to life on earth
- Cosmology – Weak Lensing
- Cosmology – SnIa
- Things that go bump in the night – exploration of the time domain

Derived Requirments

- Image budget dominated by natural seeing over field of view - OTA
- PSF characterization over focal plane
- 1 percent photometry over the whole sky, 5 millimag capabilty
- 30 mas absolute asrometry, 10 mas relative astrometry
- Real time data reduction, latency less than 15 minutes
- Pre-survey for PS4

Pan-STARRS Technological Innovations

• OTA guiding	(stable PSF)
• OTA bright-star observations	(dynamic range)
• Curved focal surface	(IQ over FOV)
• Continuous wave-front sensors	(focus, alignment, astigmatism correction)
• Monochromatic Calibration Unit	(consistent flat-field construction)
• Fringe frame construction	(high-quality background correction
• Photflat Calibration	(ZP over FOV)
• Imaging Sky Probe	(ZP over time, sky brightness)
• Spectroscopic Sky Probe	(real atmospheric transmission curve, absolute sky brightness)
• Meteorological Modeling	(characterize atmosphere)
• Rich Metadata	(quality assurance / quality control)

- UNDERSTAND SYSTEMATICS !!! – Physics experiment

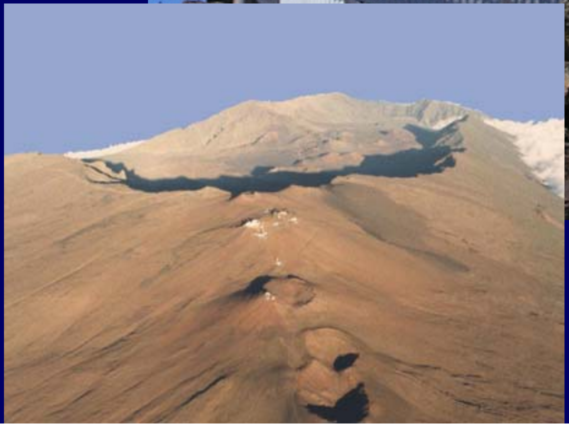
PS1

Optics installation in April

Integration of Telescope and Camera this summer

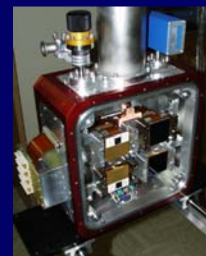
Commissioning this fall

PS1 Mission January 2007



Pan-STARRS Development Schedule

- Development, infrastructure, and testing (2003-2005)
- Integration and Commissioning 2006
- PS1 Science Mission (2007-2009)
- PS2 , PS3, PS4 (Development and Construction 2007-2009)
- PS4 Mission (2010 – 2020)
- PSX….

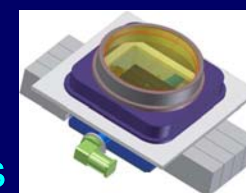


- Test Cameras 1-2
- Test Camera 3

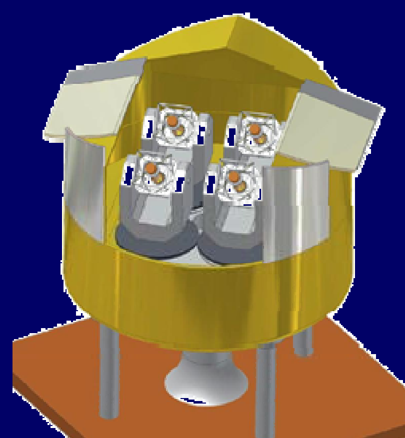
360 Mpix

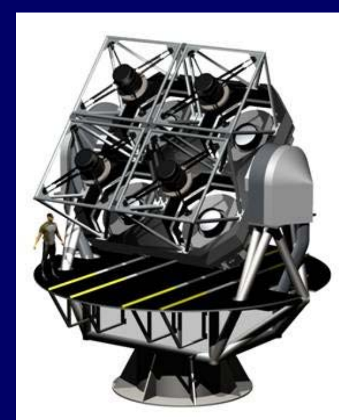
- Gigapixel Camera 1

1.4 Gpix



- Gigapixel Cameras

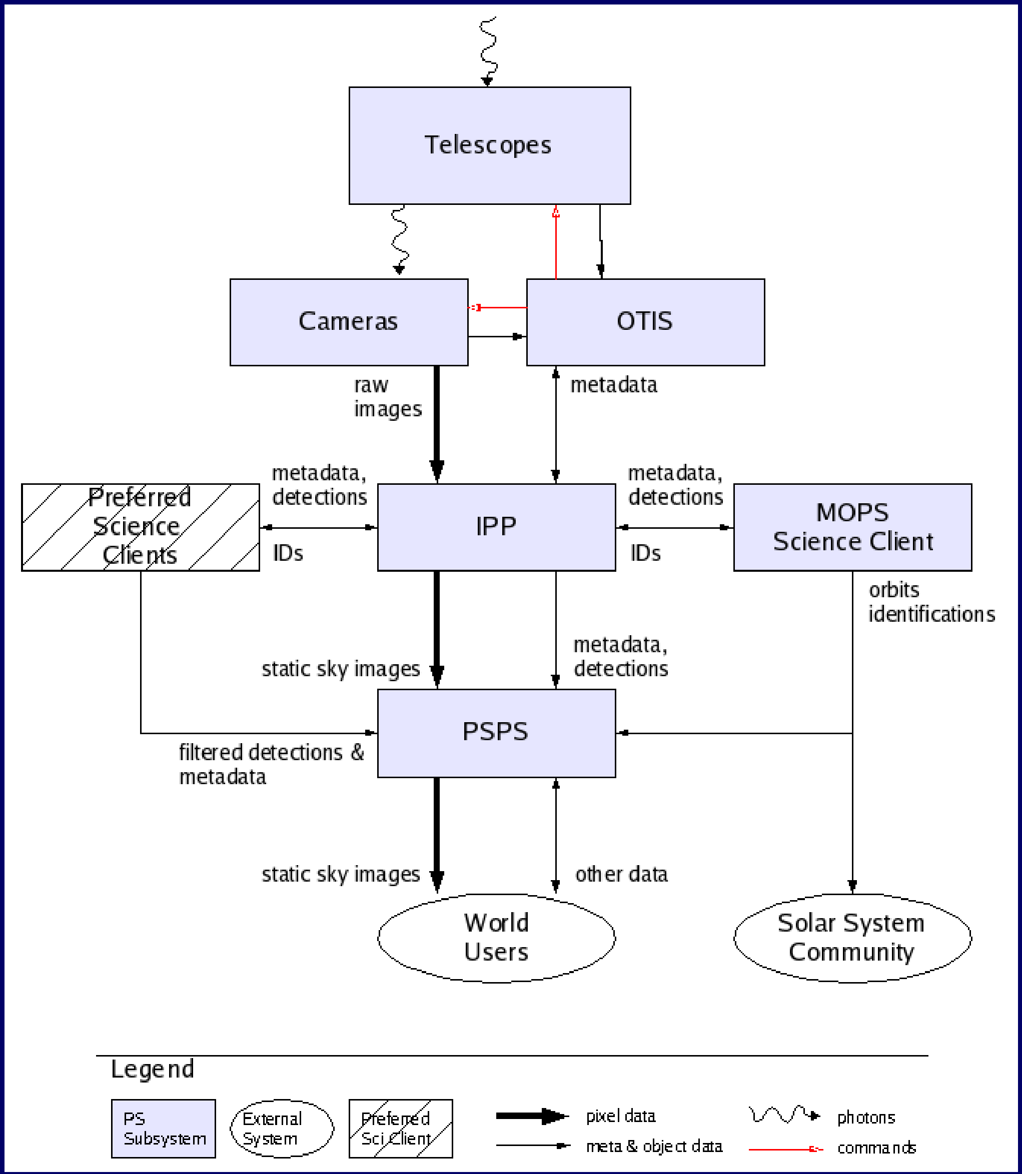




Pan-STARRS in a Nutshell

- Telescopes
  - Four 1.8 meter telescopes
  - Ritchey-Chretien with 3 element WFC
  - 7 square degree FOV
  - Atmospheric Dispersion Corrector
  - Site: Mauna Kea or Haleakala
  - six filters: g, r, i, z, y, w
- Detector and controllers
  - 10^9 0.26" pixels per camera
  - Image motion compensation
  - 512 channel controller
  - 2 second readout
  - $4e^-$ read-noise
- Extensive Calibration and MetaData
  - Monochromatic 1.8m Calibration Unit
  - Atmospheric Transmission and Emission Monitoring and Modeling
  - Meteorological Modeling
- Data-Processing System
  - Multicolor summed images
  - Difference images for detection of moving and variable objects
  - Catalogs of static, moving, transient objects
- Published Science Products System
  - Transient alerts
  - Moving object detections and orbits
  - Database of catalogs, images, metadata

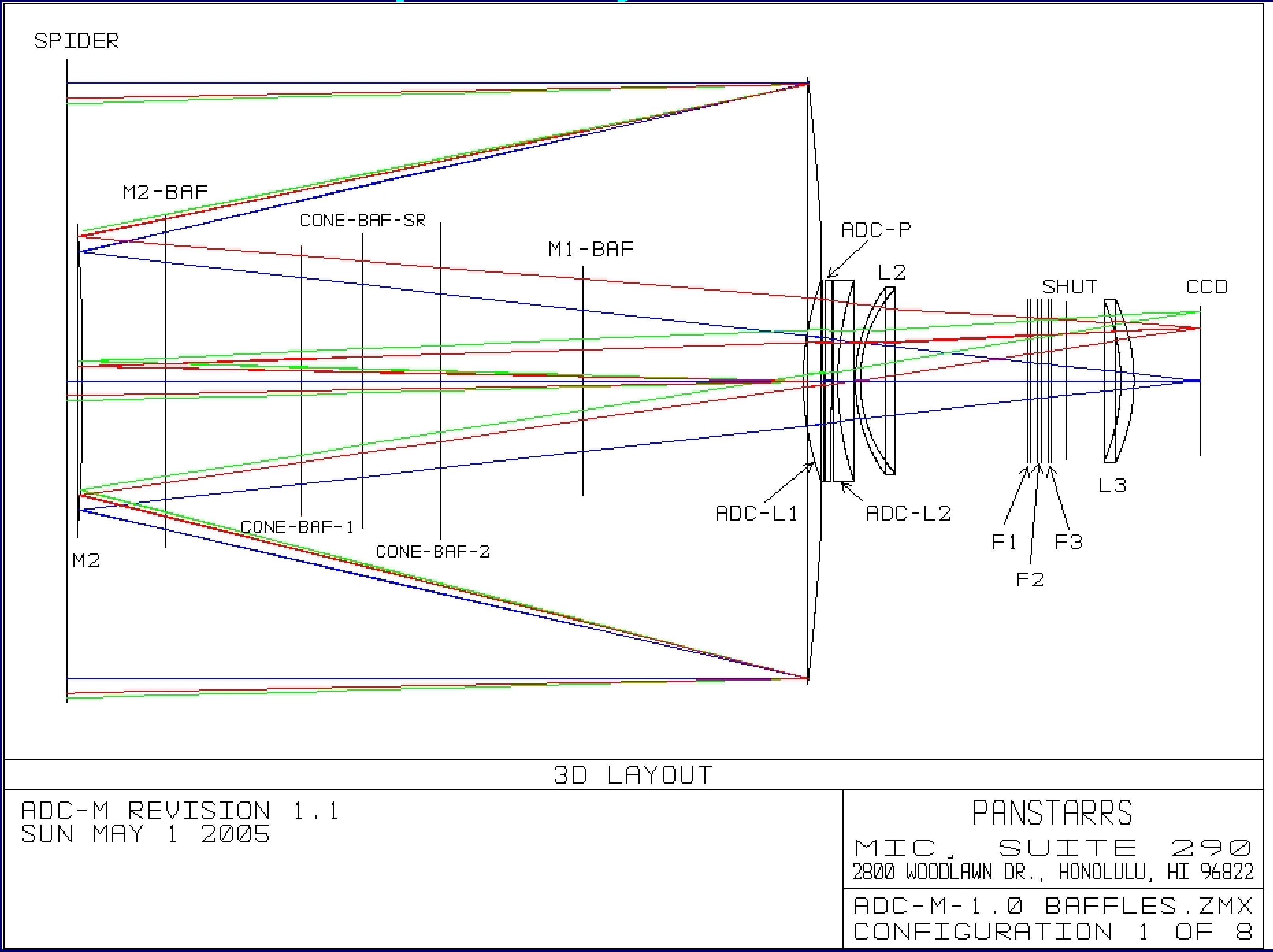
Pan-STARRS Overview



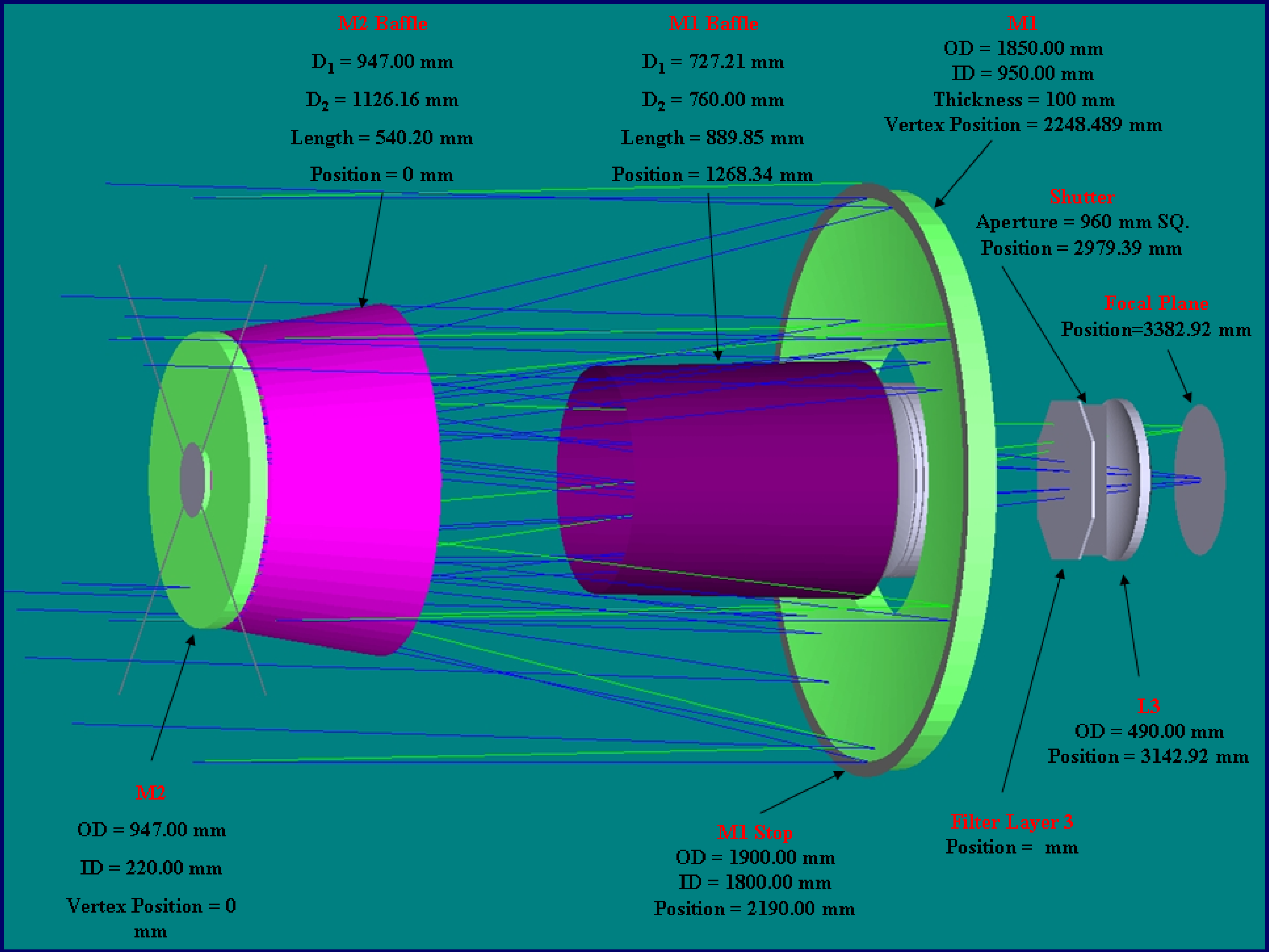
Pan-STARRS Subsystems

- TEL – Telescopes
- CAM – Cameras
- OTIS – Observatory, Telescope & Instrument Software
- IPP - Image Processing Pipeline
- MOPS – Moving Object Processing Software
- PSPS – Published Science Data Products

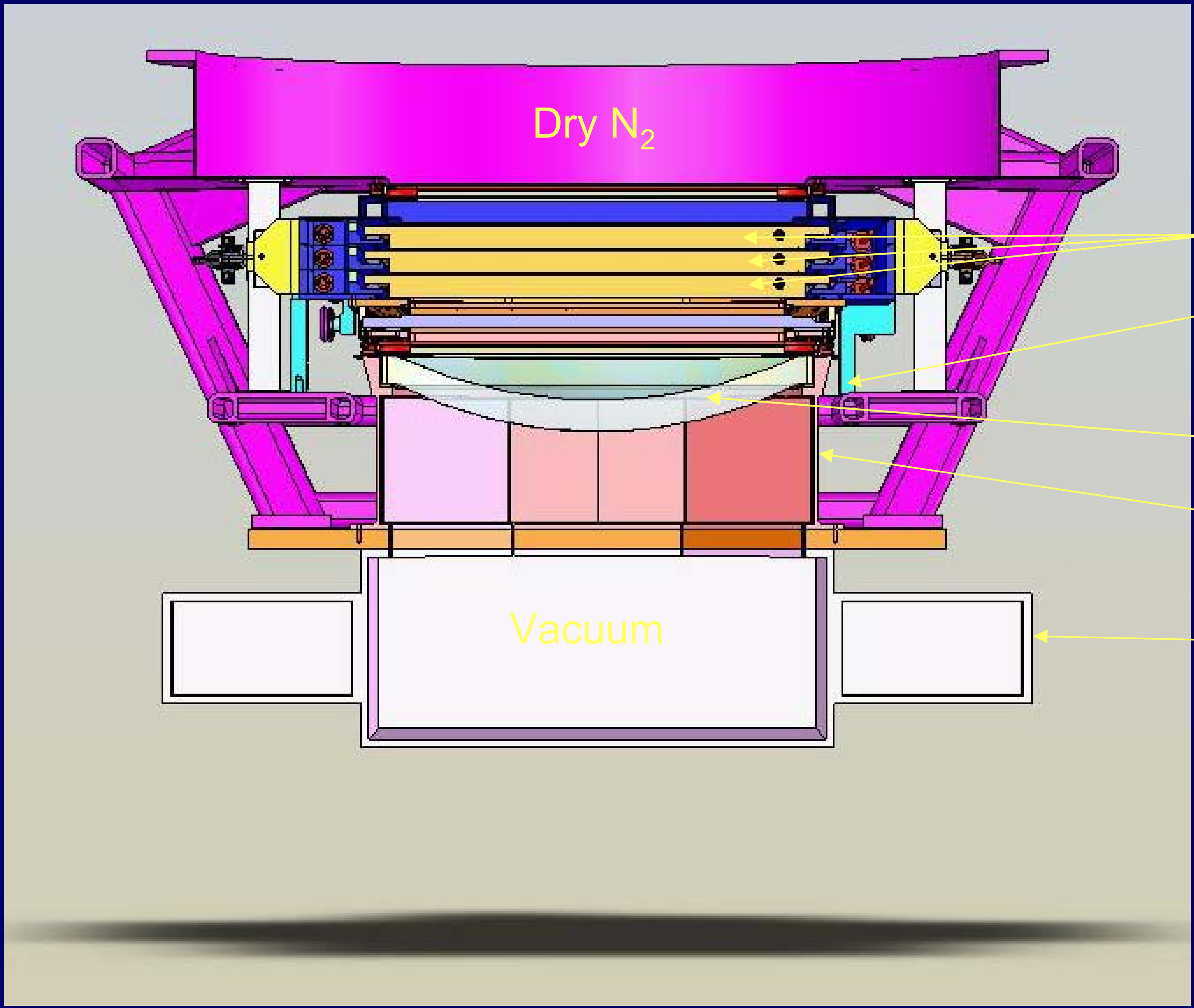
PS-1 Optical Layout with Baffles



Baffle Design



The Lower Cassegrain Core: Sectional View



- Filters 1-6
- Filter Mechanism support feet (3)
- L3
- Wave front sensors chamber
- CTI cooling heads (camera envelope shown here is only an approximation)

The PS1 Pineapple Slicer

University of Bonn

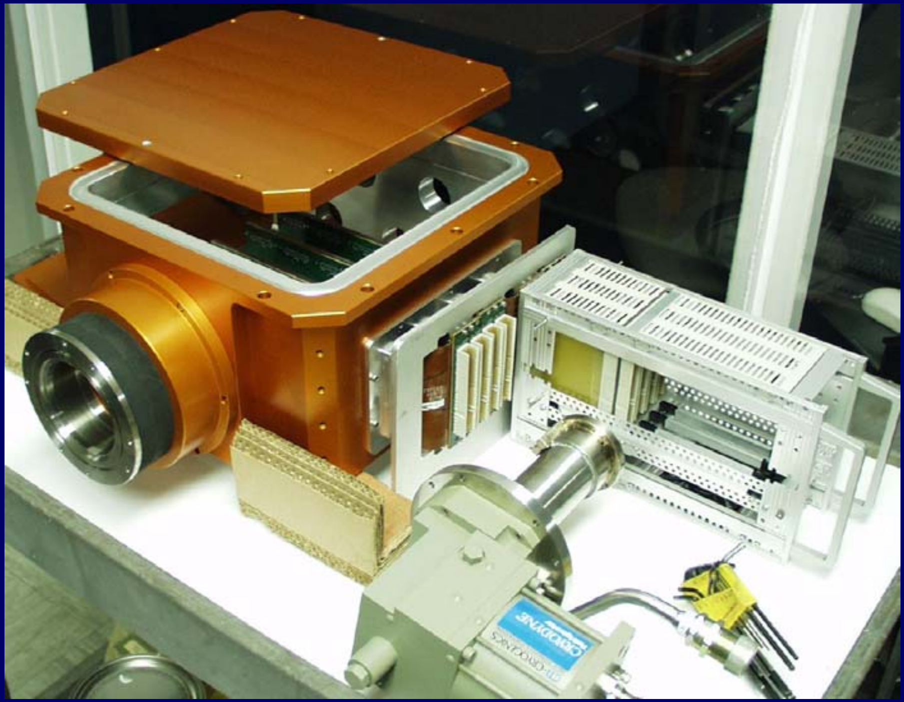
40 cm aperture

twin blade Shutter

Trajectory repeatable to10 millisec!

