Summary of Science Driven Telescope Specifications

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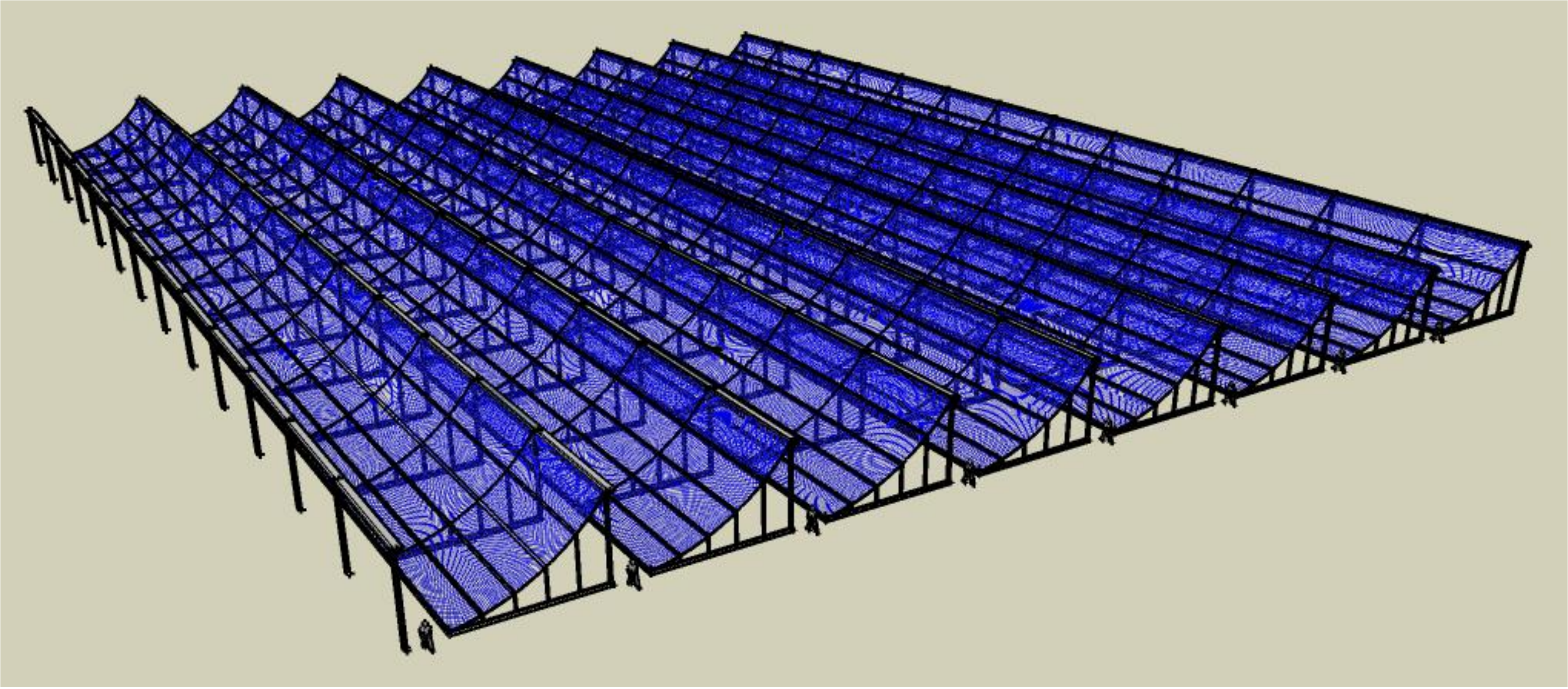
Requirement Process

- Define the science
  - Dark energy
- Define parameter that measures success
  - Dark Energy Task force Figure of Merit
- Define science technique
  - Baryon Acoustic Oscillations with intensity mapping
- Pick an Instrument
  - Develop a rough engineering model
  - Estimate the cost versus science of the instrument
  - Pick a parameter set or "punt"

Instrument
The Cylindrical Radio Telescope Array (CRT)



The CRT

- An array of cylindrical telescopes in which each cylinder is oriented along the north-south meridian
- The telescope operates in a drift scan mode. The cylinders are fixed.
- Along the focus of each cylinder is a uniformly spaced array of antenna feeds
- The antenna beams along the north-south meridian are formed by taking the spatial Fourier transform of the array of antenna feeds
- The antenna beams along the east-west direction are formed by either correlations or a Fourier transform.

The CRT

- Advantages
  - Survey area (lots of pixels)
  - Signal to Noise (lots of redundant baselines)
  - Simplicity (no moving parts)
- Disadvantages
  - Calibration
    - Lose phase information? (zero-padding?)
    - Individual feeds see all of the sky - no strong point sources
    - Pair correlation calibration is a concept that can work but requires extra hardware
  - Resolution
  - No source tracking

CRT Constraints

- Divide survey into two by dividing frequency span into two bands
  - <u>Performance maximized by noise performance</u>
  - Noise match easier over smaller bandwidth
  - Larger digitizer dynamic range for smaller bandwidth
- Bands are adjacent
- Fractional bandwidth of each band < 33%
- Limit the maximum span to half the digitizer bandwidth
- Digital electronics are re-used for each band
- Number of electronic channels are the same for both bands
- Reflector width and spacing the same for both bands

Parameter Set

- Static Engineering Parameters (STE)
- Dynamic Engineering Parameters (DYE)
- Derived Engineering Parameters (DRE)
- Scientific Parameters (SCI)

Parameter Set

- Static Engineering Parameters (STE)
  - The static engineering parameters are independent parameters that are
    - important in describing the telescope
    - not easily changed for design optimization
  - such as the latitude of the telescope site, amplifier temperature, etc.

