Summary of Science Driven Telescope Specifications

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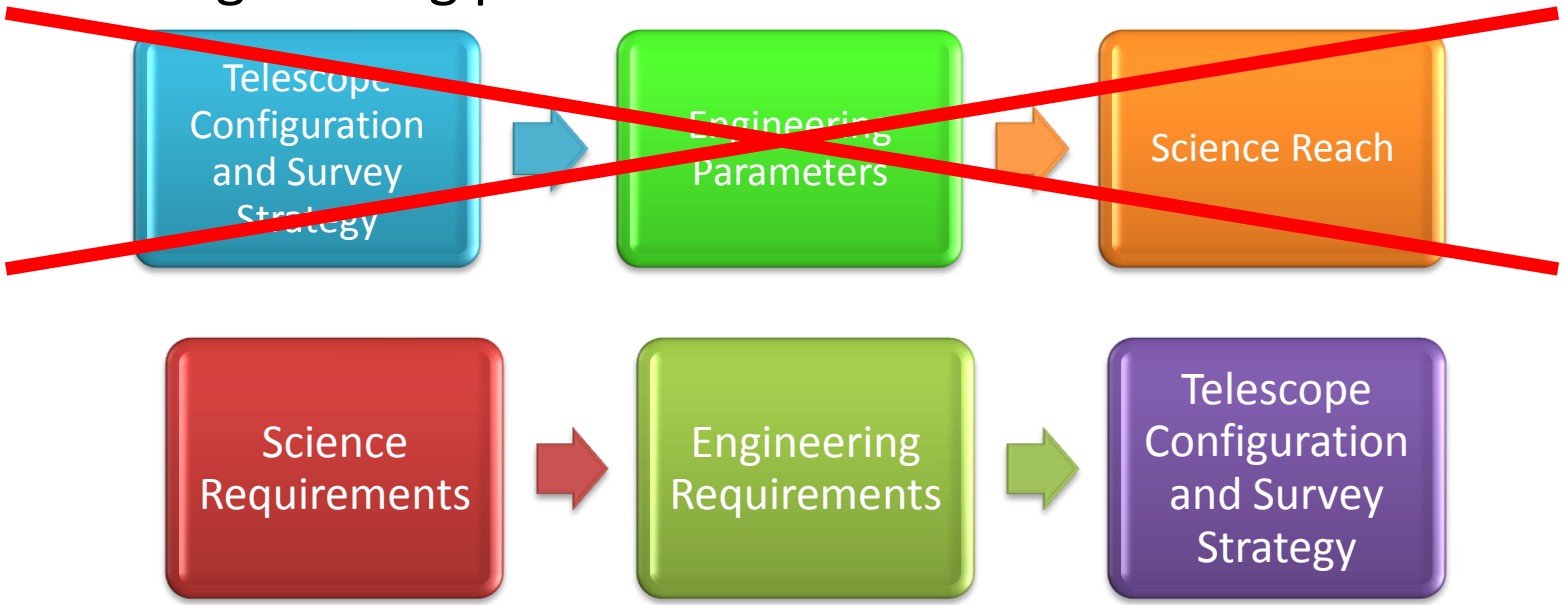
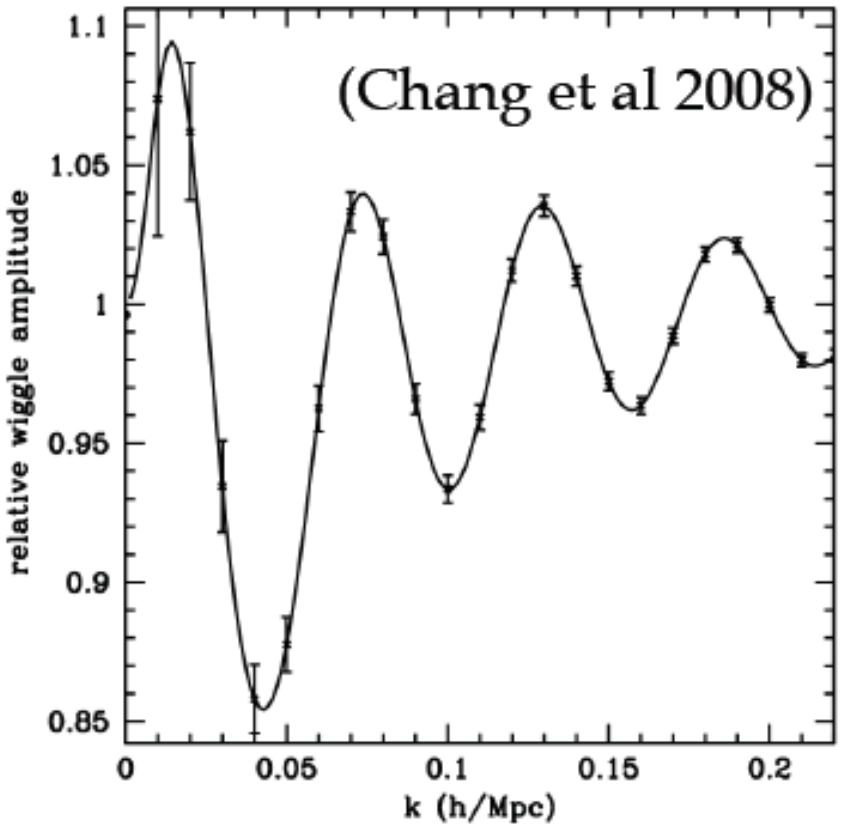
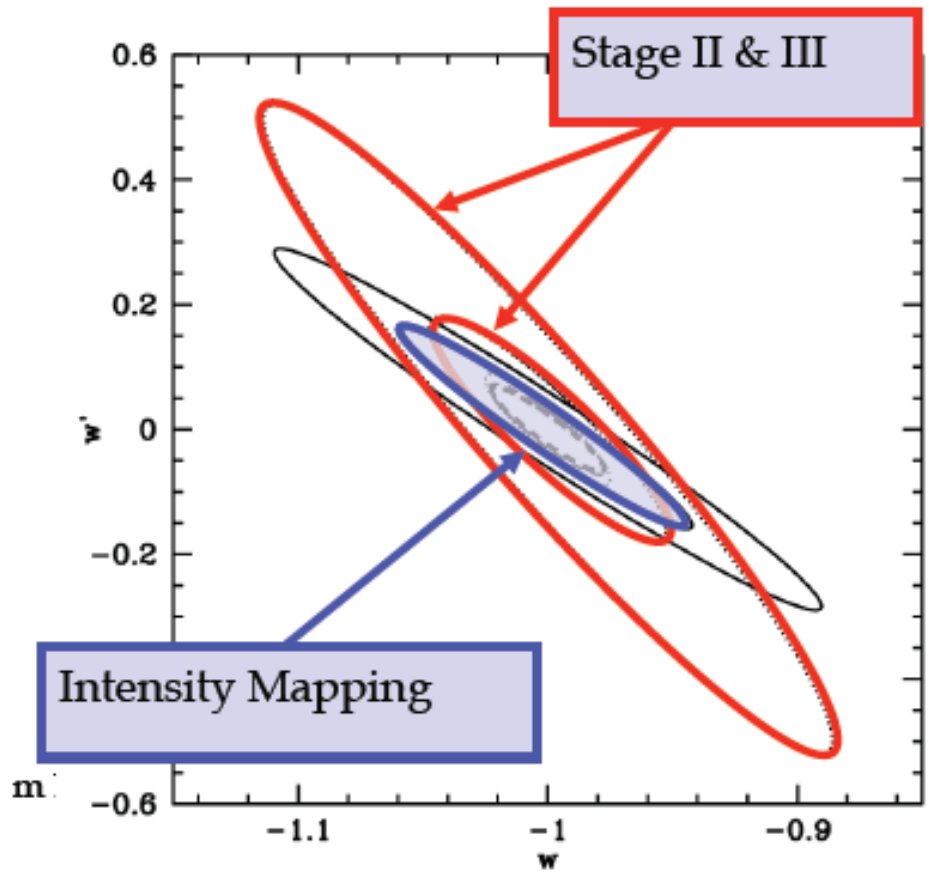
Telescope Requirements

- We cannot design the CRT before we have a well defined set of science requirements.
- From the science requirements, the engineering parameters are derived
- The science requirements and engineering parameters are <u>independent</u> of the telescope configuration
- Derive the telescope configuration and survey strategy from the engineering parameters



Science Requirements





Science Requirements (a.k.a The Five Magic Numbers)

- Red-shift Range - size of the survey in z
- Angular Survey Area (in steradians)
- Angular Resolution (in radians)
- Survey Length (in years)
- Amplitude sensitivity (in Kelvin)

Major Engineering Parameters

- Center Frequency
- Frequency Span
- Resolution Bandwidth
- Meridian span
- Number of digital channels
- Length of Cylinder
- Width of Cylinder
- Number of Cylinders
- Integration time per pixel
- Observation Duty Factor
- Antenna Efficiency
- Amplifier Noise

Survey Area

The survey area for a drift telescope

$$\mathrm{A} = \int_0^{2\pi} d\phi \int_{-\Delta\theta/2}^{\Delta\theta/2} \cos(\theta)\, d\theta = 4\pi sin\left(\frac{\Delta\theta}{2}\right)$$

where $\Delta\theta$ is the angular span of the telescope beam along the meridian.

