

The Large Aperture Telescope (LAT)

Terry Herter, Ed Kibblewhite (presenters)

Mel Ulmer, Laird Thompson (in attendance)

Al Harper, Rich Kron, Jason Tumlinson, Don York

Riccardo Giovanelli, Gordon Stacey

18-Mar-03

LAT Consortium

- Current institutions
 - Cornell and Illinois (Chicago, Illinois, and Northwestern)
- Project to construct a 20-m class telescope
 - Located at a low-water vapor site with good C_N^2 profile
 - Operation at $\lambda > 1 \mu\text{m}$ using adaptive primary mirror
- Focused Science Program
 - Determine star formation history of the Universe ($1 < z < 10$)
 - Dedicate most resources to this effort
 - Combines near-IR spectroscopic and Far-IR continuum surveys
- Other science programs:
 - Lesser priority (interleaved with main science program)

LAT = Large Aperture Telescope

Project Uniqueness/Strengths

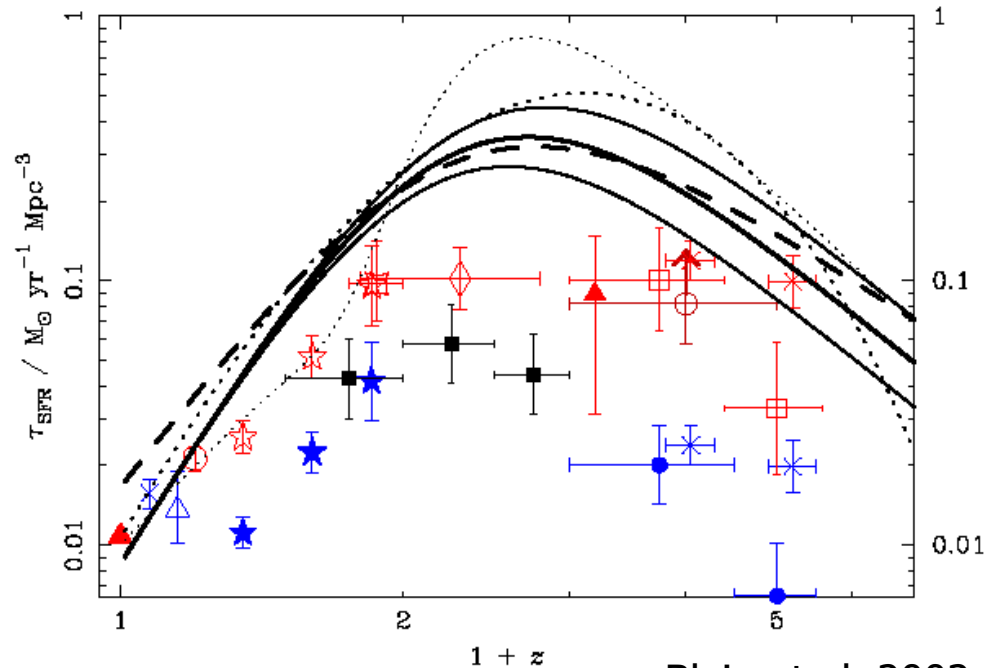
- Focused science program
 - Lots of time: > 1000 hours/year & well defined instruments
- Site selection
 - Low water vapor site (likely Atacama or Antarctic)
 - Good ground layer AO correction capability
- Optimized for $\lambda > 8 \mu\text{m}$
 - At $10 \mu\text{m}$, $\lambda/D = 0.14\text{-}0.07$ arcsec (for 15-30 m)
 - With correct mirror surfaces, $\lambda > 1 \mu\text{m}$ has excellent performance
- Adaptive Primary
 - Increased performance (wind loading, 1st order AO)
 - Potential cost savings

LAT Science Drivers

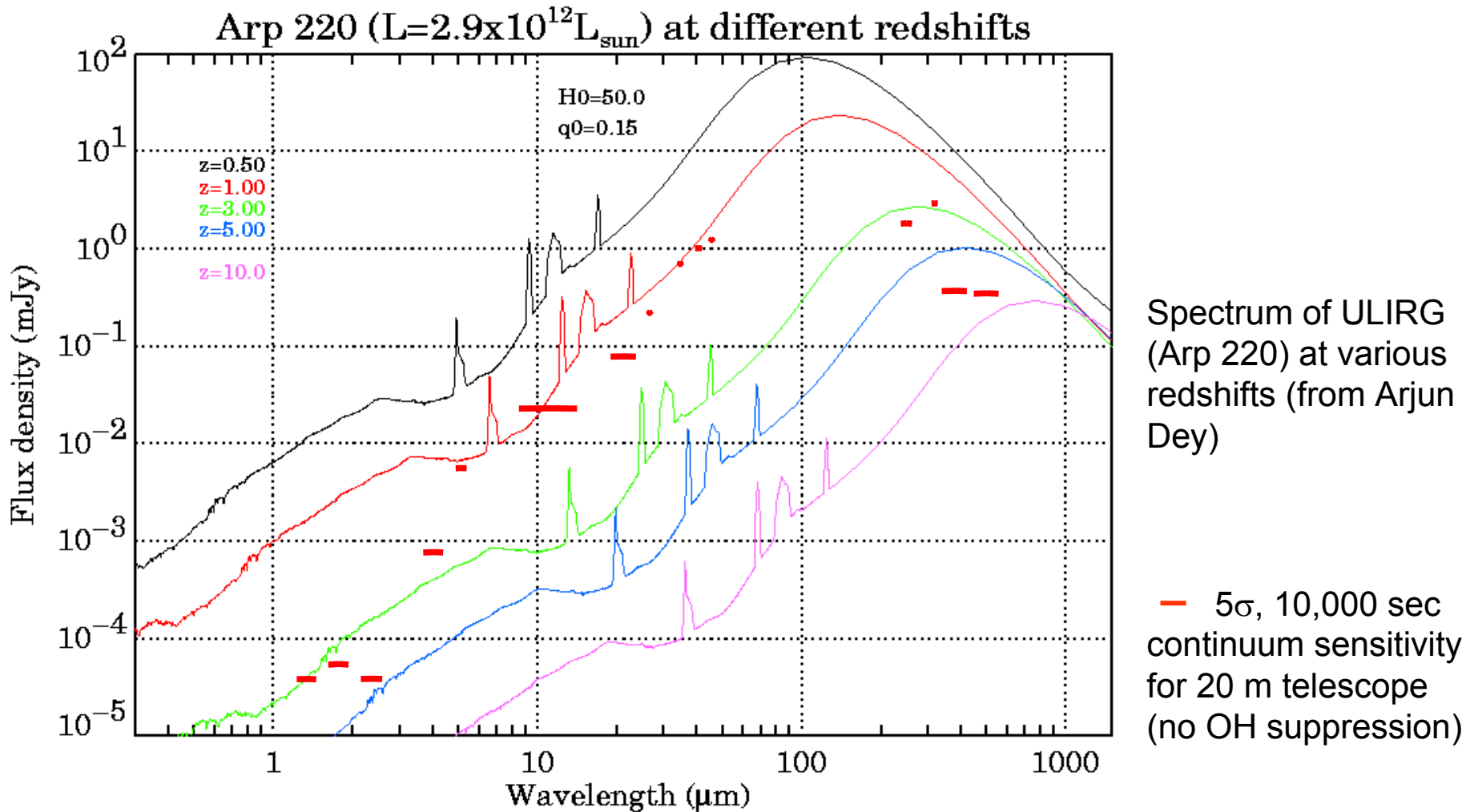
- Star Formation History of the Universe:
 - Explore the era of galaxy assembly
 - Directly measure star formations rates vs. z
- Large Scale Structure
 - Provide an SDSS-like survey for $z > 1$
- Formation of planetary systems
 -
- Galactic Star formation
 -
- The AGN – starburst – black hole connection
 -

Star Formation in the Early Universe

- Optical surveys indicate that the mean SFR in the Universe was much greater at $z > 1$ (e.g. Madau et al. 1996)
 - COBE revealed a cosmic far-IR background with energy $>$ the integrated UV/optical light \Rightarrow dust extinction is important in the early Universe!
 - ISO surveys indicate possibly even greater rates of star formation.
- \Rightarrow To accurately determine the SFR requires both optical and far-IR/submm surveys.