Test Camera 3 (TC3)

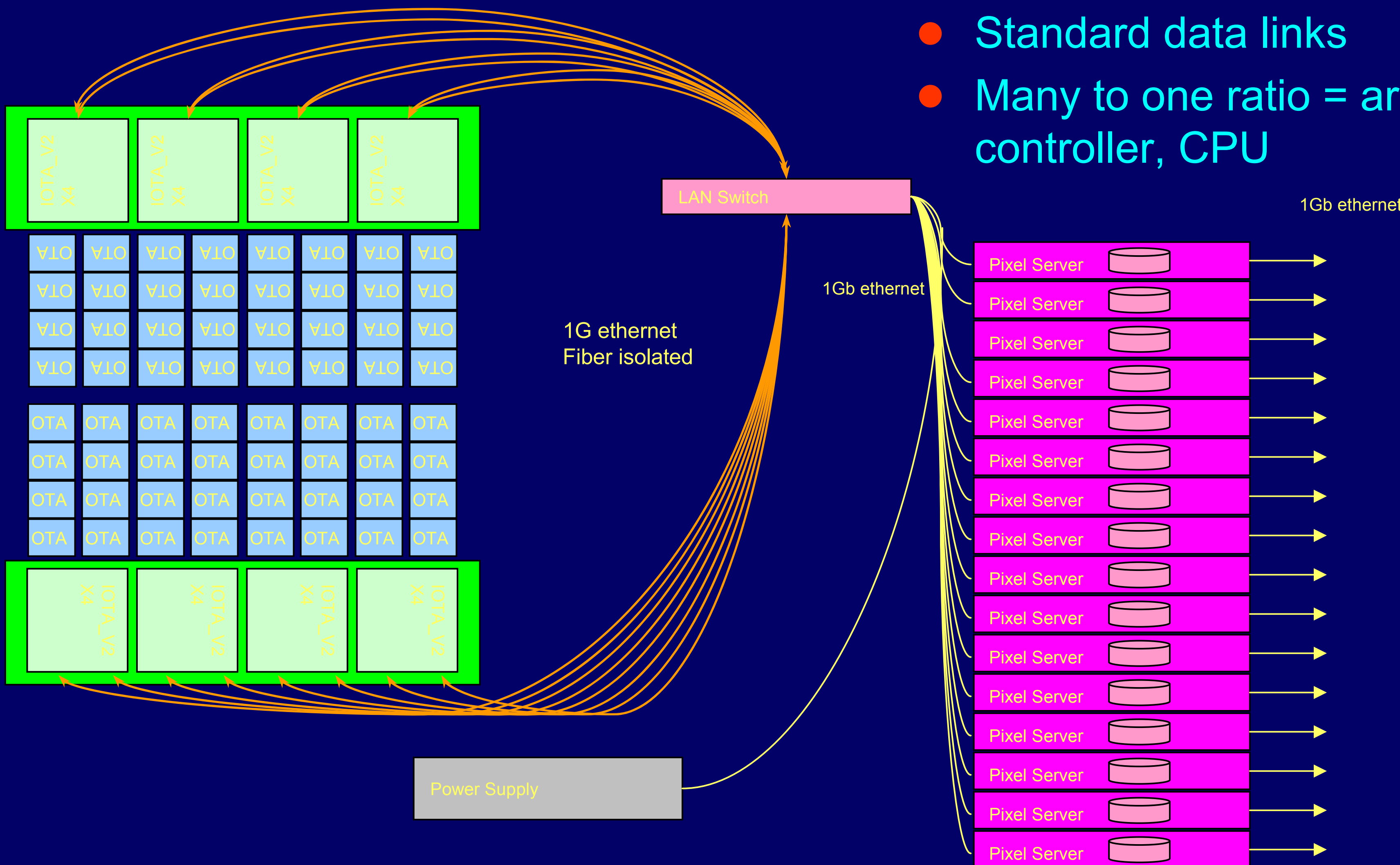
- TC3 is the stepping stone to GPC, allows us to test innovative technology and revise it for GPC: TC3 is almost an exact quarter GPC1.
  - Focal plane: Alumnum, curved.
  - Close packing of devices and controllers
  - CTI cryocoolers
  - Thermal management of focal plane
  - Implementation of wavefront sensors



- GPC1 will not be used for First Light,TC3 will be used for early subsystem commissioning tasks

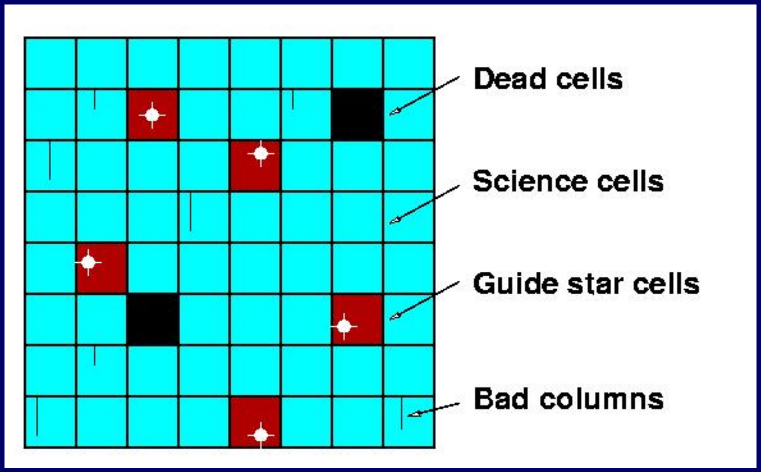
New Controller Architecture

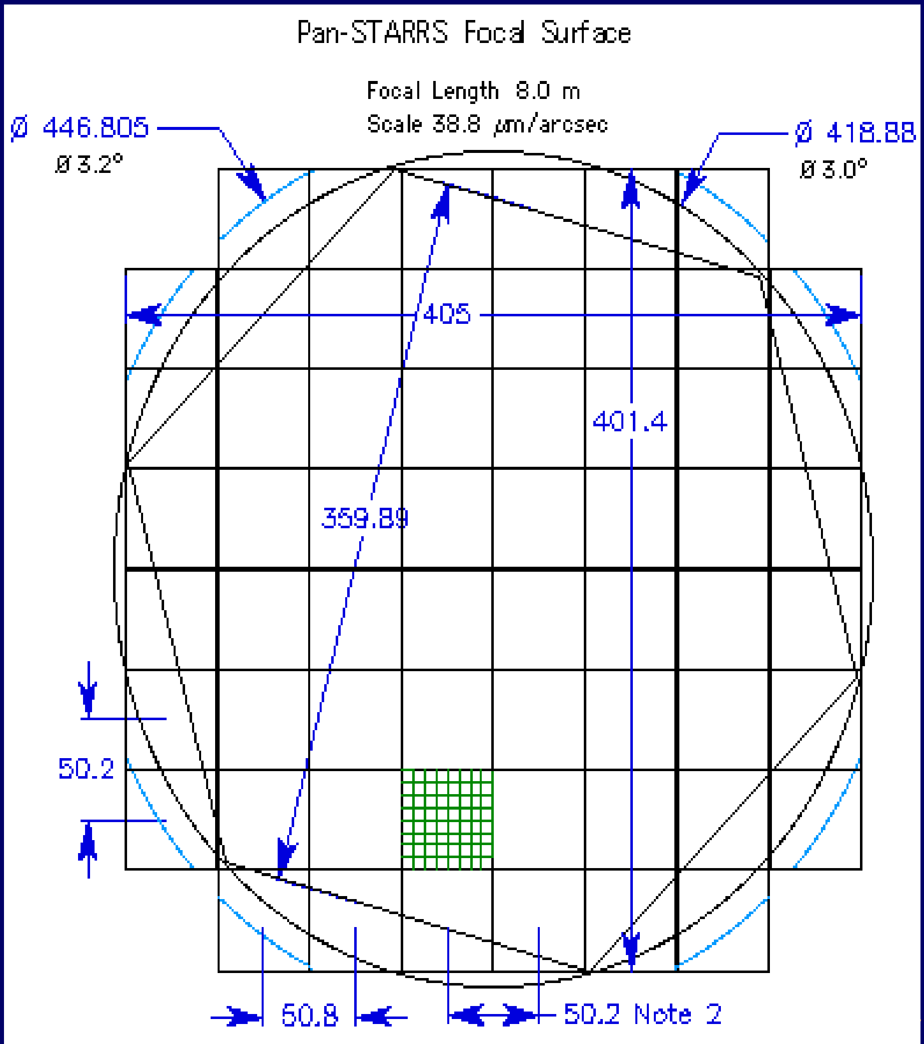
- Large number of arrays
- Standard data links
- Many to one ratio = array, controller, CPU



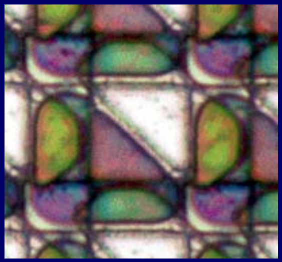
Pan-STARRS Focal Plane

- The Gigapixel Camera is an array of arrays
- Each OTA can assign cells to be guide star cells
- Those can command local cells to track motion of guide stars

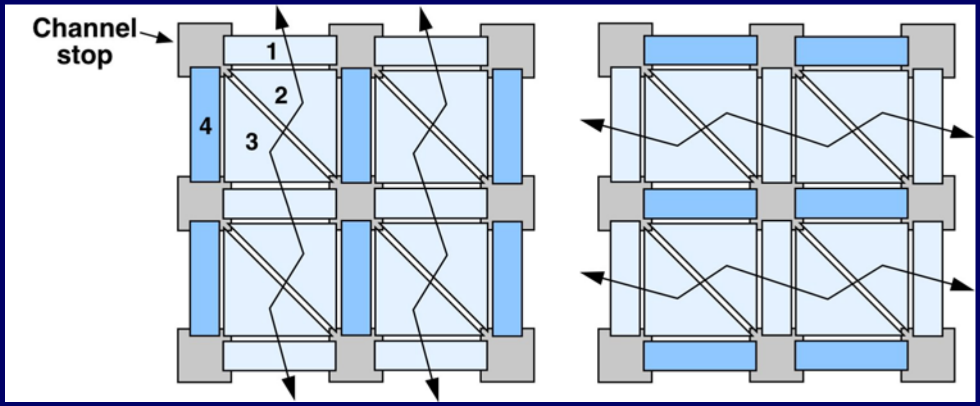


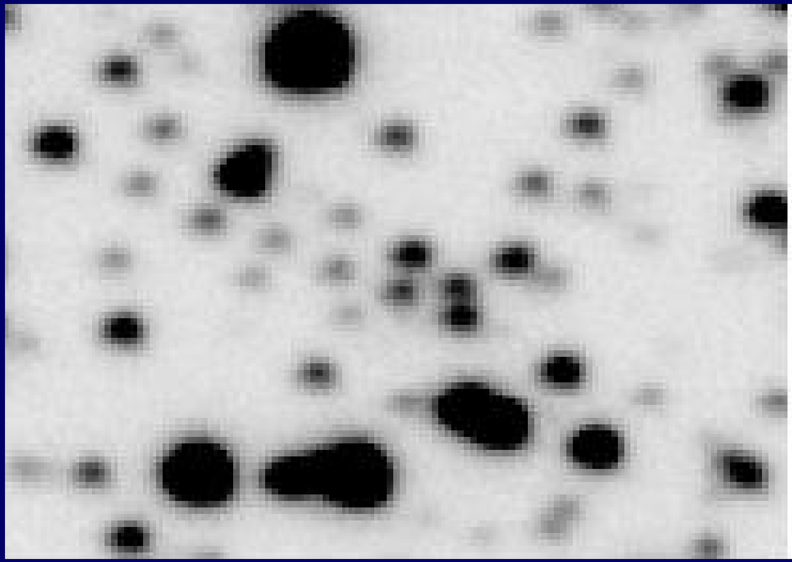


Orthogonal Transfer Arrays

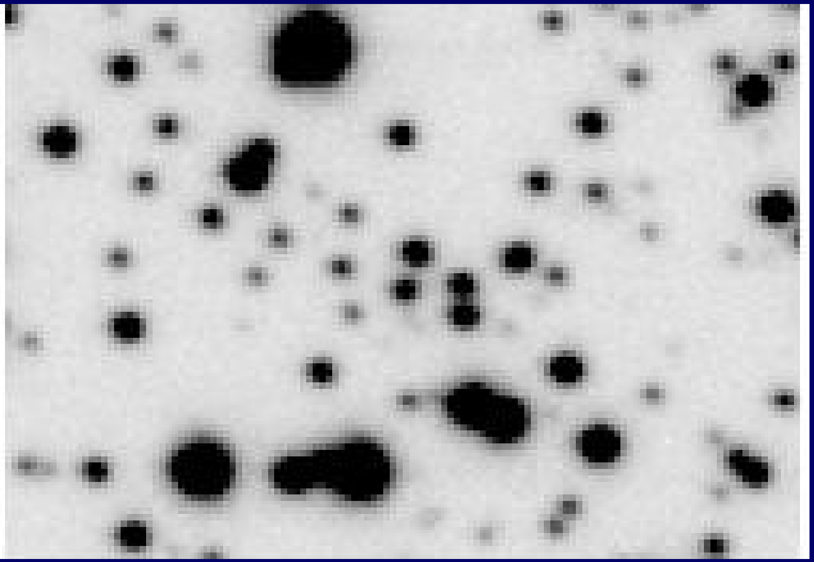


- Orthogonal Transfer Array
  A new pixel design to noiselessly remove image motion at
  high speed (~10 usec)





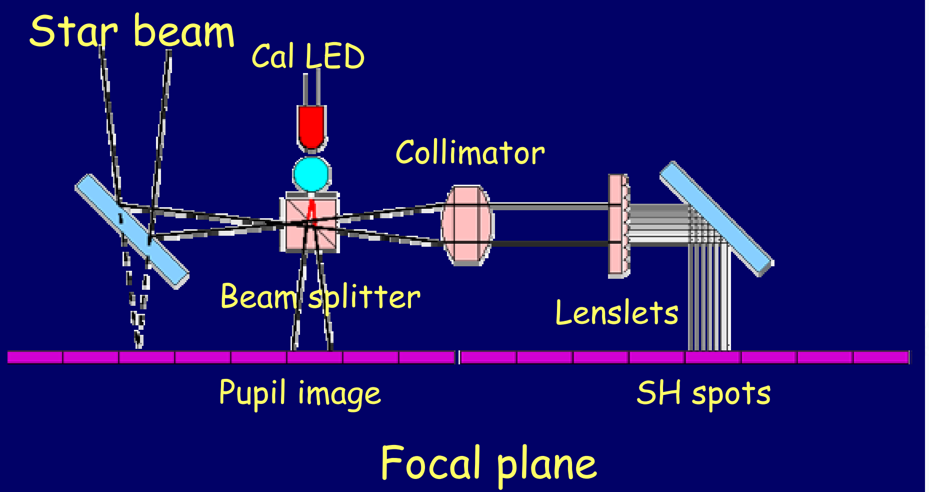
Normal guiding (0.73”)

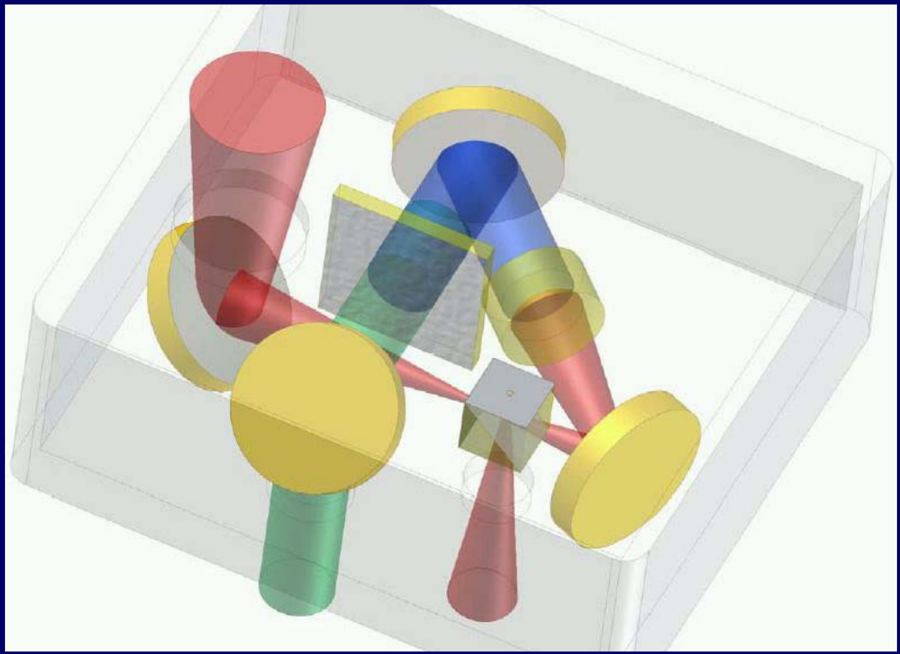


OT tracking (0.50”)

Shack-Hartmann Wavefront Sensing

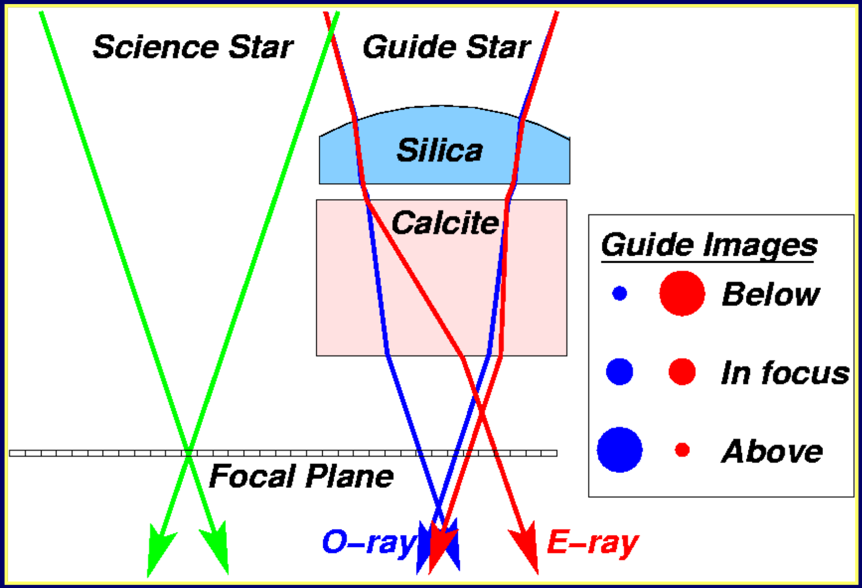
- Deployable WFS located in antechamber of camera extends out over focal plane to pick off a star for analysis
- Lenslet images and pupil images are parfocal with normal telescope images
- S-H sensor parked out of field of view for normal operations





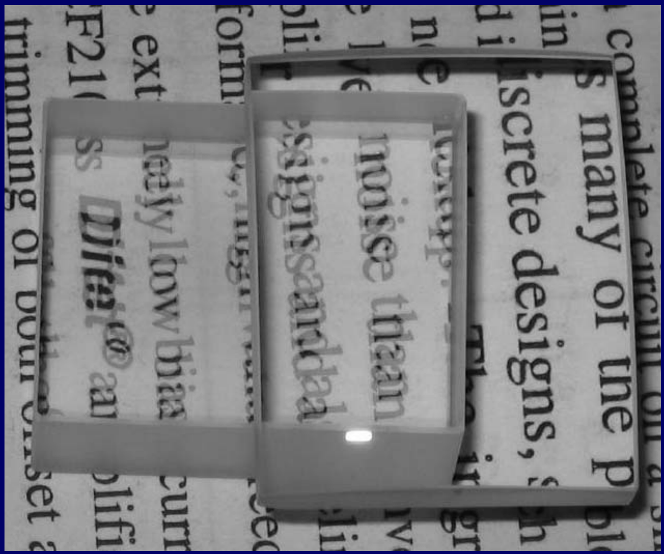
Curvature Wavefront Sensing

- Curvature sensing design
  - 2—4 locations, above focal plane but outside 3 deg FOV
  - Converging lens and block of calcite
- Two images of every star provide above and below focus donuts
  - Difference is quite sensitive to wavefront aberrations
  - Operates automatically and continuously with every exposure, no special pointing or overhead.
  - Results available within 30 sec.

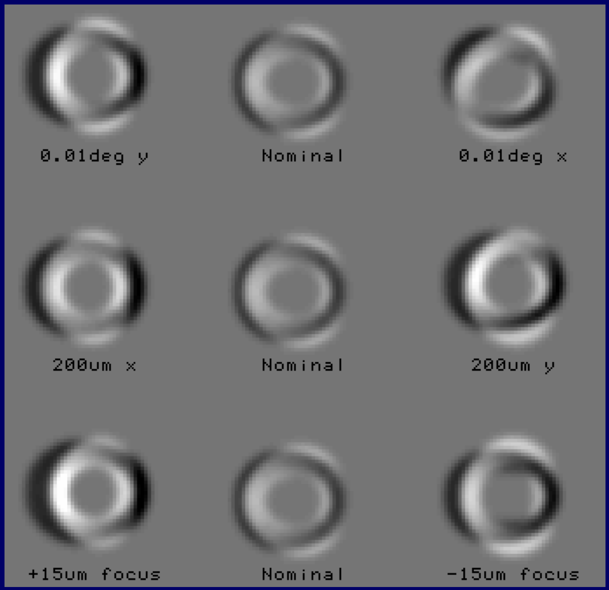


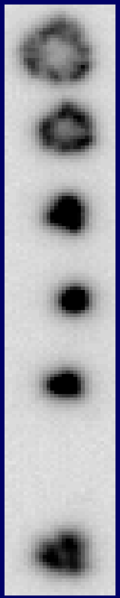
Curvature Wavefront Sensing

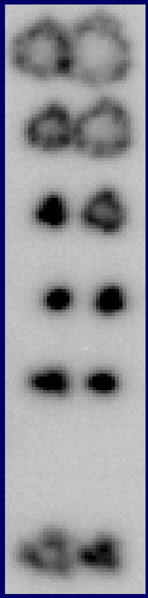
- Calcite blocks and converging lens (8 acquired)
- Placed above edge of focal plane on a “diving board”.
- Height adjustable to tune equal size images when in focus (convenient, not necessary).



- Ray-traced images show sensitivity to M2 focus, tilt, and decenter.
- Degeneracies between tilt and decenter lifted by images separated by 90°
- Prototype demonstrated using OPTIC on 88”

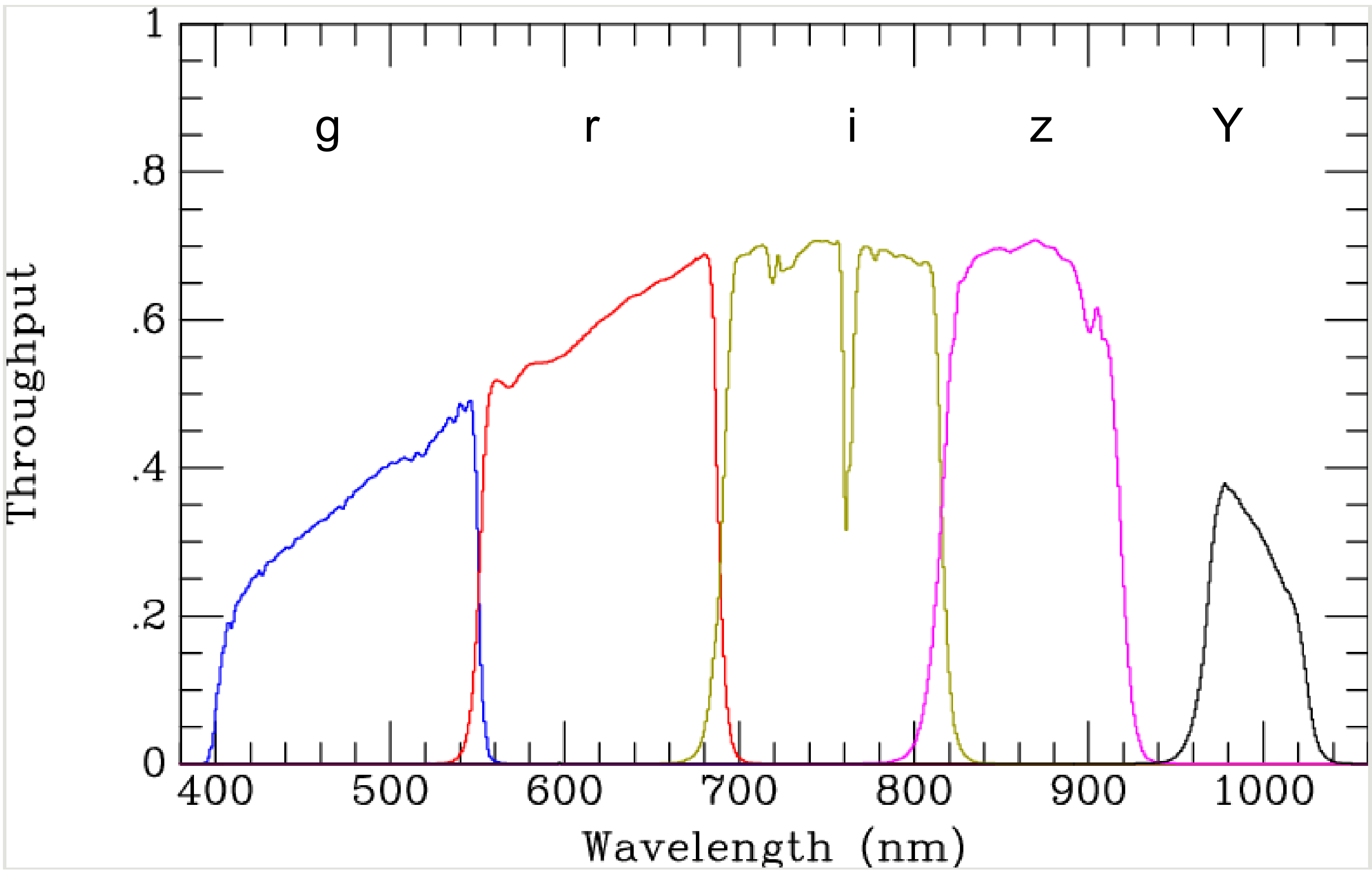






Total System Throughput

- top of atmosphere to detector
- uses measured QE of 75-micron-thick deep depletion devices



75 micron devices have good throughput!

PS1 Design Reference Mission

- Astrometry and Photometry Survey (3π Steradians)

  Five band (grizy) all sky survey, including galactic plane, once per year

  - 20 Calibration Fields (12 are MD fields)
  - 5 sec Bright Star mode in 2^{nd} year
  - Each band matched with i band – primary astrometric band
  - Overlap Regions from approximate hexagonal tesslation with aproximate circular FOV constitute important sub-survey for transients

- Medium Deep Survey

  Five band medium deep survey of 84 square degrees.

  - 7 fields visted every night, 5 colors in 4 nights: (g+r),i,z,y

- Solar System Survey in wide band w = g+r+i (or r band)
  - ``sweet spots'' 2 rectangels 10 x 15 degree
  - opposition region +/- 30 degrees
  - 2 visits per night, 6 visits per lunation ,95% complete irrespective of weather
  - Overlap Regions consitute very rich transient survey!