For an FFT telescope which is oriented along the meridian, the first grating lobe occurs when:

$$\frac{\lambda}{\mathrm{d}} = 1 + sin\left(\frac{\Delta\theta}{2}\right)$$

Survey Area

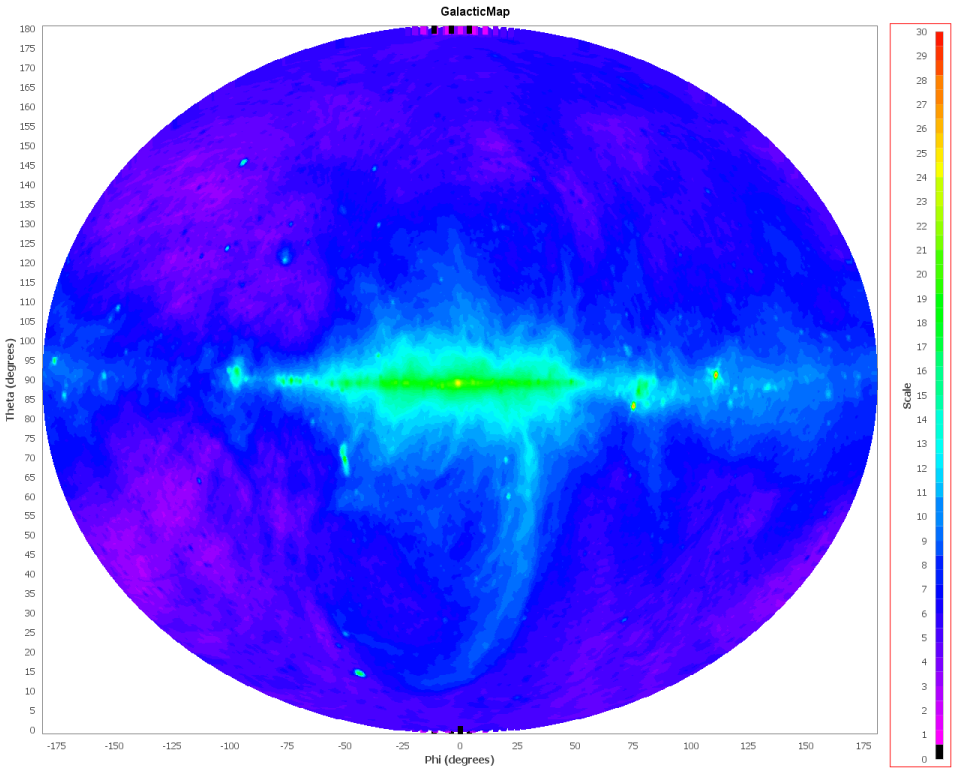
The survey area that is not aliased is:

$$A = 4\pi\left(\frac{1}{d/_{\lambda}} - 1\right)$$

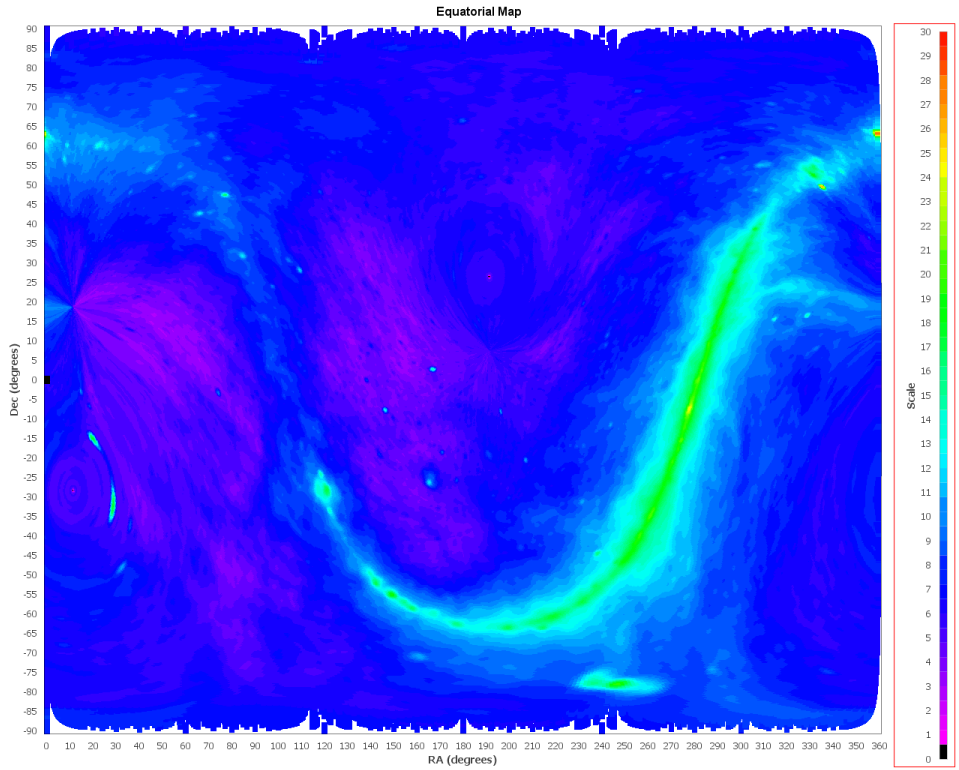
The number of un-aliased beams is:

