Performance Margin

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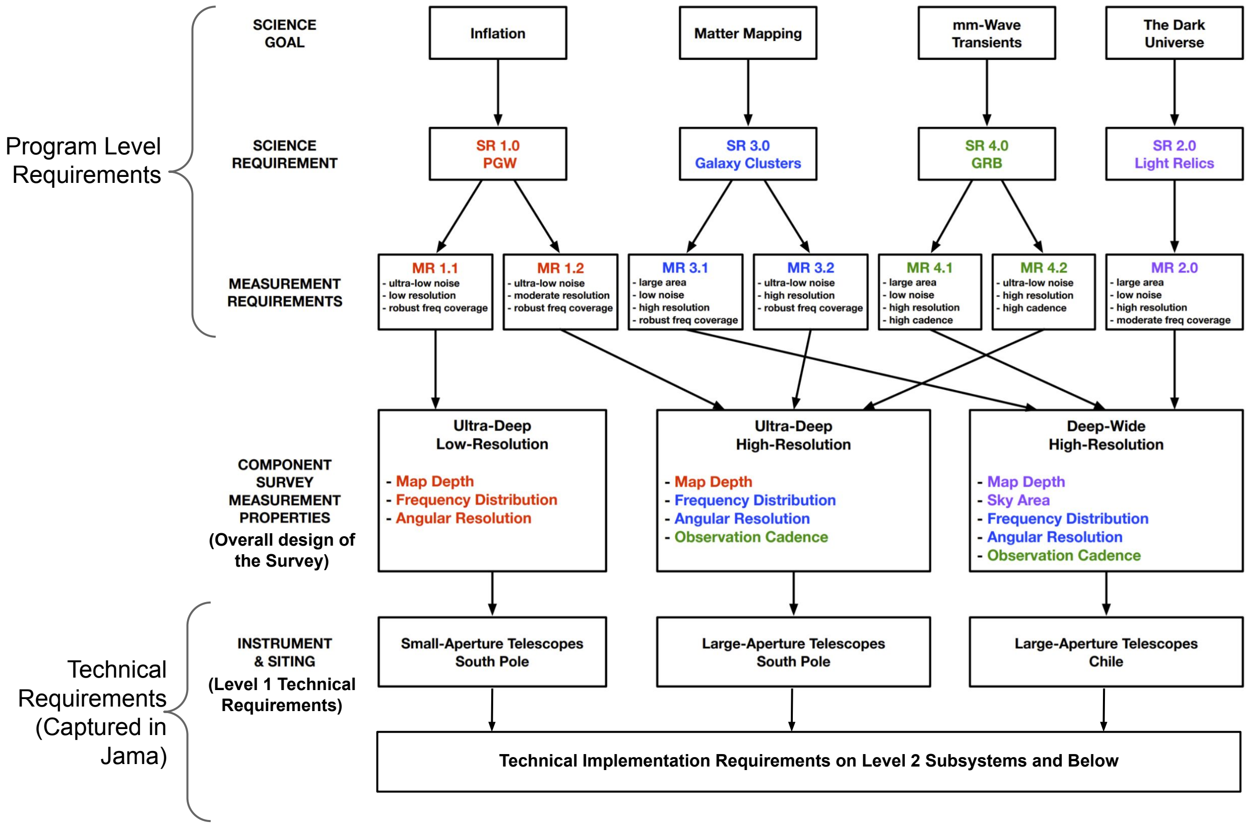
CMB-S4

Outline

- Requirements Flowdown
- Performance Margin Definition / Motivation
- Margin building approach
- Current focus
- Observing Efficiency
- Performance margin estimate calculation
- Current status /Work to do

Program Level Requirements (CMBS4-doc-671) define the Science Goals, Science Requirements, and Measurement Requirements

- The Measurement Requirements flow down from the Science Goals and Requirements
- Meeting the CMB-S4 Measurement Requirements will just meet the Science Requirements and Science Goals, with pessimistic assumptions about foregrounds
- The technical requirements that define the implementation of the experiment must enable the experiment to meet the Measurement Requirements in the defined Survey duration