Design Reference Mission

Mode	*PSY*	*Area*	*Cad.*	w	g	r	i	z	y
SS NEO	1.1d 0.2b	7000	h/d/m	27.3 300					
SS KBO	1.0d 0.2b	3π	hdmy	26.3 60					
Var.	0.8d 0.8b	133	4 min	29.2 22000	28.6 7400		28.5 4400		24.9 4400
3π	1.3d 2.5b	3π	14d		25.9 30	25.6 30	25.4 60	23.9 20	22.3 30
Med. Deep	0.6d 0.9b	1200	4d		27.1 271	27.0 460	27.3 1200	25.0 1900	24.0 600
Ultra Deep	0.5d 0.7b	28	4d		29.1 10000	29.0 18000	28.0 6300	27.0 6700	26.0 26000

5-σ limit (AB)

Total int. (min)

Fast Transients from Overlap Regions

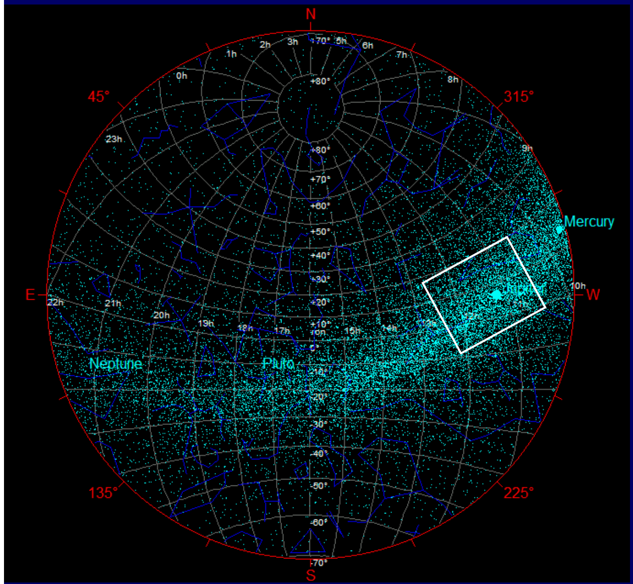
- P & A Survey Overlap – 4000 square degrees at 30 sec cadence

- Solar System Surveys – 6000 square degrees with 30 sec cadence

- Problem is follow-up

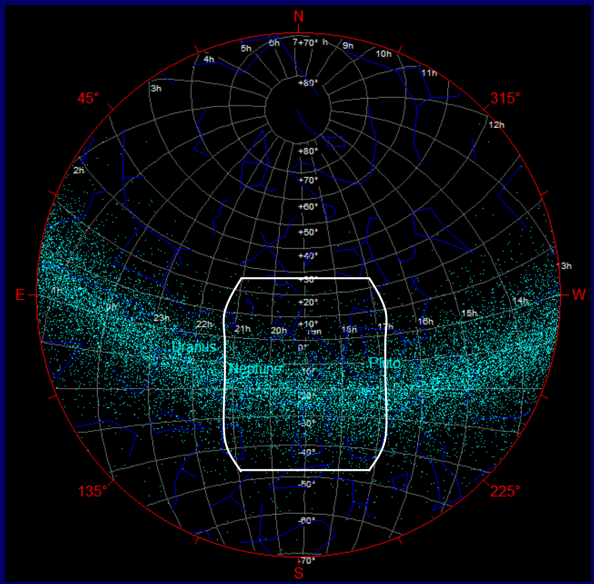
Solar System Survey

19:00 HST



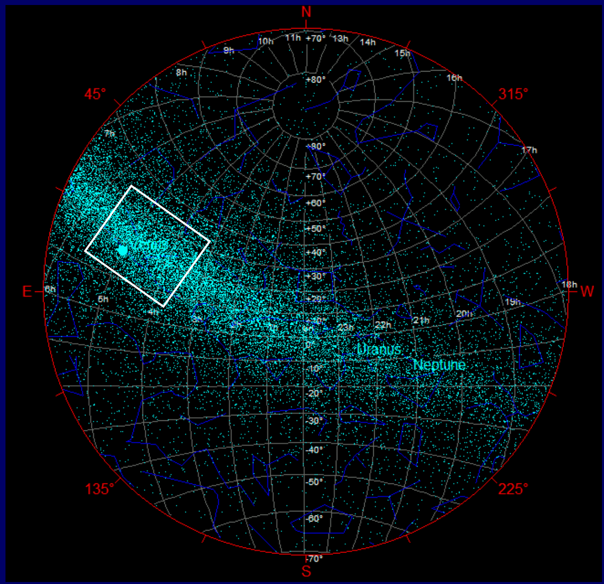
Evening Sweet Spot

00:00 HST



Opposition

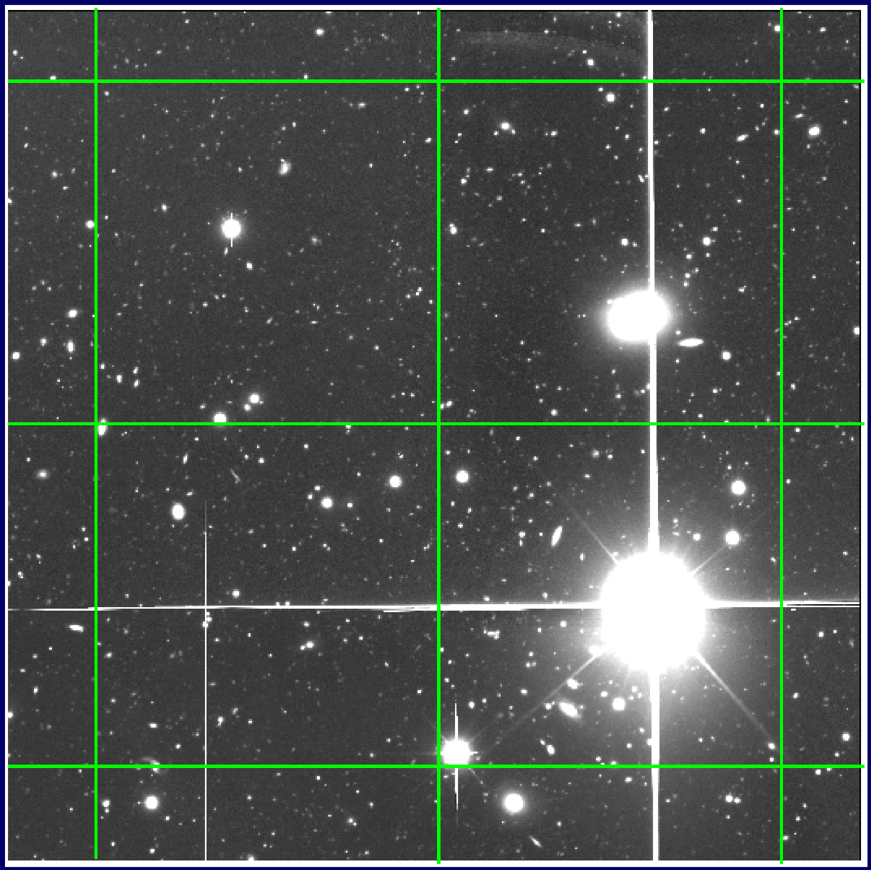
05:00 HST



Morning Sweet Spot

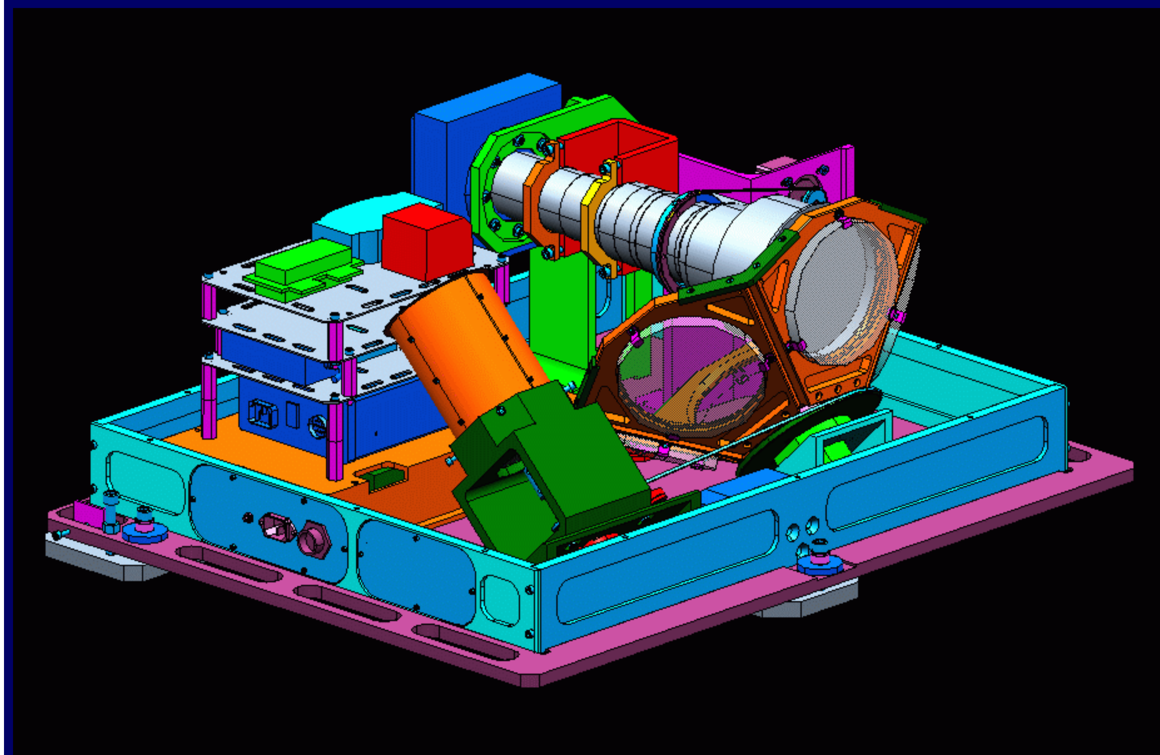
OTA Fast Readout for Bright Stars

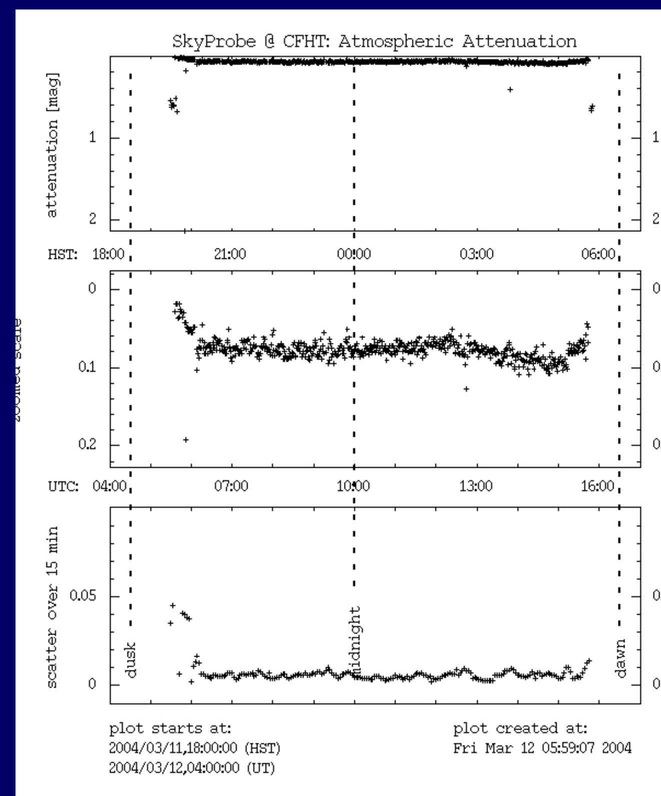
- "Bright Star" Observing Mode
- Exposure times of <10 ms
- Practical observations of stars 8 mag or brighter
- Astrometric calibration directly to Tycho, maybe even Hipparchos
- Photometric calibration directly to Landolt, Oke&Gunn, etc.
- Photometric check with Tycho
- AP Survey will span 8-20 mag with consistent, high-quality photometry & astrometry



PS1 Imaging Sky Probe

- large detector (2048^2)
- back-side illumination
- larger aperture (120 mm)
- 5 filters (*grizy*)
- Good sampling (5 arcsec)
- controlled focus





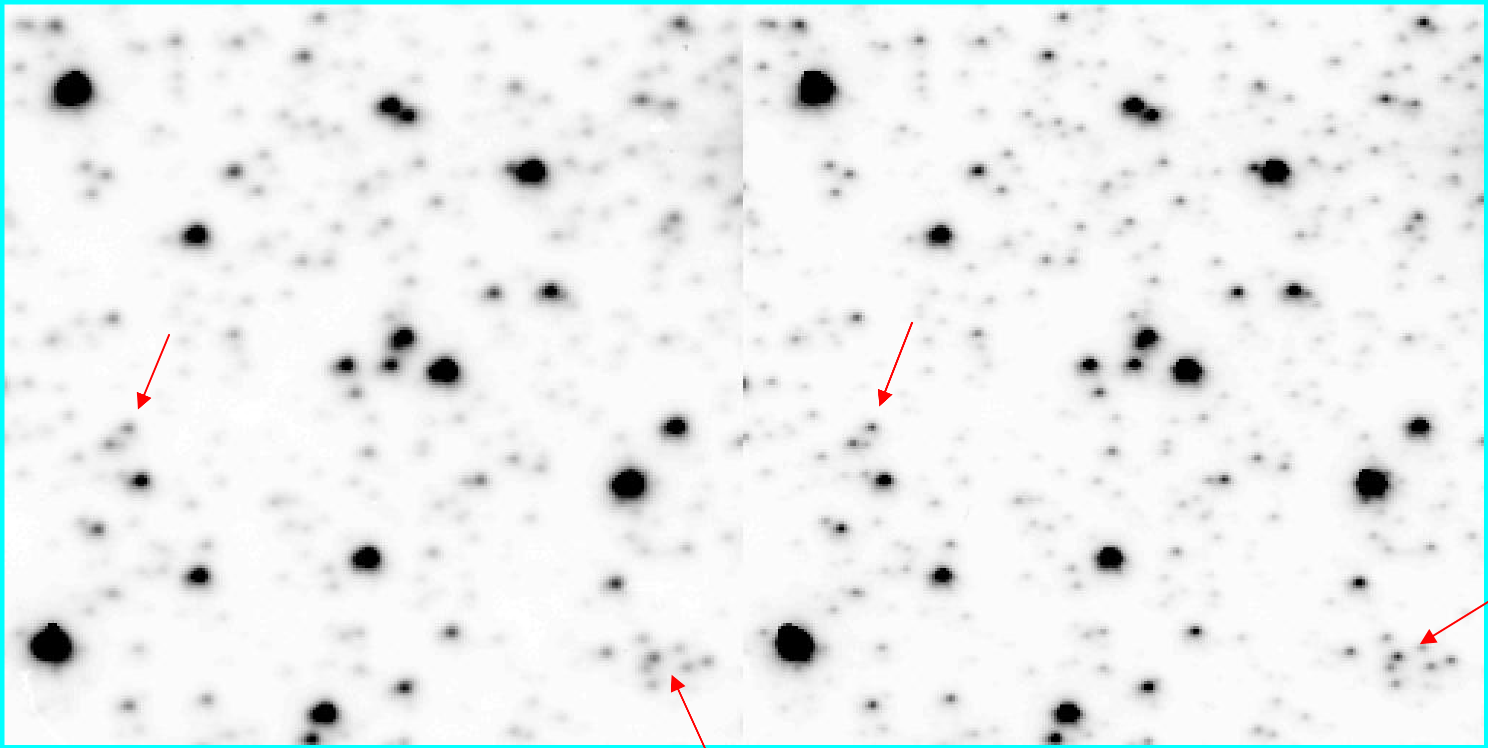
SkyProbe @ CFHT

Pan-STARRS Basic Data Products

- Instrumental catalogs
  - Instrumental magnitudes, coordinates
  - For precision astrometry/photometry
  - Postage stamps for bright objects
- Cumulative static sky images
  - Signal + exposure maps
  - Best + working + compressed intermediate saves
- Static sky catalogs
  - Includes time history of object magnitudes
- Difference image detection stream
- Recent (~1 month) source and difference images

Final Science Products

- Sky, the wallpaper:
  - 10 Tpix x 6 colors x N versions
- Sky, the movie:
  - 10 Tpix x 6 colors x 50 epochs
- Sky, the database:
  - 2×10^{10} objects (x 6 colors x 20-60 epochs)
    - Photometry to < 0.01 mag, astrometry to < 5 mas
    - Photometric redshifts of most of these objects
    - Identification and redshifts for *all* galaxy clusters
  - 10^9 proper motions (complete over 3π)
  - 10^8 variable stars and AGN
  - 10^7 asteroids (10^4 NEO/PHA)
  - 10^7 transients (SN, GRB, etc.)
  - 3×10^5 stars within 100 pc (with good parallax)



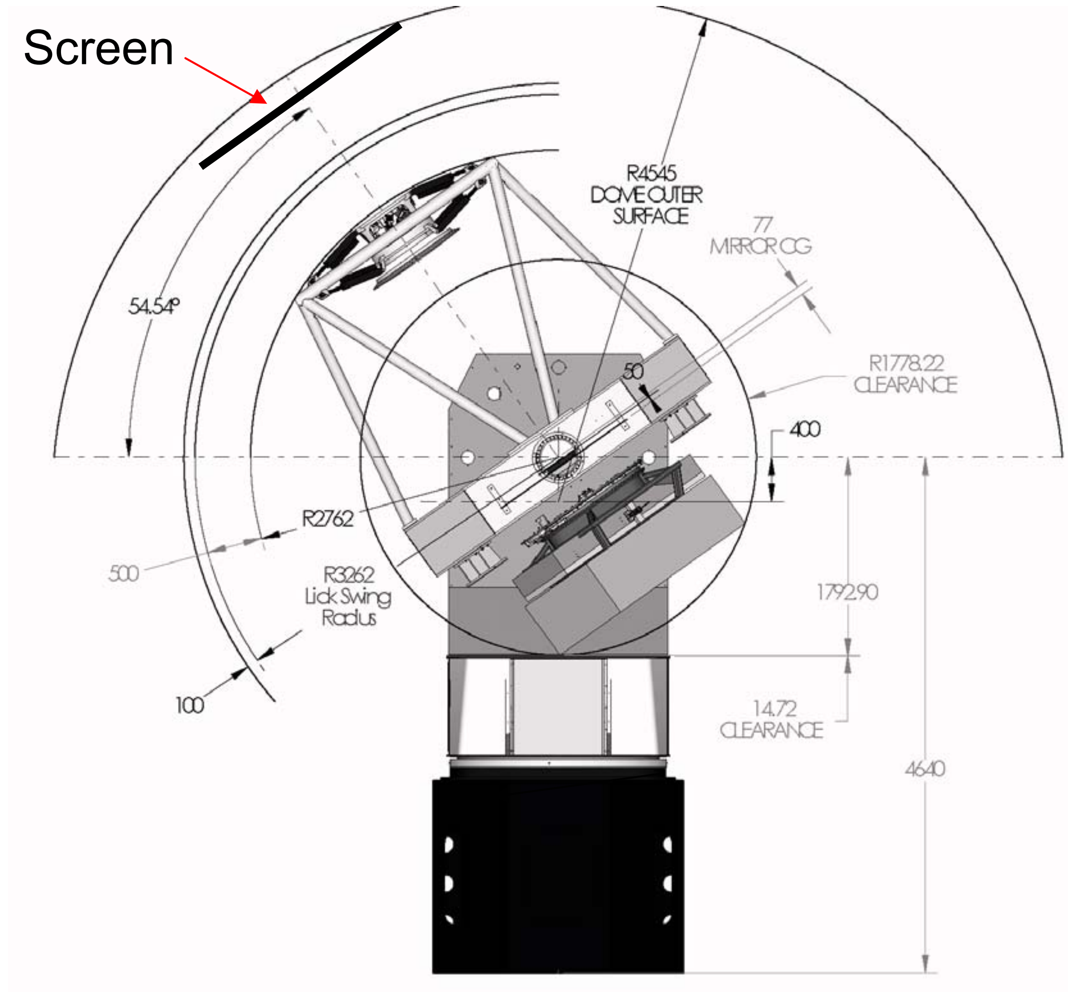
M13 I band
300 sec

Telescope guiding only
0.59" FWHM psf

With OT tracking
0.45" FWHM psf
7 Hz frame rate

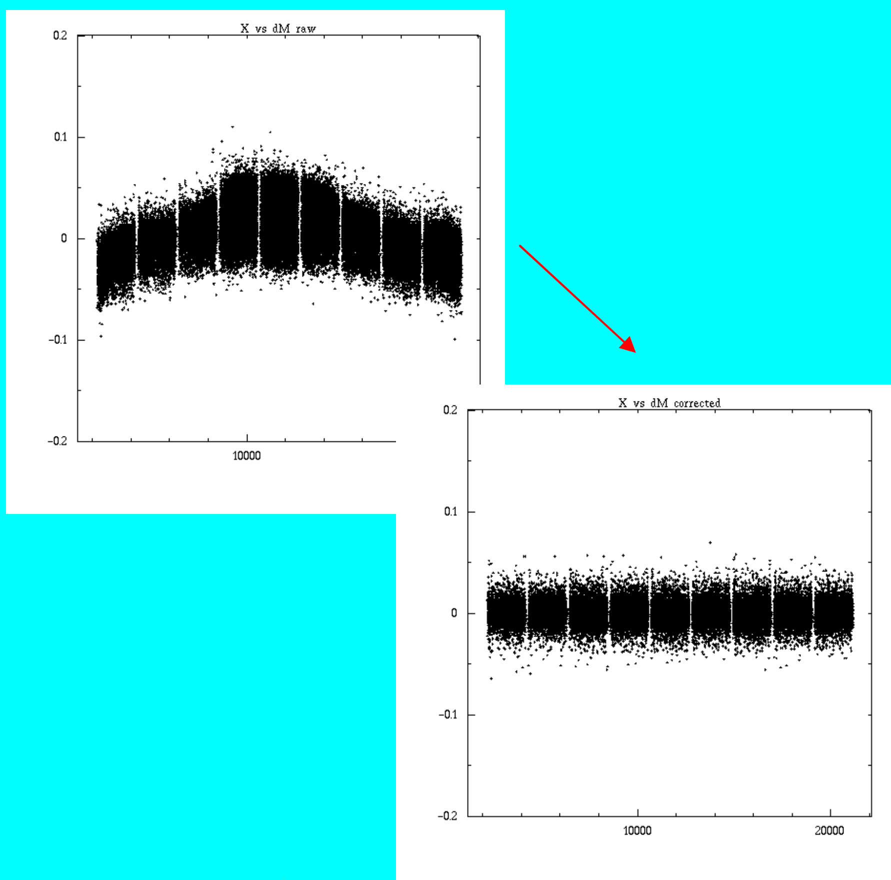
Calibration Screen

- 1000 points of light
- Fiber fed from light source
- Continuum source for flat-field
- Monochrometer for fringe-field
- Advantages
  - Repeatability
  - Uniformity
  - Stability
  - Shuttered light source

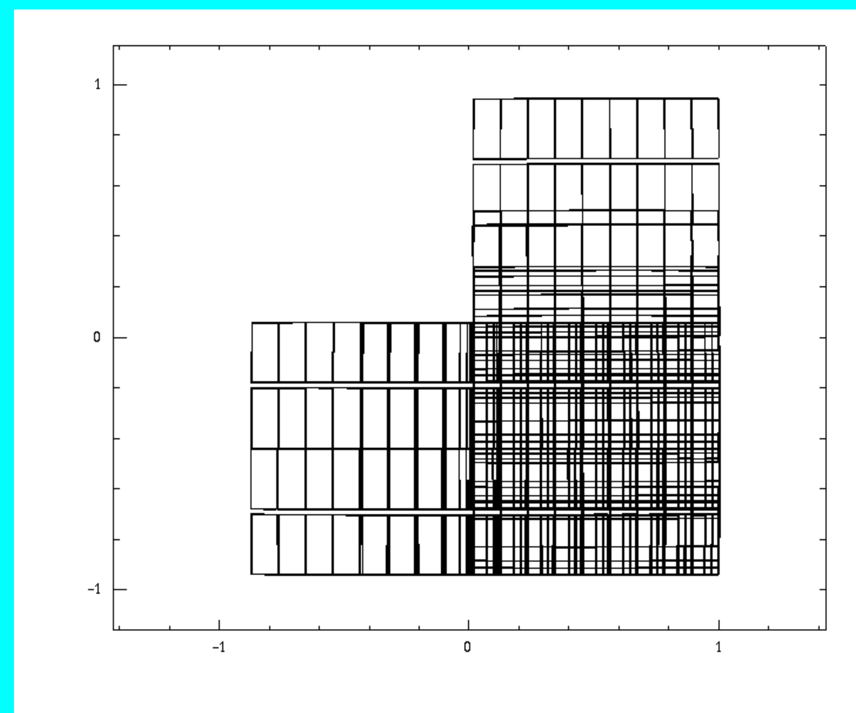


Photflat Correction

- Flat-fields correction based on stellar photometry
- Will use higher density dithers than megacam
- Will build high-density photometric reference field
- Will enable photflat construction from single observations



Megacam photflat dither pattern



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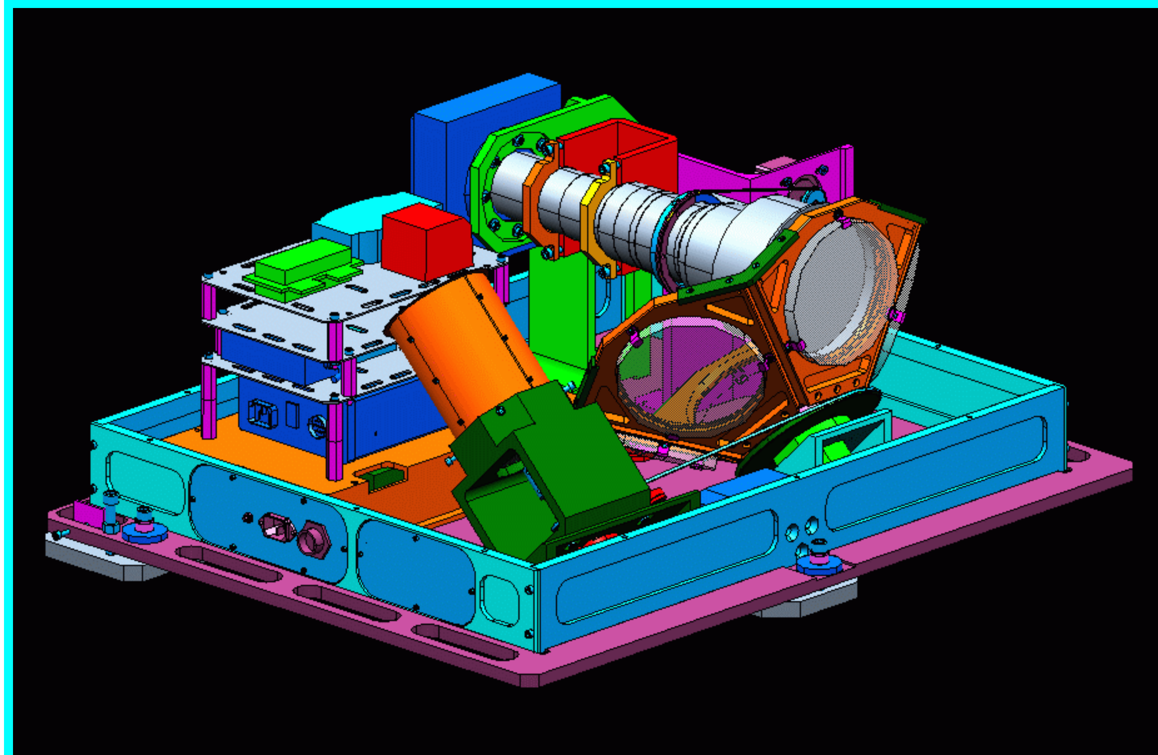