$$2n_{max} = 2N\left(1 - \frac{d}{\lambda}\right)$$

Survey Area – Haslam Map Extrapolated to 750 MHz

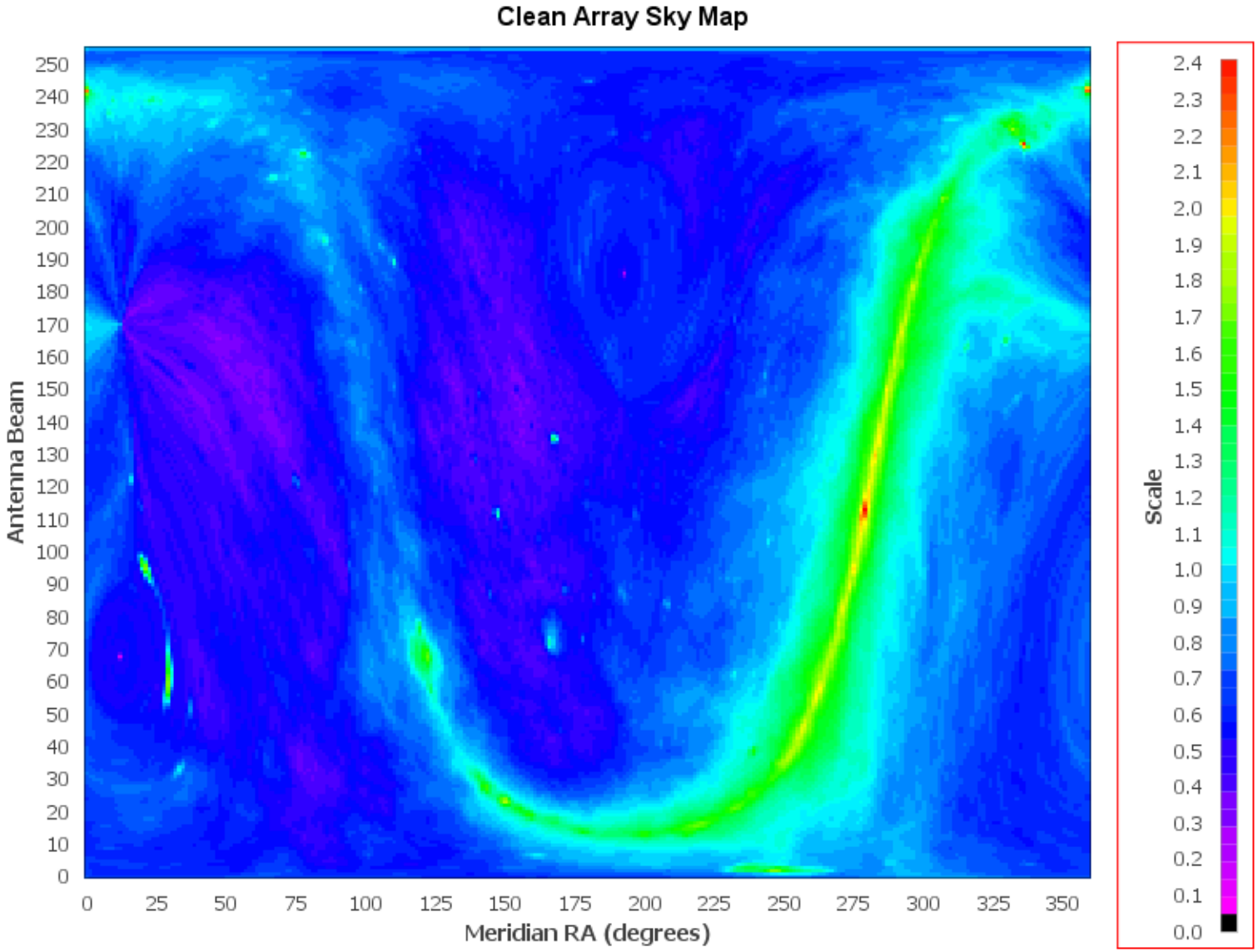


Galactic Oval View

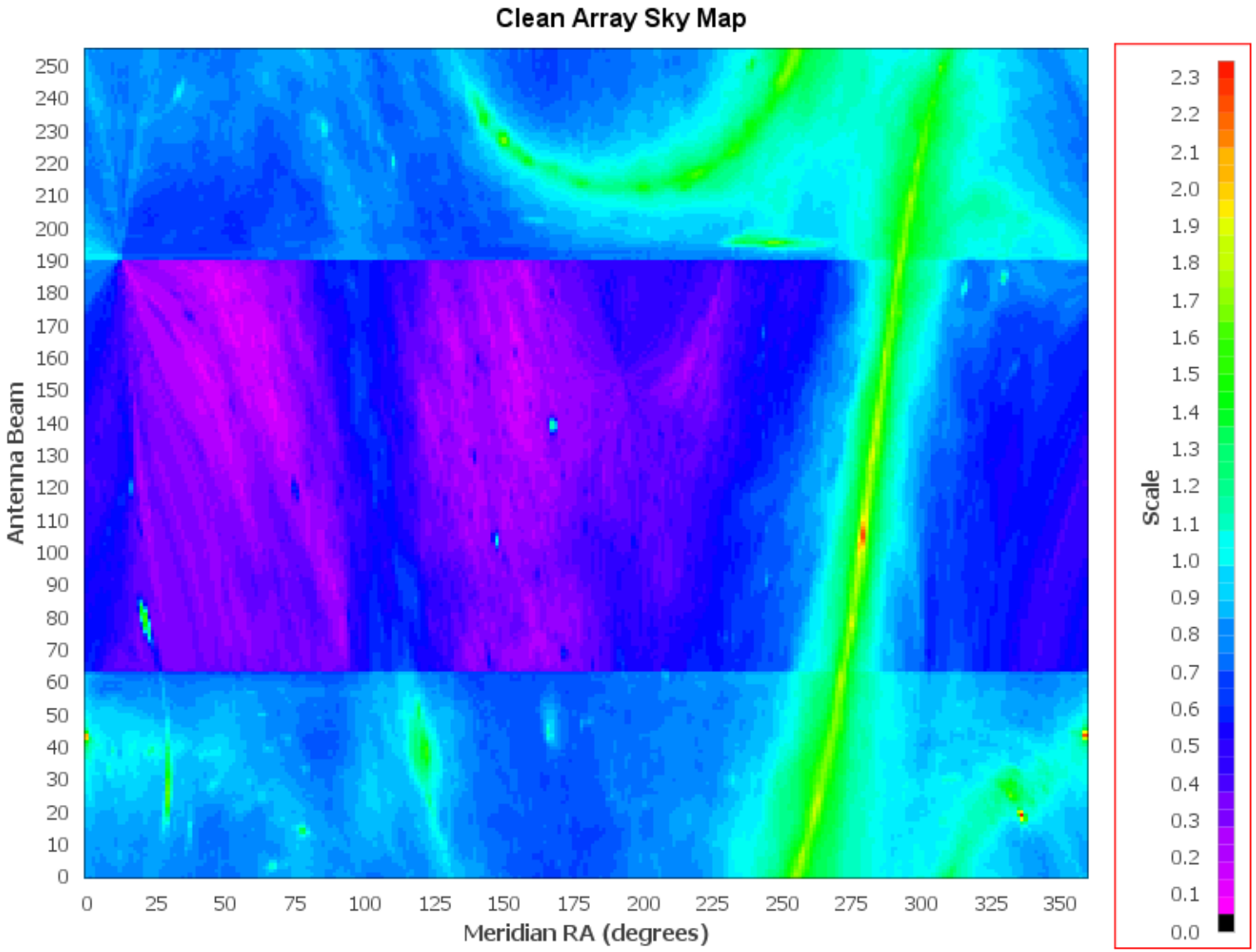


Equatorial Rectangular View

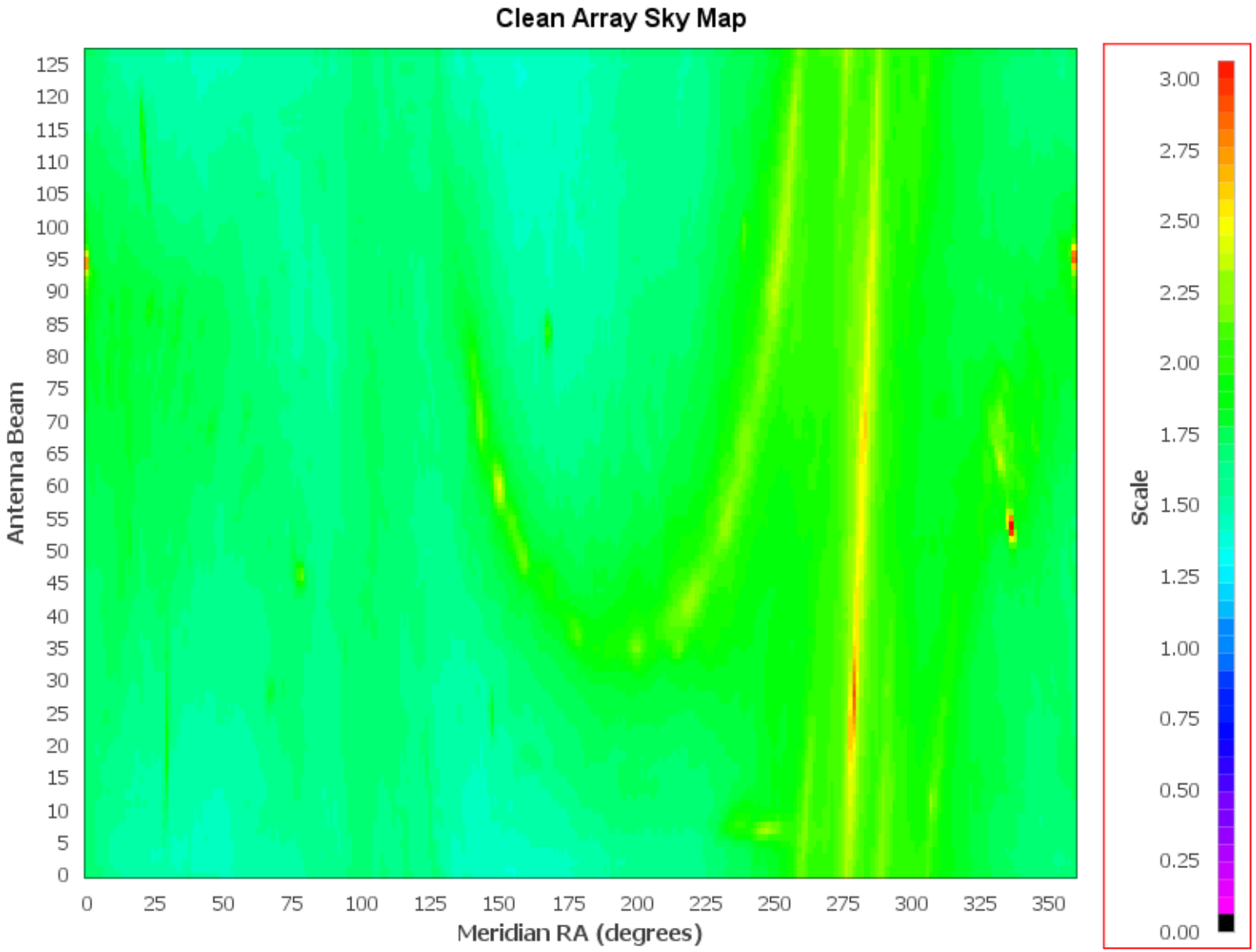
Single Feed per Digitizer Telescope Response $\lambda/d=0.5$