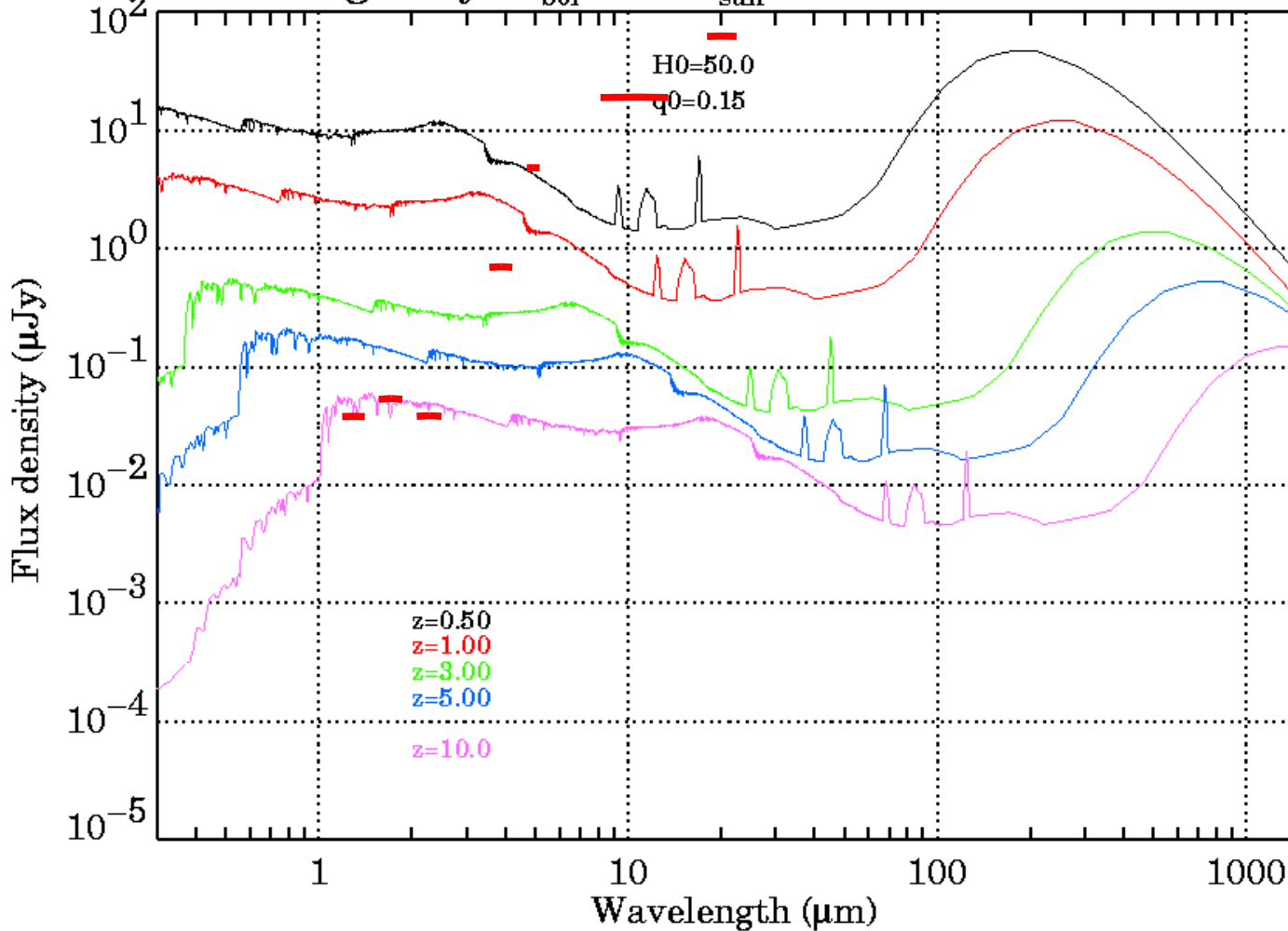


ULIRGs: Energy Emerges in Far-IR



Protogalaxies: Energy Emerges in UV/Optical

Protogalaxy ($L_{\text{bol}}=10^{11}L_{\text{sun}}$) at different redshifts



Predicted spectrum of protogalaxy at various redshifts (from Arjun Dey)

— 5σ , 10,000 sec
continuum sensitivity
for 20 m telescope
(no OH suppression)

Star Formation History of the Universe

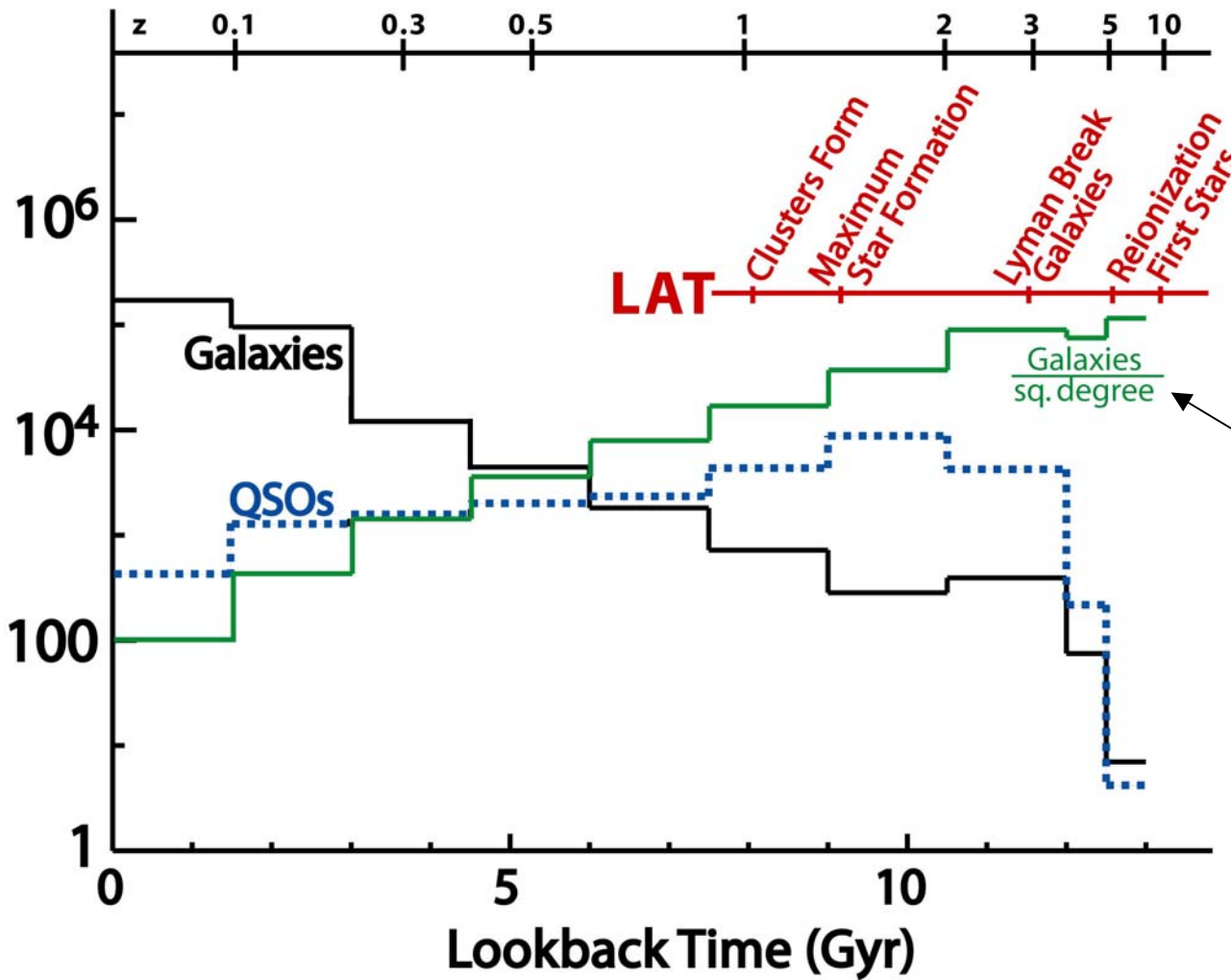
- Perform an SDSS-like survey of > 2 (TBD) sq. deg.
 - Spectroscopically detect $\sim 2,000,000$ galaxies
 - $\sim 200,000$ galaxies per ~ 1.5 Gyr intervals to $z \sim 10$
 - Down to $\sim L^*$
 - Dedicate > 1000 hr/yr until complete
 - Progressive release of data to public when calibrated
 - Catalog of observations with 1.5-2.0 years for first release
- Survey in near-IR and far-IR
 - Chase the processed UV light from star formation
 - Multi-object/IFU, near-IR, OH-suppression spectroscopy
 - Far-IR photometric survey and follow-up line surveys
- Programmatics
 - Sets aperture and instrumentation requirements for start of operations

Survey Scope: View different epochs

LBTZ index	z	Look back (Gyr)	Survey Vol. (Gpc ³)	D _L (Gpc)	No. of Galaxies per square deg.
1	0.12	1.5	0.523	0.56	100
2	0.26	3.0	4.791	1.32	426
3	0.43	4.5	18.98	2.37	1420
4	0.65	6.0	54.93	3.89	3590
5	0.95	7.5	134.7	6.2	7960
6	1.40	9.0	304.6	10.00	17000
7	2.20	10.5	679.9	17.46	37400
8	4.10	12.0	1587	36.92	90500
9	5.8	12.5	2274	57.70	75800
10	10.0	13.0	3519	103.84	116900

$H_0 = 70 \text{ km/sec}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$

Columns: 1) zone index, 2) redshift, 3) look back time, 4) integrated volume over whole sky, 5) luminosity distance all to the edge of the shell, and 6) number of galaxies within a one sq. deg. patch assuming a comoving density of $7.6 \times 10^6 \text{ galaxies/Gpc}^3$.