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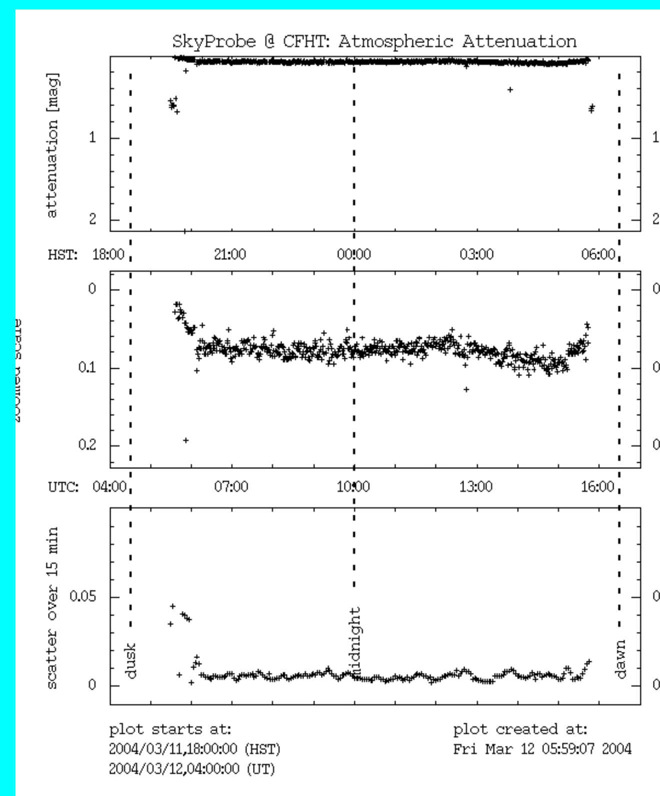
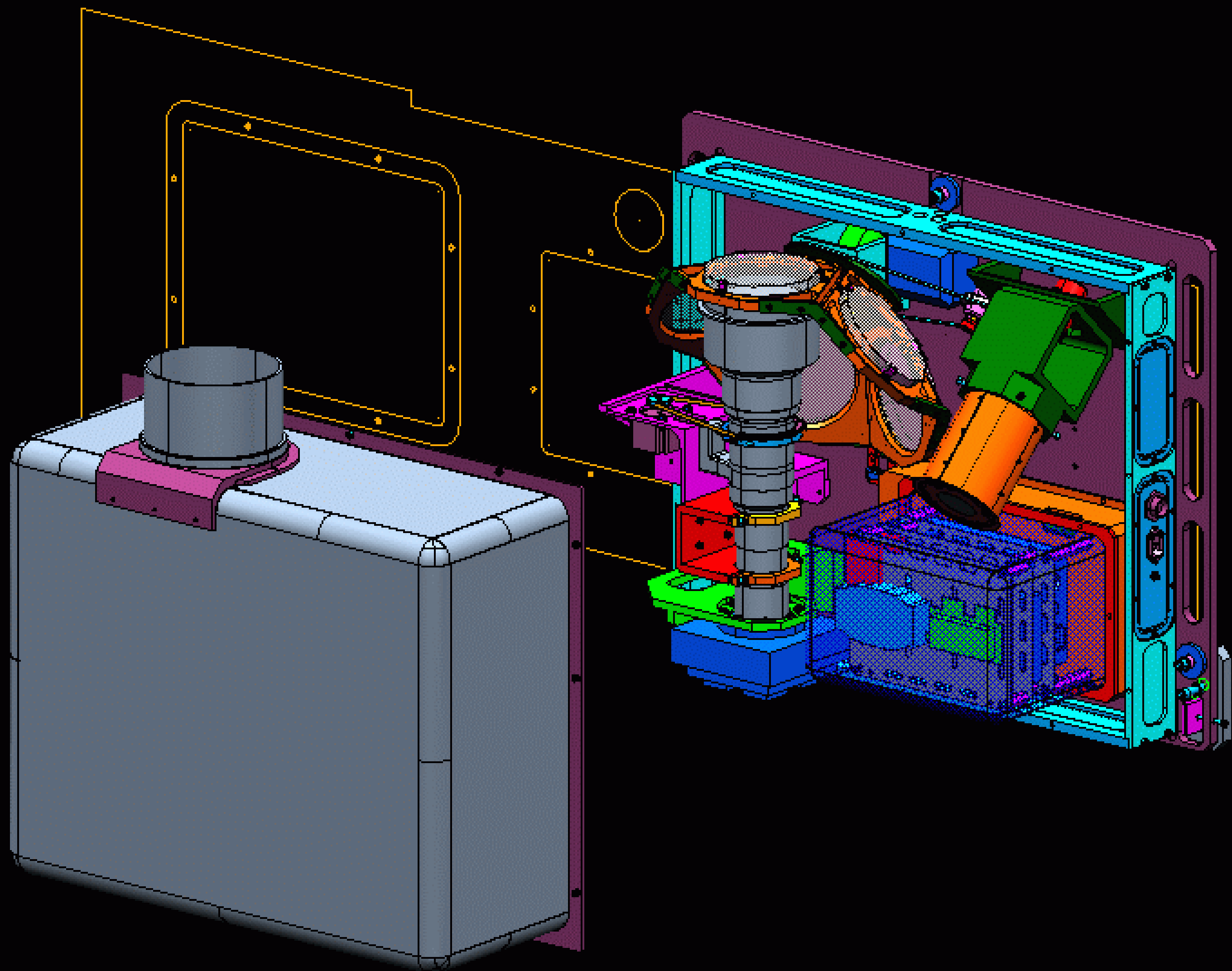


SkyProbe @ CFHT



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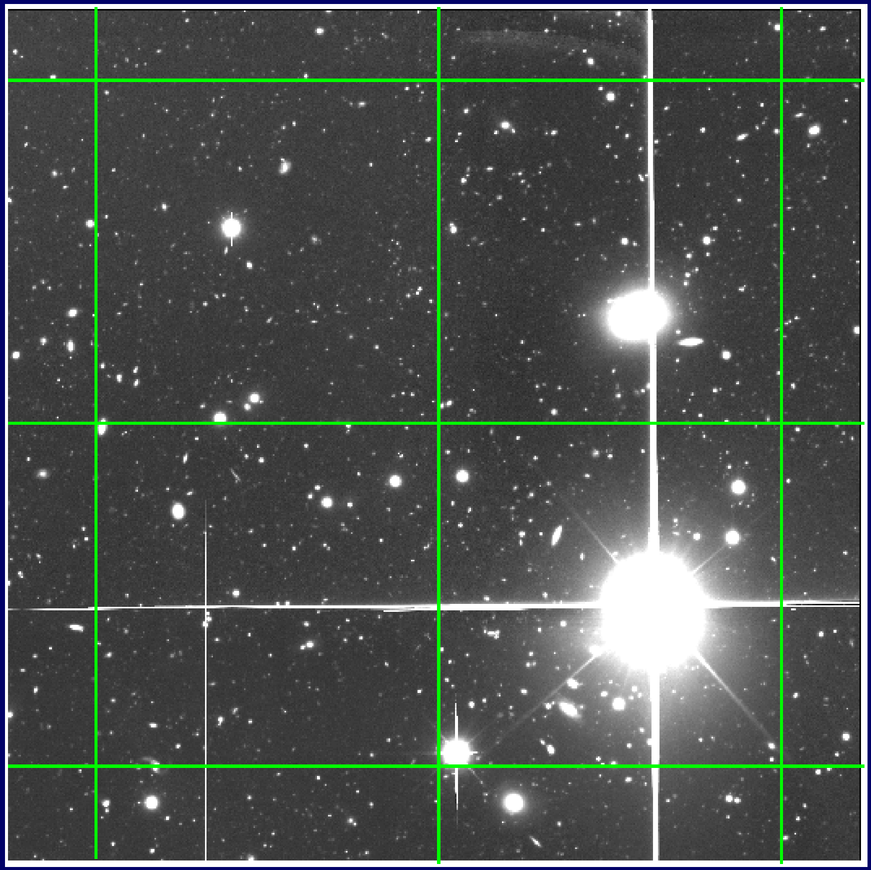
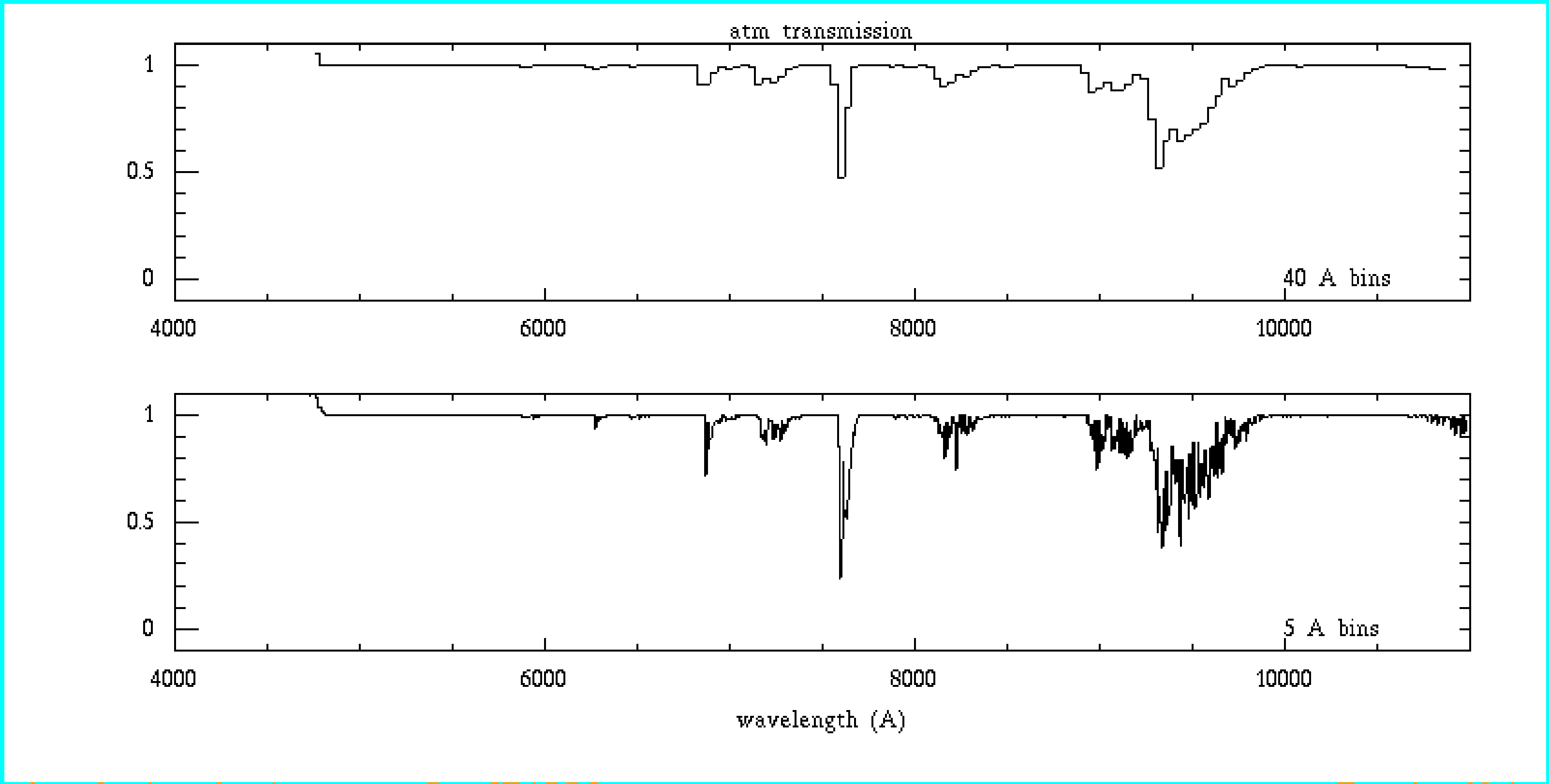


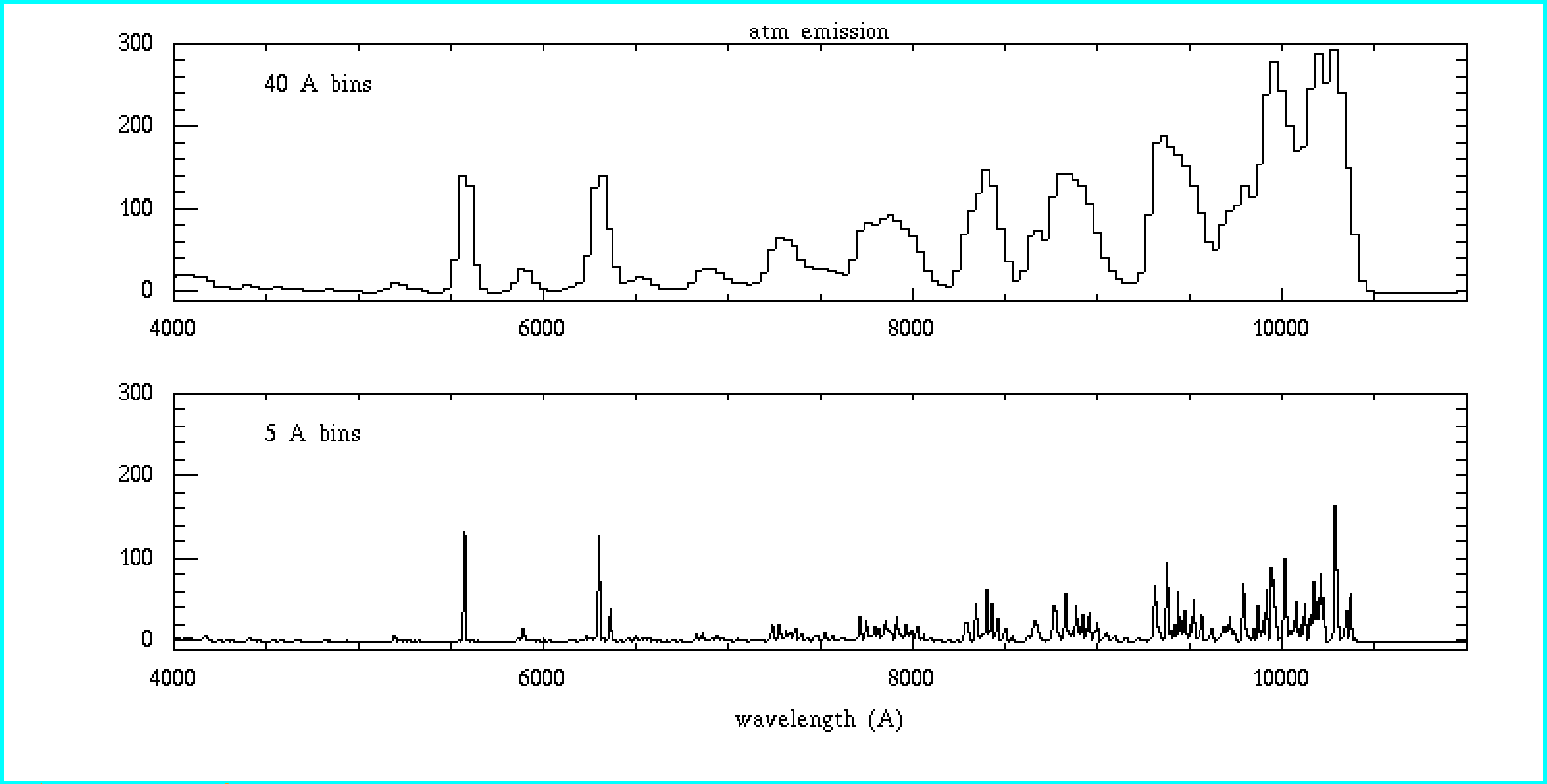
Spectroscopic Sky Probe (absorption)

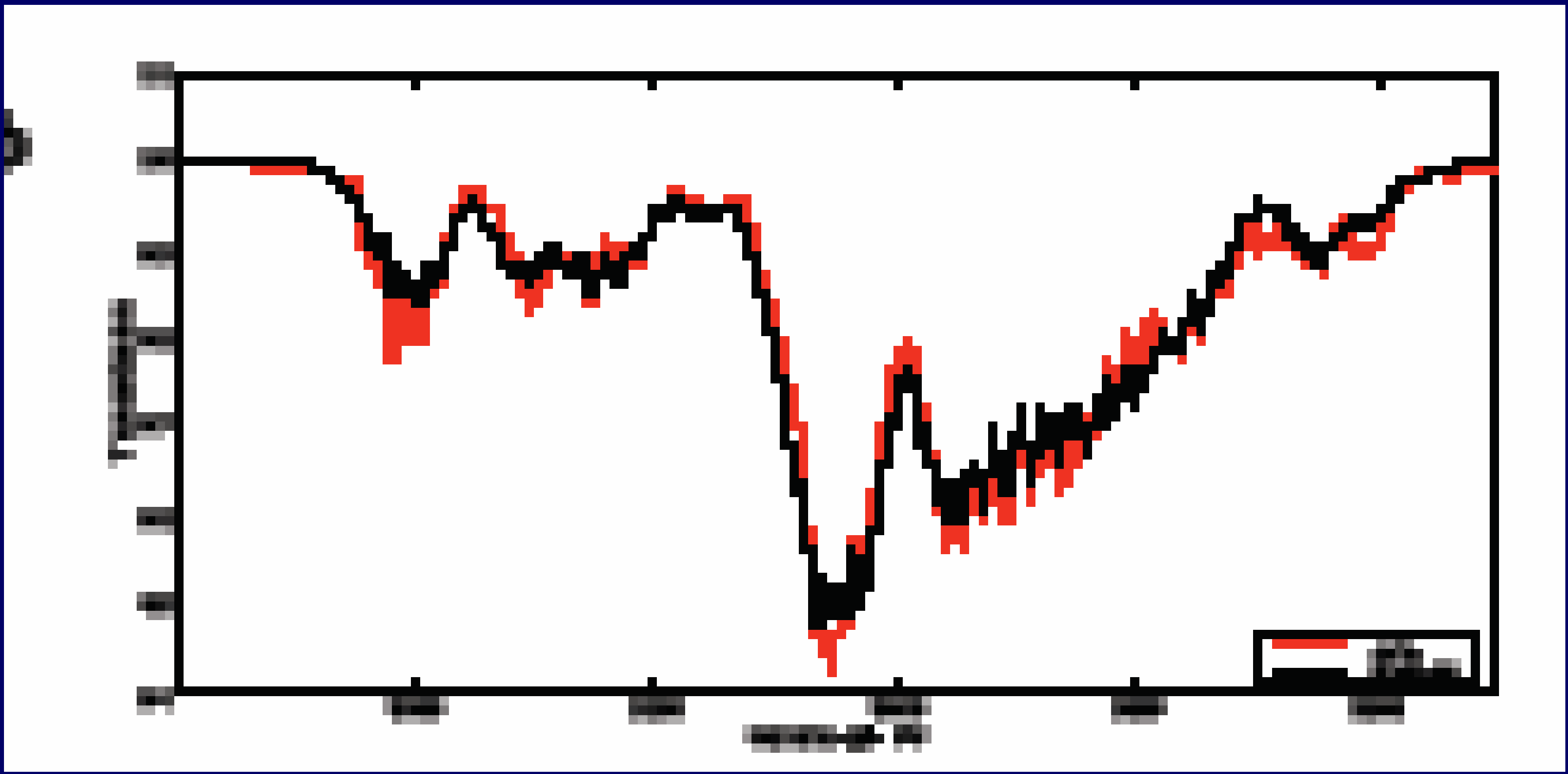
- real-time spectra of bright stars in field
- may use slit and/or slitless spectra
- 500mm f/4 camera lens
- 2k back-side detector
- modest resolution (2A/pix)
- comparison with high-resolution atm model spectra
- real-time atm effective filter function!

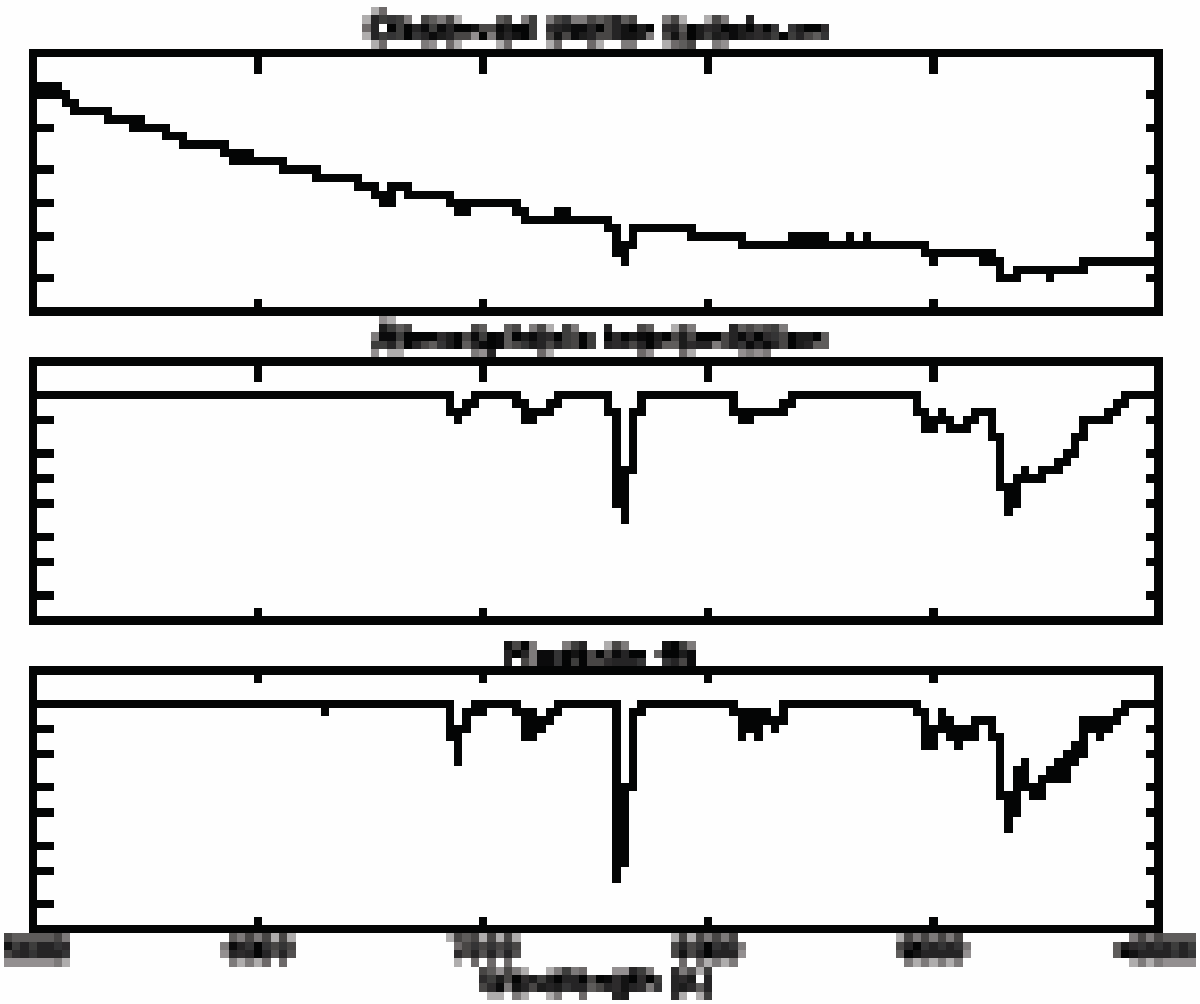


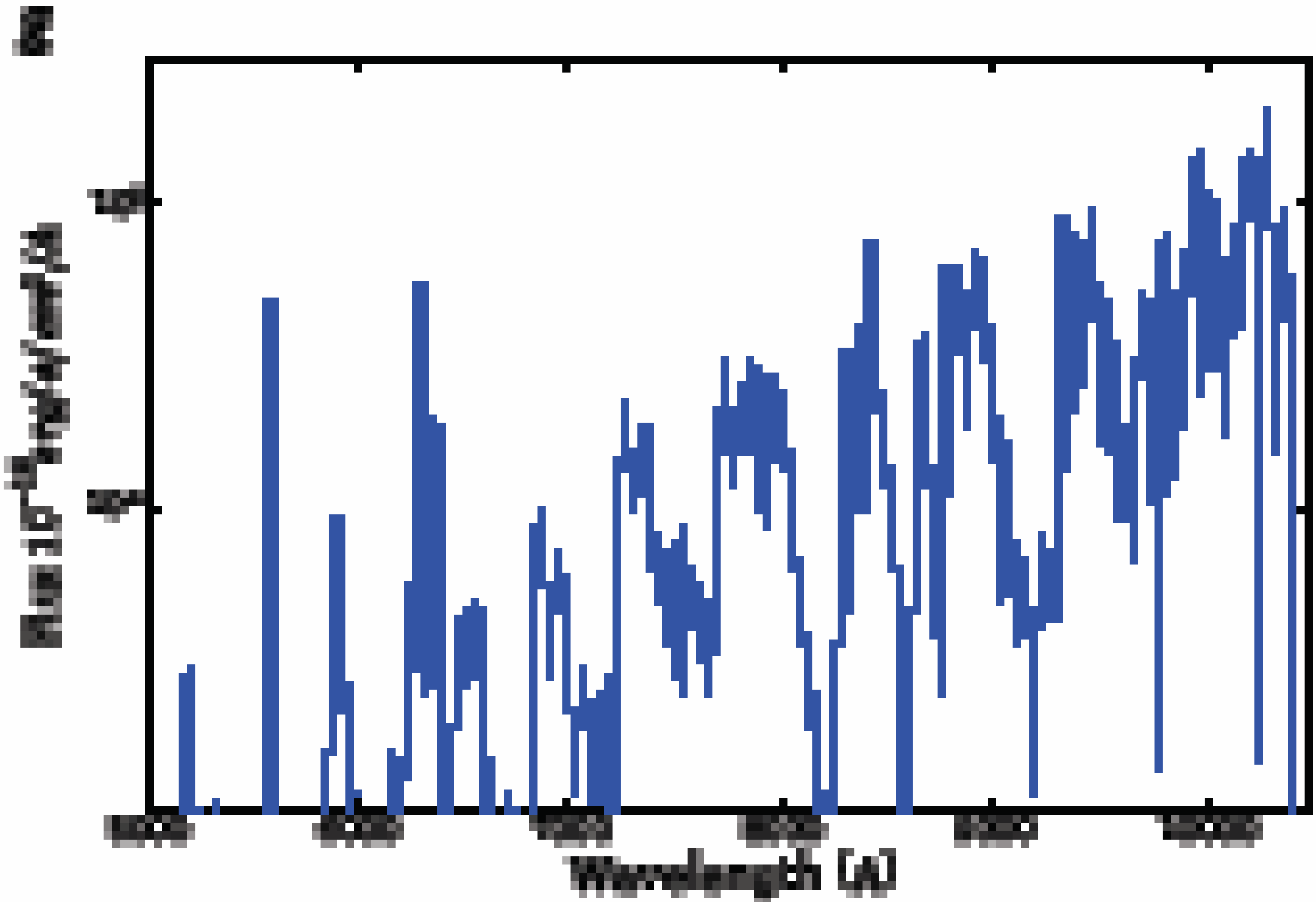
Spectroscopic Sky Probe (emission)

- real-time spectra of sky emission spectrum
- comes for free from slit-mode SpecProbe
- comparison with high-resolution atm model spectra
- input to fringe-frame master creation and application








Wavelength (Å)

Proceedure for =<5 millimag photometry

- Precision Meteorlological Data and real time atmosphere model
- Imaging Sky Probe Photometry – measure transparency
- Spectroscopic Probe – measure low dispersionatmospheric absorption along line of sight
- Spectroscopic Probe – measure sky emission lines along line of sight
- Model with NonLTE code – get high resolution absorption and emission
- Model astronomical object – add real absorption and sky emission
- Iterate photometry with model spectrum of astronomical object

Medium Deep Survey

Goals for Image Processing Pipeline Verification Program

Total of 7200 seconds in 5 filters once every four nights.