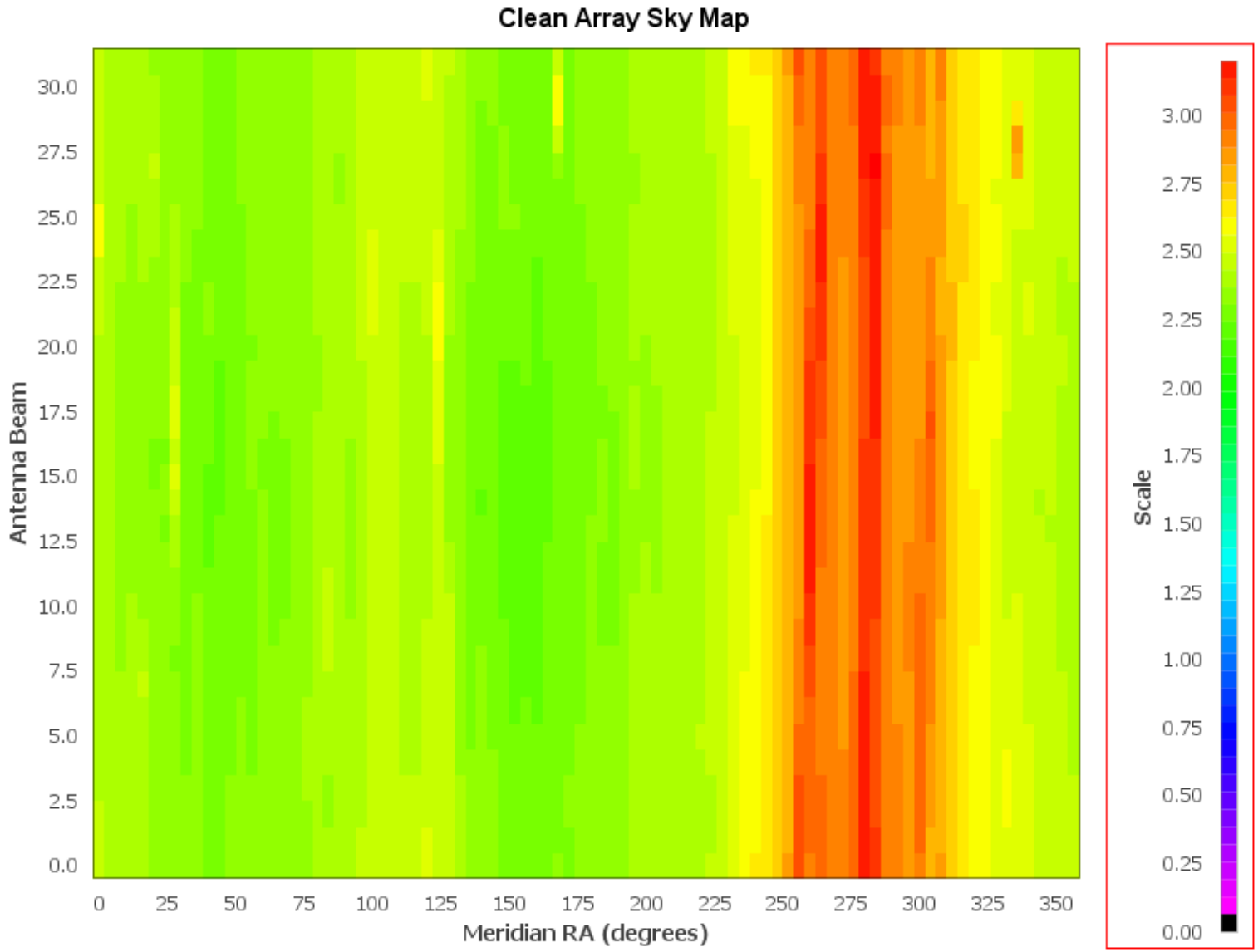
Single Feed per Digitizer Telescope Response $\lambda/d=0.75$



Two Feeds per Digitizer
Telescope Response $\lambda/d=0.50$



Four Feeds per Digitizer
Telescope Response $\lambda/d=0.70$



Resolution

Meridian Resolution

$$\delta\theta = \frac{\lambda}{L_{cyl}} = \frac{\lambda}{N_{feed}d}$$

Azimuthal Resolution

$$\delta\phi = \frac{\lambda}{N_{cyl}W_{cyl}}$$

For a “uniform cubic” pixel

$$\delta z \approx 0.436 \times \delta\theta(\text{radians}) \times z(z+2)$$

$$\delta F = \frac{1.4GHz}{(1+z)^2}\delta z$$

$$\delta F \approx 610MHz \times \delta\theta(\text{radians}) \times \frac{z(z+2)}{(1+z)^2}$$

Survey Speed

Amount of time a sky slice is integrated in one day:

$$\Delta\tau_{day} = 24 \times 3600\text{sec} \times \frac{\lambda/W_{cyl}}{2\pi}$$

The number of measurements made on sky slice:

$$M = \Delta\tau_{total}\delta F$$

Pixel Sensitivity:

$$\delta T = \frac{1}{\sqrt{M}}\left(\frac{1}{g_a}T_a + T_{sky}\right)$$

Maximum Cylinder width:

$$W_{cyl} = \lambda\left(\frac{g_a\delta T}{T_a + g_a T_{sky}}\right)^2 D_f N_{year}\delta F\frac{365 \times 24 \times 3600\ \text{Sec}}{2\pi}$$

Duty factor less than ~ 0.5 ?

Survey Sensitivity

Total integration time required as a function of wavelength:

$$\Delta\tau_{total} = \frac{\lambda}{\lambda_{ref}} \left(\frac{T_a + g_a T_{sky}}{g_a \delta T_{ref}} \right)^2 \frac{1}{\delta F_{ref}}$$

Pixel sensitivity as a function of wavelength

$$\delta T = \delta T_{ref} \sqrt{\frac{\lambda_{ref}}{\lambda} \frac{\delta F_{ref}}{\delta F}}$$