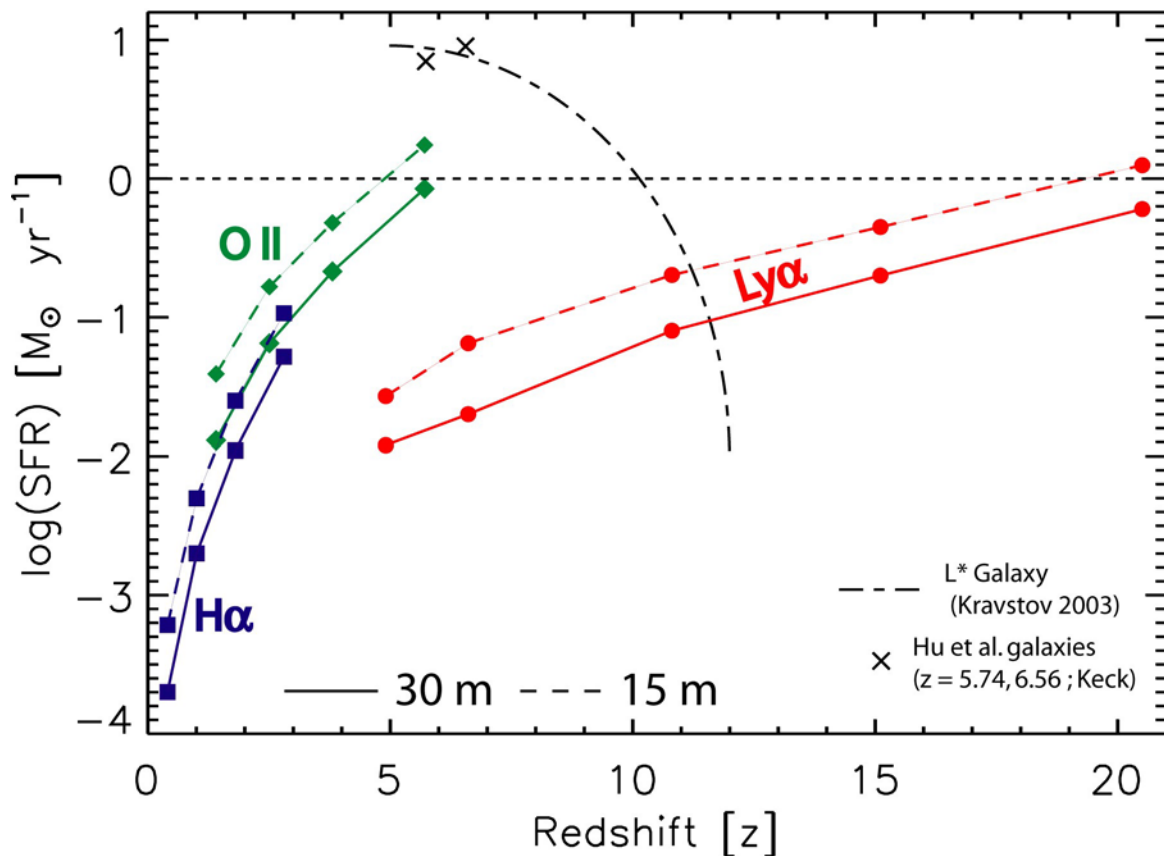


Scope of the Survey

Galaxies detected per square deg. with the survey over ~ 1.5 Gyr intervals.

- Red Line: Survey galaxies per look back time interval. The survey will obtain redshifts for 200000 galaxies per zone expanding current statistical samples by 100 – 100000x in most zones
- Black and blue lines are current state of knowledge according to NED.

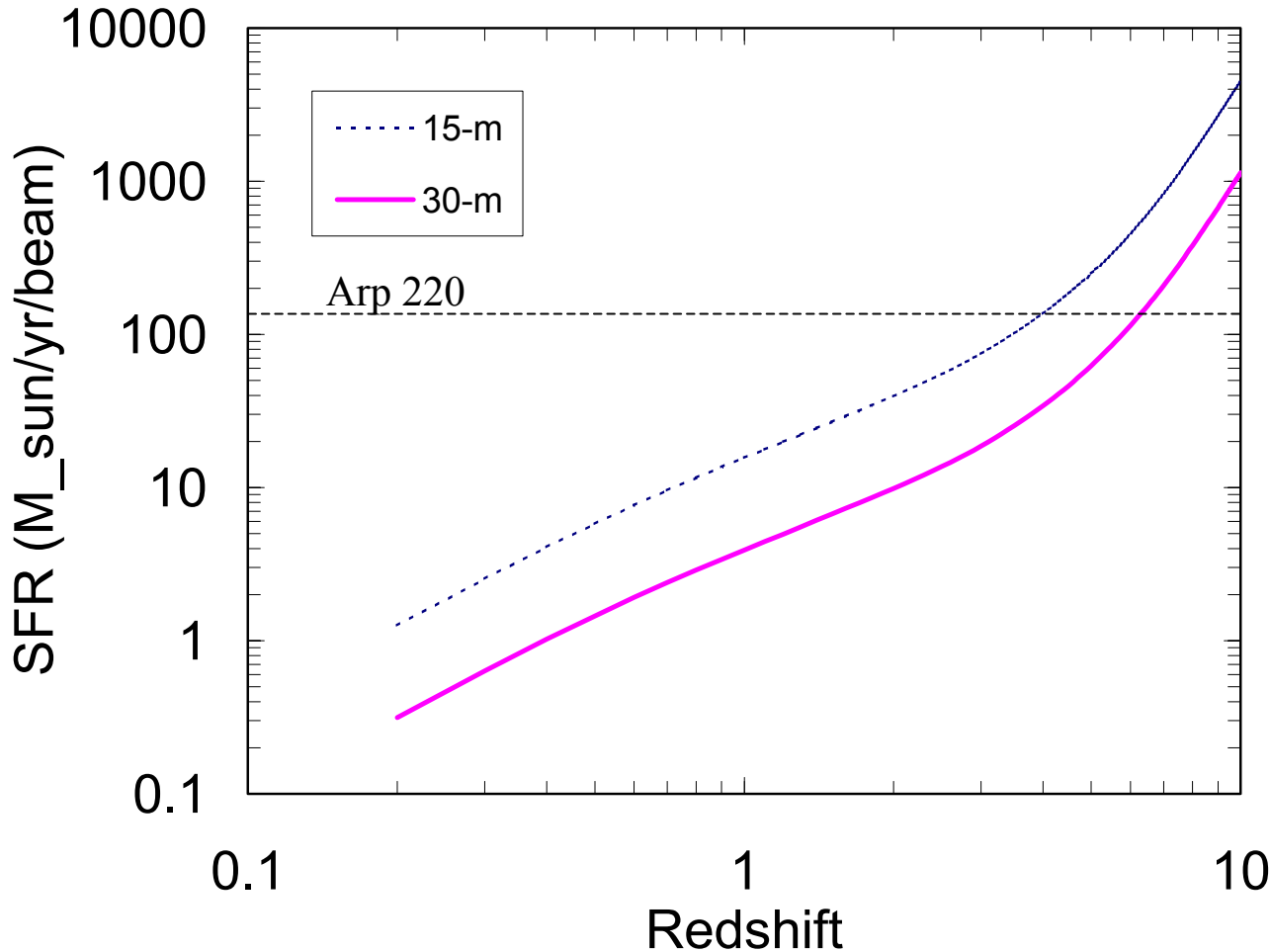
NIR Star Formation Rate Sensitivity



- Survey mode SFR sensitivity for 15 and 30 m telescopes in 1000 seconds for line emission.
- Survey is sensitive to $\sim 1 M_{\odot}/\text{yr}$ at all redshifts.

- There will be “sweet spots” in redshift space with overlapping coverage (i.e. more than one Balmer series line, $H\alpha + OII$, $H\alpha + OIII$, $Ly\alpha + HeII$ for metal-free stars)

FIR Star Formation Rate Sensitivity



- SFR sensitivity for sensitivity for 15 & 30 m telescopes in 10000 seconds for the far-IR (350 mm) continuum.

- Arp 220 is $\sim 130 M_{\text{sun}}/\text{yr}$. For star forming galaxies, $L_{\text{FIR}} \sim 100 L_{\text{H}\alpha}$ (Condon 1992).