Definition of and Motivation for building performance margin

- The Project's purpose and commitment is to deploy an experiment that can meet the Measurement Requirements in no more than the planned survey duration

- Overall performance margin here is defined as:
  - (promised max survey duration) / (survey duration needed to meet measurement req'ts) - 1

- In much the same way as the project will have budget and schedule contingency above the baseline, it also needs to have performance margin to account for risks and uncertainties
- Performance margin helps ensure that the science goals will be met in the planned survey duration, even if/when some of these risks are realized

- To first order, the technical implementation described in the Preliminary Baseline Design Report is predicted to just meet the Measurement Requirements with a seven-year survey
- Performance improvements over the PBDR implementation yield survey margin
- Our approach to making improvements and building margin is described on next slides

Margin-Building approach

1. Characterize the baseline performance of CMB-S4 as described in the PBDR
    a. Analyze performance of previous/current experiments (which form the basis for our performance simulations) by breaking down (factorizing) elements that affect their performance to the smallest practical level
2. Examine each factor to understand its quantitative value on those experiments
3. Determine which of these factors offers S4 opportunities to improve upon
4. Study what needs to happen for each factor and what improvements are feasible (enabled by CMB-S4's scale, funding, and previous lessons learned)
5. Document the improvements that are credibly achievable, and how to achieve them
6. Implement design changes and codify in the requirements and Current Best Estimates
7. Roll up the product of these improvements in calculating overall performance margin

Current Areas of Focus

- Ongoing efforts are identifying areas where performance can be improved over the baseline configuration, to build performance margin
- Functioning Detector Channel Fraction
  - PBDR simulations assume 80% of deployed detector channels are useful for mapping, based on previous/current experiments
  - CMB-S4’s longer production runs and project funding level mean we can have higher acceptance thresholds for detector modules
  - We plan to increase our projected percentage of useful deployed detector channels by ~10%
- Observing Efficiency
  - Opportunities exist to increase the fraction of calendar time that CMB-S4 is mapping relative to previous/current experiments
  - Process of identifying and exploiting those opportunities described on the next slides

Observation Efficiency Factorization

Factor	Subfactor	Definition
f_year		Fraction of each year that the telescope is operating in nominal science operations
	f_season	Nominal observing season, includes time for annual calibration and maintenance
	f_uptime	Fraction of time remaining after downtime
f_scan		Fraction of good observing time spent observing the CMB
	f_field	Field efficiency
	f_turnaround	Fraction of time remaining after cutting out the turnarounds in the scans.
	f_scanset	Fraction of time in each observation scanset spent observing the CMB
	f_cal_maint	Planned calibration + maintenance performed on a regular cadence (daily, weekly, monthly)
f_pass(***v***)		Fraction of data that pass the data quality cuts
	f_quality(***v***)	Fraction of data that pass the data quality cuts
	f_PWV(***v***)	Fraction of the data remaining after data is cut due to poor PWV

