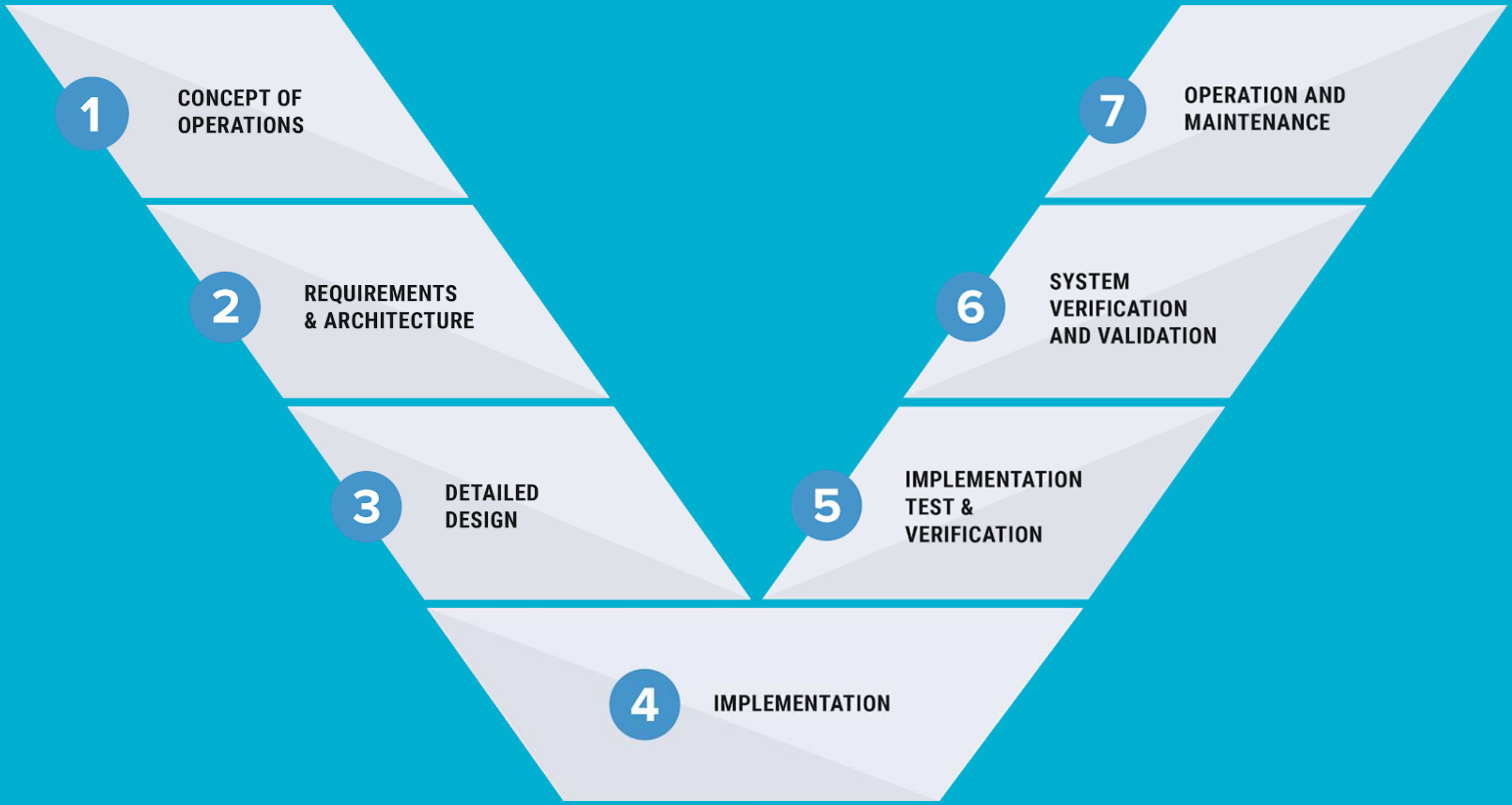
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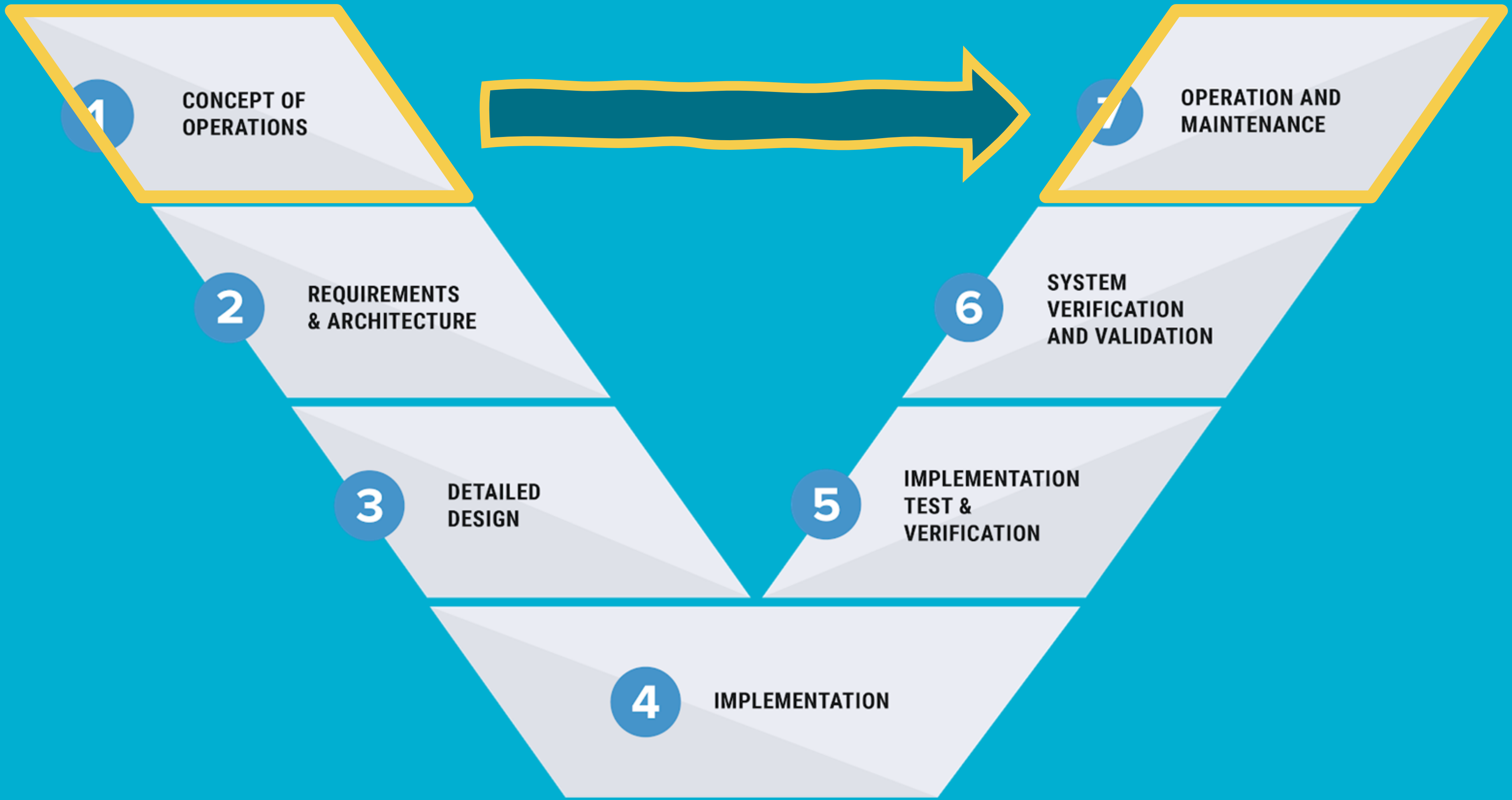