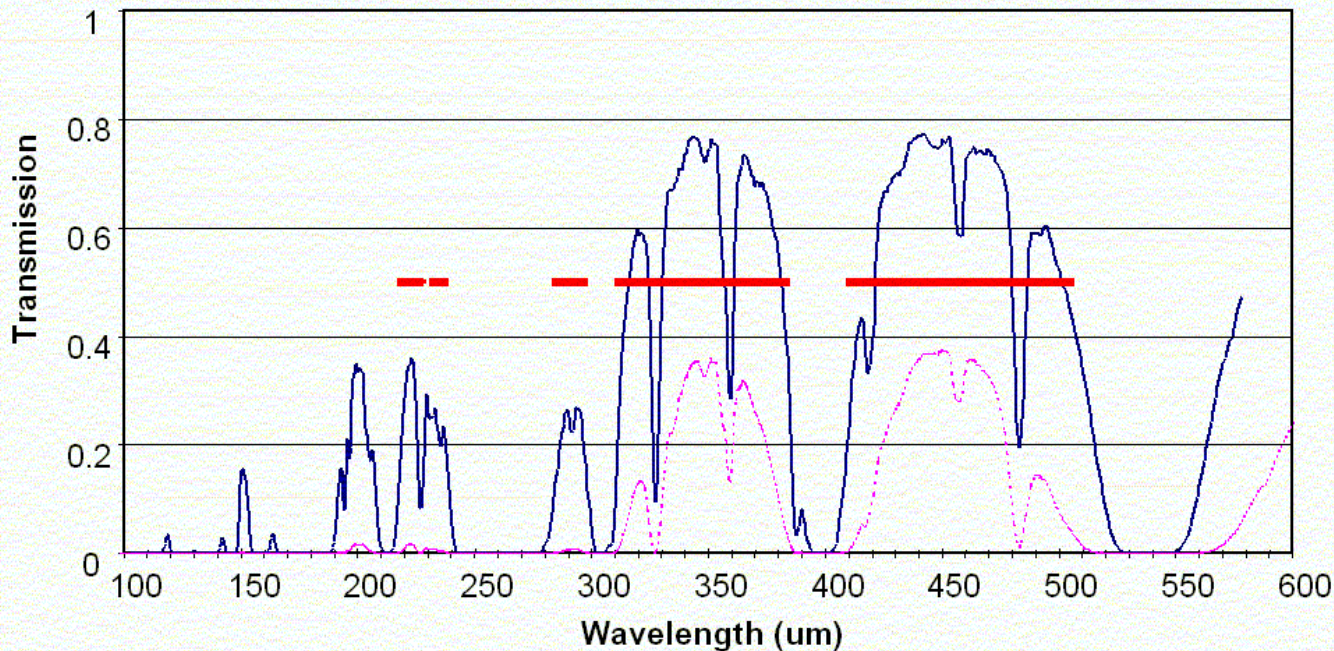
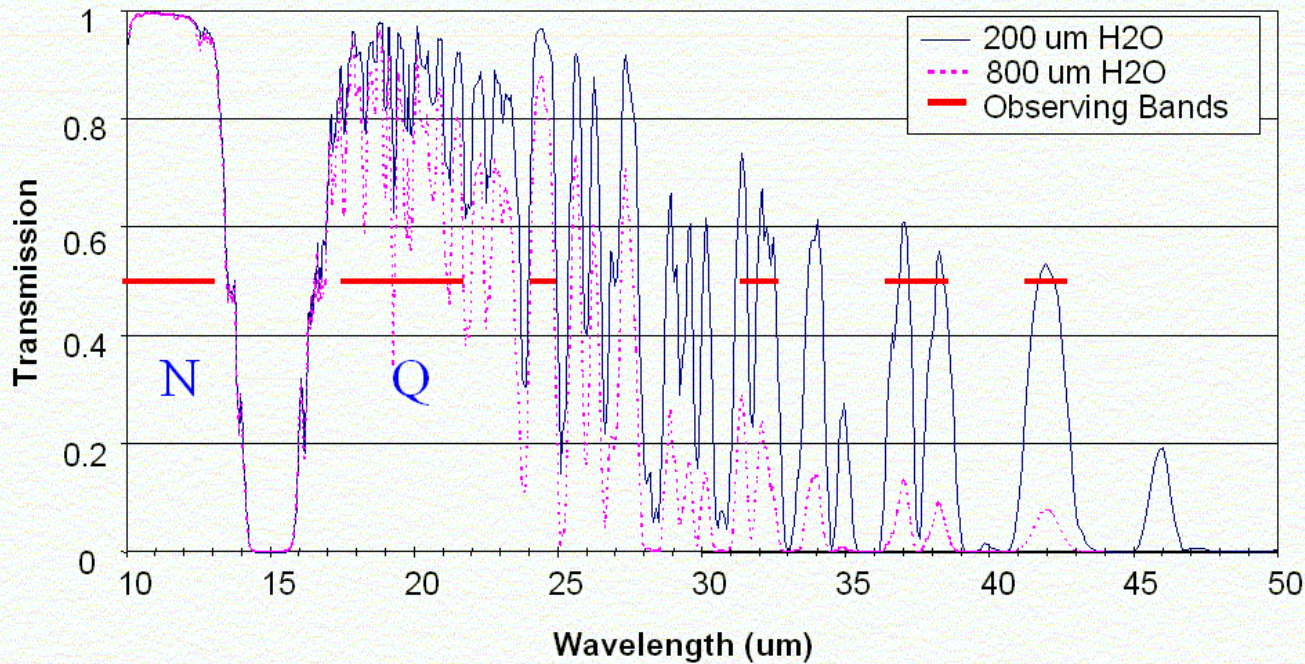
Near IR Instrument Requirements

- Multiplex advantage
 - 2,000,000 galaxies @ 1000 seconds/gal => 555,000 hours
1000 hr/yr => 555 years (without multiplex advantage)
 - For 100 galaxies/ observation => 5.5 years to complete
 - With simultaneous observations in J, H and K bands
- Number of spectral pixels (per spatial element)
 - $N_{\text{pix}} = \Delta\lambda_{\text{band}}/\Delta\lambda_{\text{pix}} = \Delta\lambda_{\text{band}} * 2R/\lambda \sim 2 * 6000/5 = 2400$
 - Since sample 2 pix/res. element and $\lambda/\Delta\lambda_{\text{band}} \sim 5$
 - => 7200 pixels for a J-H-K spectrum
- Field-of-view
 - Gal. density $\sim 400,000/\text{sq. deg.}$ => ~ 100 galaxies in 1'x1' FOV
- No. of pixels (MOS)
 - For spatial 6 pix/gal => One 2048^2 array equivalent
- No. of pixels (IFU w/ 0.2"/pix => 300x300 over FOV)
 - Total: 6.5×10^8 => 154 2048^2 arrays (77 for 50 gals/obs).

Far IR Instrument Requirements

- Do simultaneously with NIR survey
- Field of view
 - For a 3'x3' FOV
 - $N_{\text{pix}} = \text{FOV}/(\lambda/2D) \sim 180''/2.4'' = 75$ pixels (15-m)
 - Array format: 75 x 75 (150x150 for 30-m)
- Integration time per field
 - Can spend ~ 9 times longer on field than NIR
 - \Rightarrow 9000 seconds per field
 - Matches sensitivity on slide 12
- Complimentarily
 - with SIRTf, SOFIA, Herschel, ALMA, etc.

Telluric Transmission



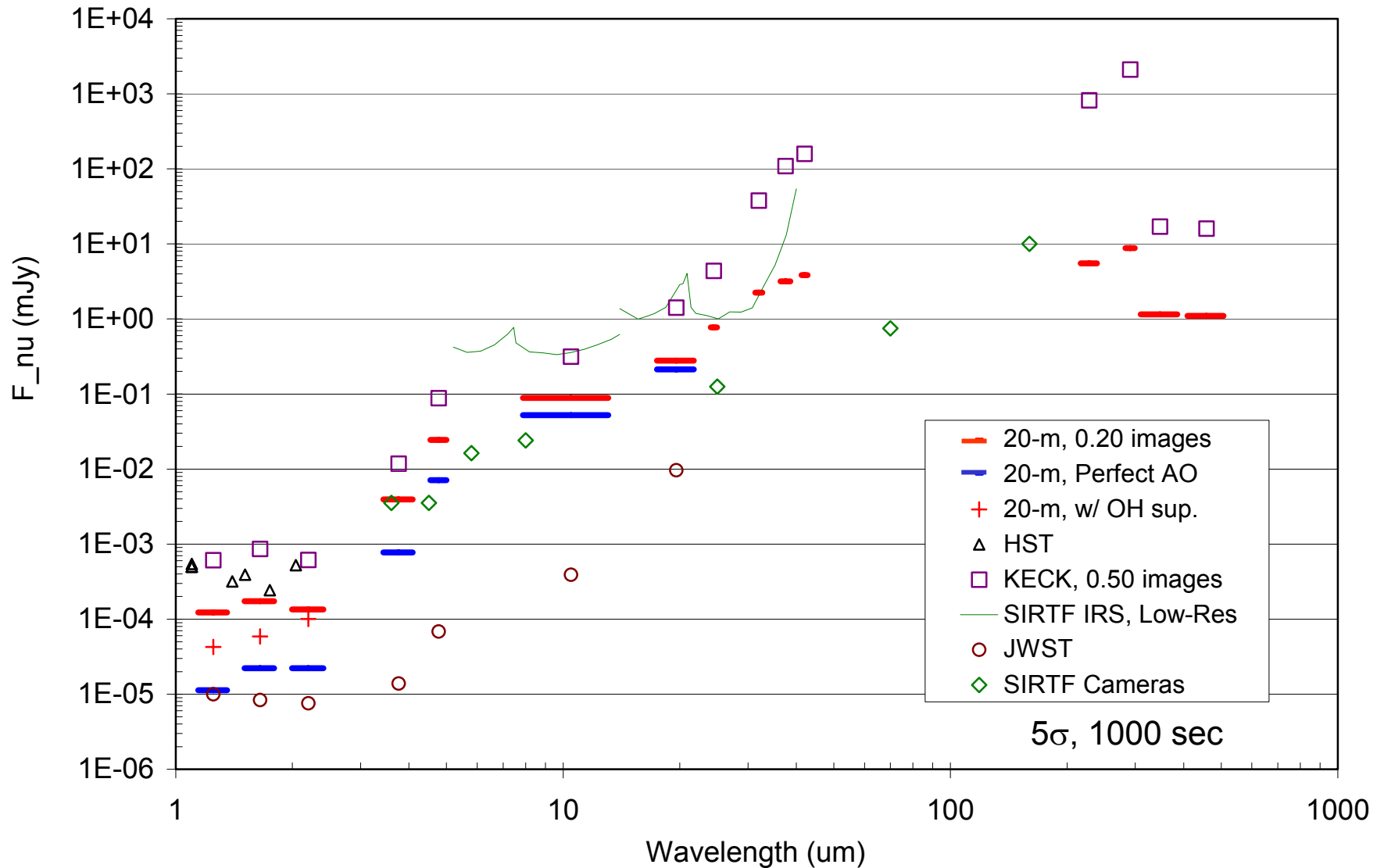
Atmospheric transmission for mid-IR (top) and far-IR/sub-mm (bottom) for 200 μm and 800 μm of precipitable water vapor at 30° from zenith. Red horizontal bars represent potential observing windows.