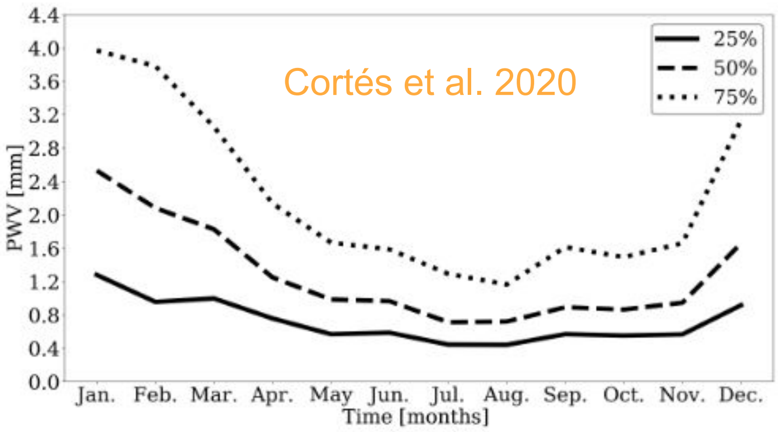
General Approach

- First set of numbers were derived from the performance of previous experiments→ work to put these into a common notation
- These are the baseline numbers for observation efficiency→ These are held fixed unless there is strong understanding and approval of change (PBD Updates column)
  - Recovery of fridge cycling time due to planned use of DR (minus regular maintenance)
  - More granular breakdown/redistribution of numbers to standardize definitions
  - If we need more calibration time due to increased detector/telescope count
- Identify and quantify (where possible) areas that may have margin (Potential Factors column)

CHLAT	Numbers with potential margin that has not been quantified are highlighted in light blue				
			PBD	PBD Updates	Potential Factors
f_total (25 GHz)			0.31	0.31	0.38
f_total (40 GHz)			0.31	0.31	0.38
f_total (90 GHz)			0.31	0.31	0.38
f_total (150 GHz)			0.31	0.31	0.38
f_total (230 GHz)			0.28	0.28	0.34
f_total (280 GHz)			0.28	0.28	0.34

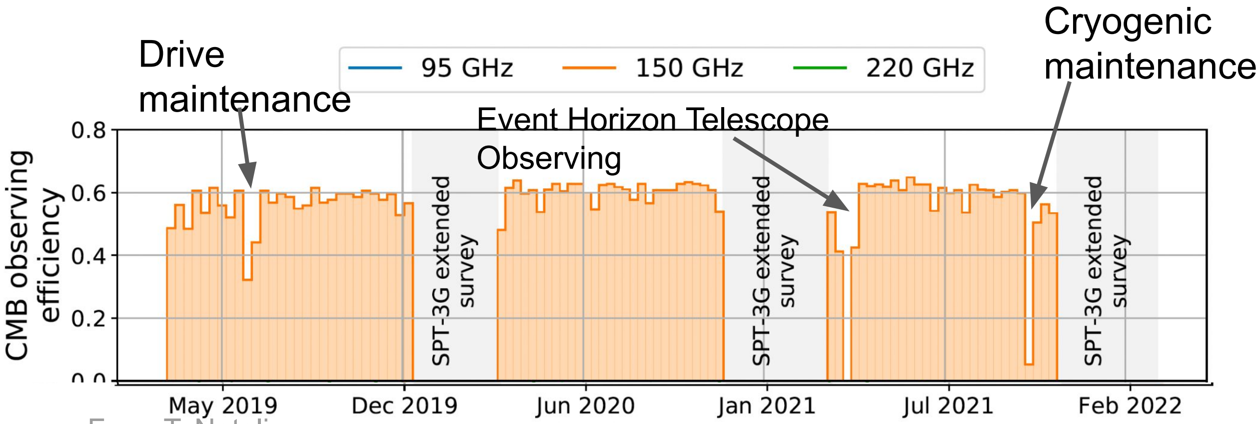
CHLAT Updates and Ongoing Studies

- f_season: Is there significant good observing time outside the nominal Chile observing dates? (Darcy B. and Ian B.)
  - Not just PWV but also its stability
- f_uptime: 10% of downtime due to weather events→generator power is lost after a weather event and causes the telescope to be down for several days
  - Snow plow→ reduce recovery time
  - Solar power→ extend recovery window
  - Note: Recovery time is even more important for CMB-S4 due to increased cooldown time if cryostat warms
- f_scanset: Exploring per scanset calibration time
- f_cal_maint: working to understand planned regular maintenance and regular calibration schedules (Nick E. and Tyler N.)



SPLAT Updates and Ongoing Studies

- f_season: Season dates from SPT-3G set by sun avoidance due to diffractive sidelobes from paneled mirror→ TMA has monolithic mirror
  - Working to understand time needed for annual calibration and maintenance
- f_scanset: Exploring per scanset calibration time
- f_cal_maint: working to understand regular maintenance and regular calibration (Nick E., Tyler N., Tom C., Kimmy W.)