Static Engineering Parameters (STE)

Number	Description	Symbol
STE.01	Survey Time	τ_s
STE.02	Observing Duty Factor	D_f
STE.03	Latitude of telescope site	α_L
STE.04	Average Sky Temperature	T_s
STE.05	Maximum Frequency Span per band	$\Delta F_{b_{max}}$
STE.06	Maximum Fractional Bandwidth per band	$\delta_{f\ b}$
STE.07	Number of Polarizations	N_p
STE.08	Antenna Feed Power Efficiency	g_a
STE.09	Cylinder Width / Cylinder Spacing	x_{cyl}
STE.10	Equivalent Amplifier Temperature	T_A
STE.11	Electronics Cost per Channel	R_e
STE.12	Feed Structure Cost per meter	R_f
STE.13	Reflector Cost per Cylinder volume	R_r

Dynamic Engineering Parameters (DYE)

- Dynamic engineering parameters are independent parameters that can be easily varied during the design stage
  - such as feed spacing and the number of channels per cylinder

Number	Description	Symbol
DYE.01	Center Frequency of both bands combined	F_c
DYE.02	Average Feed Spacing	D_f
DYE.03	Number of digital channels per cylinder per polarization	N_f
DYE.04	Average Number of possible cylinder locations	N_L
DYE.05	Average Cylinder packing factor	p_f
DYE.06	Target Cost	C_T

Derived Engineering Parameters (DRE)

- Derived engineering parameters are design specific parameters
  - such as cylinder length and width
  - but are derived from the static and dynamic engineering parameters.

Derived Engineering Parameters (DRE)

Number	Description	Symbol
DRE.01	Number of Cylinders	N_c
DRE.02	Cylinder Length	L_c
DRE.03	Cylinder Width	W_c
DRE.04	Cylinder Spacing	S_c
DRE.05	Declination Span	$\Delta\theta_d$
DRE.06	Feed Length	h_f
DRE.07	Feed Spacing	d_f
DRE.08	Band Center Frequency	F_{cb}
DRE.09	Wavelength	λ
DRE.10	Band Frequency Span	ΔF_b
DRE.11	Resolution Bandwidth	δf
DRE.12	Minimum Digital Memory	M_d
DRE.14	Integration Time per Pixel	τ_p
DRE.15	Number of Channels per polarization	N_{fT}
DRE.16	Electronics Cost	C_e
DRE.17	Feed Structure Cost	C_f
DRE.18	Reflector Cost	C_R
DRE.19	Total Cost	C_T

Derived Engineering Parameters (DRE)

$$\delta_f < \frac{F_c}{\Delta F_{b_{max}}} \frac{2}{1 + \sqrt{\frac{4F_c - \Delta F_{b_{max}}}{2F_c}}}$$

$$F_{c_\pm} = F_c \frac{4 \pm 2\delta_f}{4 + \delta_f{}^2}$$

$$\Delta F_\pm = \delta_f F_{c_\pm}$$

$$N_{L_\pm} = round\left(N_L \frac{F_c}{F_{c_\pm}}\right)$$

$$d_{f_\pm} = D_f N_{L_\pm}$$

$$p_{f_+} = p_{f_-} \frac{N_{L_-}}{N_{L_+}}$$

$$N_{f_+} = N_{f_-} = N_f$$

$$N_{C_+} = N_{C_+} = N_C = p_{f_-} N_{L_-}$$

$$R_\pm = \frac{1}{2} \frac{N_C (N_C - 1)}{N_{L_\pm} - 1}$$

$$N_C > \frac{1}{2}\left(1 + \sqrt{1 + 8\left(N_{L_-} - 1\right)}\right)$$

$$p_{f_-} > \frac{1}{2N_{L_-}}\left(1 + \sqrt{1 + 8\left(N_{L_-} - 1\right)}\right)$$

$$L_{C_\pm} = N_f d_{f_\pm}$$

$$W_C = x_{cyl} S_C = x_{cyl} \frac{N_f d_{f_\pm}}{N_{L_\pm}}$$

$$\sin\left(\frac{\Delta\theta_{d_\pm}}{2}\right) = \frac{\lambda}{2d_{f_\pm}}$$

$$A_f = h_f W_C$$

$$\sin\left(\frac{\Delta\theta_f}{2}\right) = \frac{\lambda}{2h_f}$$

$$h_{f_\pm} = d_{f_\pm}$$

Telescope Cost

- It is not intended that these costs include everything that would arise in designing and building a large radio telescope
  - such as site preparation, non-recoverable engineering costs, overhead, contingency etc.,
- These costs should only be used in trying to compare sets of design parameters.
- The cost of the digital electronics is assumed to scale only with the number of feeds:

$$C_e = N_f N_c N_p R_e$$

Telescope Cost

- The cost of the telescope structure is broken into two parts.
- The feed line is the most complicated part of the reflector system and this cost will scale as the total length of the array.