Star Formation Rate Sensitivity

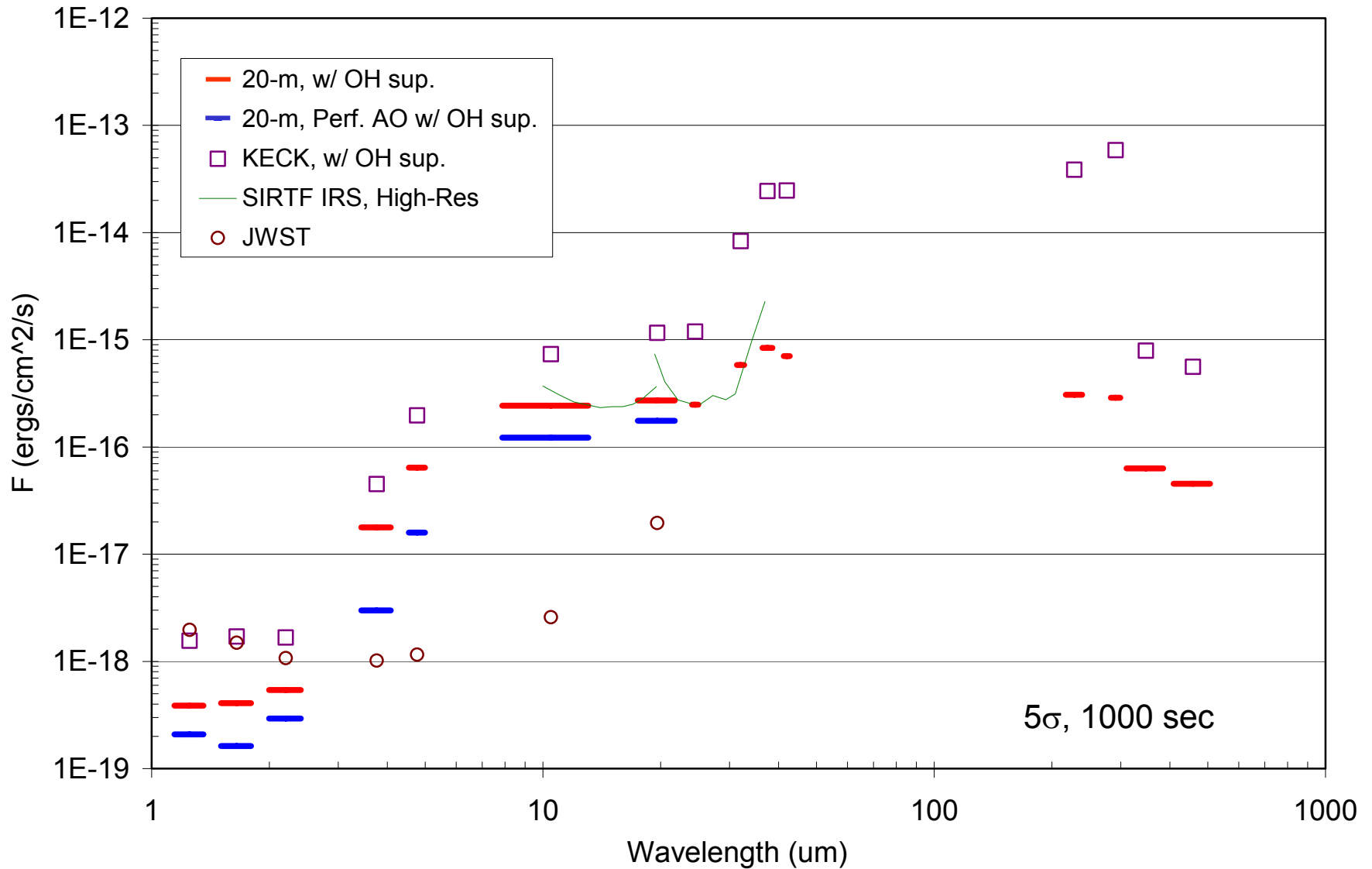
Parameter		15-m telescope				20-meter telescope				30-meter telescope			
		I	J	H	K	I	J	H	K	I	J	H	K
Aperture	(m)	15	15	15	15	20	20	20	20	30	30	30	30
t_int	(sec)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
lambda	(um)	0.79	1.25	1.65	2.2	0.79	1.25	1.65	2.2	0.79	1.25	1.65	2.2
beam size	(arcsec)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
throughput		0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
read noise	(e-)	2	5	5	5	2	5	5	5	2	5	5	5
background	(uJy/''^2)	30	70	200	900	30	70	200	900	30	70	200	900
background	(ph/sec/beam)	0.0400	0.0933	0.2667	1.2001	0.0711	0.1659	0.4741	2.1336	0.1600	0.3734	1.0668	4.8006
t_back	(sec)	909	2435	852	189	511	1370	479	107	227	609	213	47
Total Noise	(e-)	7.48	13.90	19.15	36.06	9.33	16.31	23.96	47.26	13.27	21.76	34.16	70.00
Flux (S/N=5)	(erg/cm^2/sec)	3.55E-19	4.17E-19	4.35E-19	6.15E-19	2.49E-19	2.75E-19	3.06E-19	4.53E-19	1.57E-19	1.63E-19	1.94E-19	2.98E-19
z	H-alpha		0.4 - 1.0	1.3 - 1.8	2.0 - 2.8	0.4 - 1.0	0.4 - 1.0	1.3 - 1.8	2.0 - 2.8		0.4 - 1.0	1.3 - 1.8	2.0 - 2.8
Adopted z			1	1.8	2.8	1	1	1.8	2.8		1	1.8	2.8
Lum Dist.	(Gpc)		6.639	13.82	23.79	6.639	6.639	13.82	23.79		6.639	13.82	23.79
L(Halpha)	(10^6 L_sun)		0.56	2.55	10.67	0.34	0.37	1.80	7.87		0.22	1.14	5.18
SFR	(M_sun/yr/beam)		0.006	0.026	0.107	0.003	0.004	0.018	0.079		0.002	0.011	0.052
z	[OII] 3727		1.4 - 2.5	3.0 - 3.8	4.3 - 5.7	1.4 - 2.5	1.4 - 2.5	3.0 - 3.8	4.3 - 5.7		1.4 - 2.5	3.0 - 3.8	4.3 - 5.7
Adopted z			2.5	3.8	5.7	2.5	2.5	3.8	5.7		2.5	3.8	5.7
Lum. Dist.	(Gpc)		20.72	34.59	55.58	20.72	20.72	34.59	55.58		20.72	34.59	55.58
L(OII)	(10^6 L_sun)		5.49	15.98	58.25	3.28	3.62	11.25	42.95		2.15	7.12	28.27
SFR	(M_sun/yr/beam)		0.165	0.479	1.748	0.098	0.109	0.337	1.288		0.064	0.214	0.848

Assumes: $SFR = L(H\alpha)/10^8$ and $H\alpha/[OII] = 3$
 $R=6000$, Signal-to-Noise Ratio = 5
 $N_{pix} = 4$, Flux Fraction = 1.0

LAT Continuum Sensitivity Comparison



LAT Line Sensitivity Comparison



Summary of Project Concept

Requirement	Comment/Goal
20-m class telescope	<ul style="list-style-type: none">• Adaptive primary mirror
$\lambda > 1.0 \mu\text{m}$	<ul style="list-style-type: none">• Diffraction limited for $\lambda > 8 \mu\text{m}$• 0.2" image quality ($\lambda > 1 \mu\text{m}$) at first light
emissivity < 10%	<ul style="list-style-type: none">• Emissivity < 5%
low water vapor site	<ul style="list-style-type: none">• Excellent transmission in mid-IR (20-40 μm) and sub-mm windows (250, 350, & 450 μm)
key projects	<ul style="list-style-type: none">• Survey of star formation history of the Universe ($1 < z < 10$)
survey instruments	<ul style="list-style-type: none">• Multi-object/IFU, near-IR OH-suppression ($R \sim 6000$) spectrograph• Far-IR/sub-mm camera

Adaptive Primary Mirror Technology for the LAT- a scalable design for GSMTs

Ed.Kibblewhite, Laird Thompson, Mel Ulmer, Al Harper, Terry Herter.

18-Mar-03

What is meant by an adaptive primary mirror?

- Density of control actuators $\approx r_0^2$
 - $r_0 \approx 0.5\text{m}$ @ 1μ
 - 50 cm segments have 73 nm fitting error (15 actuators/m²)
- Control loop time constant < Atmospheric time constant
 - 16 Hz bandwidth gives 100 nm error in 10m/s wind speed
 - Bandwidth \gg Structure fundamental resonance
 - Servo design challenge
 - Overcomes effects of wind loading

Rationale for developing APM Technology #1

- LAT needs AO correction at near and mid -IR wavelengths to meet its science goals.