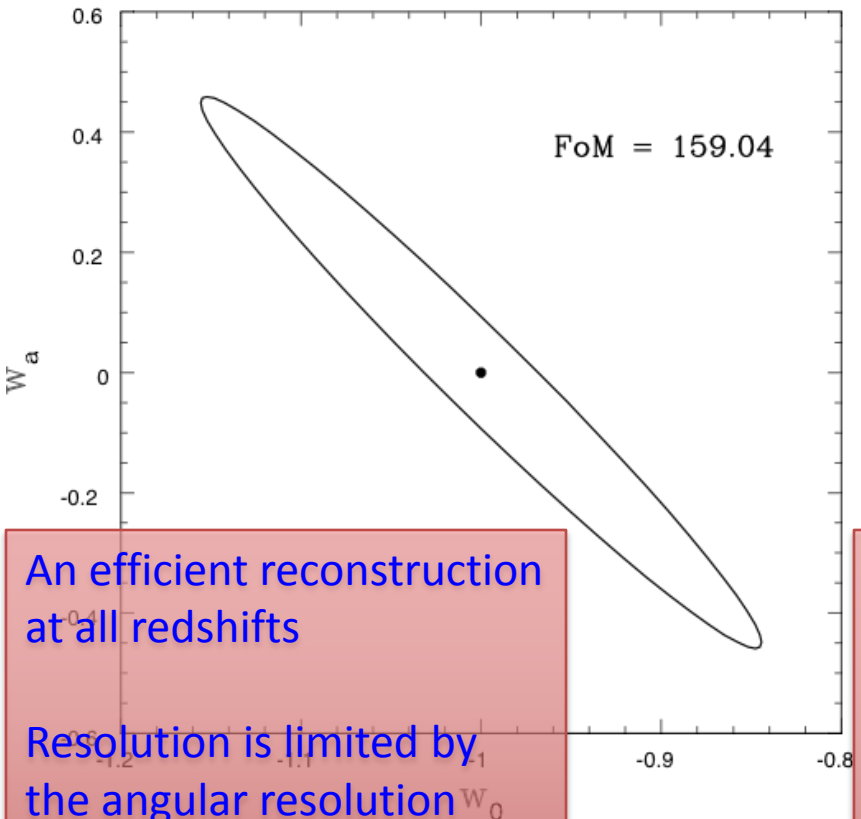
Example Design Parameter Table

Number	Requirement	Limit	Average	Limit	Unit	Parent Requirements							
1.01	Redshift Range	1.80	0.87	0.40									
1.02	Survey Area	4.00	2.58	0.94	π steradians								
1.03	Angular Resolution	33.1	22.1	16.6	arc-Min								
1.04	Survey Time		0.90		Years								
1.05	Sensitivity per Pixel	88.6	147.0	236.5	uK								
1.06	Polarization Imbalance		-20		dB								
2.01	Minumum Antenna efficiency		80		%								
2.02	Maximum Sky Temperature		10		K								
2.03	Maximum Amplifier Noise Temp		50		K								
2.04	Observing duty Factor		50		%								
2.05	Latitude		0		degrees								
3.01	Center Frequency		750		MHz	1.01							
3.02	Frequency Span		500		MHz	1.01							
3.03	Resolution Bandwidth	5.1	2.8	1.4	MHz	1.01	1.03						
3.04	Feed Spacing		24.3		cm	1.02	3.01						
3.05	Declination Span	180.0	80.3	27.0	degrees	1.02							
3.06	Number of Digital Channels per Cylinder per Polarization		256			1.03	3.01	3.04					
3.07	Number of Feed Antenna per Cylinder per		256			3.06							
3.08	Length of Cylinder		62.2		meters	3.04	3.06						
3.09	Width of Cylinder		10.4		meters	1.04	1.05	2.01	2.02	2.03	2.04	3.01	3.03
3.10	Number of cylinders		6.0			1.03	3.01	3.09					
3.11	Integration Time per pixel	1.51	1.01	0.76	days	1.04	2.04	3.01	3.09				

BAO Simulations

- Fermilab (Hee-Jong Seo) has developed a tool to predict the figure of merit for the dark energy parameters derived from BAO simulations for different telescope configurations.
- The model closely matches Chang etal. predictions.
- The model is still a work in progress.

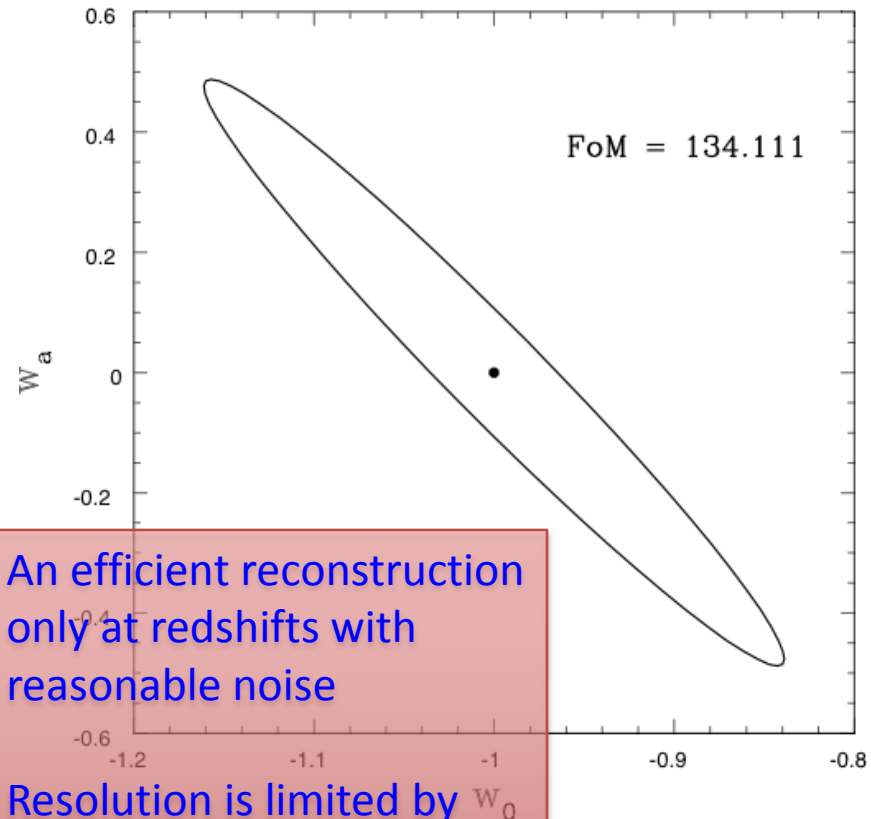
Chang's case



An efficient reconstruction at all redshifts

Resolution is limited by the angular resolution (i.e., df~1.5MHz).

All sky

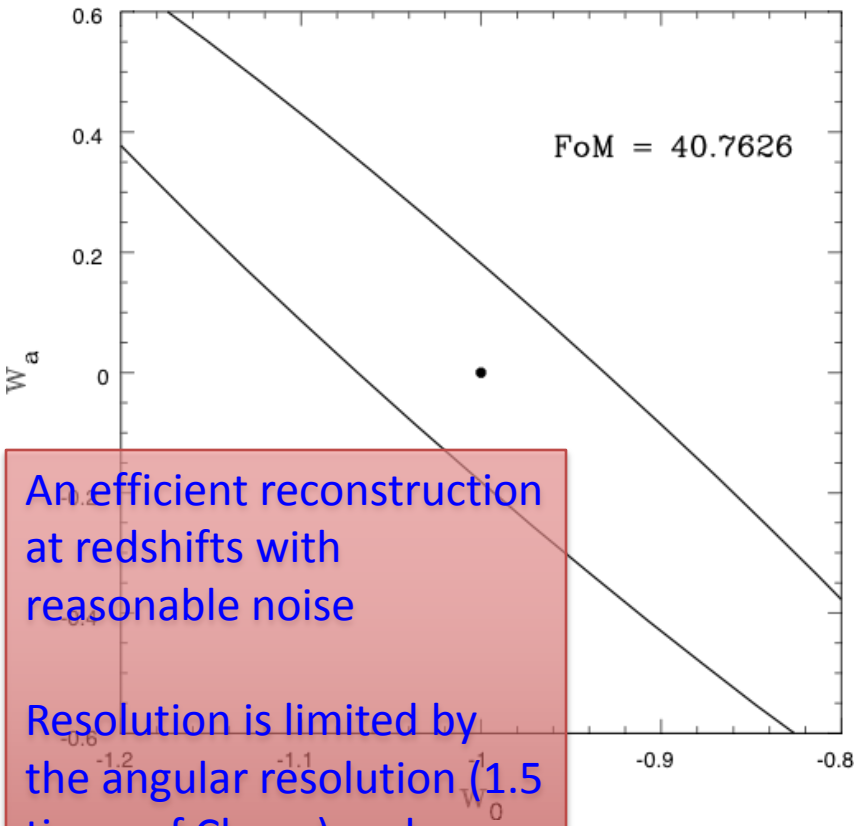


An efficient reconstruction only at redshifts with reasonable noise

Resolution is limited by the angular resolution (i.e., df~1.5MHz).