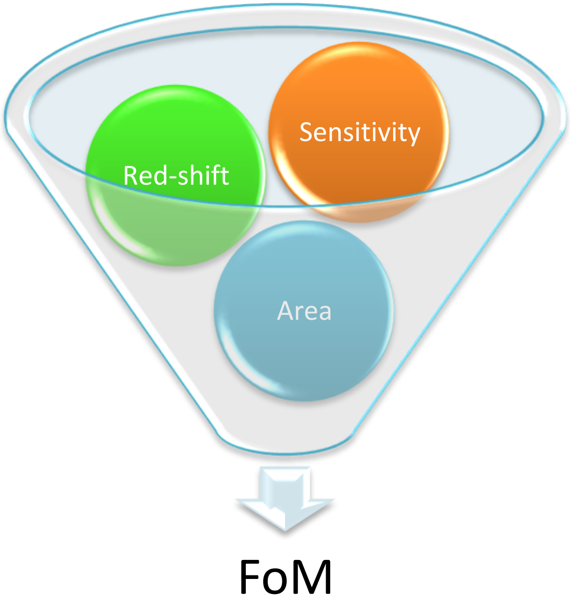
$$C_f = L_c N_c R_f = N_f N_c d_f R_f$$

- The cost of the main reflector surface will not only be proportional to area
  - but height as well since tall structures will be more difficult to build.
  - For a fixed f-ratio, the height will scale with cylinder width.

$$C_r = L_c N_c W_C^2 R_f = N_f N_c d_f W_C^2 R_f$$

Scientific Parameters (SCI)
(a.k.a. the 5 magic numbers)

- We want to have a set of numbers that
  - Describe the science
  - Can be derived from **ANY** telescope configuration
- The magic numbers for determining dark energy parameters using BAO
  - Minimum red-shift
  - Maximum red-shift
  - Survey area
  - Pixel Resolution
  - Pixel Sensitivity



Scientific Parameters (SCI)

Number	Description	Symbol
SCI.01	Maximum Red-shift	z_{max}
SCI.02	Minimum Red-shift	z_{min}
SCI.03	Angular Resolution	$\delta\psi$
SCI.04	Survey Area	A_s
SCI.05	Sensitivity per Pixel	δT_p
SCI.06	Figure of Merit with Plank Priors	FoM_p
SCI.07	Figure of Merit with Stage II Dark Energy Priors	FoM_{II}

Scientific Parameters (SCI)

$$z_{min\pm} = \frac{1.42GHz}{F_{c\pm} - \frac{1}{2}\Delta F_{\pm}} - 1$$

$$M_{d\pm} = \frac{2\Delta F_{\pm}}{\delta f_{\pm}}$$

$$z_{\pm} = \frac{1.42GHz}{F_{c\pm}} - 1$$

$$A = \int_0^{2\pi} d\phi \int_{\theta_{d\,min}}^{\theta_{d\,max}} \cos(\theta)\, d\theta = 2\pi\left[sin(\theta_{d\,max}) - sin(\theta_{d\,min})\right]$$

$$z_{max\pm} = \frac{1.42GHz}{F_{c\pm} + \frac{1}{2}\Delta F_{\pm}} - 1$$

$$\theta_{d\,max} = \alpha_L + \frac{\Delta\theta_d}{2} \quad if \quad \alpha_L + \frac{\Delta\theta_d}{2} < \frac{\pi}{2}$$

$$\theta_{d\,max} = \frac{\pi}{2} \quad if \quad \alpha_L + \frac{\Delta\theta_d}{2} > \frac{\pi}{2}$$

$$sin(\delta\psi_{\pm}) = \frac{\lambda}{N_f d_{f\pm}}$$

$$\delta z_{\pm} \approx 0.436 \times \delta\psi_{\pm}(\text{radians}) \times z_{\pm}(z_{\pm} + 2)$$

$$\theta_{d\,min} = \alpha_L - \frac{\Delta\theta_d}{2} \quad if \quad \alpha_L - \frac{\Delta\theta_d}{2} < -\frac{\pi}{2}$$

$$\theta_{d\,min} = -\frac{\pi}{2} \quad if \quad \alpha_L - \frac{\Delta\theta_d}{2} < -\frac{\pi}{2}$$

$$\delta f_{\pm} = \frac{1.4GHz}{(1 + z_{\pm})^2}\delta z_{\pm}$$

Scientific Parameters (SCI)

$$\sin(\psi_n) = \left(-\frac{1}{2} + \frac{n}{N_f}\right)\frac{\lambda}{d_f}$$

$$\theta_n = \psi_n + \alpha_L$$

$$\Delta\phi_C = \frac{\lambda}{W_c}$$

$$\sin\left(\frac{\Delta\varphi_{RA_n}}{2}\right) = \frac{1}{cos(\theta_n)}\sin\left(\frac{\Delta\phi_C}{2}\right)$$

$$\tau_p = \frac{\tau_s D_f}{N_f + 1}\sum_{n=0}^{N_f}\frac{\Delta\varphi_{RA_n}}{2\pi}$$

$$\delta T_{p_\pm} = \frac{1}{\sqrt{\tau_{p_\pm}\delta f_\pm}}\left(T_s + \frac{1}{g_a}\frac{1}{p_{f_\pm}}\frac{d_{f_\pm}}{h_{f_\pm}}\sqrt{\frac{N_f}{(N_f - 1)}}\sqrt{\frac{N_c}{(N_c - 1)}}T_A\right)$$