	Requirement	Goal
Effective psf FWHM (arcsec)	0.2	0.1
Field of view (arcmin)	1	2
On-axis Strehl ratio at 1.6 μ	0.4	0.6
Wavefront error (nm)	250	180
Telescope FOV (mid - far IR) (arcmin)	5	10

Rationale for developing APM Technology #2

- Adaptive Primary Mirror allows superb image quality in the Infra-red with minimum number of surfaces.
 - Allows convenient trading of resolution and field of view
 - Adaptive Primary provides conjugate ground layer correction for optimum MCAO. High altitude layers are seen through the corrected ground layer. Prim
- Lower overall system complexity
 - AO and segment control integrated into single system
 - Complex, massive adaptive secondary not required at the end of a long structure
- Lower overall Cost
 - Savings in Segment fabrication, telescope structure, dome and site construction
- Scalable technology
 - LAT can be the prototype of 50-100 m telescopes

Technological Challenges

- Reaction forces on the backing structure
 - For 1/2 arcsecond seeing, $\lambda = 1 \mu$, Wind speed 15 m/s, 16 Hz bandwidth RMS acceleration is $8 \times 10^{-3} \text{ m/s}^2$
 - For 25 kg/m² segment mass density average pressure $\approx 0.2 \text{ Pa}$ (equivalent wind speed 0.4 m/s)
- Damping of Support Structure
 - Mean Square structure motions to wind/atmospheric turbulence scales as:
 $(1/Q \text{ factor}) \times (\rho/E)^{5/6} \times \text{Size}^{5/3}$
 - High Q is already a problem for ELTs, Lightweight segments allow “new” materials and technologies to be used to provide damping.
- System Complexity
 - Overall system complexity is less than GSMT with AO

Key to solving many technical problems is the development of ≈ 0.5 m lightweight segments

- Mass of Primary /unit area scales as (support spacing)²
 - Use high support density OR small segments

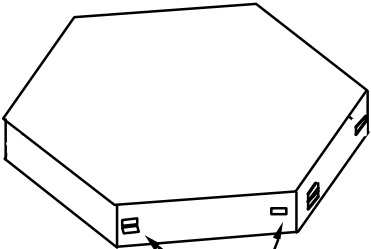
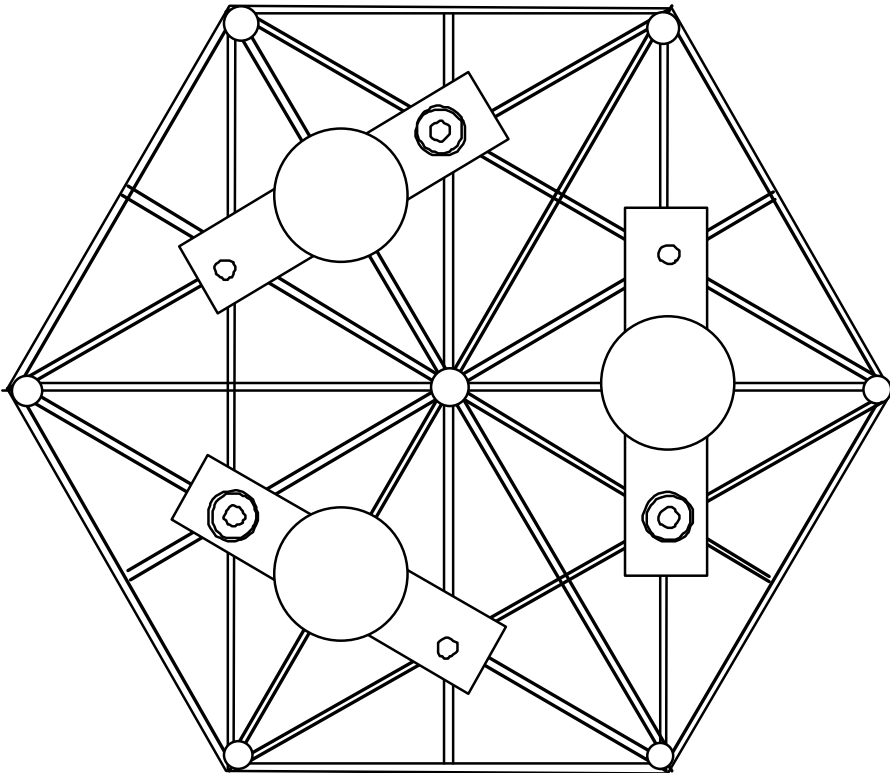
- Small segments are easier to make at fast f-ratios.

$$\alpha_{22} \approx d^2 / (512 F^3 D) \quad (\text{Astigmatism})$$

$$\alpha_{31} \approx d^3 / (256 F^3 D^2) \quad (\text{Coma})$$

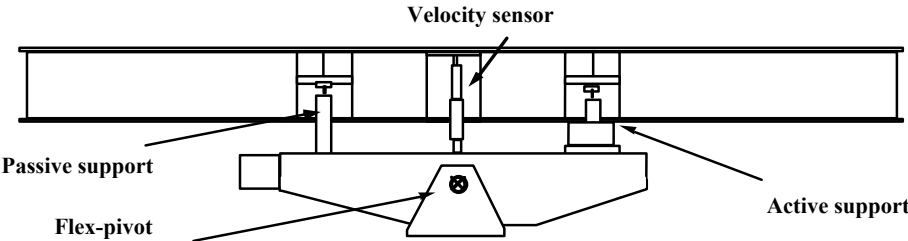
- Small segments correct atmospheric turbulence better.
- Light weight segments allow use of direct coupled electromagnetic actuators
 - Low cost, high reliability support of segments
 - High bandwidth, active damping of structure