Total of 84 square degrees in twelve fields spaced evenly in RA.

Table 5: IVP Survey in 5 bandpasses

Filter	Central wavelenth (nm)	Limiting magnitude (single exposure)	seconds	limiting mag after 80 integrations of column 4 duration	IfA SURFS UP Limiting magnitude
1	2	3	4	5	6
g	475	25.2	1600	27.6	
r	625	24.6	1600	27.0	27.25
i	772	23.5	400	25.9	26.75
z	890	23.0	1000	25.4	25.75
y	1020	21.8	2700	24.2	

Ground-based Searches for Cosmological SnIa

Project	Start - End	GPix	Harvest	Clrs	Sampling
Essence CTIO 4m	2001 - 2005	0.06	40 per yr	2	2 week campaign
CFHTLS CFHT 3.6m	2003 - 2008	0.4	200 per yr	3	2 week campaign
Pan-STARRS Telescope #1	2006 - 2007	1	100 per mo	5	Every 4 days
Pan-STARRS	2007 -	4	1000 per mo	5	Every 4 days

An Ecliptic Plane Survey of the Solar System

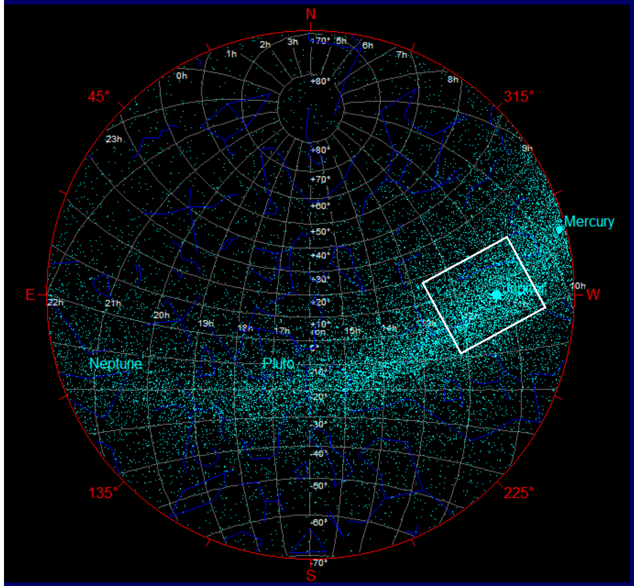
- Two Standard `Sweet Spots' consist of a total area of 1,200 sq. deg (|beta| < 10, and |lambda| < 15).
- Each integration consists of four 30 second consecutive exposures to simulate PS4.
- Each is followed a Unit Time Interval (UIT) later by another integration.
- After a zero epoch, this is done three times per lunation to establish an orbit.

Table 7: MVP Survey in Solar System Filter

Filter	Bandpass (nm)	Limiting mag (AB)	Exposure (sec)	Cadence
w	520–825	24.0	4×30	consecutive
w	520–825	24.4	2×120	UIT
w	520–825	25.0	$120 + 3 \times 240$	lunation

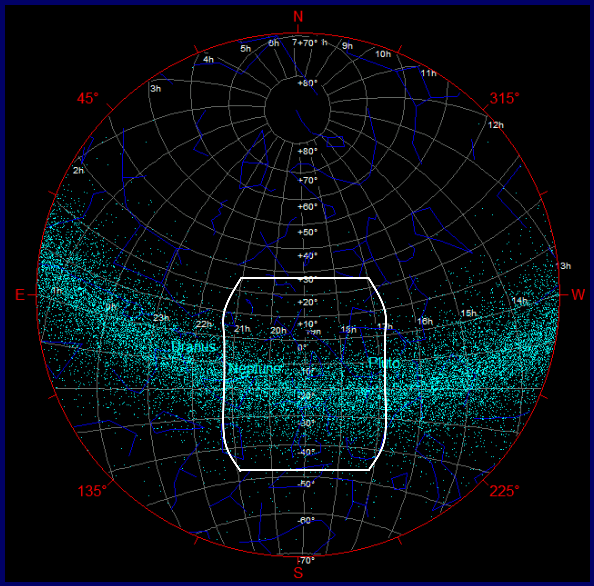
Solar System Survey

19:00 HST



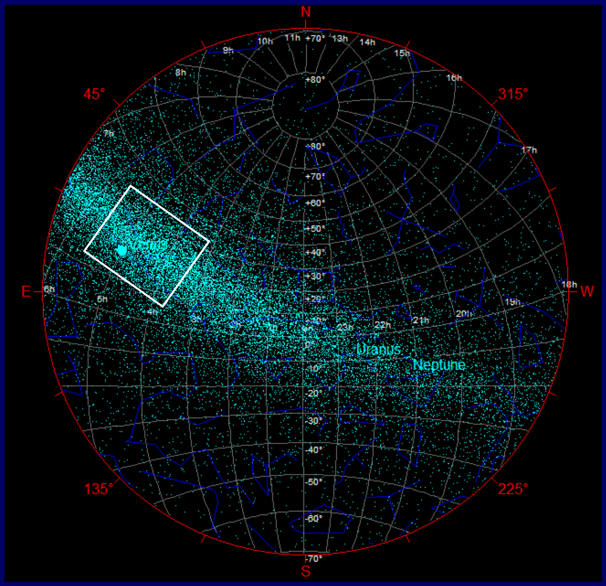
Evening Sweet Spot

00:00 HST



Opposition

05:00 HST



Morning Sweet Spot

Solar System Survey Simulator

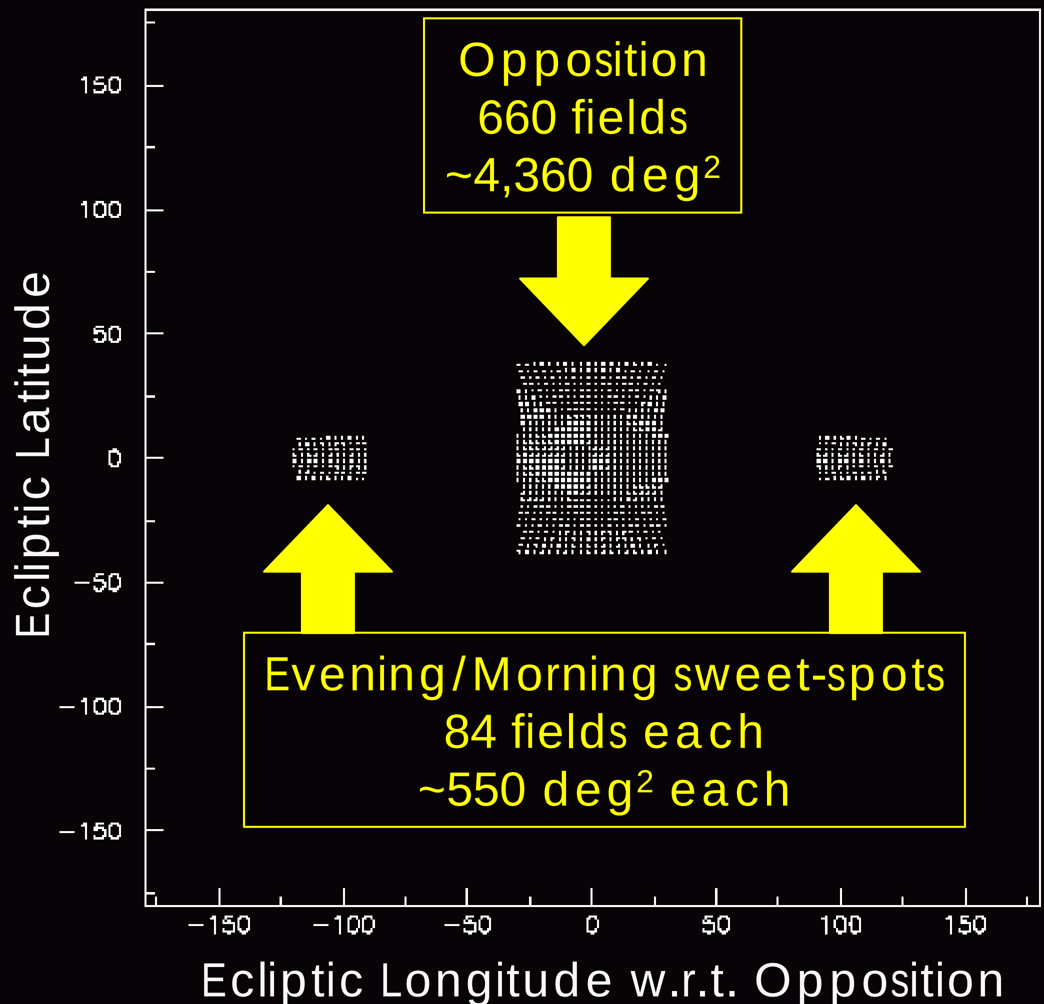
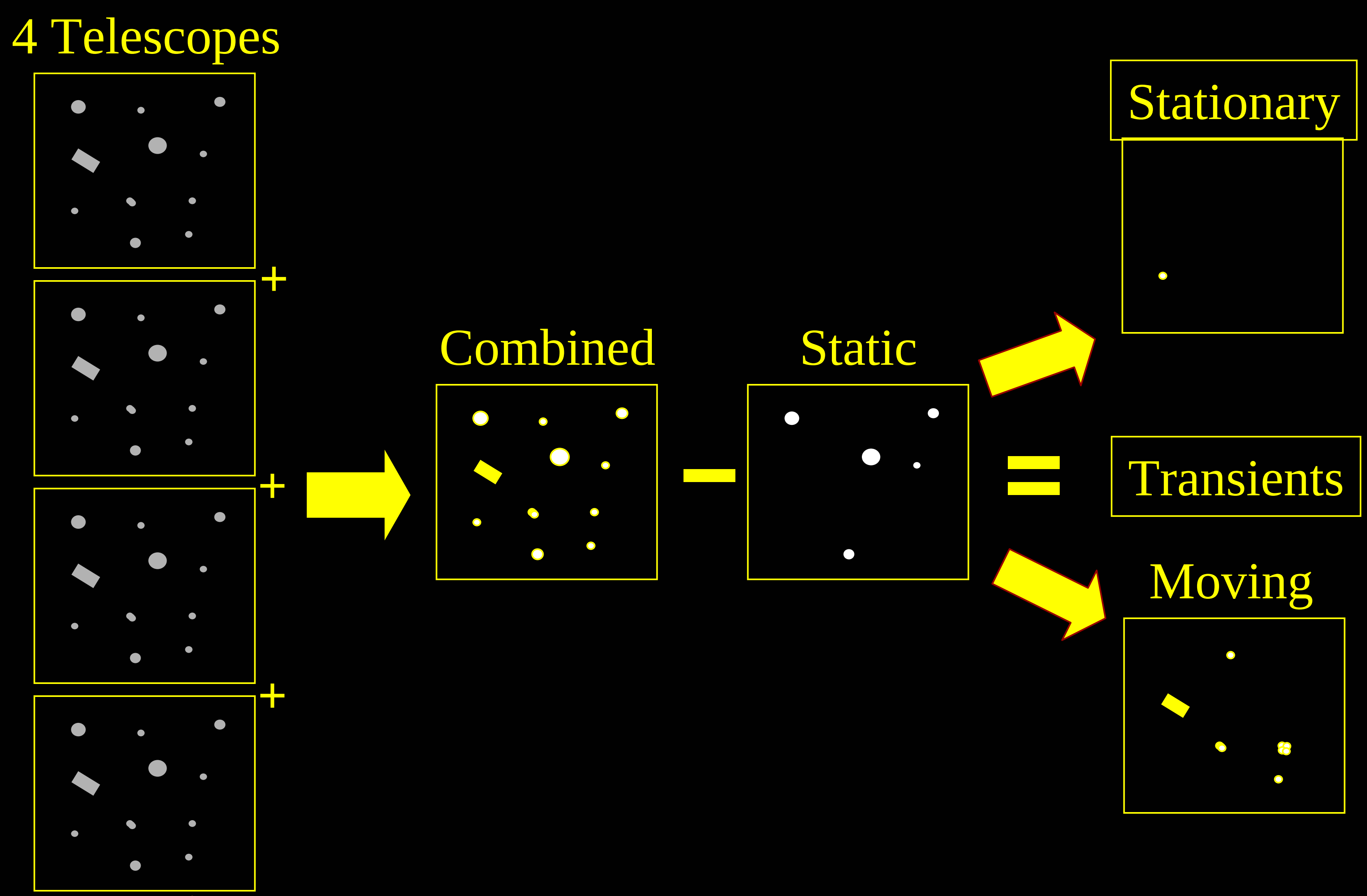
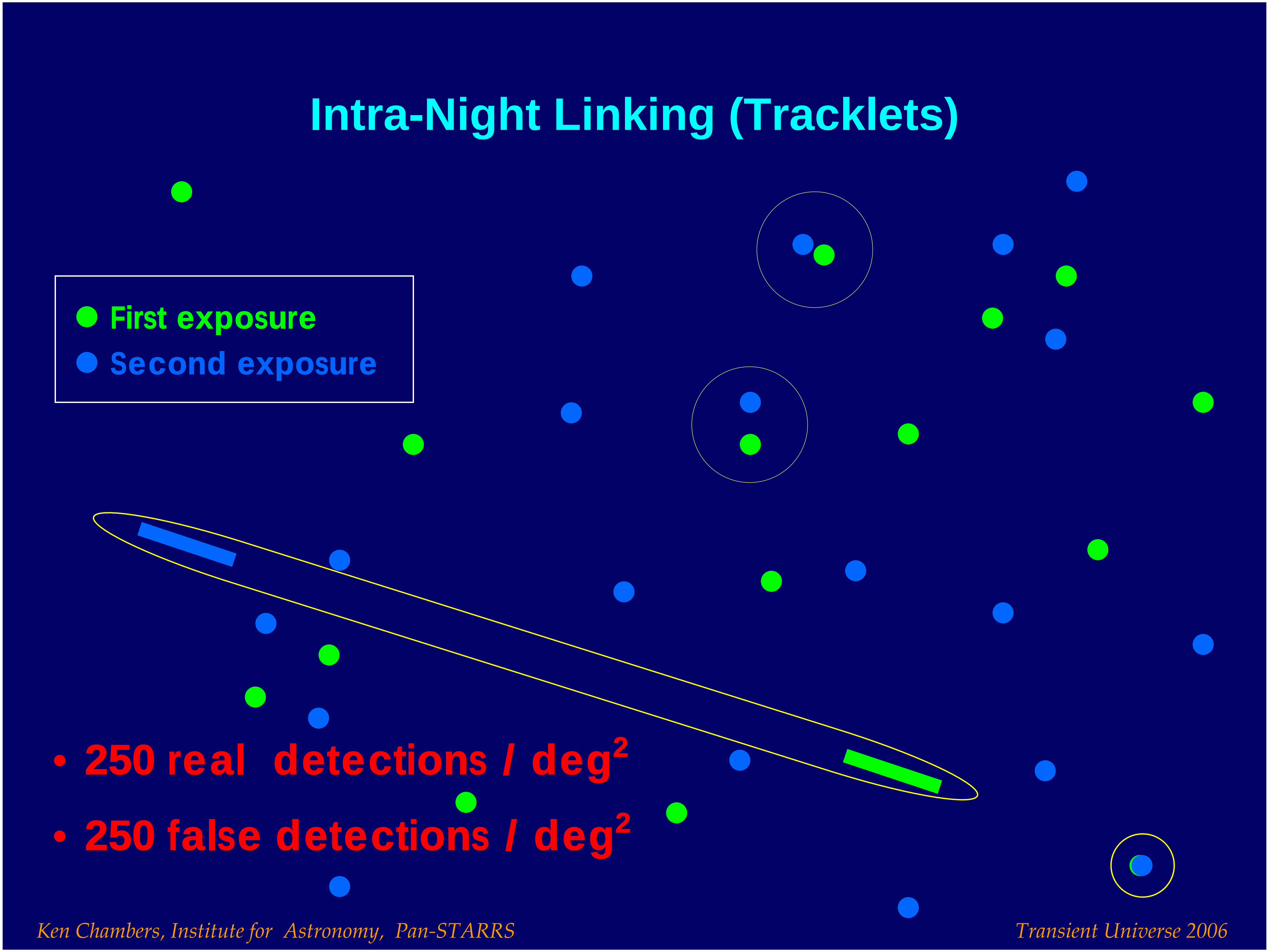


Figure 3 - 828 equally spaced points in the (λ, μ) plane after the Hammer-Aitoff transformation that form the solar system survey. There are 660 points in the large opposition region in the center of the figure. There are 84 points in each of the smaller sweet spot regions. The evening(morning) sweet spot is on the left(right).

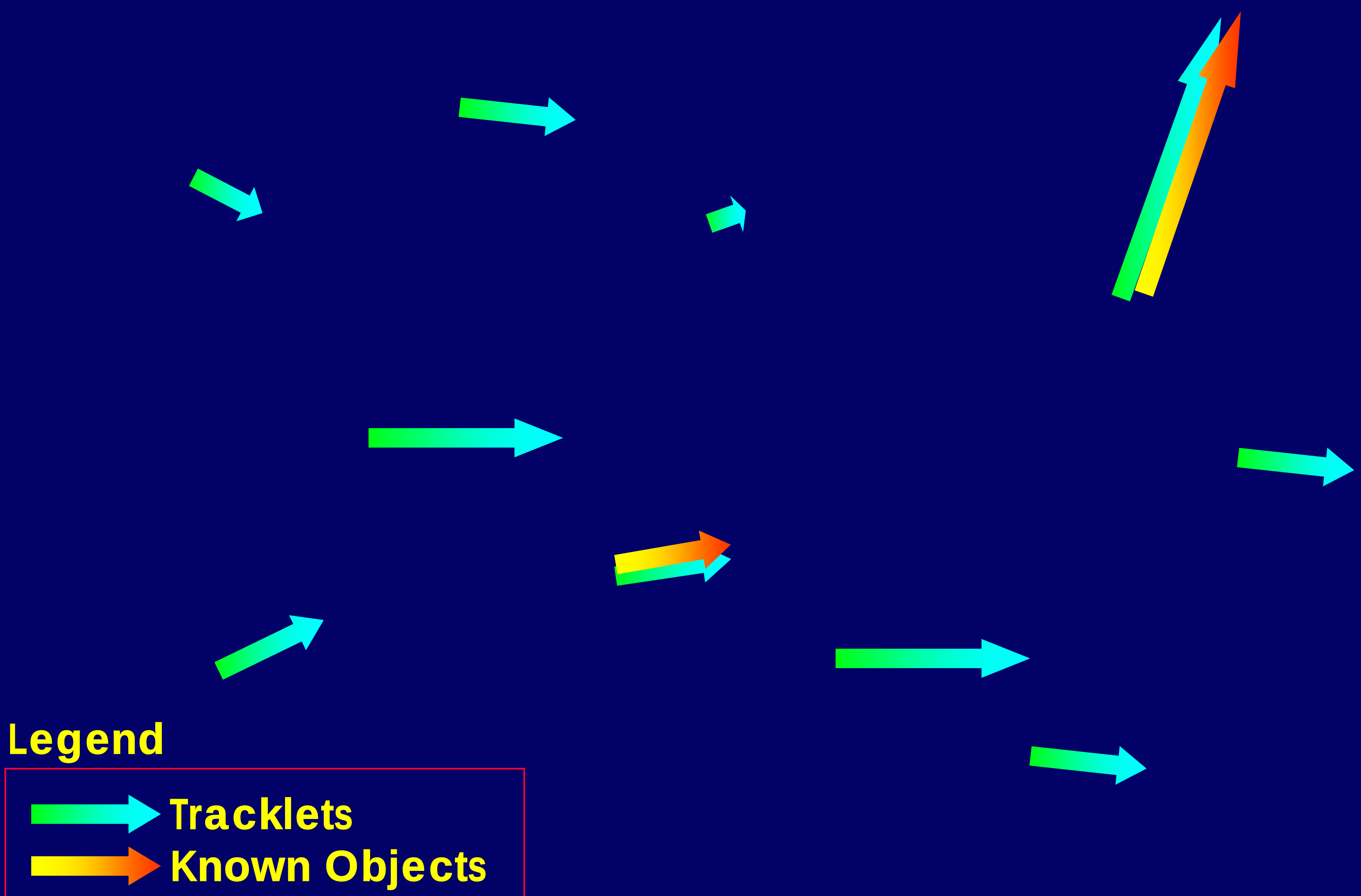
TOTAL
828 fields
~5,460 deg^2

Transient Detection (IPP)

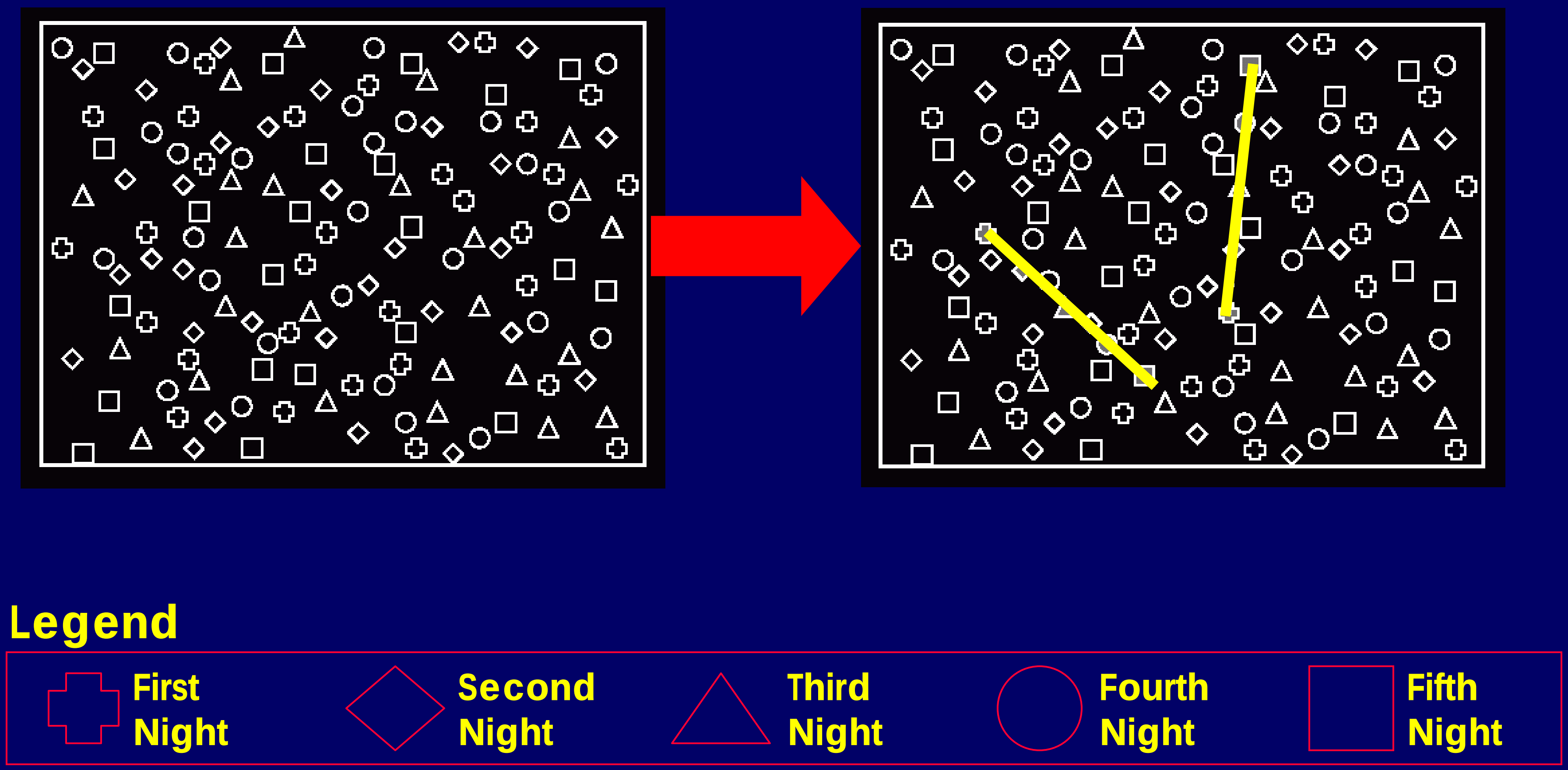



Intra-Night Linking (Tracklets)
First exposure
Second exposure
• 250 real detections / deg^2
• 250 false detections / deg^2
Ken Chambers, Institute for Astronomy, Pan-STARRS
Transient Universe 2006