Vacuum Windows and the V

By Miranda Eiben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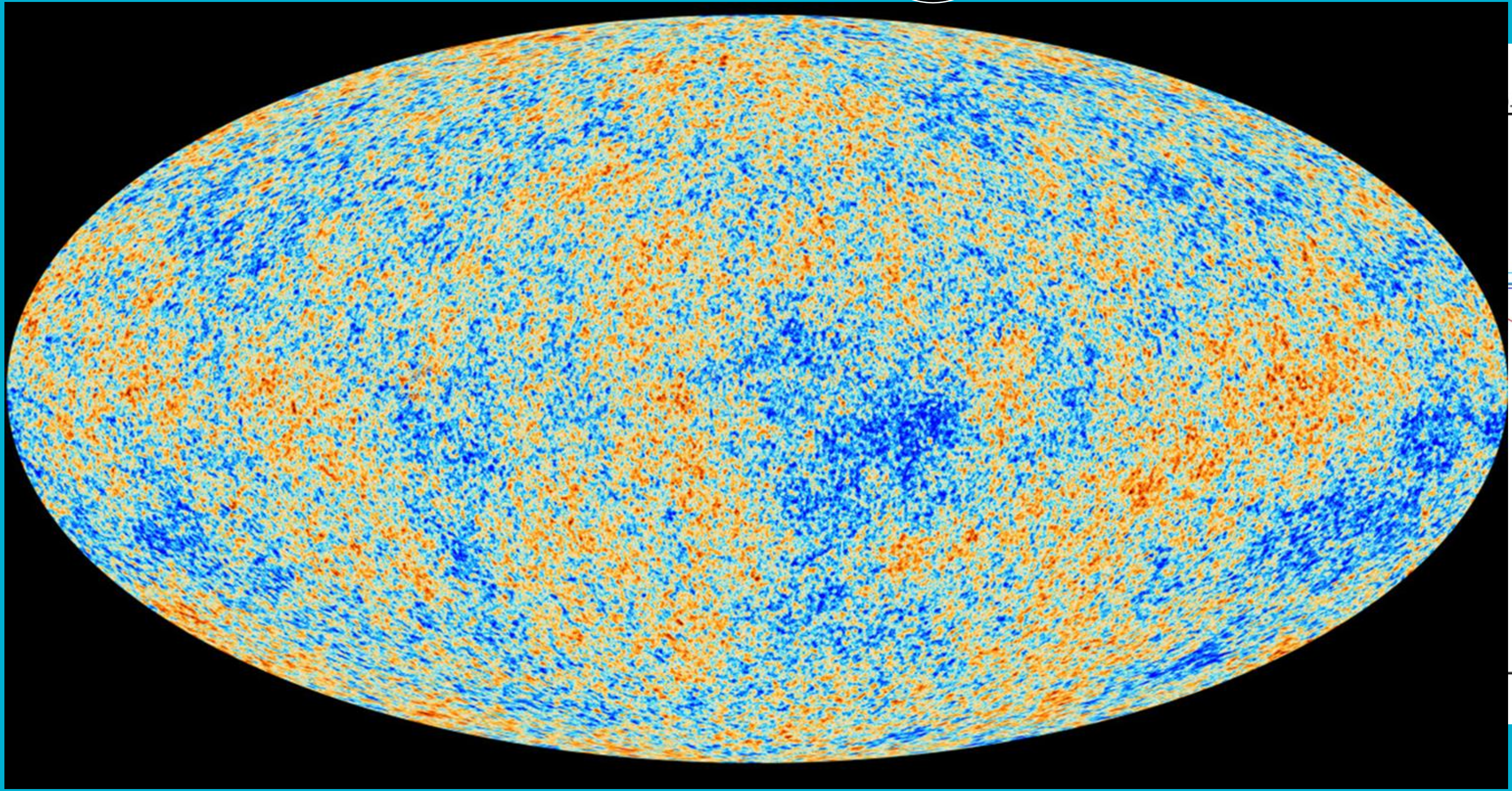