Example Design

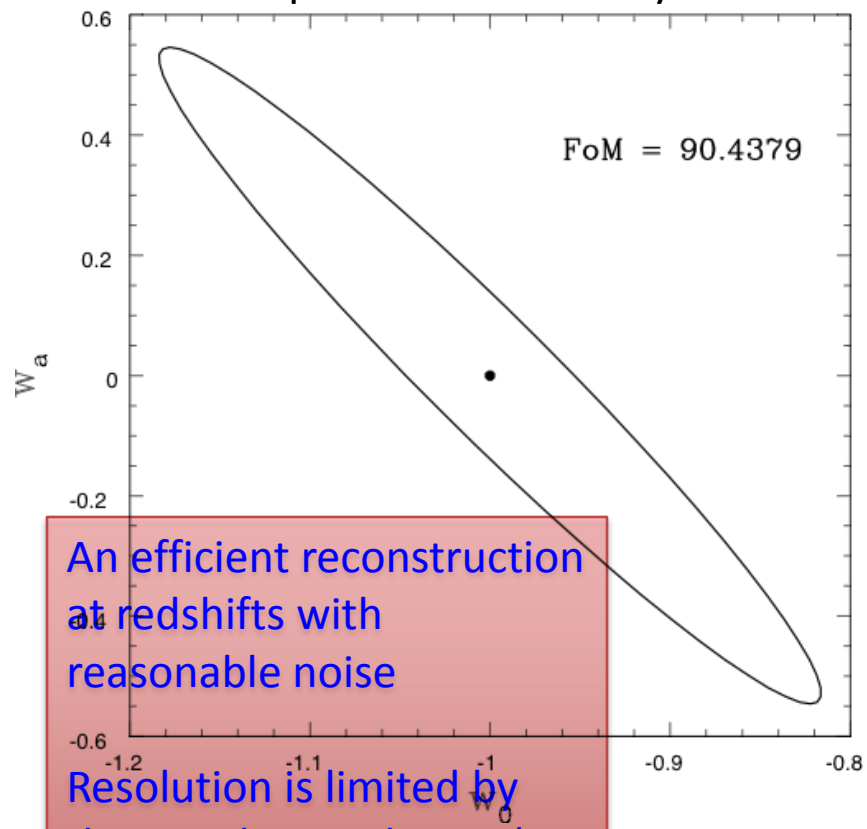
Example



An efficient reconstruction at redshifts with reasonable noise

Resolution is limited by the angular resolution (1.5 times of Chang) and df~3.0MHz

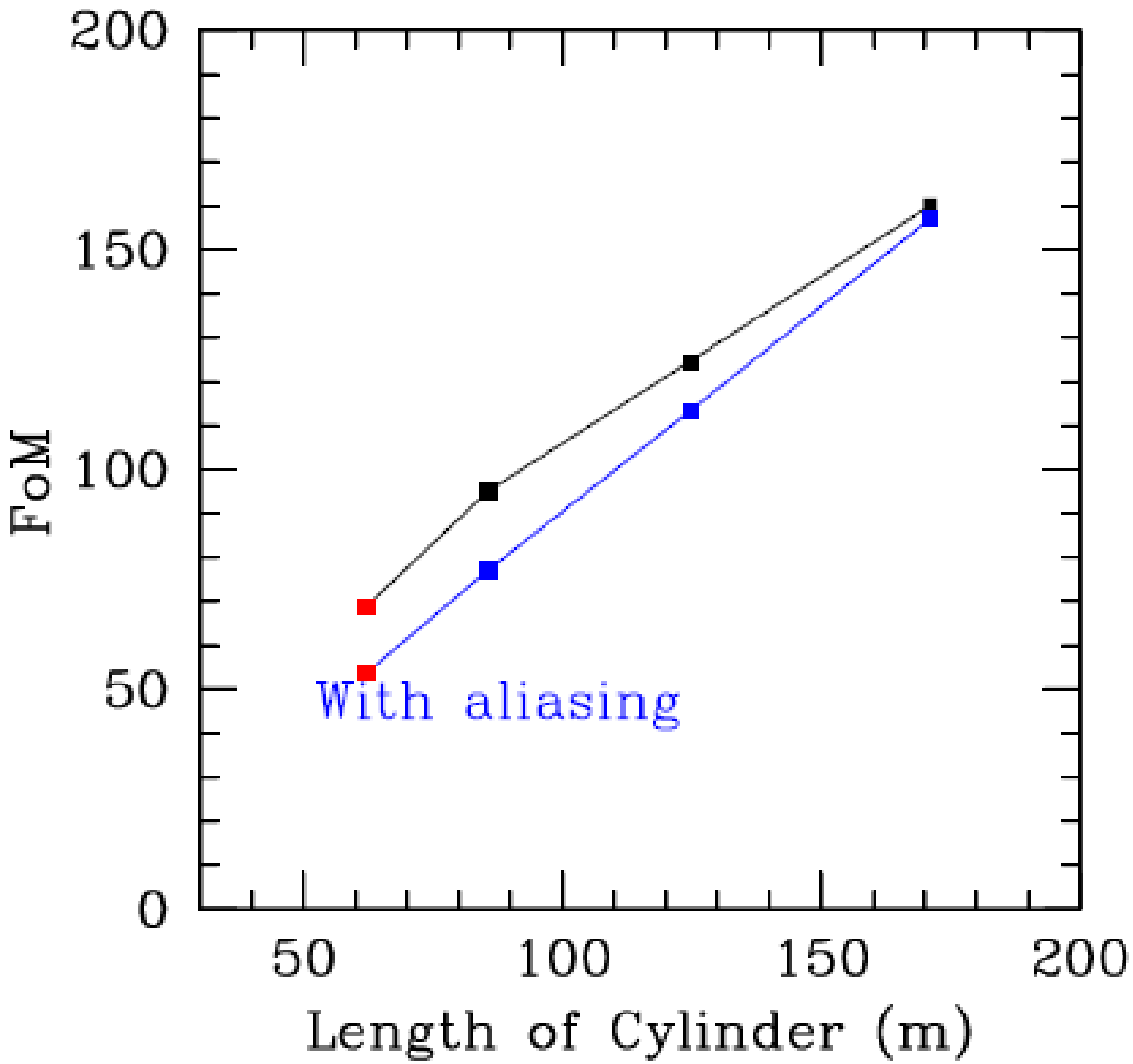
Half freq resolution + all sky



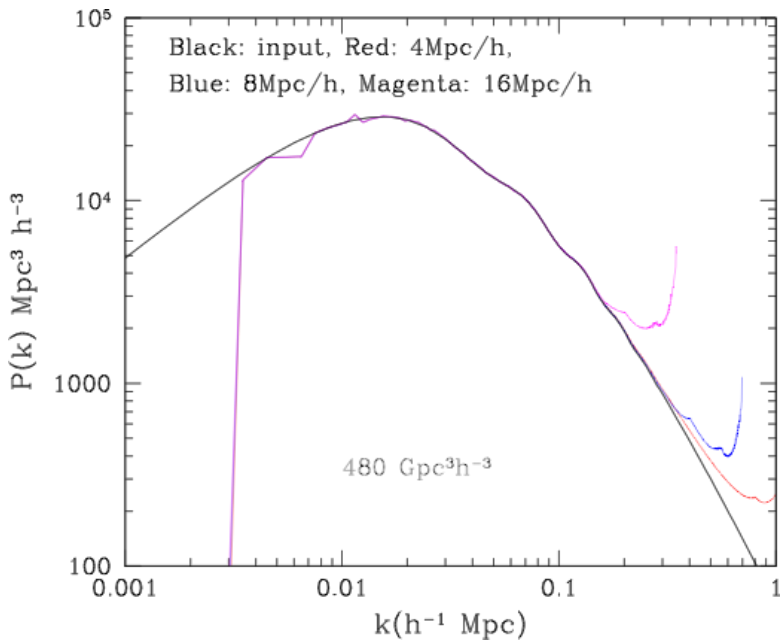
An efficient reconstruction at redshifts with reasonable noise

Resolution is limited by the angular resolution (Df~1.5MHz)

FoM vs Angular Resolution



Aliasing Effect due to a limited resolution



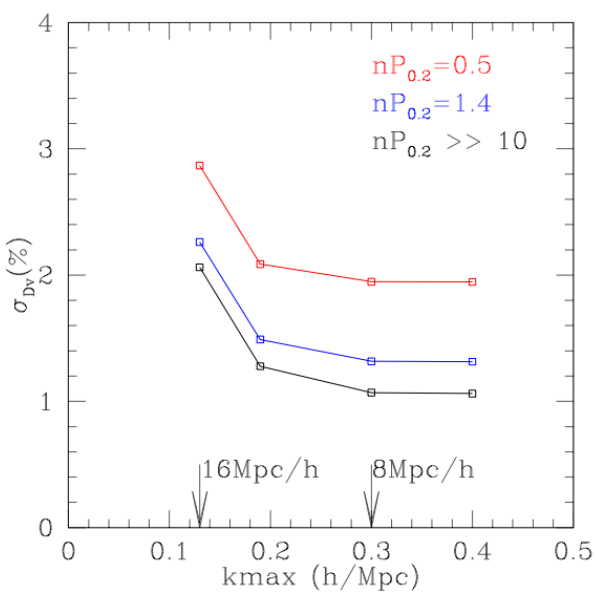
P(k) for various resolutions, after the window func is corrected

Effects

- Decreases the available range of the wave number more than k_{nyq}
  - Harder to fit. Fitting is unstable.
  - Errors on distances increase.
  - Reconstruction will not help much if the resolution is too low.
- Features on smaller wave numbers will be aliased and mixed
  - Aliased residual BAO might cause a shift?
  - It seems that the additional shift < 0.1% of distances.