Example of Segment support structure



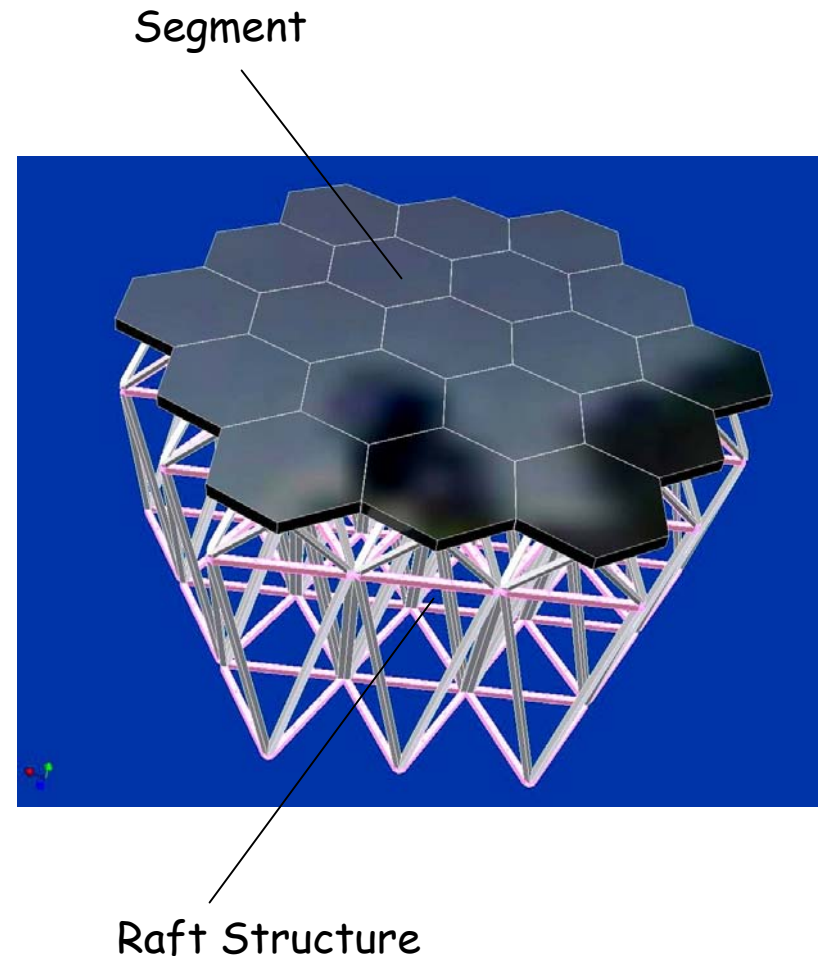
Capacitive/Inductive position sensor

Schematic Drawing of Segment Support
EK 03/17/02

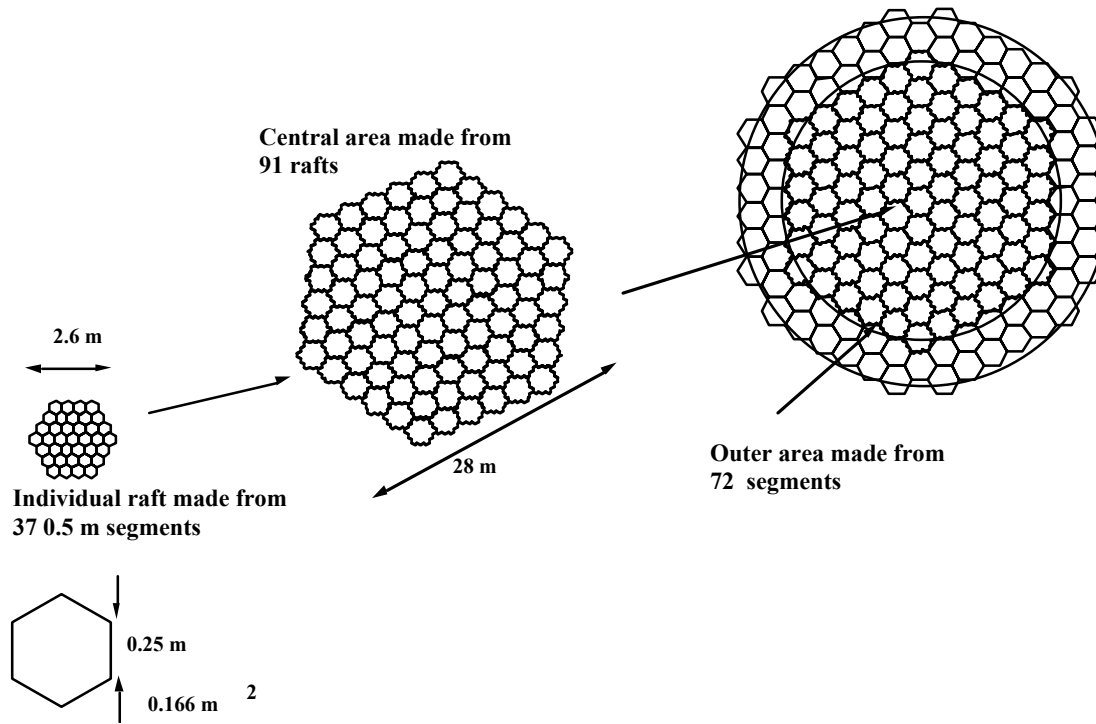


Segments are pre-assembled in rafts

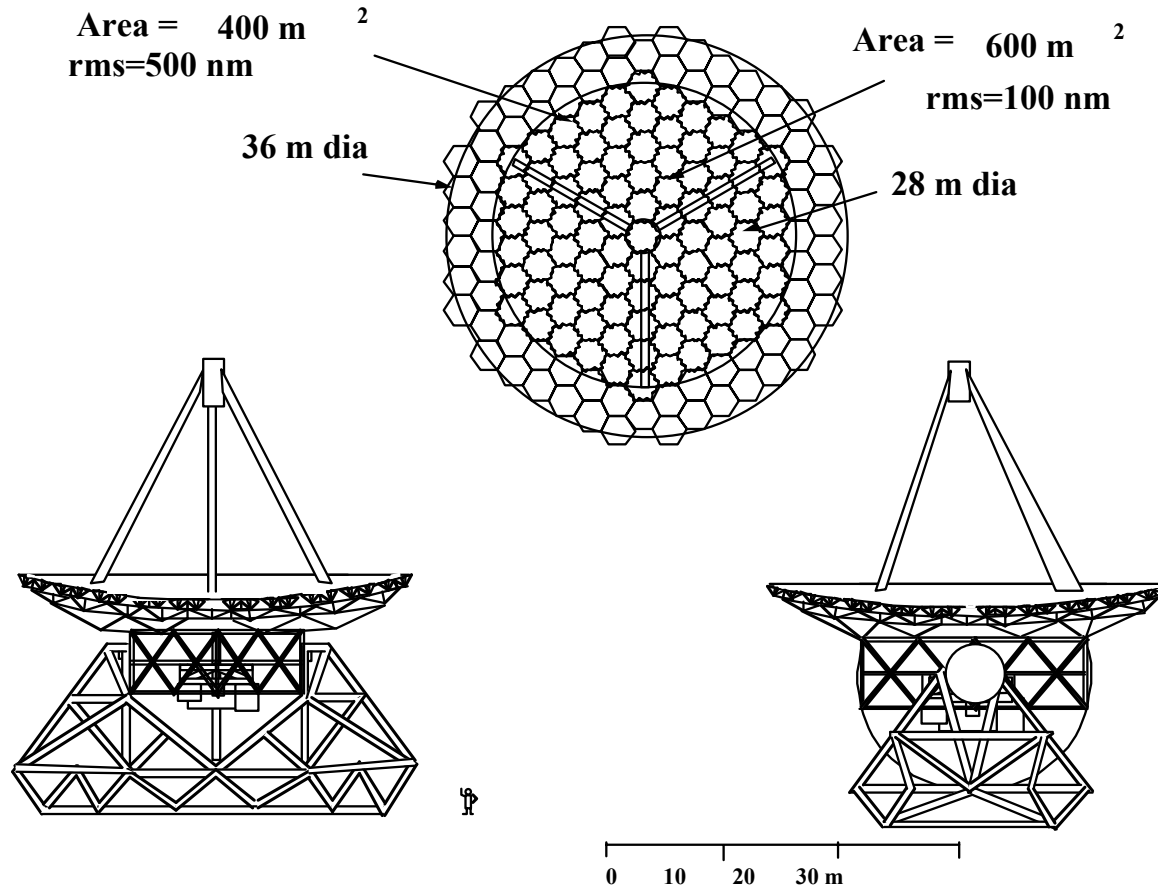
- Actuators have force of $1.5 \text{ kg/w}^{1/2}$ and 3 mm stroke.
- High bandwidth analog tacho-loop provides active damping.
- Inductive edge sensors measure relative positions to 40 nm.
- Laser beacon +WFS measures wavefront errors to 80 nm.
- Damped Graphite Epoxy Support Structure



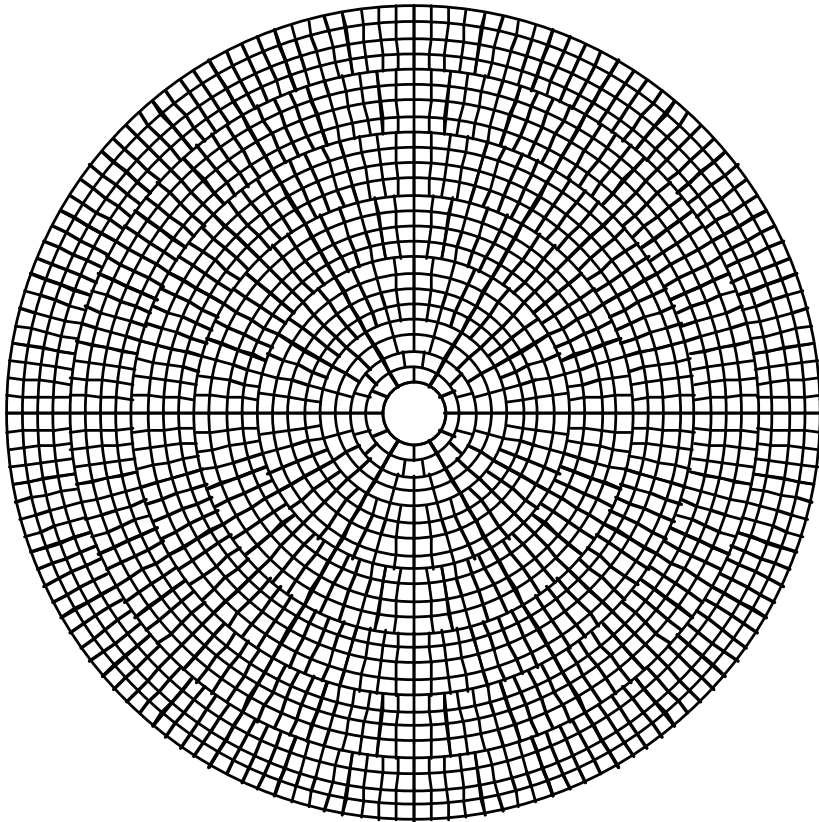
Rafts are assembled at the telescope to make the primary mirror



One design of LAT with high accuracy inner surface



Alternate Primary Mirror Design



- 25 meter Primary Mirror Diameter 1998 trapezoidal segments arranged in 24 rings
- Rafts made up of 16 segments
- Advantages:
 - Ease of manufacture (only 24 segment types)
 - Circular Aperture Function
- Disadvantages:
 - Worse Fitting Function than hexagon
 - More complex wavefront sensor optics.