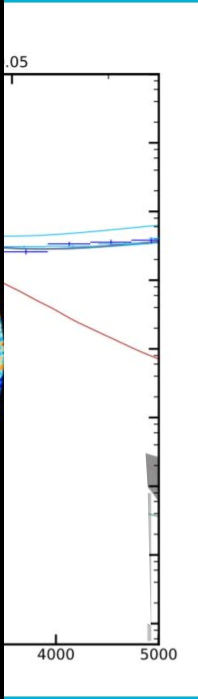
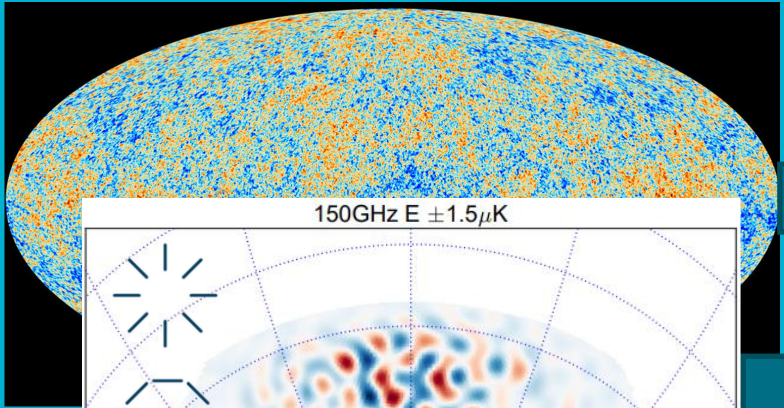
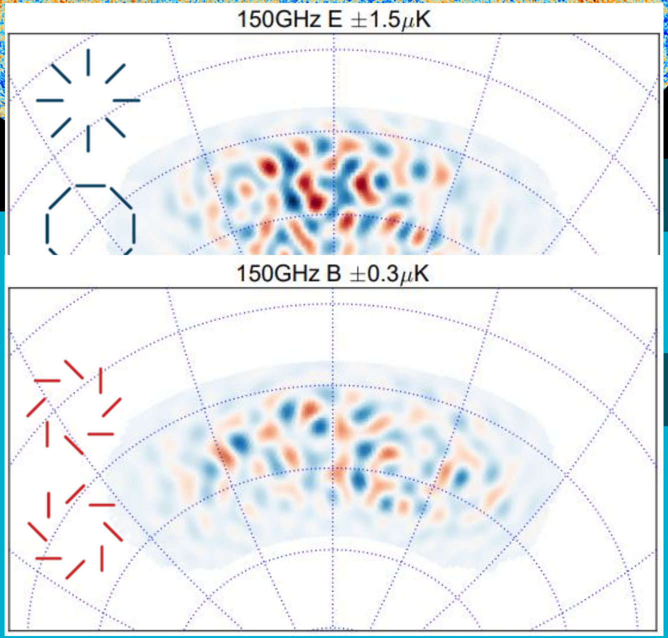