Effect on FoM

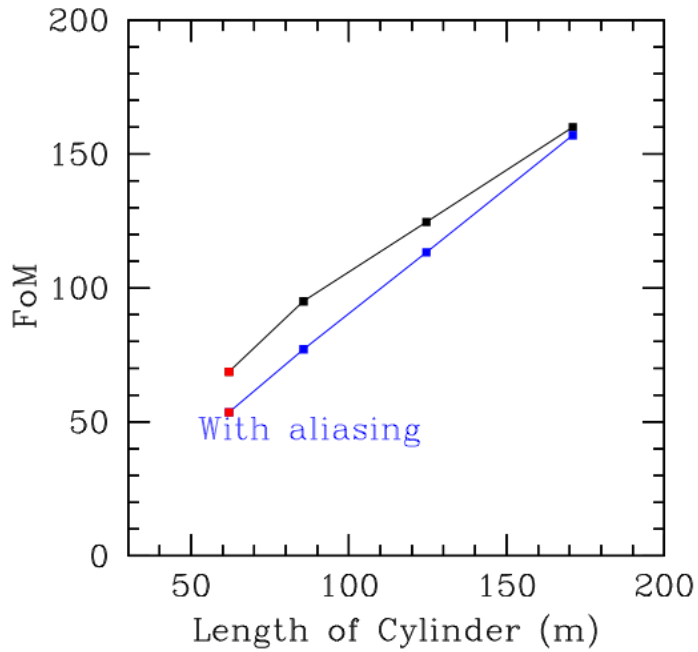
Fisher matrix estimation of distance errors due to aliasing effect at z=1.



For 16Mpc/h resolution, k_{max} ~0.13h/Mpc <k_{nyq}
For 8Mpc/h resolution, k_{max} ~0.3h/Mpc < k_{nyq}

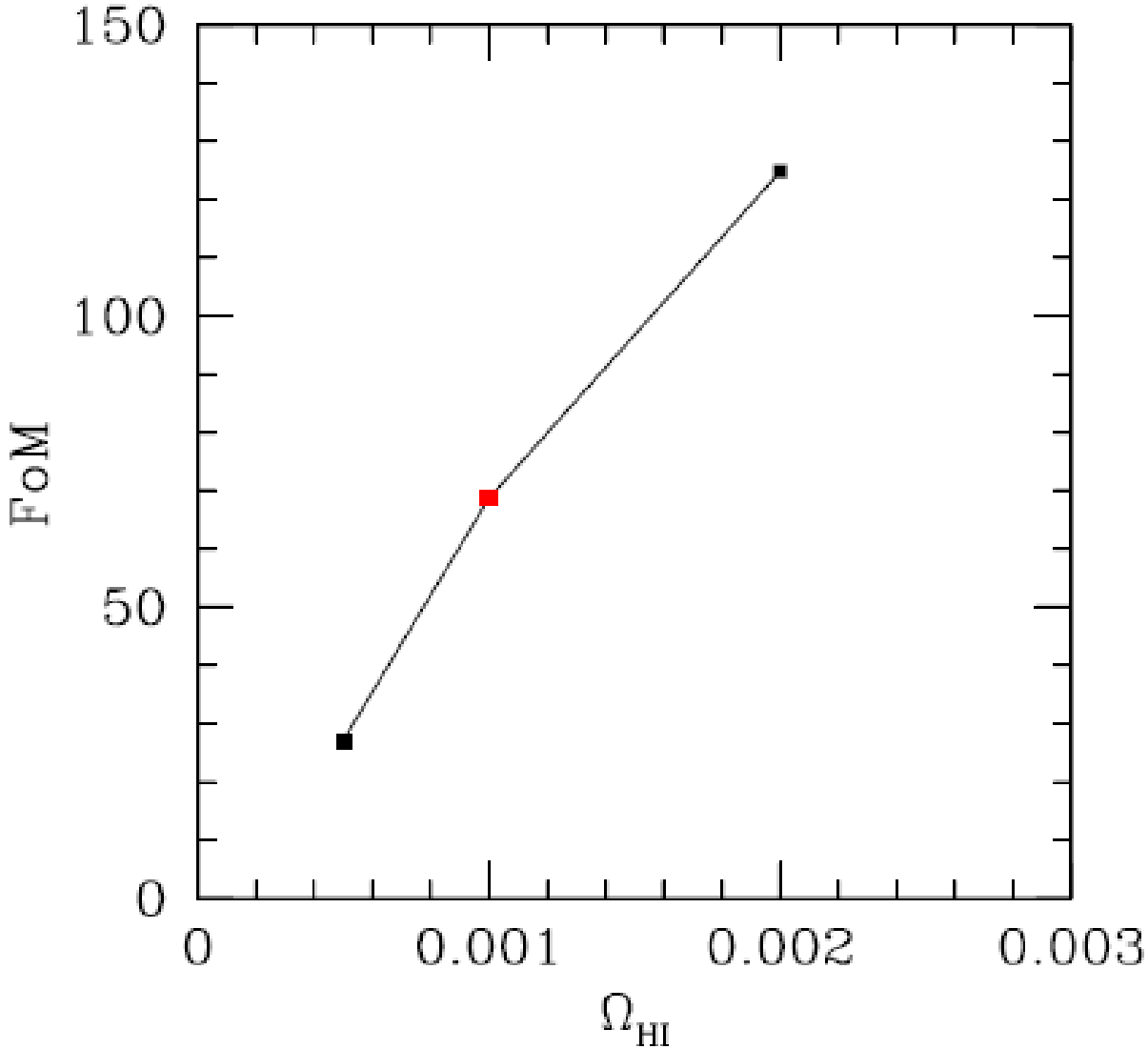
A factor of 2 difference in error between 16 and 8Mpc/h resolution