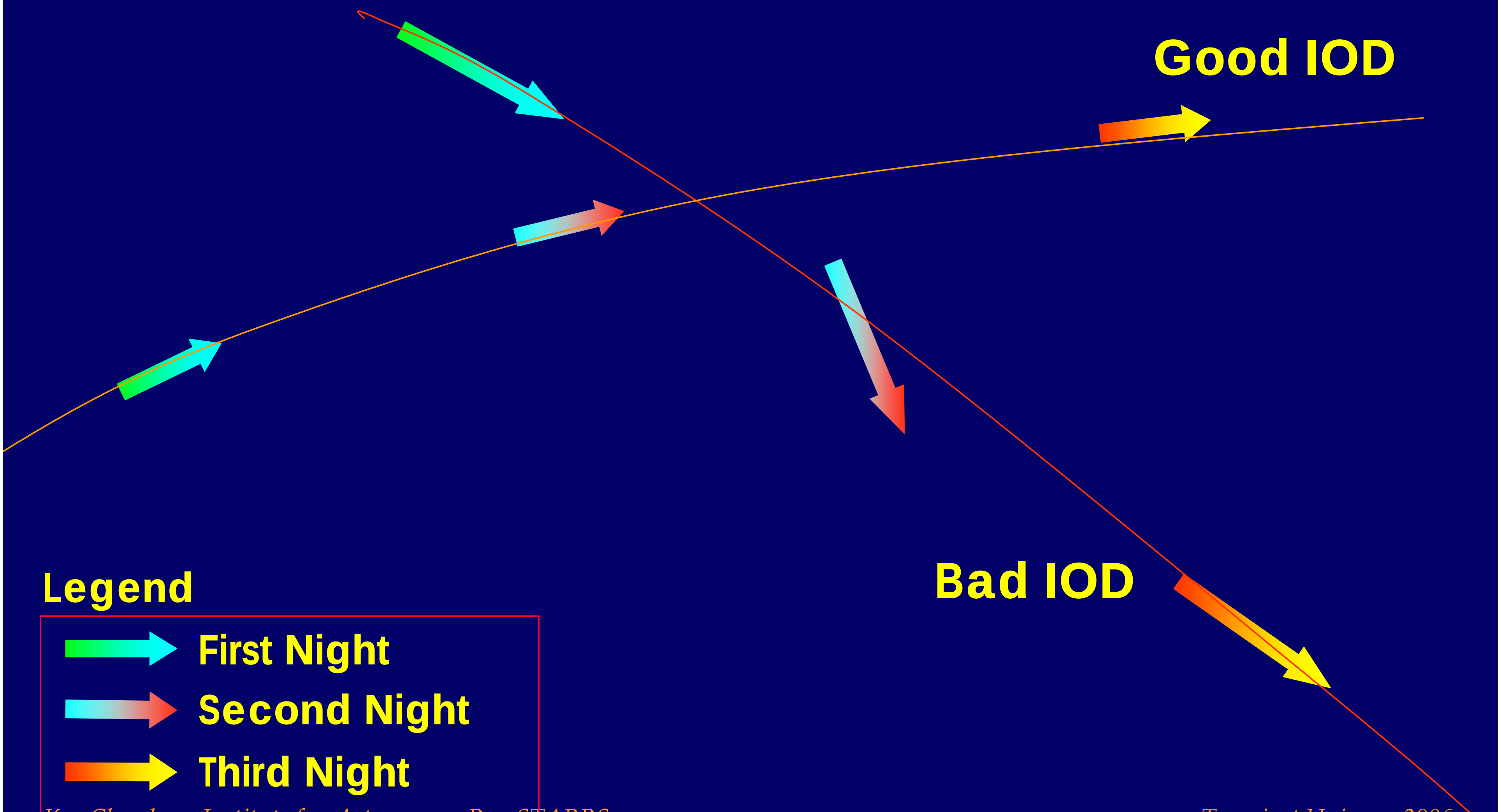
Attributions



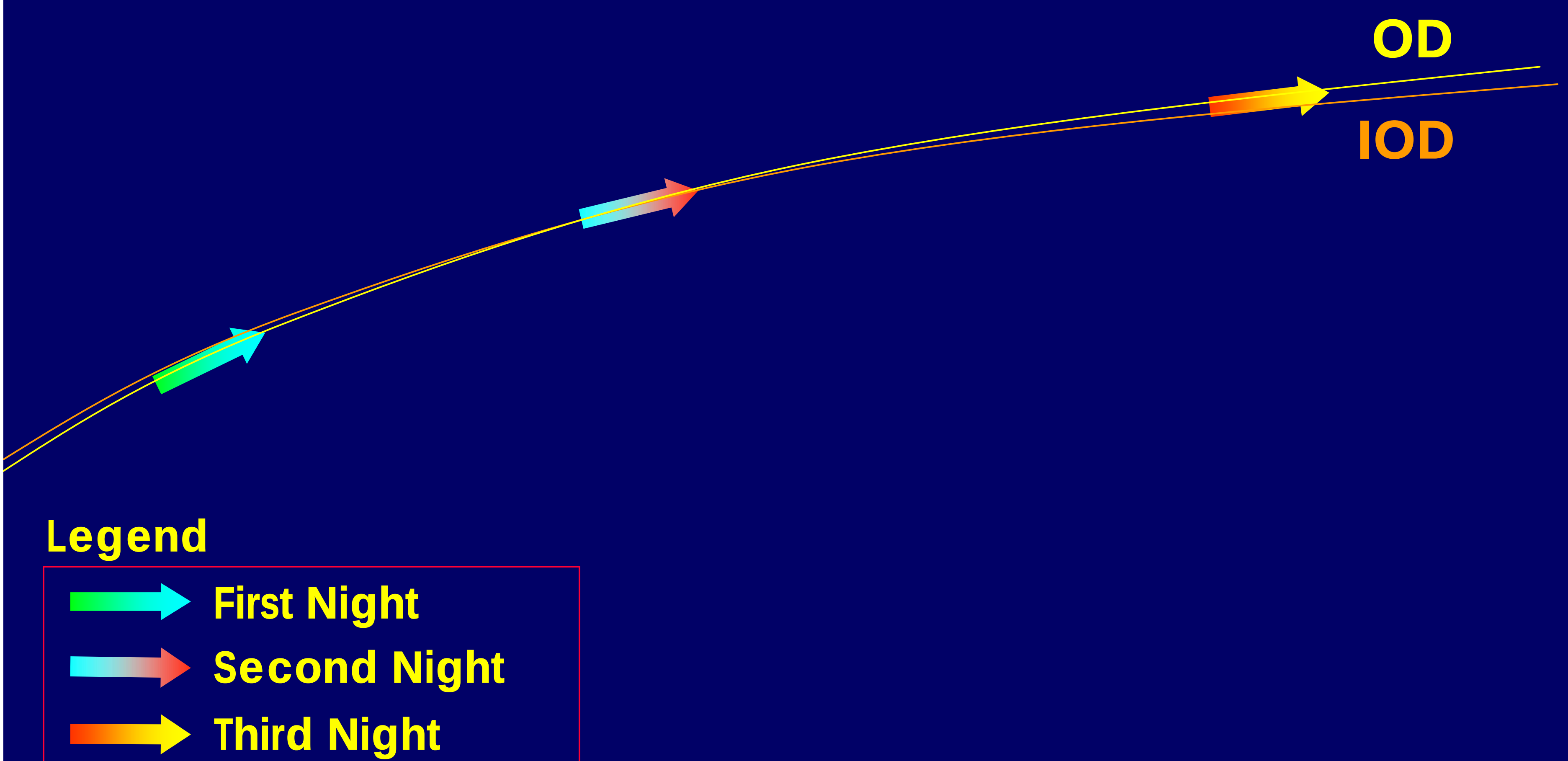
Inter-Night Tracklet Linking (tracks)



Initial Orbit Determination



Differential Orbit Determination



PS1 Data Storage Requirements

- We can save all the raw data from year 1 and one stacked image with about 0.5 Petabytes of storage.
- With this approach it will possible to re-reduce the AP survey during year 2 with the global astrometric and photometric solutions.

Table 12: Raw Data Storage Requirements for Year 1

Survey	Total Number of Images	Terabytes raw data
AP	97,603	195
IVP	68,250	136
MVP	13,800	28
Total	179,653	359

Table 13: Data Storage Requirements for Stacked Reduced Images in First Year

Survey	Area (sq. deg.)	Terapixels ($0.2''$/pix)	No. Filters	Terabytes (4 bytes/pix) image+ (s/n) map	Terabytes raw data (Table 12)	Total Terabytes Year 1
AP	31,000	10	5 ($grizy$)	200	195	395
IVP	84	0.03	5 ($grizy$)	1	136	137
MVP	3,000	1	1 (w)	4	28	32
Total				205	359	564

END

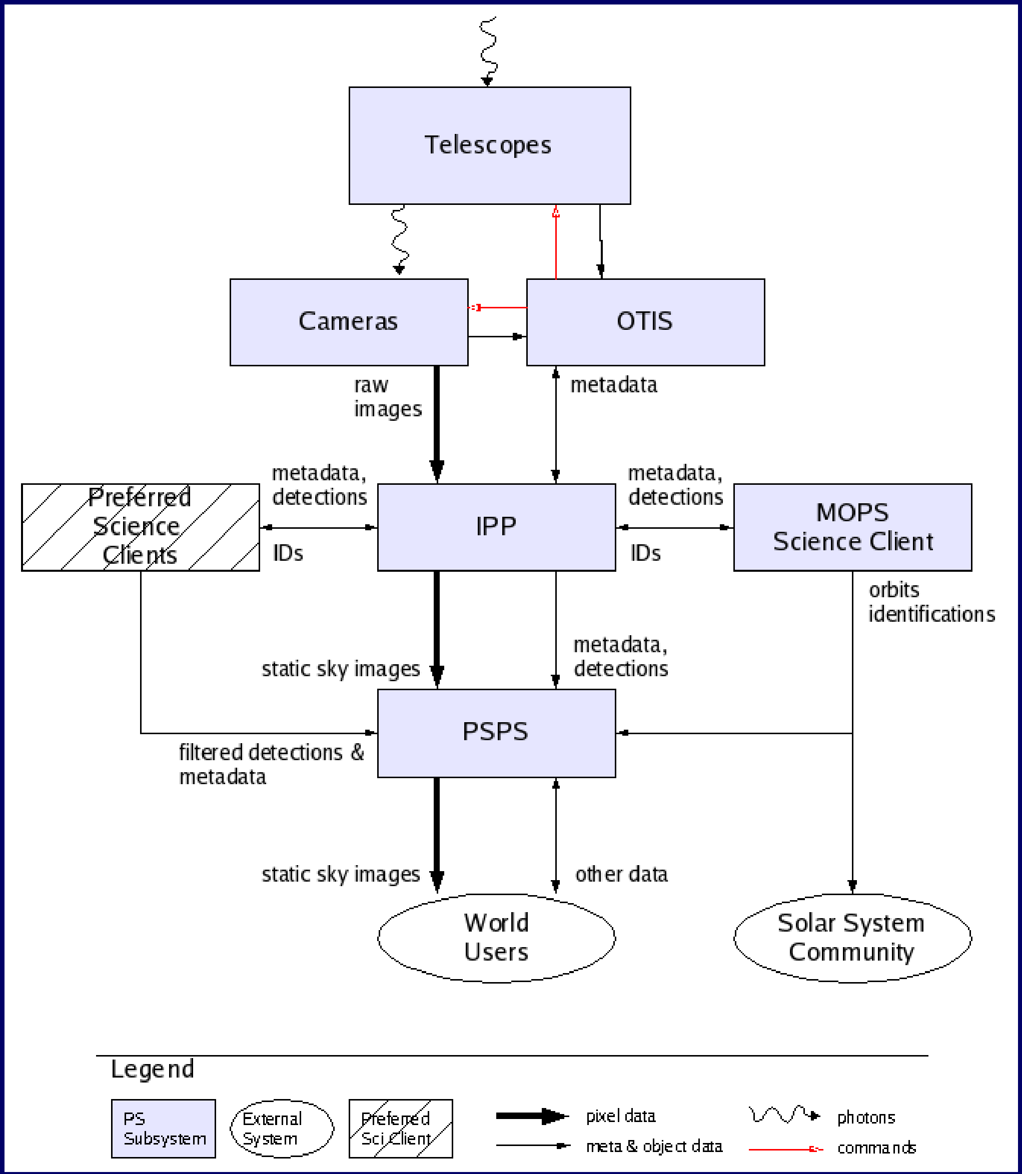
Astrometry with PS1

Derived Requirements: Astrometric Performance

- PS1 astrometric accuracy for commissioning phase: 750 mas
- PS1 astrometric accuracy for reference catalog phase: 250 mas
- PS1 astrometric accuracy for normal operations: 100 mas
- PS1 astrometric reference catalog within 6 months of end of PS1 AP Survey

- PS4 astrometric reference astrometry accuracy: 100 mas (abs), 30 mas (rel)
- PS4 astrometric reference proper motion accuracy: 20 mas / year

Pan-STARRS Overview



Pan-STARRS Subsystems

- TEL – Telescopes
- CAM – Cameras
- OTIS – Observatory, Telescope & Instrument Software
- IPP - Image Processing Pipeline
- MOPS – Moving Object Processing Software
- PSPS – Published Science Data Products

OTIS

Observatory, Telescope, & Instrument Software

Observatory, Telescope, & Instrument Software (OTIS) Requirements

Critical System Level Requirements that drive conceptual design of OTIS:

- The system shall be capable of timing observations to meet the science requirements (SGS-4.2.1; 4.2.2; 4.2.6).
- The system shall have the capability to determine the schedulable fraction of a specified science program.

Observatory, Telescope, and Instrument Software (OTIS)

Critical Subsystem Requirements that drive the conceptual design

- OTIS shall be capable of operating the observatory robotically.
- OTIS shall enable an observing efficiency > 65% TBR
- OTIS shall ensure the observation time devoted to each survey mode averaged over a year matches the goals of the total science program.
- OTIS shall schedule calibration observations sufficient to maintain an absolute photometric precision in the zeropoints of < 0.01 magnitudes.
- OTIS shall verify, maintain, and track the mechanical and optical performance of the telescope, instruments, and observatory.
- OTIS shall control the telescope such that the contribution to the image budget from the telescope does not exceed 0.31" FWHM.

Observatory, Telescope, and Instrument Software (OTIS)

More Critical Subsystem Requirements: (Scheduling of observations)

- OTIS shall be capable of scheduling a given cadence.
- OTIS shall be capable of scheduling cadences over a given duration.
- OTIS shall be capable of scheduling a given depth per visitiation.
- OTIS shall be capable of scheduling any chronological night-to-night pair-wise cadence.
- OTIS shall be capable of scheduling pairs of observations per night i.e. separated by a Transient Time Interval (TTI).
- OTIS shall be capable of scheduling observations with maximum lunar illumination requirements.

.

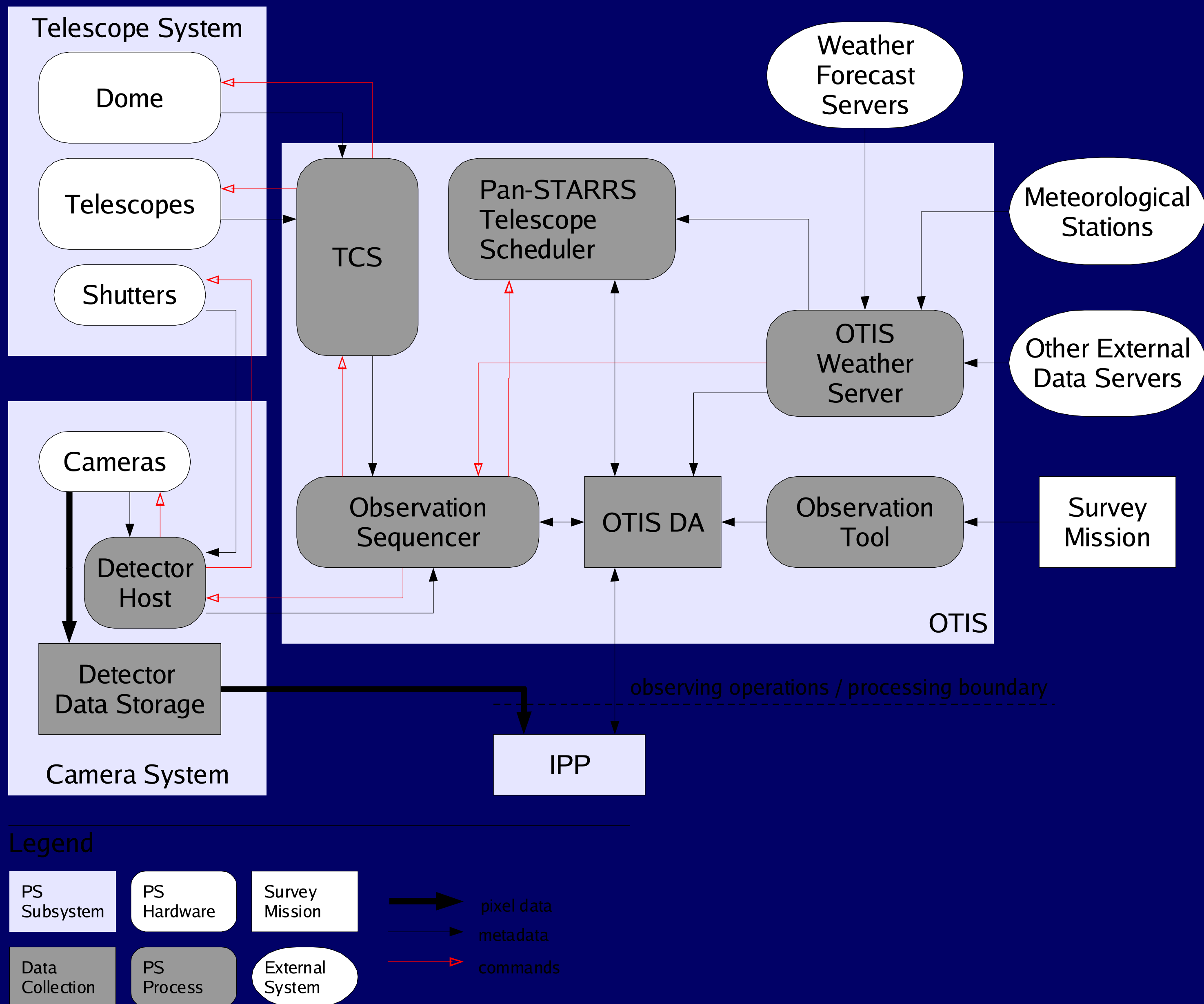
OTIS Conceptual Design:

Divide tasks and functions among six separate modules:

- OTIS Observation Tool (OOT)
  Interactive and autonomous creation of *Observe Files*
- Pan-STARRS Telescope Scheduler (PTS)

  Determines which Observe File to be executed at a given date and time.
- Observation Sequencer (OBS)
  Task manager that commands observatory, telescope, and camera.
- Telescope Control Software (TCS)
  Controls telescope, dome, and calibration unit, monitors internal environ.
- OTIS Weather Server and External Data Processor (OWS)
  Monitors meteorological station, procures external data, forecasts
- OTIS Data Archive (ODA) Archives all metadata, logs, commands