Segment Fabrication

- Requirements:
 - Time to make segments 3 years or less
 - Low ($\sim 30 \text{ kg/m}^2$) total areal density

- Segment Properties

Material	TBD
Segment Size	0.5 m
Mass	$\sim 5 \text{ kg}$
F-ratio of Primary	~ 0.8

Some Segment Technologies:

- SiC, ion polishing
- ULE glass, ion polishing
- Replication [examples]:
 - “Classic” Composites
 - Electroforming
 - Novel Materials: Plasma Sprayed Alumina or Silica or Glass “micro-spheres, Elastic Memory composites
 - Injection molded Pyrex

Segment Fabrication Option #2

- Material : Si C
 - Manufacture Lightweight blank
 - Astigmatic warping
 - Planetary Polishing to sphere
 - Ion figuring for Coma
- Volume of material removed for Coma
 $= k (\pi D^2) d^3 / (F^3 D^2)$
 - Independent of size of telescope!
- Kodak Ion Polisher with 0.025 meter beam removes $0.5 \times 10^{12} \mu^3/\text{day}$
 - Ion figuring of primary mirror using 0.5 meter F/0.8 segments takes 1000 days with one station

- Segment Properties

Material	Si C
Segment Size	0.5 m
Mass	5 kg
Telescope Diameter	25 m
F-ratio of Primary	0.8
α_{22} (astigmatism)	54 μ
α_{31} (Coma)	1 μ

Si C significantly more expensive than electroforming

Segment Cost Estimates for SiC

Segment Diameter	0.45 m	1m
Mass/segment	2.5 kg	27 kg
Mass of primary	15,000 kg	34,000 kg
Reaction Force	0.008 N	0.1 N
Reaction Pressure	0.05 Pa	0.13 Pa
Mirror Blank Cost/Segment	\$2.5K	\$27K
Figuring Cost/Segment	\$3.5K	\$66K
Support Cost/Segment	\$2.8K	\$12K
Cost/Segment	\$8.8K	\$105K
Cost/m ²	\$53K	\$134K

Control Issues

Telescope Diameter	20 m	36m
No of segments	1600	6000
No of edge sensors	9600	36,000
WFS sampling/segment	8x8	8x8
Minimum CCD size	512x512	1024x1024
Segments/Raft	16	32
Maximum matrix size	12800x4800	48,000 x18000
Computer power/raft	50 x10 ⁶ ops/s	100 x 10 ⁶ ops/s
No of Computers	100	200
Intra computer data bandwidth	100 Mbits/s	100 Mbits/s

Laser Beacons will be used to measure wavefront and segment alignment

- WFS subapertures determine slopes within segments and at segment boundaries
- Edge sensors can be used to determine zero order position OR
- Two wavelength laser beacon used to increase capture range to 1 μ .
 - Sodium beacon at 0.589 μ used as primary beacon
 - Ti-Sapphire laser tuned to Potassium line at 0.766 μ used to determine white light fringes
 - K beacon is 3 magnitudes fainter but only needed to determine white light fringe (low bandwidth)
- Rayleigh beacons also an attractive solution

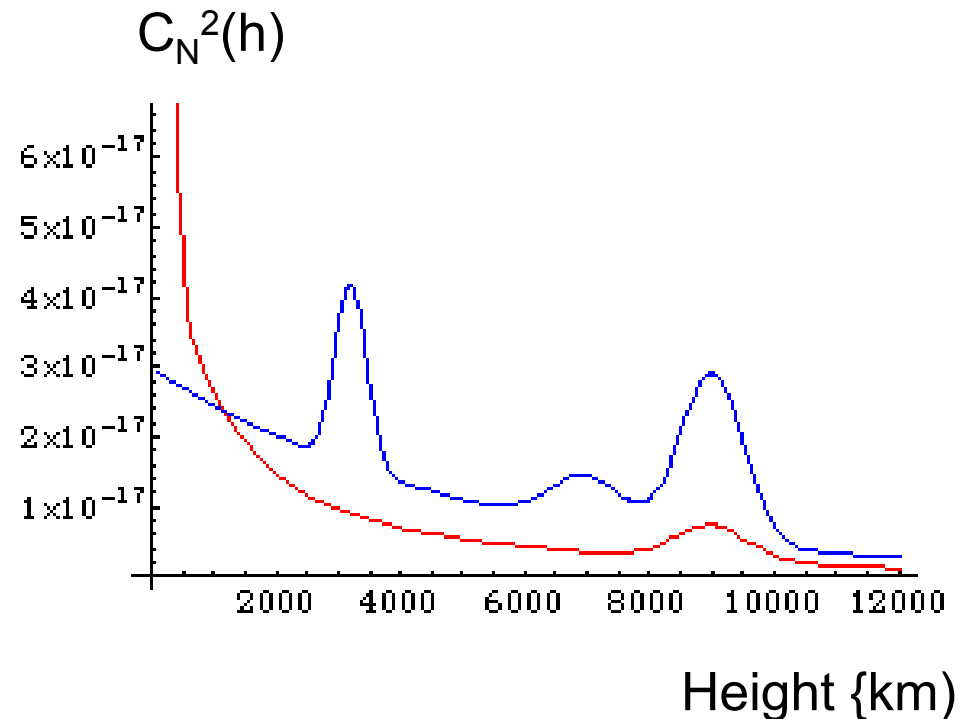
Increasing the field of view of an AO system #2 Segment Correction

- Isoplanatic angle depends on (D/r_o) and is much bigger for $(D/r_o) < 3$
 - We can phase individual rafts or clusters of rafts and not attempt correction across the whole field
- For $r_o = 0.8$
 - 2m raft @ $1.6 \mu\text{m}$ has FWHM ~ 0.16 arcsec ($D/r_o = 2.5$)
 - 4m raft @ $2.3 \mu\text{m}$ has FWHM ~ 0.12 arcsec ($D/r_o = 3.2$)
- Depends on $C_N^2(h)$ profile
- Use of segmented mirror important

<psf> \rightarrow <psf of raft cluster>

Increasing the field of view of an AO system #1

- Field of view can be increased by only correcting the ground layer
- The effectiveness of this depends critically on the C_N^2 profile
- South Pole is best known site



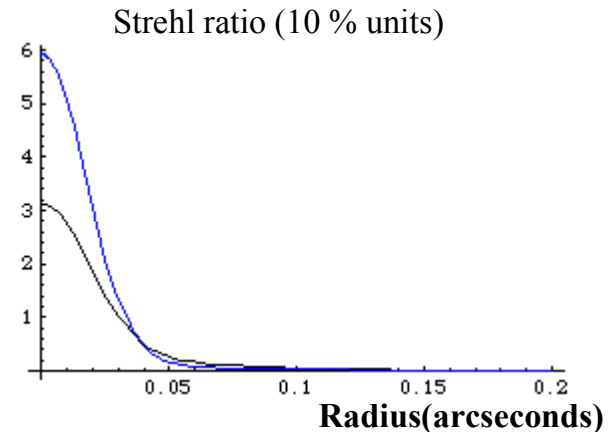
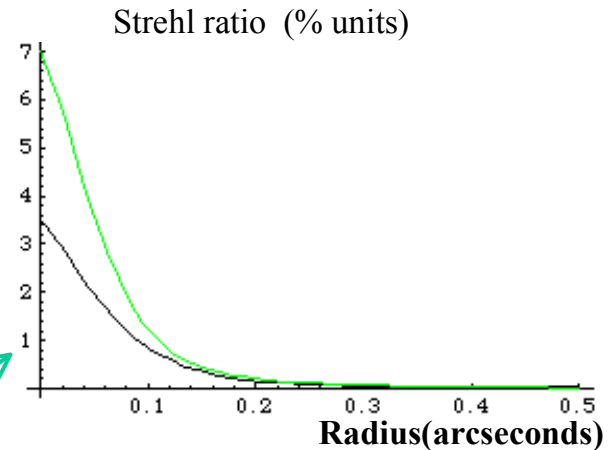
- Blue : Mauna Kea
- Red: South Pole

Field of View with adaptive Primary at the South Pole

- Analytic Point Spread Functions assuming that we can correct all the turbulence up to a given height and none above this height
- Calculation assumes a 50 cm subaperture and an infinite outer scale length.

Height	FWHM (arcsec)	Field of View (arcmin)	(km)
0.1	0.25	17	
1.0	0.1	5.4	
10	0.04	1	

Calculations assume a 12 m telescope operating at 2.2 μ



AO Error Budget

Segment Size	0.45 m	0.9 m
Fitting Error	56 nm	100 nm
Edge Sensor Noise	40 nm	40 nm
High order segment figure error	60 nm	100 nm
Photon Noise	80 nm	75 nm
Servo Bandwidth	120 nm	160 nm
Cone Effect Residuals	150 nm	150 nm
Calibration noise	60 nm	60 nm
RMS surface error	240 nm	280 nm

Technical Summary of APM concept

- Mass produced lightweight 0.5 meter segments with voice coil actuators pre-assembled on 2 meter size rafts
- Edge Sensor Cophased for $\lambda \geq 5 \mu$, Two wavelength Laser Guide Star used $\lambda < 5 \mu$
- Damped Support Structure
- Radio Telescope Mount Technology
- Wide-field low order AO correction in Phase 1, MCAO option plan

AO Equations used in Calculations

- Residual Fitting Error $\sigma_f \approx 200 (D \alpha)^{5/6}$ nm
- Error due to Servo Bandwidth $\sigma_t \approx 200 (D \alpha / f)^{5/6}$ nm
- RMS Acceleration $\approx 9 \times 10^{-15} (v \alpha)^2 \sigma_t^{-7/5}$ m/s²
- Cone Effect $\sigma_f \approx 30 D^{5/6}$ nm

D is diameter of telescope

α is seeing in arcseconds at 0.5 μ

f is 3 db bandwidth of control system

V is effective wind velocity

Next Steps: Design Studies

- Primary Mirror Technology
 - Segment fabrication & Segment control
 - Wind loading
 - Primary mirror support
- Site survey studies
 - C_N^2 profile most important
- Instrument
 - Trade offs (survey strategy, sensitivity limits, time to complete, instrument complexity, etc.)
 - Design
- On-site fabrication
 - Either high-altitude or South Pole