For our fiducial survey parameters

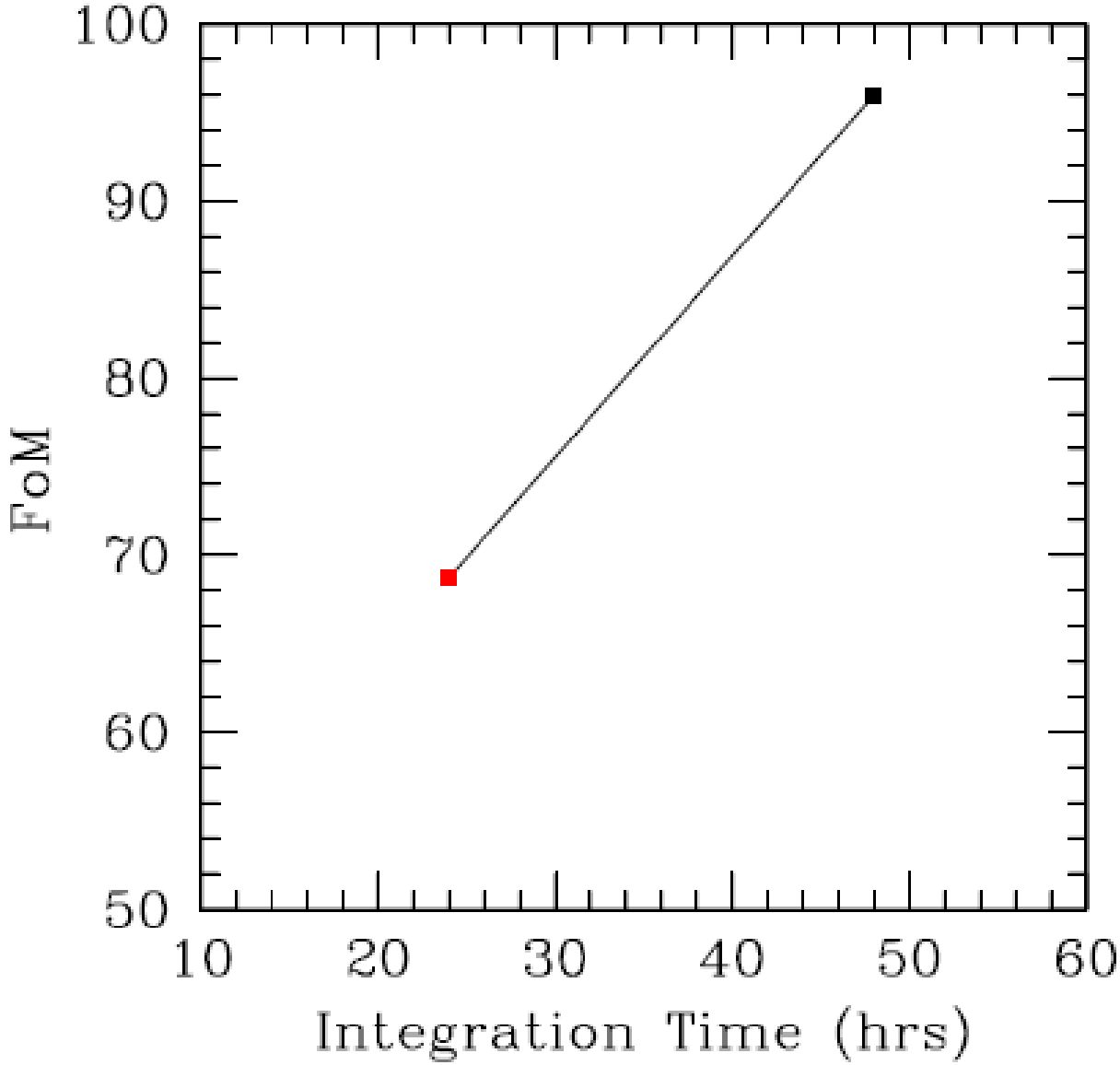


Effect does not seem severe, as the constraining power is at low redshift for w_0-w_a model and the resolution is not too bad at low redshift.

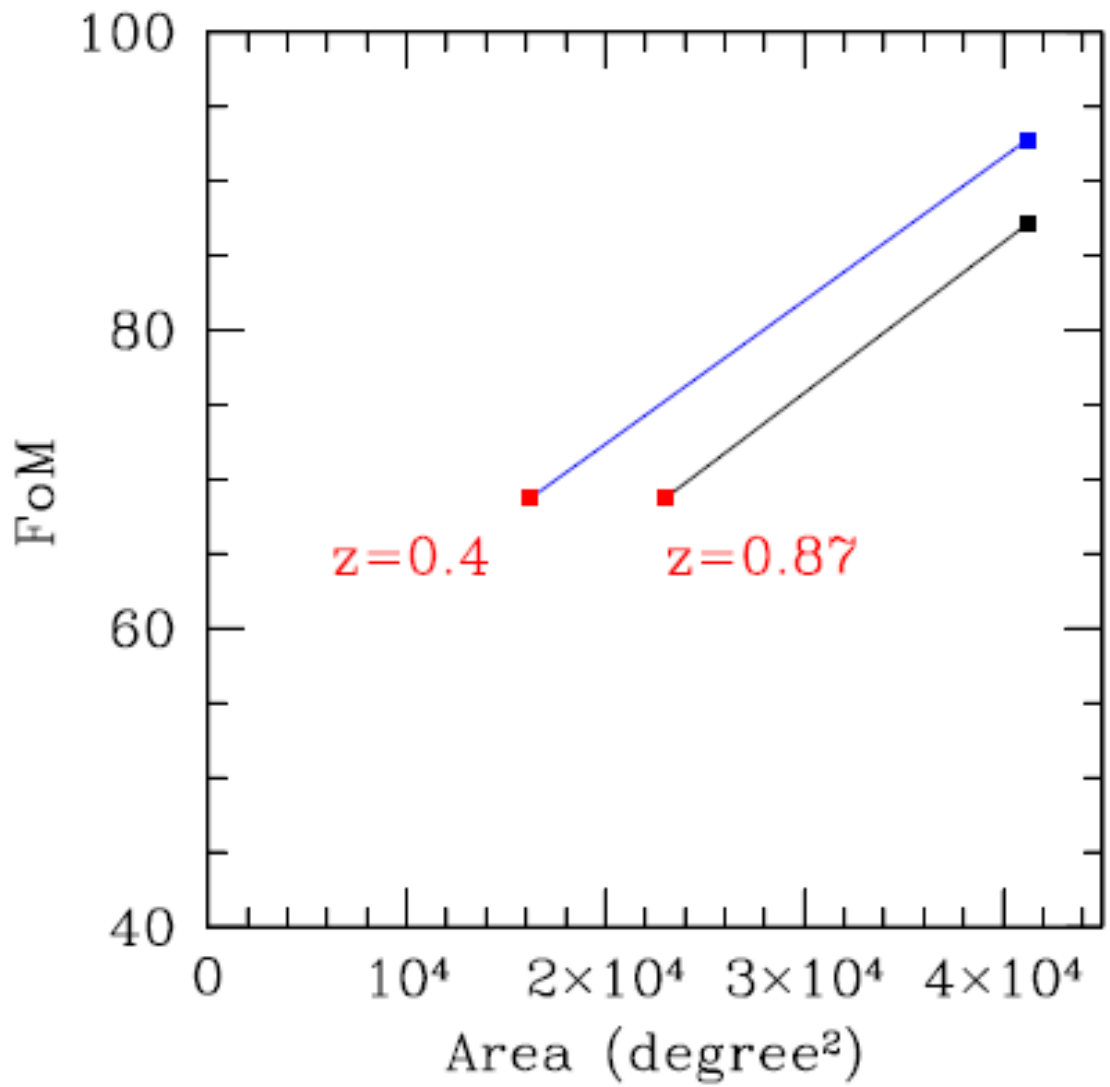
FoM vs Ω_{HI}



FoM vs Integration Time



FoM vs Survey Area



Two Band Design

Number	Requirement	Limit	Average	Limit	Unit
1.01	Redshift Range	0.87	0.60	0.40	
1.02	Survey Area	4.00	3.02	2.14	π steradians
1.03	Angular Resolution	13.7	11.8	10.3	arc-Min
1.04	Survey Time		1.10		Years
1.05	Sensitivity per Pixel	174.4	220.0	280.6	uK
1.06	Polarization Imbalance		-20		dB
2.01	Minumum Antenna efficiency		80		%
2.02	Maximum Sky Temperature		10		K
2.03	Maximum Amplifier Noise Temp		50		K
2.04	Observing duty Factor		50		%
2.05	Latitude		0		degrees
3.01	Center Frequency		875.0		MHz
3.02	Frequency Span		249.9		MHz
3.03	Resolution Bandwidth	1.7	1.3	0.9	MHz
3.04	Feed Spacing		19.5		cm
3.05	Declination Span	180.0	98.1	64.8	degrees
3.06	Number of Digital Channels per Cylinder per Polarization		512		
3.07	Number of Feed Antenna per Cylinder per		512		
3.08	Length of Cylinder		100.0		meters
3.09	Width of Cylinder		11.1		meters
3.10	Number of cylinders		9.0		
3.11	Integration Time per pixel	1.15	0.99	0.86	days

Phase 1

Number	Requirement	Limit	Average	Limit	Unit
1.01	Redshift Range	1.80	1.24	0.87	
1.02	Survey Area	4.00	3.38	2.15	π steradians
1.03	Angular Resolution	15.5	12.4	10.3	arc-Min
1.04	Survey Time		0.85		Years
1.05	Sensitivity per Pixel	138.0	180.0	229.0	uK
1.06	Polarization Imbalance		-20		dB
2.01	Minumum Antenna efficiency		80		%
2.02	Maximum Sky Temperature		10		K
2.03	Maximum Amplifier Noise Temp		50		K
2.04	Observing duty Factor		50		%
2.05	Latitude		0		degrees
3.01	Center Frequency		625.0		MHz
3.02	Frequency Span		250.1		MHz
3.03	Resolution Bandwidth	2.4	1.8	1.3	MHz
3.04	Feed Spacing		26.0		cm
3.05	Declination Span	180.0	115.3	65.0	degrees
3.06	Number of Digital Channels per Cylinder per Polarization		512		
3.07	Number of Feed Antenna per Cylinder per		512		
3.08	Length of Cylinder		133.2		meters
3.09	Width of Cylinder		11.1		meters
3.10	Number of cylinders		12.0		
3.11	Integration Time per pixel	1.33	1.07	0.89	days

Phase 2

Conclusions

- For an FFT Telescope
  - The desired survey area should not be aliased with grating lobes
  - Summing feeds together before digitizing does not buy much and causes more problems with grating lobes – unless the summed beam is phase steered
- The cylinder width is not a independent parameter. It determines the survey speed.
- A 130m x 130m telescope could be a Dark Energy Stage 3 telescope
  - Could be built in phases by splitting the frequency band in two and building the high frequency band (low red-shift) first.