Requirement Optimization

- Developed a web application to evaluate parameter sets
  - Helps with focus loosely organized world-wide collaboration
- Uses Hee-Jong's BAO analysis technique for determining Figure of Merit
- Web application has two features
  - Evaluator
  - Optimizer

Requirement Optimizer

- Vary
  - Center Frequency
  - Feed spacing
  - Number of cylinder <u>locations</u>
  - Cylinder packing factor
- Constrain
  - Number of feeds per cylinder to reach target cost

Requirement Parameters

CRT Design Requirements II

Calculate FoM | Optimize | Iterations 40

1.01	Redshift Range	1.68	1.23	0.91		0.91	0.6	0.37	
1.02	Survey Area	3.64	2.88	2.46		3.64	2.88	2.46	pi Steradians
1.03	Angular Resolution	21.86	18.21	15.61		21.86	18.21	15.61	arc-min
1.04	Sensitivity per Pixel	76.55	91.04	161.96		70.51	88.41	176.19	uK
1.05	Plank Priors Figure of Merit				61.69				
1.06	DE II Priors Figure of Merit				182.96				
2.01	Center Frequency		626.84		773.1		877.57		MHz
2.02	Feed Spacing		0.5719		0.6046		0.5719		lambda
2.03	Digital Channels per Cylinder per Polarization				330				
2.04	Number of Cylinder locations		7		6		5		
2.05	Cylinder Packing Factor		57.14		45.61		80		%
2.06	Total Cost		9.98		10.0		9.39		M$
3.01	Survey Time				2.0				years
3.02	Observing Duty Factor				50.0				%
3.03	Latitude				35.0				degrees
3.04	Avg. Sky Temperature				10.0				K
3.05	Maximum Span				300.0				MHz

Requirement Parameters

3.08	Antenna Efficiency				80.0				%
3.09	Antenna Width Fill Factor				80.0				%
3.10	Amplifier Temperature				50.0				K
3.11	Electronics Cost per Channel				3000.0				$
3.12	Feed Structure Cost Rate				2300.0				$/meter
3.13	Reflector Volume Cost Rate				32.0				$/meter^3

3.01	Number of Cylinders				4				
3.02	Cylinder Length		90.33				64.52		meters
3.03	Cylinder Width				10.32				meters
3.04	Cylinder Spacing				12.9				meters
3.05	Declination Span	180	121.91	97.07		180	121.91	97.07	degrees
3.06	Feed Length		27.37				19.55		cm
3.07	Feed Spacing		27.37				19.55		cm
3.08	Frequency	522.36	626.84	731.31		731.31	877.57	1023.84	MHz
3.09	Wavelength	57.43	47.86	41.02		41.02	34.19	29.3	cm
3.10	Frequency Span		208.95				292.52		MHz
3.11	Res. Bandwidth	3.34	2.58	2.01		2.82	1.96	1.29	MHz
3.12	Minimum Digital Memory		207				453		
3.13	Integration Time per Pixel	11.02	10.07	4.08		8.31	7.6	2.91	days
3.14	Number of Channels per polarization				1320				
3.15	Electronics Cost		7.92				7.92		M$
3.16	Feed Structure Cost		0.83				0.59		M$
3.17	Reflector Volume Cost		1.23				0.88		M$

Requirement Optimization

		10M$	15M$	20M$	25M$	30M$	
3.01	Survey Time	2	2	2	2	2	years
3.02	Observing Duty Factor	50	50	50	50	50	%
3.03	Latitude	35	35	35	35	35	degrees
3.04	Avg. Sky Temperature	10	10	10	10	10	K
3.05	Maximum Span	300	300	300	300	300	MHz
3.06	Center Freq / Freq Span	3	3	3	3	3	
3.07	Number of Polarizations	2	2	2	2	2	
3.08	Antenna Efficiency	80	80	80	80	80	%
3.09	Antenna Width Fill Factor	80	80	80	80	80	%
3.1	Amplifier Temperature	50	50	50	50	50	K
3.11	Electronics Cost per Channel	3000	3000	3000	3000	3000	$
3.12	Feed Structure Cost Rate	2300	2300	2300	2300	2300	$/meter
3.13	Reflector Volume Cost Rate	32	32	32	32	32	$/meter^3