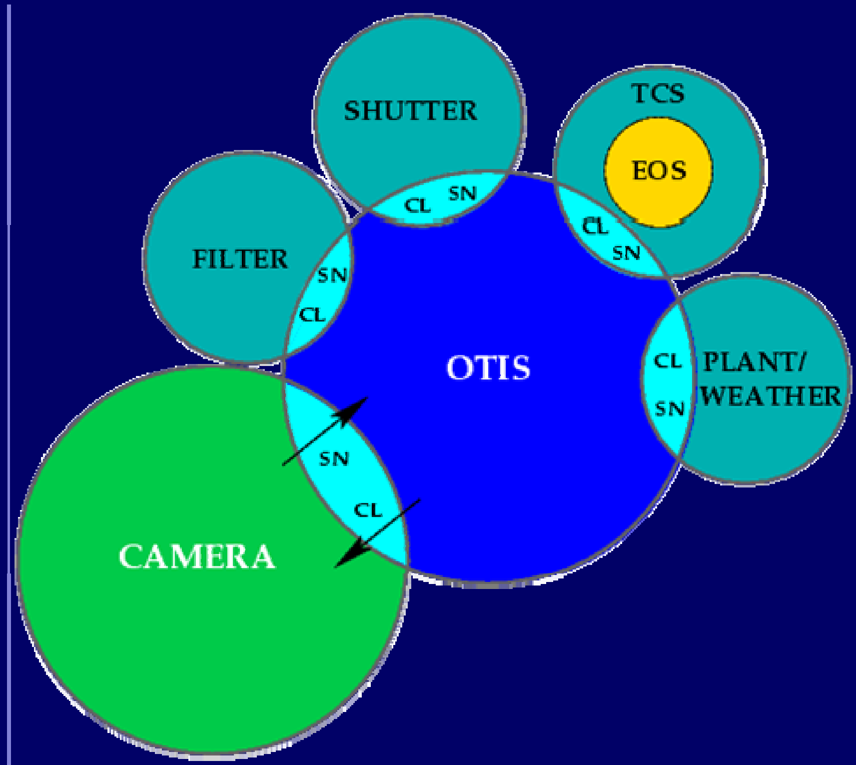
Summit Process Flow Diagram



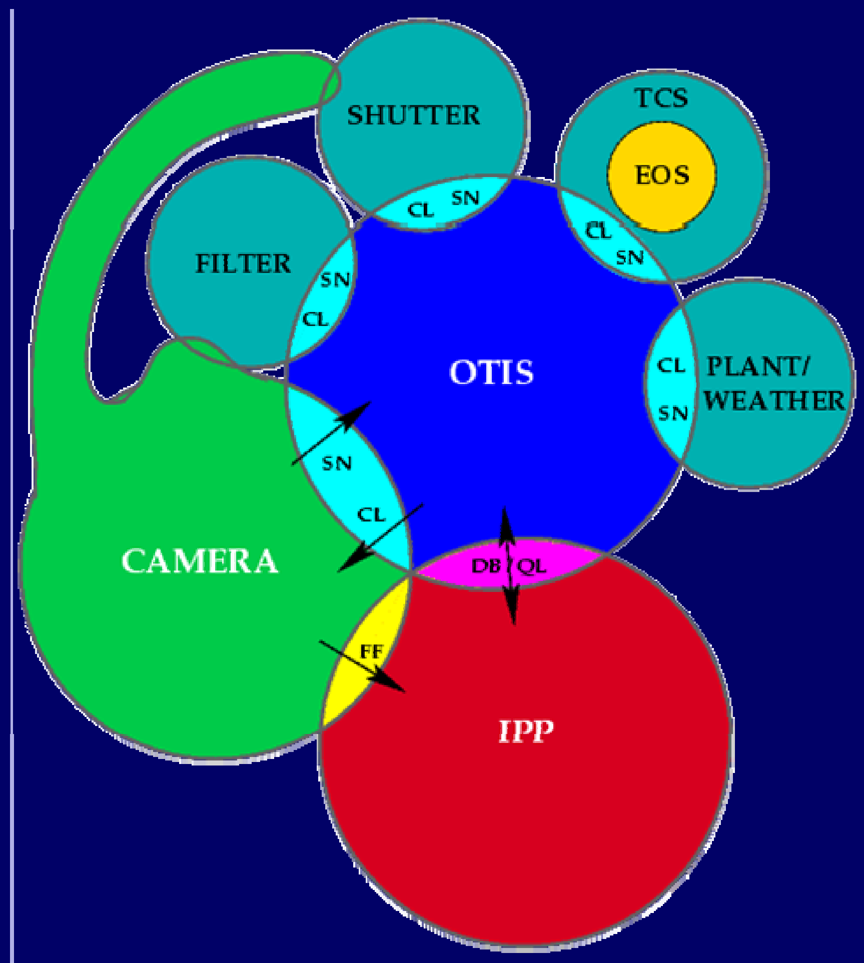
Interfaces between OTIS and Camera

CL Command Language

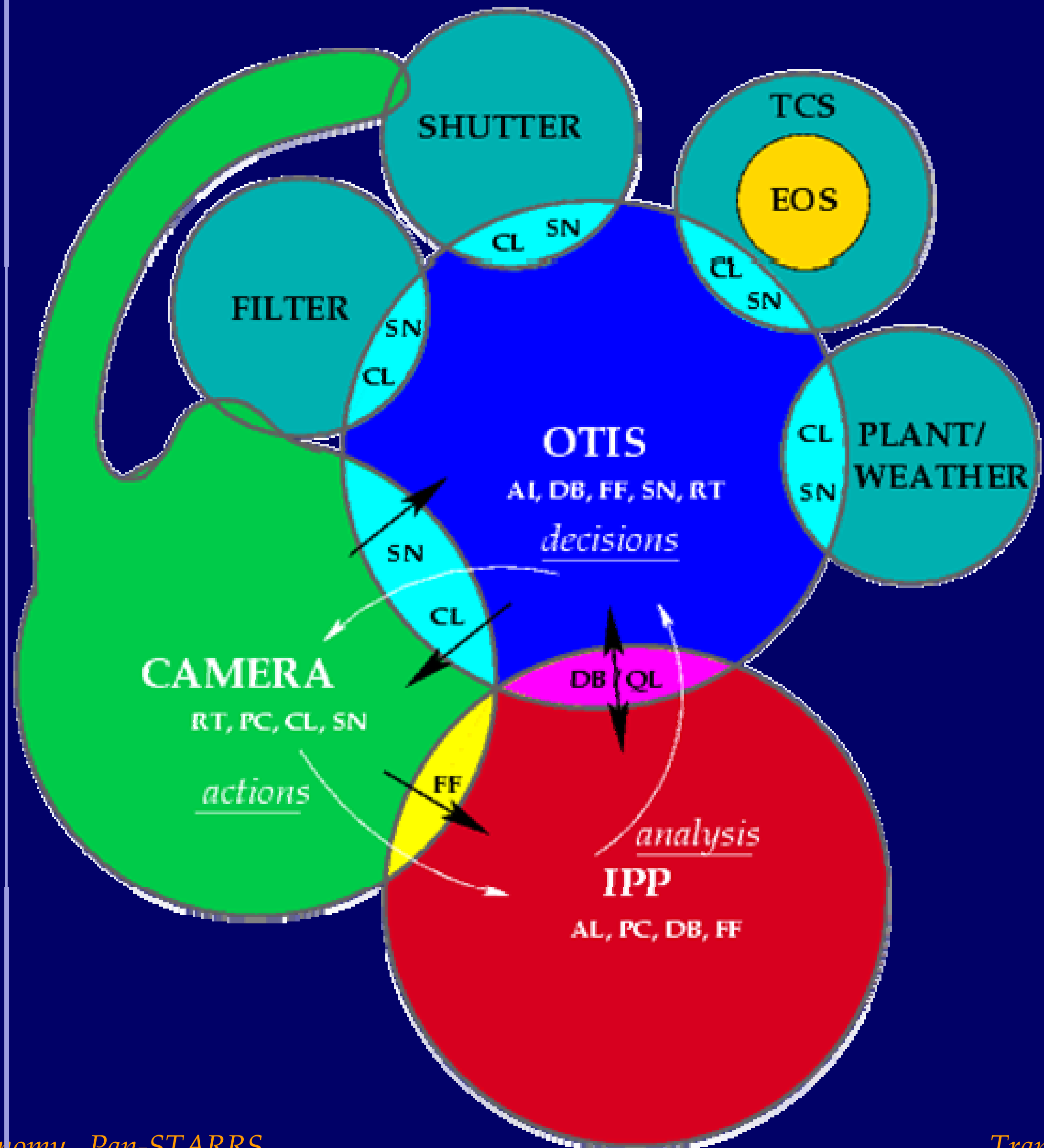
SN Shared Namespace



Interface between OTIS, Camera, and IPP



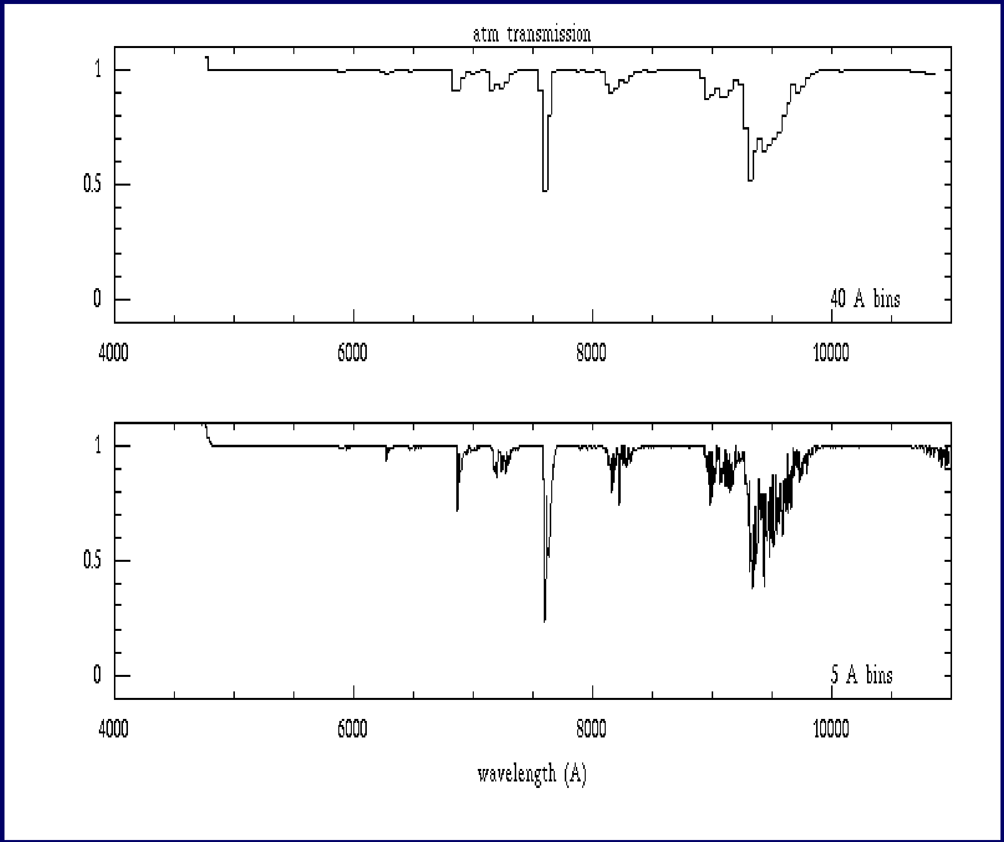
Interface between OTIS, Camera, and IPP

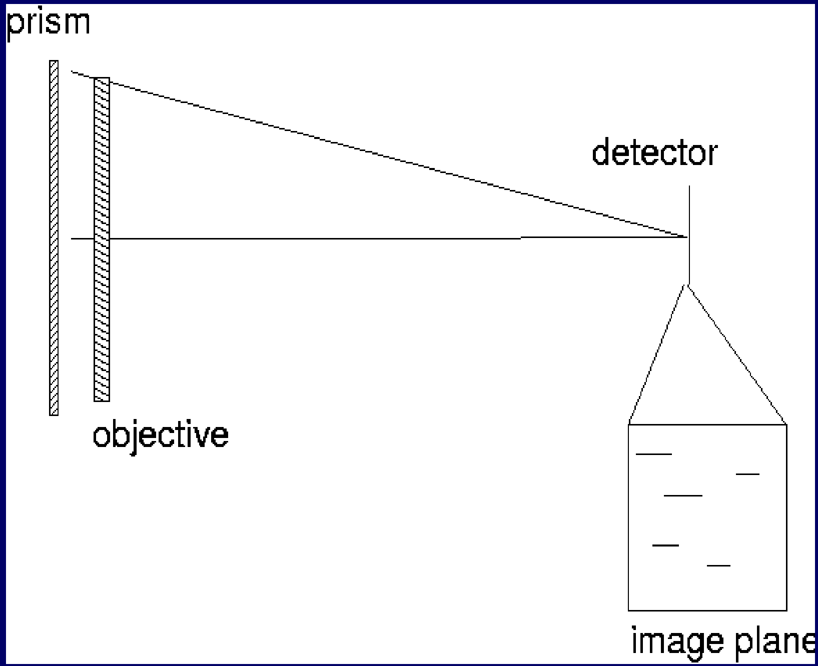


Appendicies

Photometry: Bright Stars & Flux Calibrations

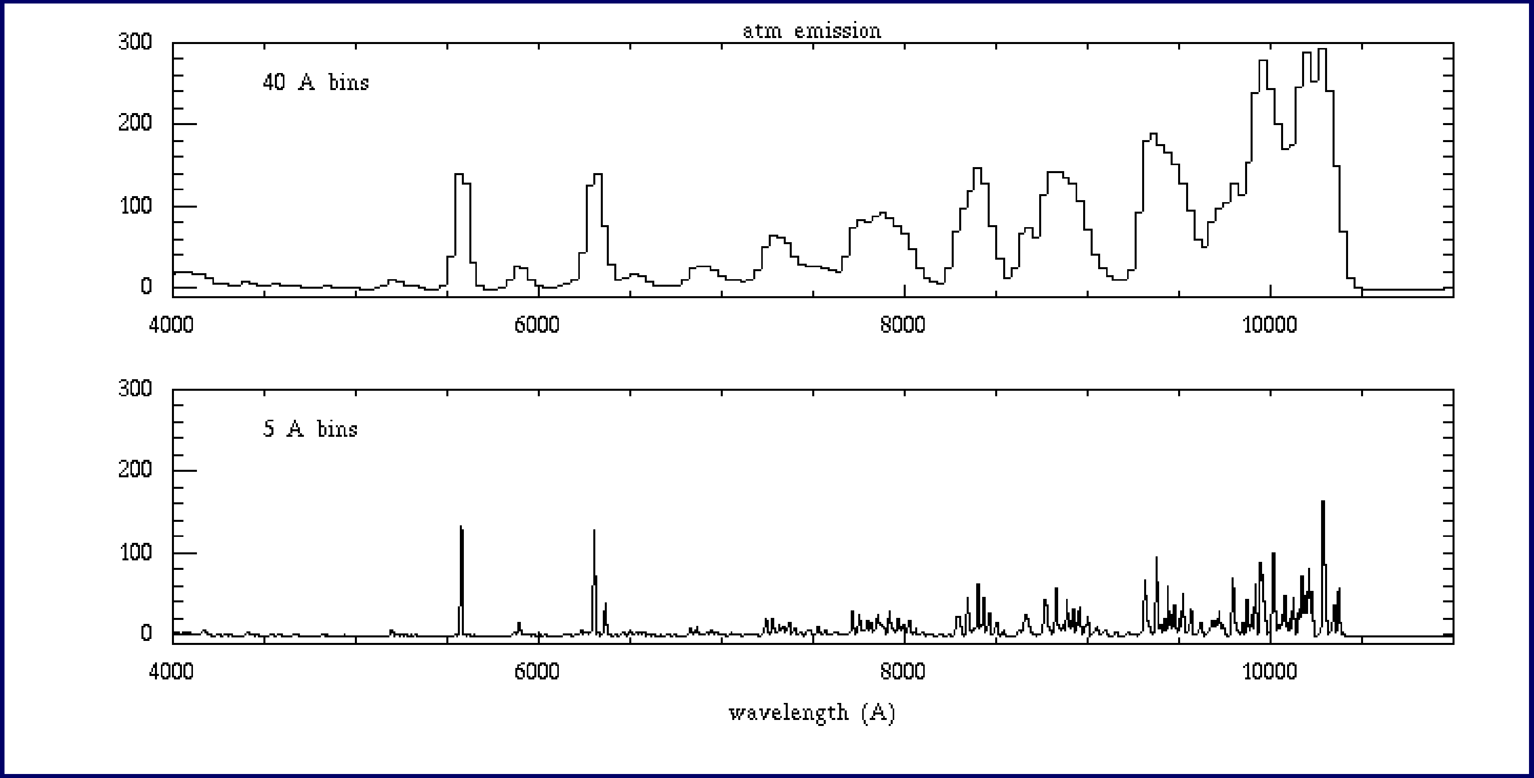
- OTA guide stars tie 30 sec exposures to 10 msec exposures
- OTA 'sweep' can yield survey of stars 8 - 14 mag
- Bright stars provide flux calibration (spectrophotometric standards)
- SkyProbe A will provide atm transmission function



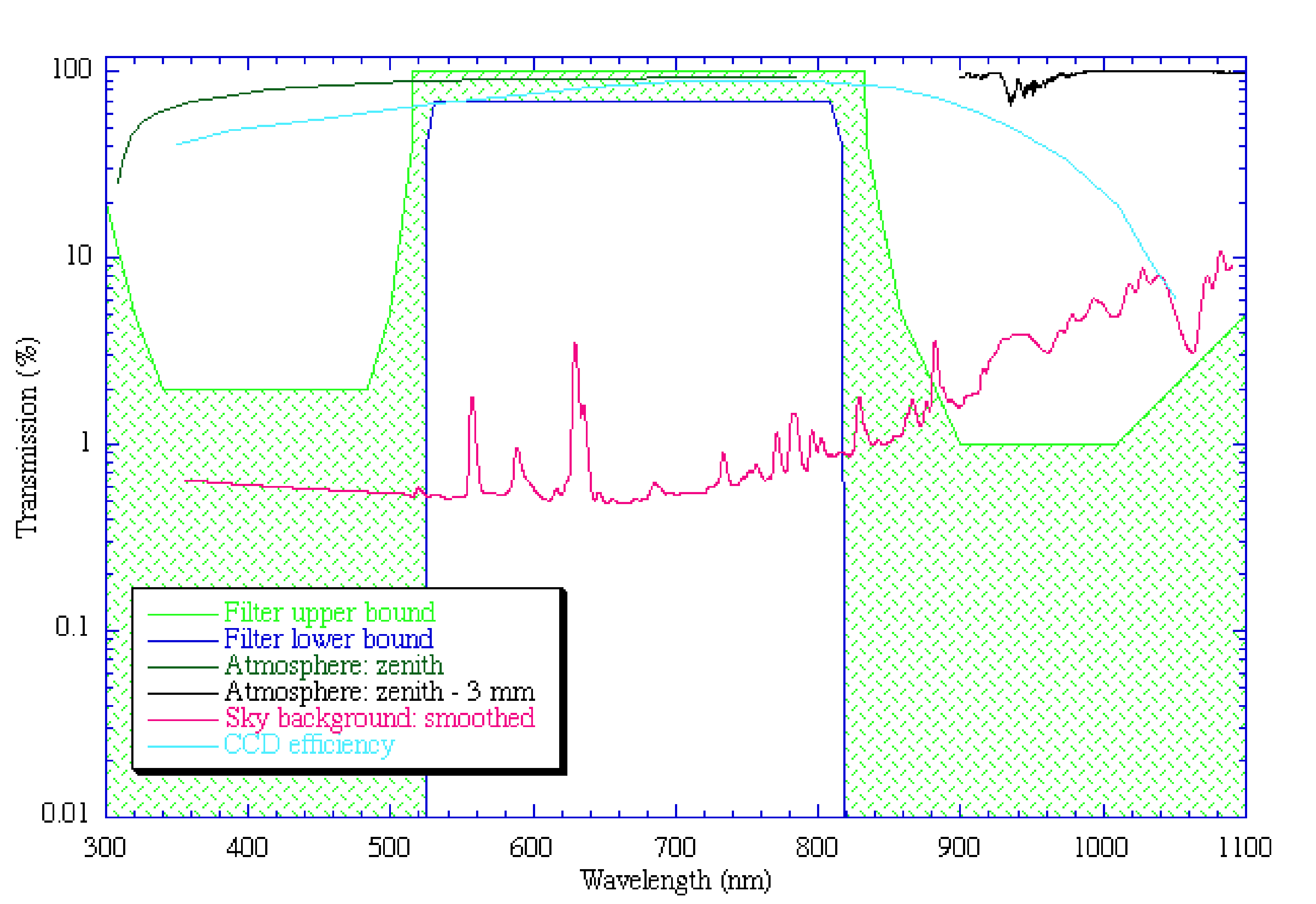


Phase 2 Issues

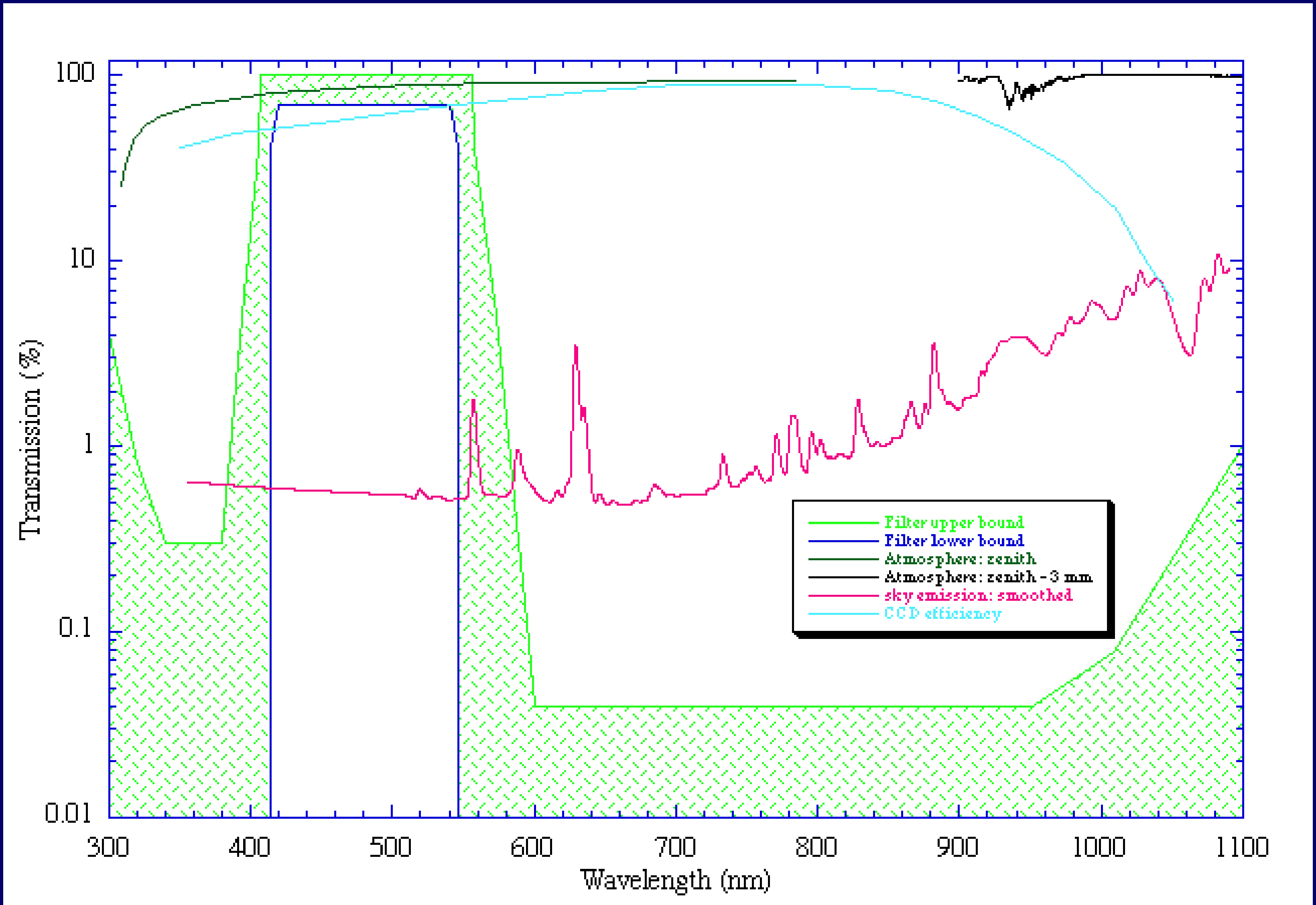
- Flat-fields are corrected based on stellar photometry
- fringe frames may be built with a monochromatic dome source
- fringe correction may be based on atm. emission line observation