Observations: BICEP Array

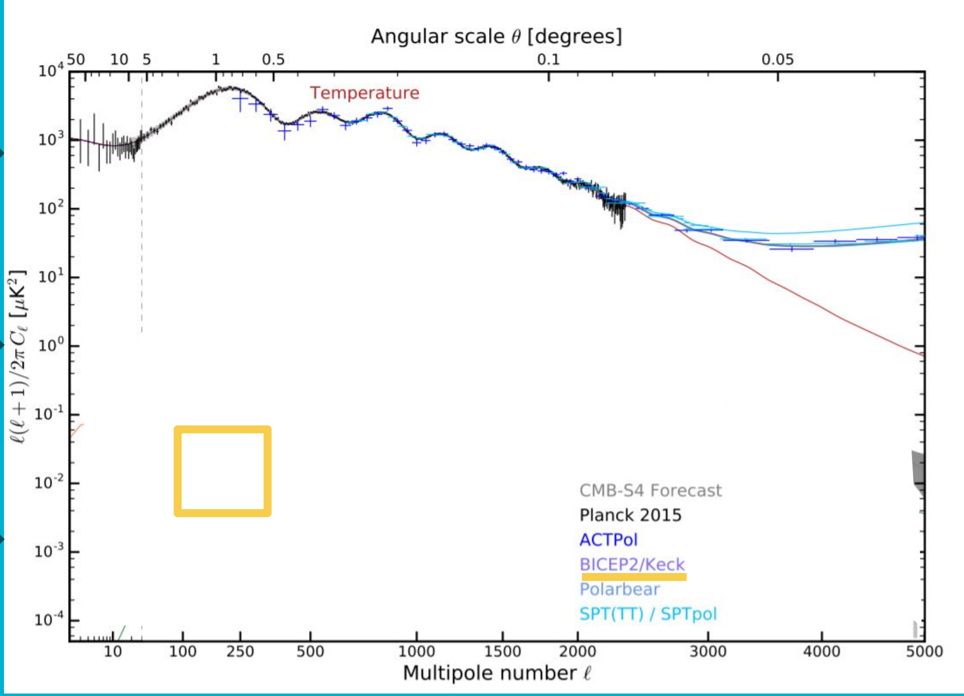




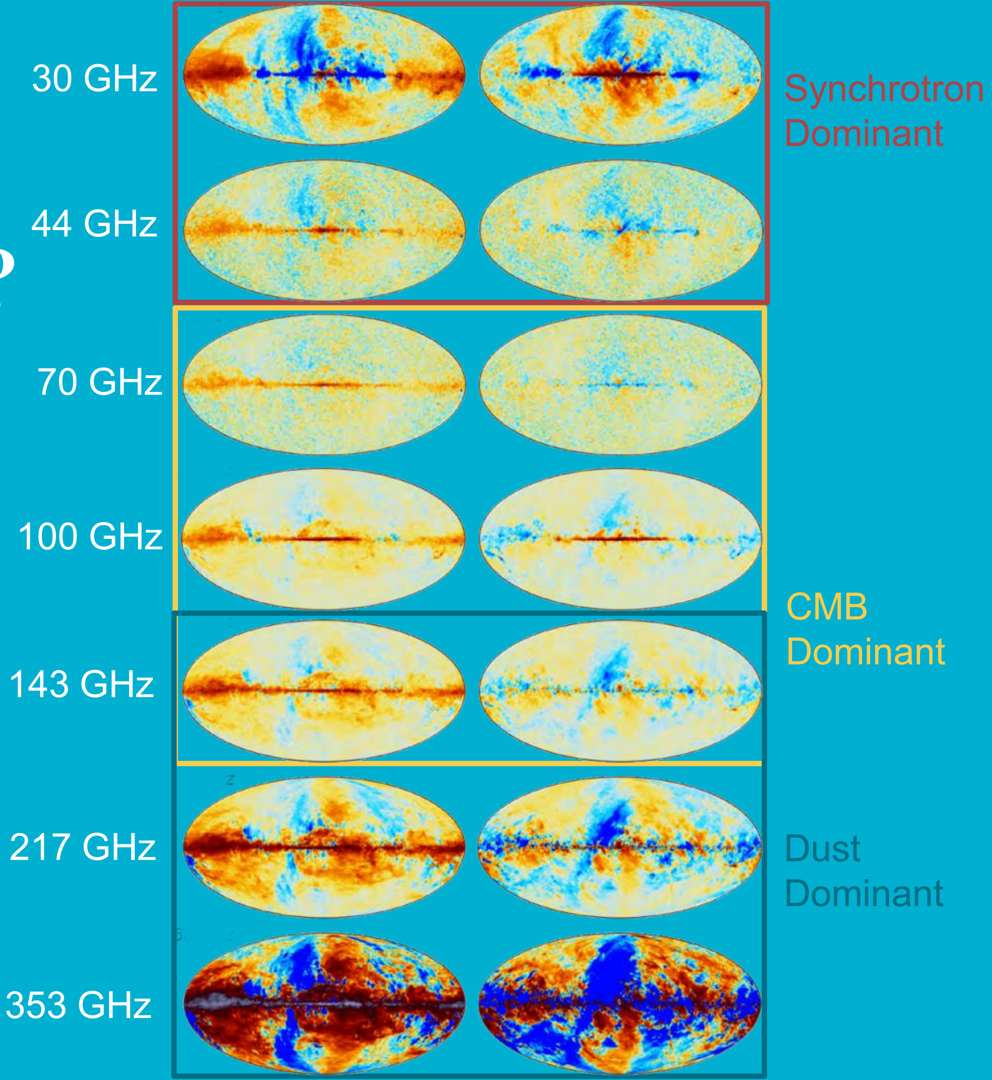