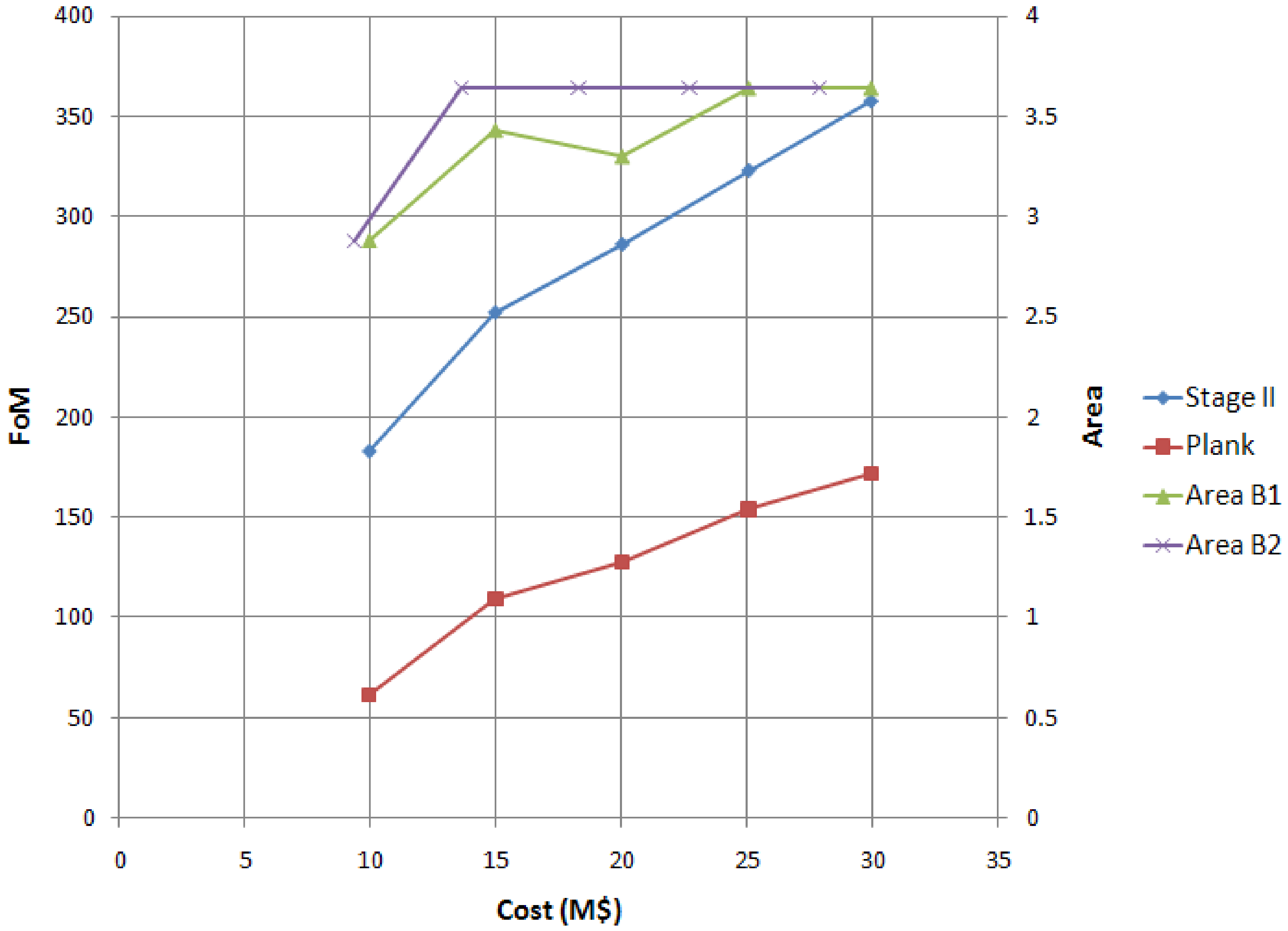
Requirement Optimization (B1)

		10M$	15M$	20M$	25M$	30M$	
1.01	Redshift Range	1.23	1.22	1.27	1.25	1.27	
1.02	Survey Area	2.88	3.43	3.3	3.64	3.64	pi Steradians
1.03	Angular Resolution	18.21	14.87	16.17	14.16	14.54	arc-min
1.04	Sensitivity per Pixel	91.04	103.45	62.58	72.4	57.16	uK
1.05	Plank Priors Figure of Merit	61.69	109.26	127.81	154.05	171.8	
1.06	DE II Priors Figure of Merit	182.96	252.23	286.31	323.16	357.78	
		10M$	15M$	20M$	25M$	30M$	
2.01	Center Frequency	626.84	630.21	616.94	621.87	616.28	MHz
2.02	Feed Spacing	0.5719	0.5068	0.516	0.4865	0.4998	lambda
2.03	Digital Channels per Cylinder per Polarization	330	456	412	499	473	
2.04	Number of Cylinder locations	7	6	6	6	7	
2.05	Cylinder Packing Factor	57.14	66.67	100	100	114.29	%
		10M$	15M$	20M$	25M$	30M$	
3.01	Number of Cylinders	4	4	6	6	8	
3.02	Cylinder Length	90.33	110.02	103.38	117.11	115.08	meters
3.03	Cylinder Width	10.32	14.67	13.78	15.61	13.15	meters
3.04	Cylinder Spacing	12.9	18.34	17.23	19.52	16.44	meters
3.05	Declination Span	121.91	161.14	151.37	180	180	degrees
3.06	Feed Length	27.37	24.13	25.09	23.47	24.33	cm
3.07	Feed Spacing	27.37	24.13	25.09	23.47	24.33	cm
3.08	Frequency	626.84	630.21	616.94	621.87	616.28	MHz
3.09	Wavelength	47.86	47.6	48.63	48.24	48.68	cm
3.1	Frequency Span	208.95	210.07	205.65	207.29	205.43	MHz
3.11	Res. Bandwidth	2.58	2.1	2.31	2.02	2.08	MHz
3.12	Minimum Digital Memory	207	256	227	263	252	
3.13	Integration Time per Pixel	10.07	7.2	7.89	6.75	8	days
3.14	Number of Channels per polarization	1320	1824	2472	2994	3784	
3.15	Electronics Cost	7.92	10.94	14.83	17.96	22.7	M$
3.16	Feed Structure Cost	0.83	1.01	1.43	1.62	2.12	M$
3.17	Reflector Volume Cost	1.23	3.03	3.77	5.48	5.1	M$