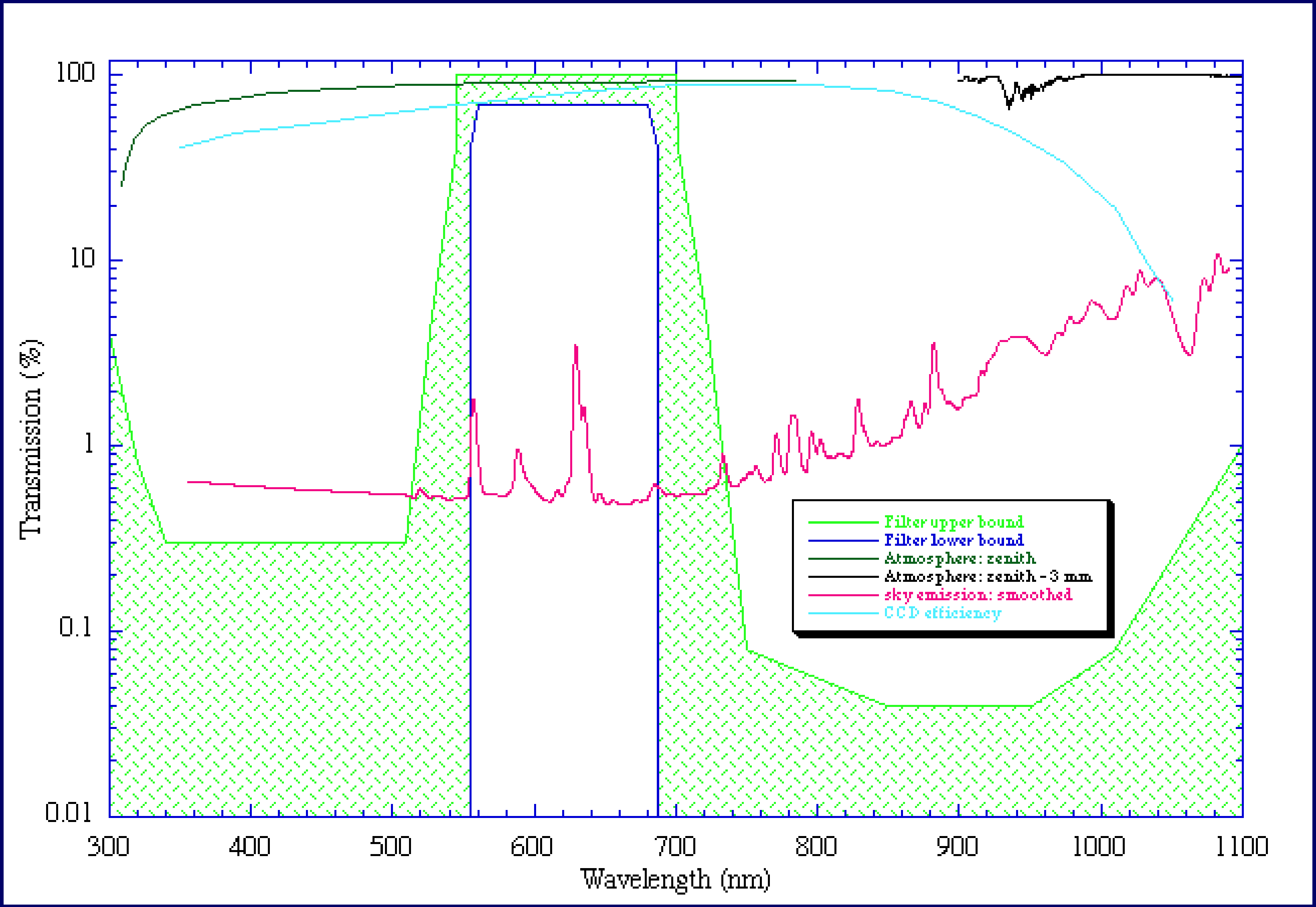
PanSTARRS Filter Set – w filter



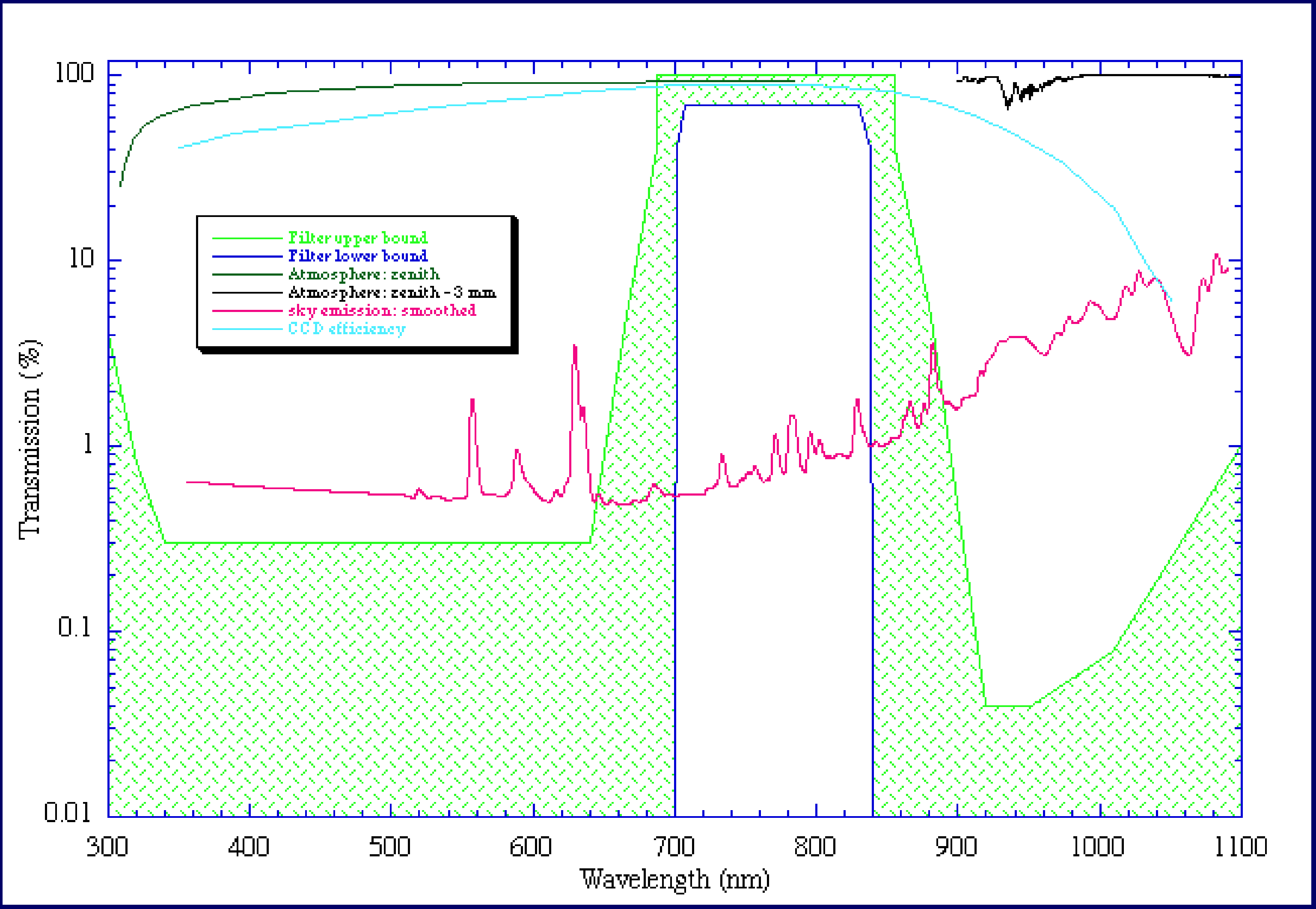
PanSTARRS Filter Set – g filter



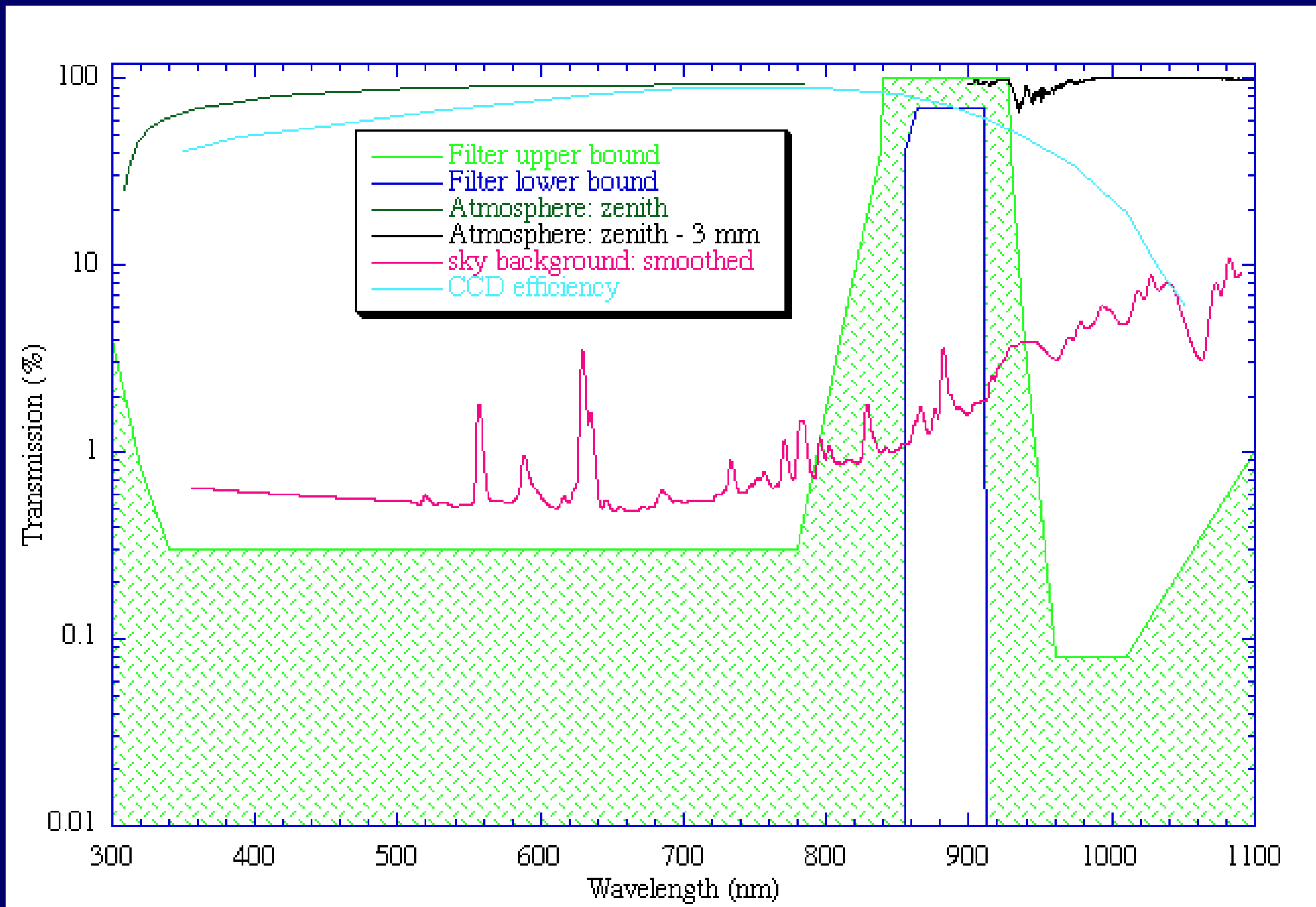
PanSTARRS Filter Set – r filter



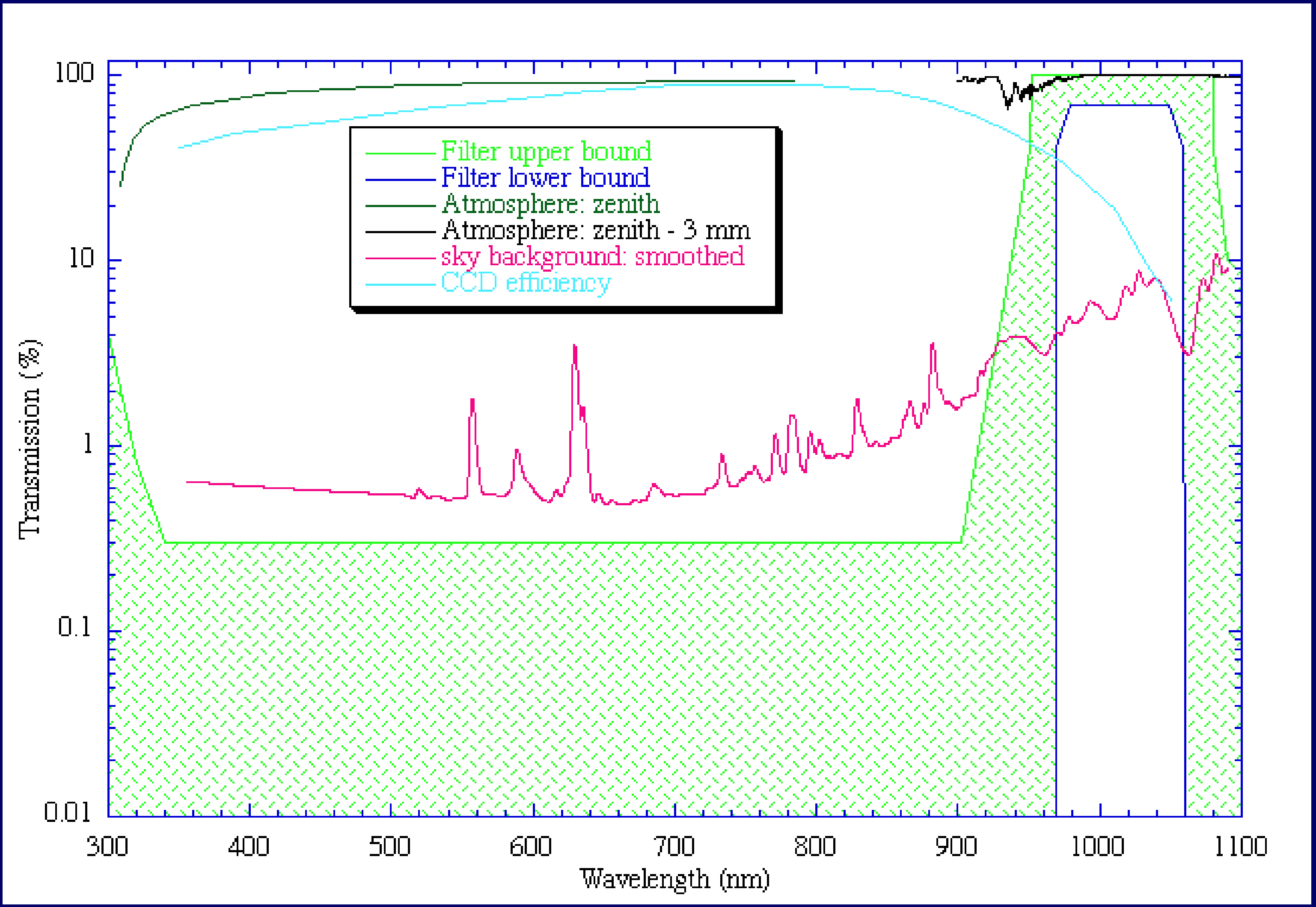
PanSTARRS Filter Set – i filter

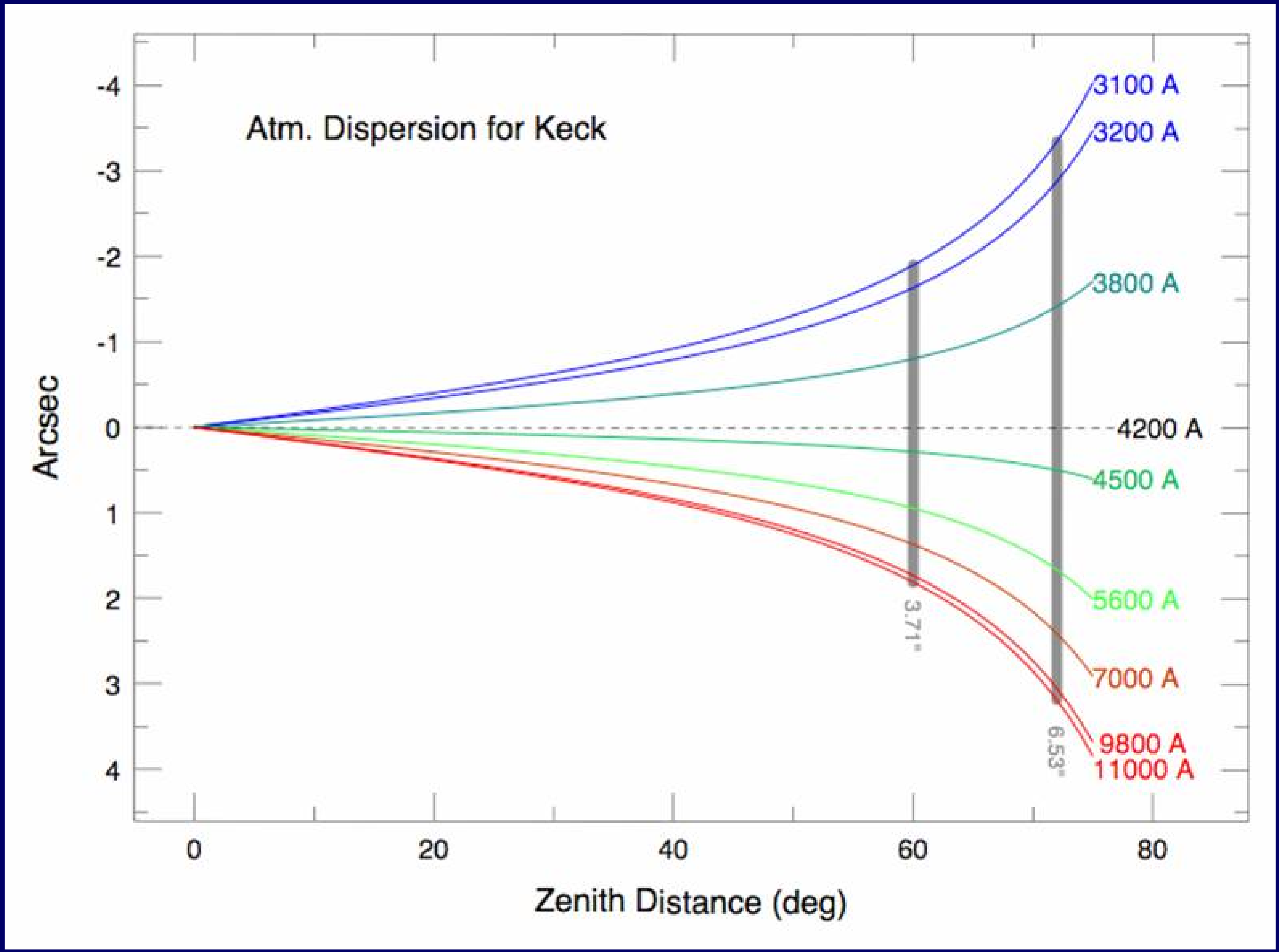


PanSTARRS Filter Set – z filter



PanSTARRS Filter Set – y filter

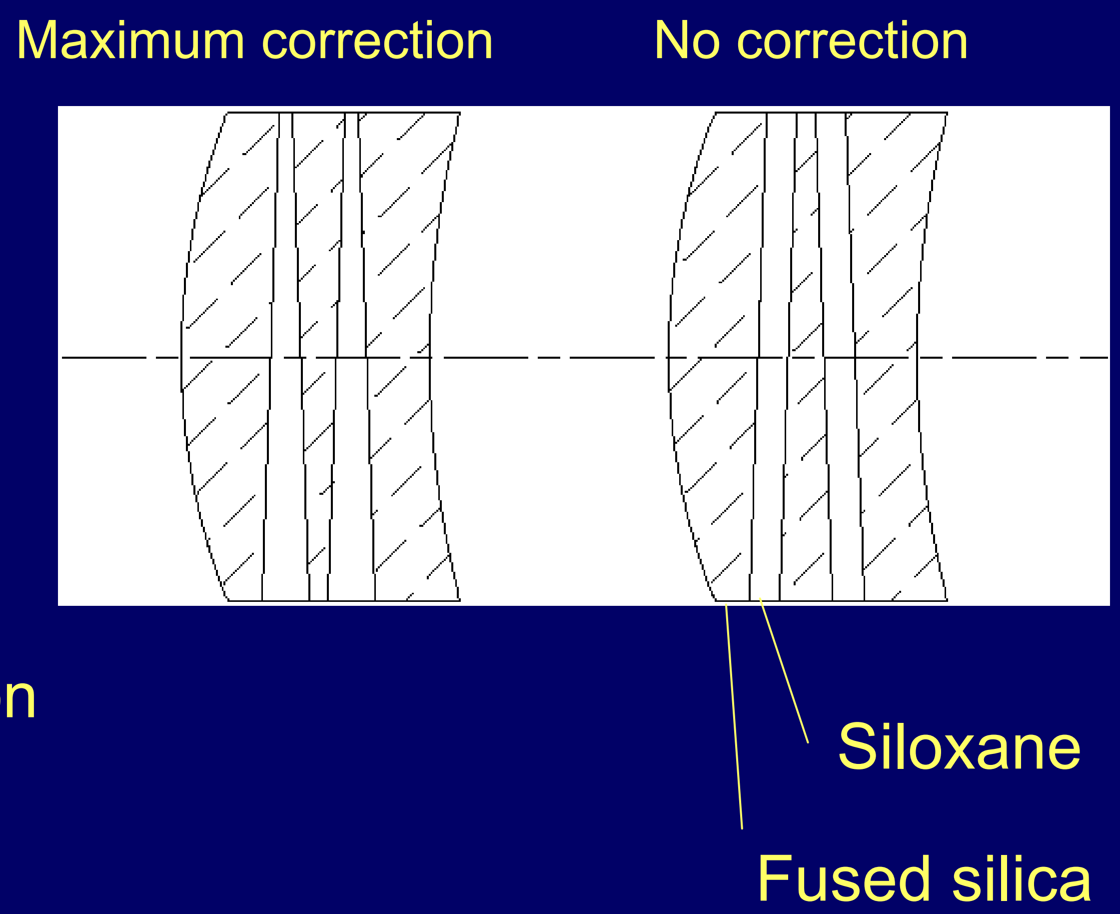



Atm. Dispersion for Keck
Arcsec
Zenith Distance (deg)
-4
-3
-2
-1
0
1
2
3
4
0
20
40
60
80
3100 A
3200 A
3800 A
4200 A
4500 A
5600 A
7000 A
9800 A
11000 A
3.71"
6.53"

ADC

The design chosen has a rotating prism between fixed lenses. This avoids the large rotary seal and presents less of an engineering challenge and schedule risk.

- Refractive indices match at 656 nm
- Zero deviation
- No added glass/air interfaces
- No large diameter rotating seals
- Relaxed tolerances on the flat surfaces



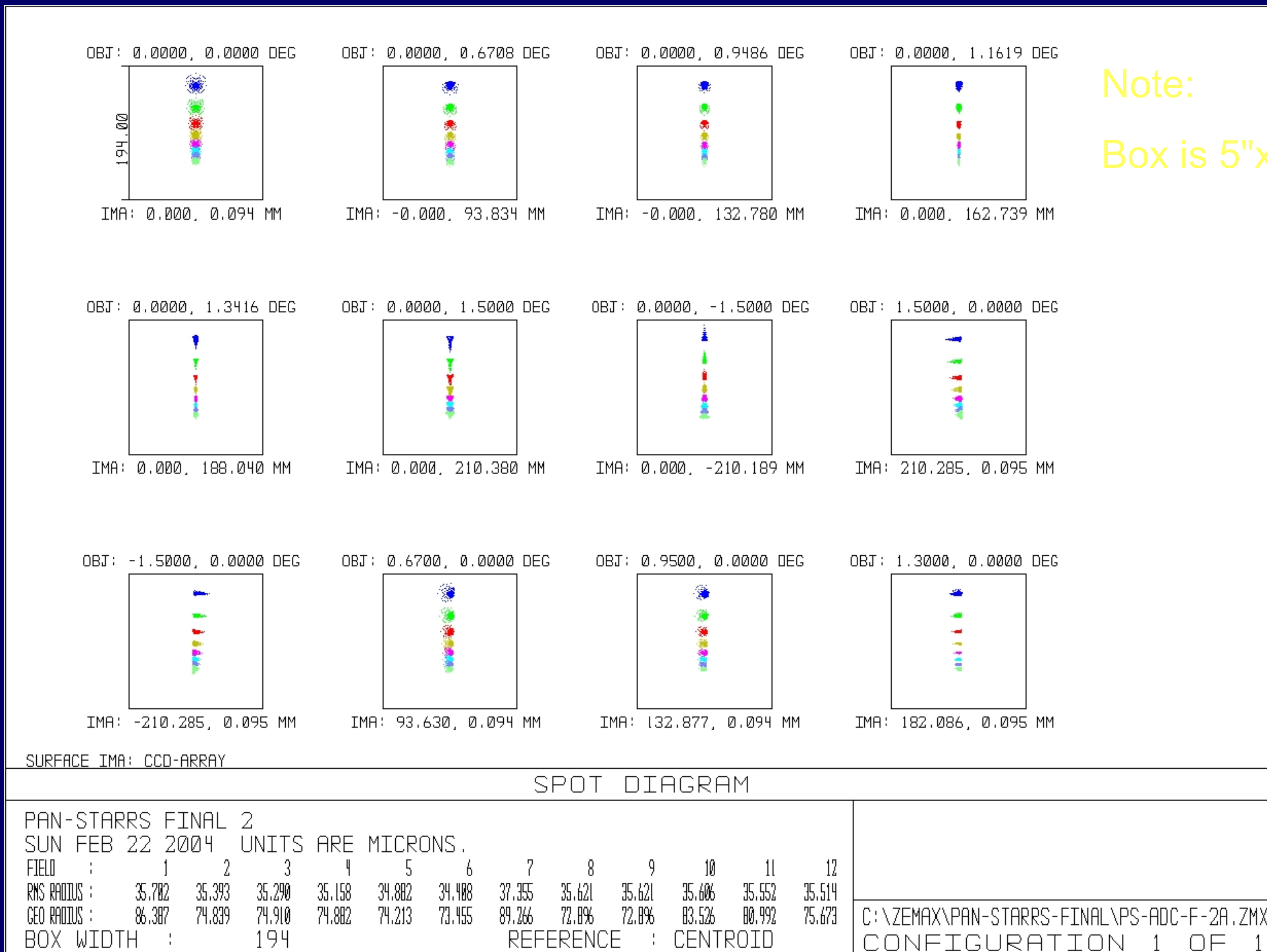
Siloxane matches the refractive index of Fused Silica, but has different dispersion

- Fused Silica (0°C)
- n(589) = 1.4585
- V(589,486) = 67.8

- Siloxane (0°C)
- n(589) = 1.4592
- V(589,486) = 42.2

No glass exists with similar matching properties to fused silica, nor is there a match for BK7.

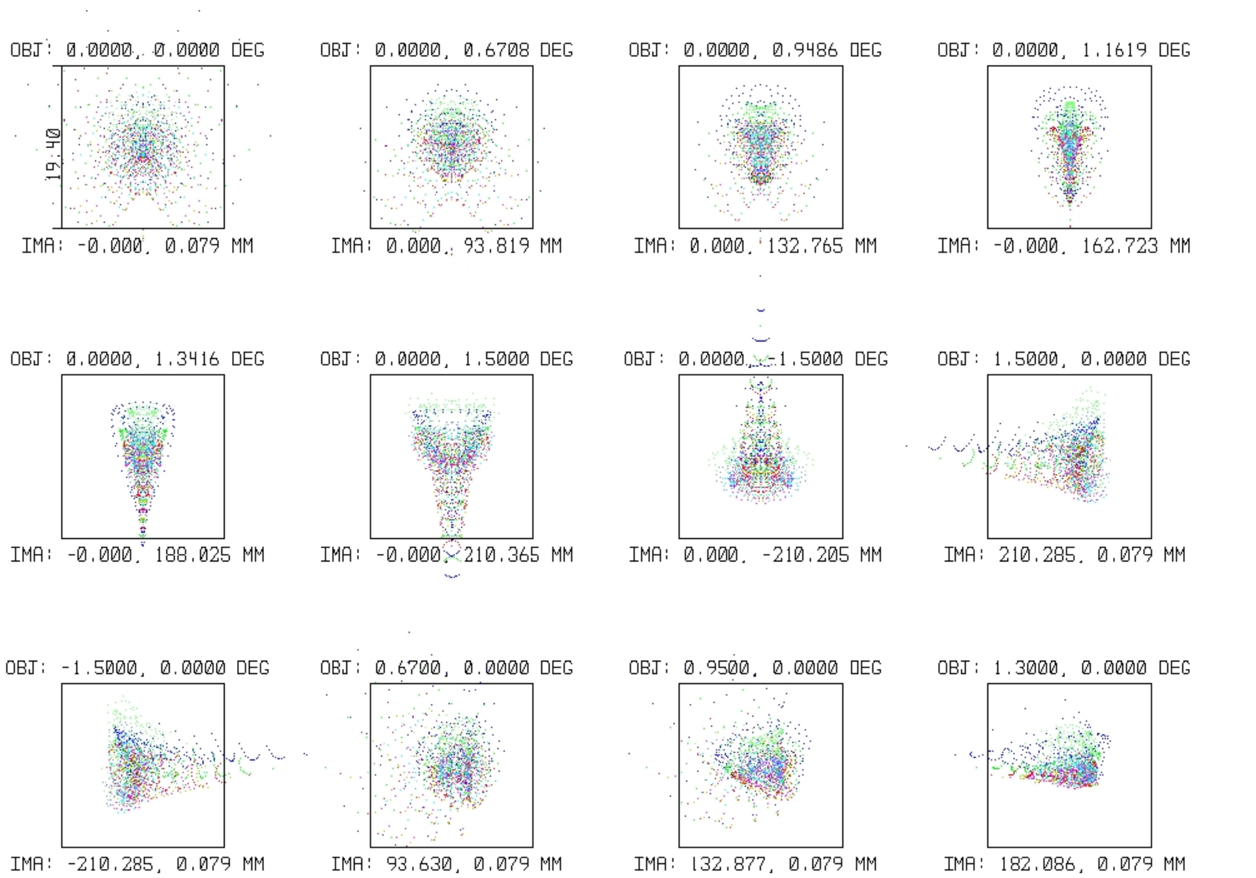
Design Pan-STARRS Final 2: ADC on maximum dispersion



Note:

Box is 5"x5"

At 75° zenith distance, the ADC fully corrects atmospheric dispersion



SURFACE IMA: CCD-ARRAY

SPOT DIAGRAM

PAN-STARRS FINAL 2
SUN FEB 22 2004 UNITS ARE MICRONS.

FIELD :	1	2	3	4	5	6	7	8	9	10	11	12
RMS RADIUS :	4.779	3.931	3.418	3.193	3.465	4.422	4.212	4.236	4.236	4.128	3.605	3.318
GEO RADIUS :	17.534	12.700	11.442	9.619	10.686	14.349	21.505	19.476	19.476	17.690	15.762	13.632

BOX WIDTH : 19.4 REFERENCE : CENTROID

C:\ZEMAX\PAN-STARRS-FINAL\PS-ADC-F-2A.ZMX
CONFIGURATION 1 OF 1

Broadcast Tower Relocation
Ulupalakua Ranch Site

Timeline

- Grant of Easement
  - Signed May 2nd 05
- Special Use Permit Variance Process
  - Site Plan Completed June 05 (rejected)
  - 3-Months to Complete (Nov 05)
- EA
  - KCE Under Contract (July 05)
  - 4-6 Months to Complete (Dec 05)
- Construction & Relocation of Transmitters
  - 6-8 Months to Complete (Aug 06)

Ulupalakua Ranch Site