From T. Natoli

SPSAT Updates and Ongoing Studies

- f_season: ~March-April typically used for beam calibration campaign (Clara V., Marion D., Kirit K.)
    - If configuration stable between years, may not need to do every year
    - If work on telescope complete earlier, beam mapping could be done before March
    - Calibrator design and more sets of calibrators would reduce time needed for calibration
- f_uptime: Time recovered from fridge cycling (minus regular maintenance), redistributing regular maintenance time to f_cal_maint
- f_turnaround: Can we use data where the telescope is accelerating and reduce turnaround cut time? (Clem P.)
- f_cal_maint: working to understand regular maintenance and calibration (Clara V., Marion D., Kirit K.)

Observing Efficiency projections are captured in a detailed workbook

The first worksheet defines the structure of the observing efficiency breakdown and what each factor includes and excludes

	A	B	C	D	E
1	This spreadsheet factorizes the observation efficiency. In this spreadsheet, we provide definitions and current best-estimates of the values based on historical data				
2	from BICEP/Keck, SPT-3G, and AdvACT. We suggest some potential ways to break down the factorizations presented here in more detail for requirements flowdown (purple),				
3	but note that the available historical data can only be broken down to the blue level. We also note that some historical data factorizes these efficiencies differently than this uniform definition,				
4	so some factors may be combined where noted. The full derivation of these factors and how they are implemented in the simulations is described in this document.				
5					
6	We also note that two factors (yield and f_weight) are no longer included in the observation efficiency. These are sensitivity factors associated with the detector performance.				
7	Yield is the total integrated detector yield, while f_weight is the sensitivity hit from non-uniform NET distributions between detectors on a wafer and between wafers.				
8	Since these factors are dependent on the detector, module, and readout performance, they have been moved to the overall instrument requirements.				
9					
10	**Version Number**	**Date**	**Description of Changes**		
11	v0	2/21/2022	Document Created		
12					
13					
14					
15					**Definition**
16	**f_total**				This is the total observation efficiency given by the multiplication of all factors
17		**f_year**			Fraction of each year that the telescope is operating in nominal science operations
18			f_season	f_season	This is the nominal observing season period (i.e. the typical season dates) used for CMB observations. This is set by when the typical observing conditions at the sites for each telescope are ideal for CMB observations. Since the conditions needed for calibration are often less stringent than those for science observations, we often use some of the off season time for annual calibrations (e.g. beam calibration campaigns for SATs, bandpass calibration, etc.). Some of this time is also typically used for annual maintenance or installing new arrays. We do not factorize this further into annual calibration and annual maintenance because the dates are solely set by observing conditions. However, we do require that the time used on annual calibration and maintenance be ≤ 1-f_season. 1-f_season must be long enough for the annual maintenance and calibration.
19			f_uptime		This is the fraction of the observing season remaining after mechanical downtime. Typically when downtime occurs during a scan set, the entire ~1-2 hour scan set is discarded. In the case where observations are azimuth-locked for the full season (e.g. some proposed SAT scans), once operations are restored, there can be some required wait time until scans can resume in the regular cadence. There are many sources of downtime, so we have factorized the uptime into the most common mechanical failures.
20				f_weather_event	1-fraction of the time that the telescope is down due to weather events. This is typically more common in Chile than the South Pole. Typically in Chile, there is a heavy snow. Access to the roads is then blocked, resulting in the generators running out of fuel and the telescope losing power. The system must then be recovered and re-cooled.
21				f_fridge_failures	1-fraction of the time that the telescope is down do to cryogenic failures in the cooling systems.
					1-fraction of the time the fridge must cycle regularly to remain cold. A dilution refrigerator (DR) allows for continual

Definitions | CHLAT | SPLAT | SAT

Observing Efficiency projections are captured in a detailed spreadsheet

The next sheets include quantitative factors from previous/ current experiments and projected improvements for CMB-S4