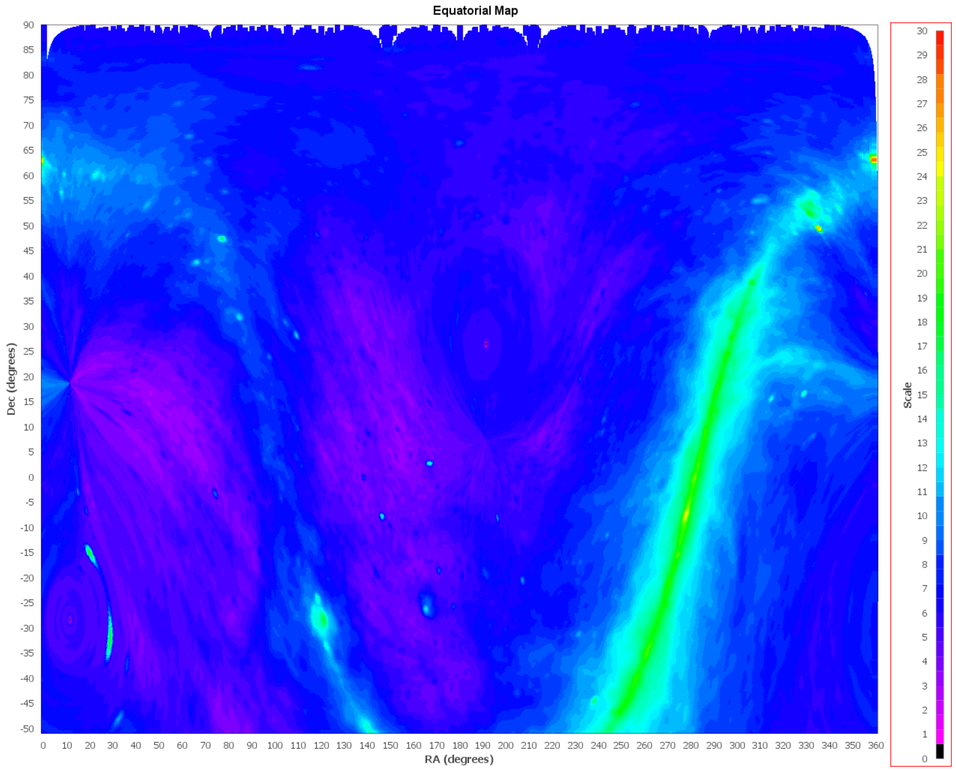
Requirement Optimization (B2)

		10M$	15M$	20M$	25M$	30M$	
1.01	Redshift Range	0.6	0.59	0.62	0.61	0.62	
1.02	Survey Area	2.88	3.64	3.64	3.64	3.64	pi Steradians
1.03	Angular Resolution	18.21	15.94	17.33	15.17	14.54	arc-min
1.04	Sensitivity per Pixel	88.41	93.71	57.7	66.76	56.89	uK
1.05	Plank Priors Figure of Merit	61.69	109.26	127.81	154.05	171.8	
1.06	DE II Priors Figure of Merit	182.96	252.23	286.31	323.16	357.78	
2.01	Center Frequency	877.58	882.29	863.72	870.62	862.8	MHz
2.02	Feed Spacing	0.5719	0.4731	0.4816	0.4541	0.4998	lambda
2.03	Digital Channels per Cylinder per Polarization	330	456	412	499	473	
2.04	Number of Cylinder locations	5	4	4	4	5	
2.05	Cylinder Packing Factor	80	100	150	150	160	%
2.06	Total Cost	9.39	13.64	18.3	22.7	27.86	M$
3.01	Number of Cylinders	4	4	6	6	8	
3.02	Cylinder Length	64.52	73.35	68.92	78.07	82.2	meters
3.03	Cylinder Width	10.32	14.67	13.78	15.61	13.15	meters
3.04	Cylinder Spacing	12.9	18.34	17.23	19.52	16.44	meters
3.05	Declination Span	121.91	180	180	180	180	degrees
3.06	Feed Length	19.55	16.09	16.73	15.65	17.38	cm
3.07	Feed Spacing	19.55	16.09	16.73	15.65	17.38	cm
3.08	Frequency	877.58	882.29	863.72	870.62	862.8	MHz
3.09	Wavelength	34.19	34	34.73	34.46	34.77	cm
3.1	Frequency Span	292.53	294.1	287.91	290.21	287.6	MHz
3.11	Res. Bandwidth	1.96	1.7	1.9	1.65	1.6	MHz
3.12	Minimum Digital Memory	453	528	453	531	538	
3.13	Integration Time per Pixel	7.6	5.23	5.66	4.88	6	days
3.14	Number of Channels per polarization	1320	1824	2472	2994	3784	
3.15	Electronics Cost	7.92	10.94	14.83	17.96	22.7	M$
3.16	Feed Structure Cost	0.59	0.67	0.95	1.08	1.51	M$
3.17	Reflector Volume Cost	0.88	2.02	2.51	3.65	3.64	M$