Similar factorizations can be performed for other performance parameters

	A	B	C	E	F	G
1	SAT	Numbers with potential margin that has not been quantified are highlighted in light blue				
2				PBD Factors	Potential Factors	Derivation and Discussion
3	**f_total (25 GHz)**			0.24	0.24	
4	**f_total (40 GHz)**			0.24	0.24	
5	**f_total (85, 95 GHz)**			0.24	0.24	
6	**f_total (145,155 GHz)**			0.24	0.24	
7	**f_total (230 GHz)**			0.17	0.17	
8	**f_total (280 GHz)**			0.12	0.12	
9		**f_year**		**0.478**	**0.478**	
10			f_season	0.586	0.586	Typicaly season dates for the SAT are April 1-December 1. Typically it has been difficult to observe when the South Pole is open due to RF environment. March is often used for a beam calibration campaign, but if the configuration is stable between years (i.e. no additional detectors/changes), they may not need to do beam calibration campaign every year. There could be some additional margin in the season dates, but it would require more study with current BICEP/Keck data.
11			f_uptime	0.816	0.816	From [1], the total f_year is 0.478. Using the value of f_seasons, we can extract f_uptime. f_uptime here includes time lost from fridge cycles and mechanical downtime. Collaborators from BICEP/Keck estimate that the mechanical downtime is on order ~5%. Most of this time is likely due to fridge cyling, but S4 will use DRs, so some of the fridge recycling time should be recoverable. In calculating how much of the cycle time is recoverable, we need to make sure that we account for the time that is spent on regular maintenance during this time. Additionally the historical data from BICEP 3 included regual maintenance and calibration time in this number, so these would need to be broken down an included in f_cal_maint below. Separating this value into mechanical downtime, firdge cyling time, and regular calibration and maintenance will require further study, but there is margin to gain here.
12		**f_scan**		**0.707**	**0.707**	
13			f_field	1	1	The Sun and Moon avoidance are negligible for the SATs, so CMB observations are essentially always available.
14			f_turnarounds	0.757	0.757	From [1], the out and back scan takes 52s, the constant velocity portions are 20 s, and the turnarounds are 6 s each. This gives the PLR number of 0.779. Because the RA range for the S4 scans is 50˚ vs 56.4˚, there is a ~5.75 s turnaround, 17.95 s nominal scan time, and 23.7 s total time per scan, which gives 0.757. If the SAT mounts could handle more acceleration, the turnaround time could be shorter, but this has proven difficult to do in the past. The data quality in the turnaround could also be explored further to determine if more turnarounf data could be used for S4. There is likely some margin here.
						From [1], there is 6.6 min of calibration/detector biasing/repointing for each 50 min of

Definitions | CHLAT | SPLAT | SAT

Near Term Plans

- Continue ongoing studies to quantify potential margin
- Some margin can only be gained with investment → cost/benefit analyses
- Incorporate more granular information with improved understanding
- Meetings are every other Monday at 11 am CT (out of cadence with low-ell BB call)
  - surveystrategy mailing list

A spreadsheet tool is used to calculate overall performance margin by folding in current best estimates for various technical parameters (values shown are preliminary)