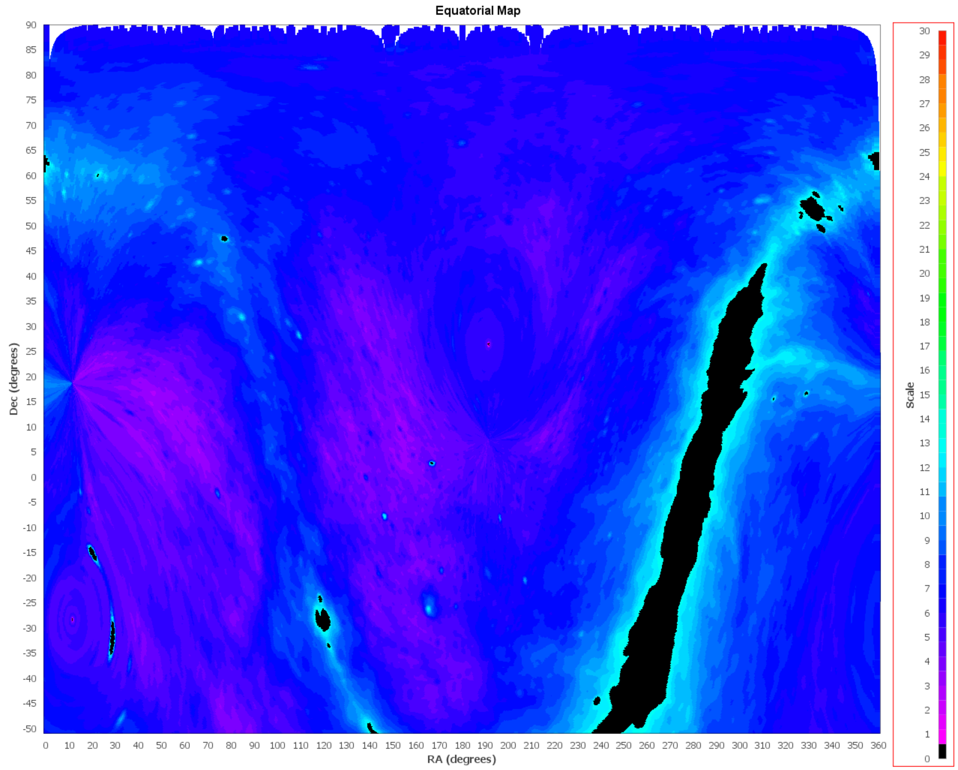
Requirement Optimization



Sky Temperature



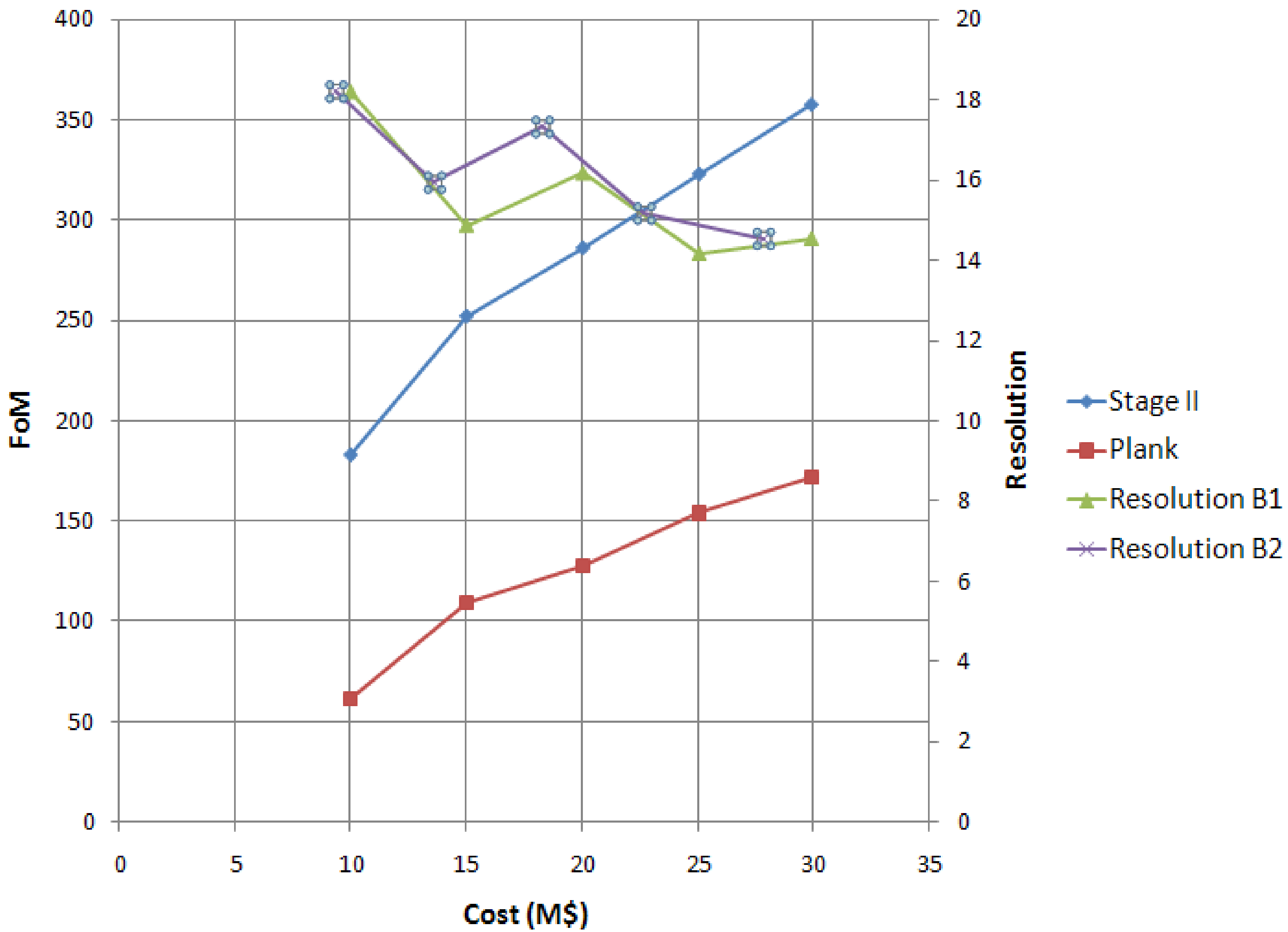
No Cut – 100% used
Average Temperature = 6.5K at
750 MHz



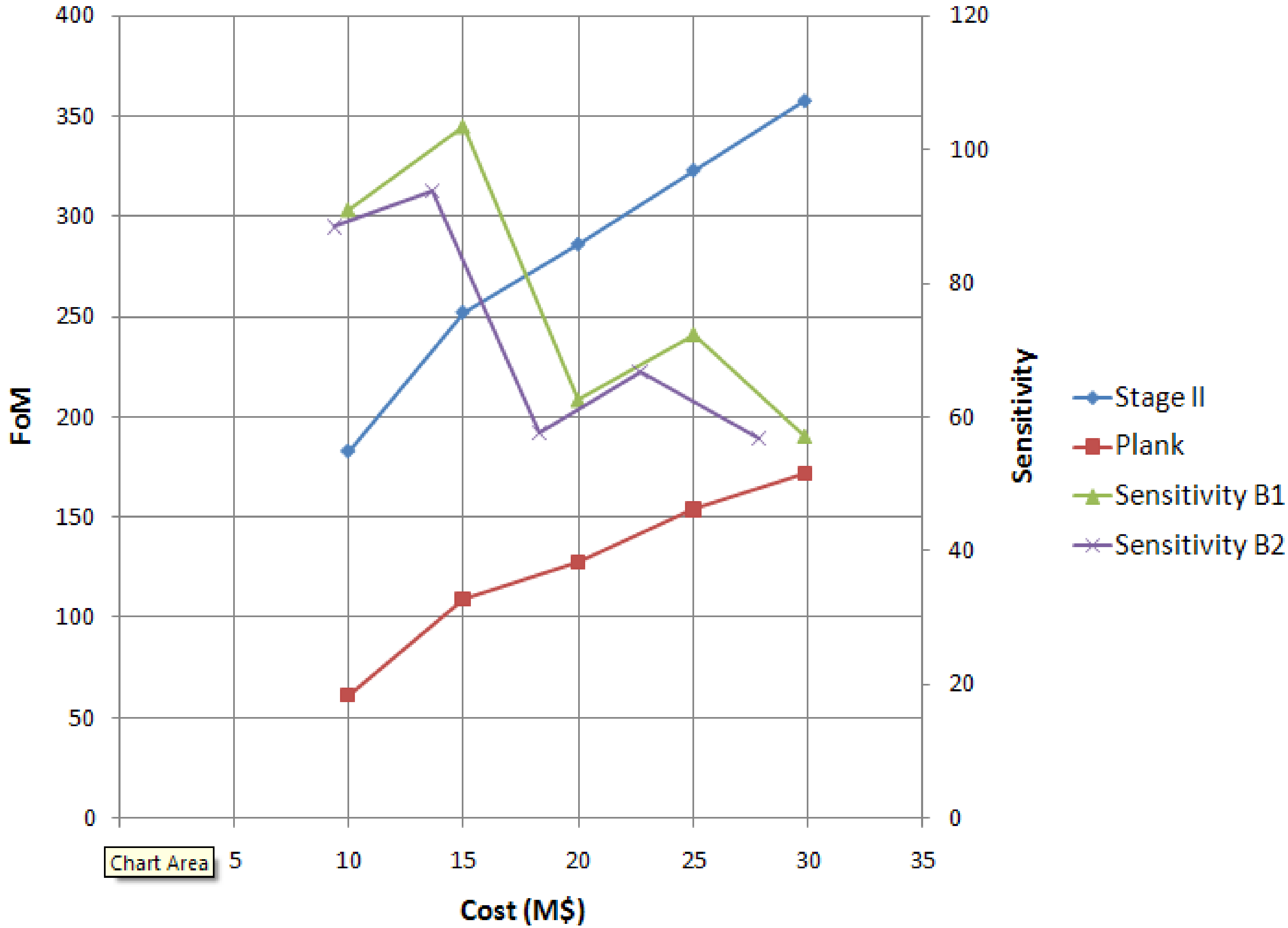
Cut at 20K-96% used
Average Temperature = 5.3K at
750 MHz

Latitude = 35 degrees

Requirement Optimization



Requirement Optimization



Conclusions

- A Dark Energy Task Force Figure of Merit of 250 can be obtained with a CRT that “costs” ~15MWampum
- Sensitivity is the most important factor in increasing the FOM for a fixed cost