A	B	C	D	E	F	G	H	I	J	K
Current Best Estimates of Performance Margin relative to Preliminary Baseline Design										
Not Freq-Dependent										
	Parameter		PBD value	CBE value	ratio	margin			Description	Where captured
	Deployed Useful Detector Fraction		0.8	0.9	1.125	13%			QA and screening improve fraction useful for mapping	Jama L1 System requirements
	Observing Efficiency, excluding f_pass		0.459	0.562	1.22	22%			f_pass varies by frequency and is tracked below	Observing Efficiency Summary Worksheet
	TOTAL				1.38	38%			This is non-frequency-dependent margin on detector-years	
Freq-Dependent										
			Band							
			LF_1	LF_2	MF_1	MF_2	HF_1	HF_2	Description	Where captured
PBD	f_pass		0.68	0.68	0.68	0.68	0.6	0.6	not part of NET calculations, mapping speed linear with f_pass	Observing Efficiency Summary Worksheet
PBD	Optical Efficiency (horn to detector)		0.7	0.7	0.7	0.7	0.7	0.7		PBD
PBD	Optical Efficiency (telescope+optics tubes)		0.145	0.266	0.161	0.270	0.508	0.549		from jbolo
PBD	Photon Loading from Instrument	[Watts/Hz]	2.12E-23	3.22E-23	2.40E-23	5.31E-23	1.44E-22	2.02E-22		from jbolo
PBD	Detector Phonon Noise	[W/sqrt(Hz)]	2.85E-18	7.26E-18	8.40E-18	1.24E-17	2.63E-17	2.83E-17		from jbolo
PBD	Readout Noise	[W/sqrt(Hz)]	1.37E-18	4.31E-18	5.38E-18	9.78E-18	2.88E-17	3.42E-17		from jbolo, adds 5% to NEP overall
PBD	NumDetectors/wafer		96	96	864	864	864	864		PBD
CBE	f_pass		0.68	0.68	0.68	0.68	0.6	0.6	not part of NET calculations, mapping speed linear with f_pass	Observing Efficiency Summary Worksheet
CBE	Optical Efficiency (horn to detector)		0.7	0.7	0.7	0.7	0.7	0.7		
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CBE	Detector Phonon Noise	[W/sqrt(Hz)]	2.85E-18	7.26E-18	8.40E-18	1.24E-17	2.63E-17	2.83E-17		
CBE	Readout Noise	[W/sqrt(Hz)]	1.37E-18	4.31E-18	5.38E-18	9.78E-18	2.88E-17	3.42E-17		
CBE	NumDetectors/wafer		96	96	864	864	864	864		
Ratio of CBE mapping speed to PBD mapping speed for freq-dependent factors			1.00	1.00	1.00	1.00	1.00	1.00		
CBE Mapping speed margin for freq-dependent factors			0.00	0.00	0.00	0.00	0.00	0.00		
CBE Mapping speed margin including freq-dependent and non-freq-dependent params			38%	38%	38%	38%	38%	38%		
NET calculations from John Ruhl Sensitivity Breakdown Spreadsheet:										
	Center frequency (actual, used in NEP_photon calc below)	[GHz]	27	39	93	145	225	278		PBD
	Optical bandwidth	[GHz]	6	18	35	40	60	45		PBD
	Atmospheric power (in front of telescope, el=50) [W/Hz]		3.81E-23	1.05E-22	1.23E-22	1.22E-22	2.32E-22	3.18E-22		from jbolo

CHLAT SPLAT SPSAT

Hypothetical example: increase telescope optical efficiency 10% for all bands

Current Best Estimates of Performance Margin relative to Preliminary Baseline Design

Not Freq-Dependent

Parameter	PBD value	CBE value	ratio	margin	Description	Where captured
Deployed Useful Detector Fraction	0.8	0.9	1.125	13%	QA and screening improve fraction useful for mapping	Jama L1 System requirements
Observing Efficiency, excluding f_pass	0.459	0.562	1.22	22%	f_pass varies by frequency and is tracked below	Observing Efficiency Summary Worksheet
TOTAL			1.38	38%	This is non-frequency-dependent margin on detector-years	

Freq-Dependent

			Band							
			LF_1	LF_2	MF_1	MF_2	HF_1	HF_2	Description	Where captured
PBD	f_pass		0.68	0.68	0.68	0.68	0.6	0.6	not part of NET calculations, mapping speed linear with f_pass	Observing Efficiency Summary Worksheet
PBD	Optical Efficiency (horn to detector)		0.7	0.7	0.7	0.7	0.7	0.7		PBD
PBD	Optical Efficiency (telescope+optics tubes)		0.145	0.266	0.161	0.270	0.508	0.549		from jbolo
PBD	Photon Loading from Instrument	[Watts/Hz]	2.12E-23	3.22E-23	2.40E-23	5.31E-23	1.44E-22	2.02E-22		from jbolo
PBD	Detector Phonon Noise	[W/sqrt(Hz)]	2.85E-18	7.26E-18	8.40E-18	1.24E-17	2.63E-17	2.83E-17		from jbolo
PBD	Readout Noise	[W/sqrt(Hz)]	1.37E-18	4.31E-18	5.38E-18	9.78E-18	2.88E-17	3.42E-17		from jbolo, adds 5% to NEP overall
PBD	NumDetectors/wafer		96	96	864	864	864	864		PBD
CBE	f_pass		0.68	0.68	0.68	0.68	0.6	0.6	not part of NET calculations, mapping speed linear with f_pass	Observing Efficiency Summary Worksheet
CBE	Optical Efficiency (horn to detector)		0.7	0.7	0.7	0.7	0.7	0.7		
CBE	Optical Efficiency (telescope+optics tubes)		0.1595	0.2926	0.1771	0.297	0.5588	0.6039		
CBE	Photon Loading from Instrument	[Watts/Hz]	2.12E-23	3.22E-23	2.40E-23	5.31E-23	1.44E-22	2.02E-22		
CBE	Detector Phonon Noise	[W/sqrt(Hz)]	2.85E-18	7.26E-18	8.40E-18	1.24E-17	2.63E-17	2.83E-17		
CBE	Readout Noise	[W/sqrt(Hz)]	1.37E-18	4.31E-18	5.38E-18	9.78E-18	2.88E-17	3.42E-17		
CBE	NumDetectors/wafer		96	96	864	864	864	864		

	LF_1	LF_2	MF_1	MF_2	HF_1	HF_2
Ratio of CBE mapping speed to PBD mapping speed for freq-dependent factors	1.18	1.15	1.16	1.16	1.14	1.14
CBE Mapping speed margin for freq-dependent factors	0.18	0.15	0.16	0.16	0.14	0.14
CBE Mapping speed margin including freq-dependent and non-freq-dependent params	63%	58%	60%	60%	57%	57%

NET calculations from John Ruhl Sensitivity Breakdown Spreadsheet:

NET calculations from John Ruhl Sensitivity Breakdown Spreadsheet:

		LF_1	LF_2	MF_1	MF_2	HF_1	HF_2	Where captured
Center frequency (actual, used in NEP_photon calc below)	[GHz]	27	39	93	145	225	278	PBD
Optical bandwidth	[GHz]	6	18	35	40	60	45	PBD

CHLAT SPLAT SPSAT Explore

Status/work to do

- Feasible areas for improvements to gain margin are being identified and documented, with opportunities for more
- Next steps include
  - Continue observing efficiency effort
  - Expand simple CHLAT spreadsheet model on previous slide to SPLAT and SP SAT
  - Work on margin opportunities in other areas e.g.:
    - Sensitivity
    - Optical efficiencies
    - Thermal Loading
    - Low-ell from SPLAT
  - Apply some of these tools, analyses, and findings to various configurations considered in Analysis of Alternatives, as appropriate

Backup

Requirements And Technical Budgets Define Experiment Performance

- Requirements
  - Minimum performance measure that a subsystem or component must meet
  - Heirarchical, flowed down from Science Goals to Technical Requirements

- Performance / Technical Budgets
  - Resources/parameters that are allocated (as requirements) among subsystems or components
  - CMB-S4 performance / technical budgets include:
    - Observing Efficiency
    - Measurement Sensitivity
    - Systematics
    - Beam quality
    - Magnetic/RF shielding
    - Electrical power
    - Data Bandwidth
    - Cooling power

Current Best Estimates (CBEs) Of Instrument Performance Parameters

- Expected values of performance parameters that are governed by requirements
- Based on the best information currently available
  - Heritage
  - Analysis
  - Prototype test results
  - As-built test results
  - Requirements (in the absence of any other valid estimate)
- These values inform simulations/analyses of predicted overall system performance (and thereby overall performance margin)