Observations: BICEP Array





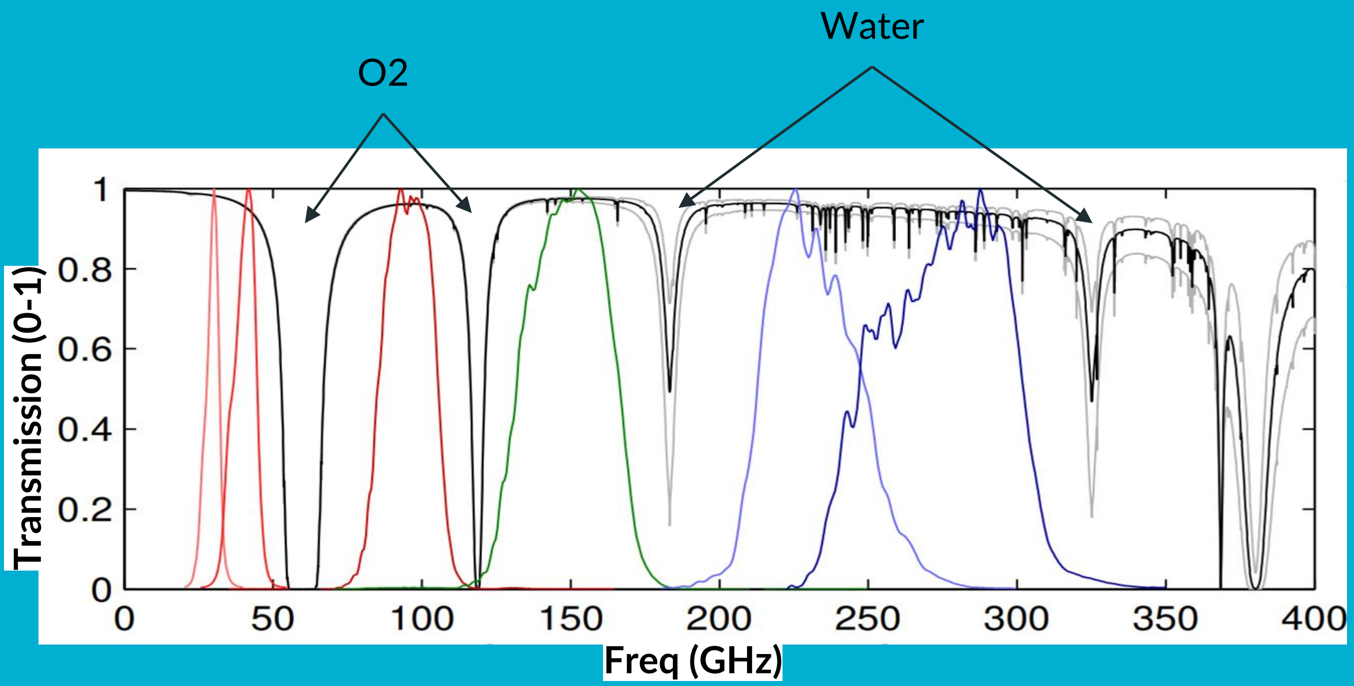


Why the Multiple Millimeter?



Bands

Ground-based millimeter wavelength observational bands are limited by atmospheric windows



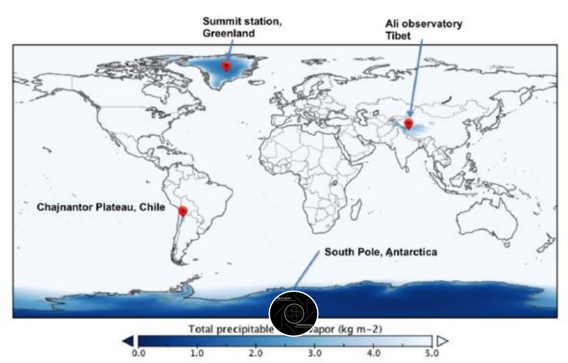
Telescope Location

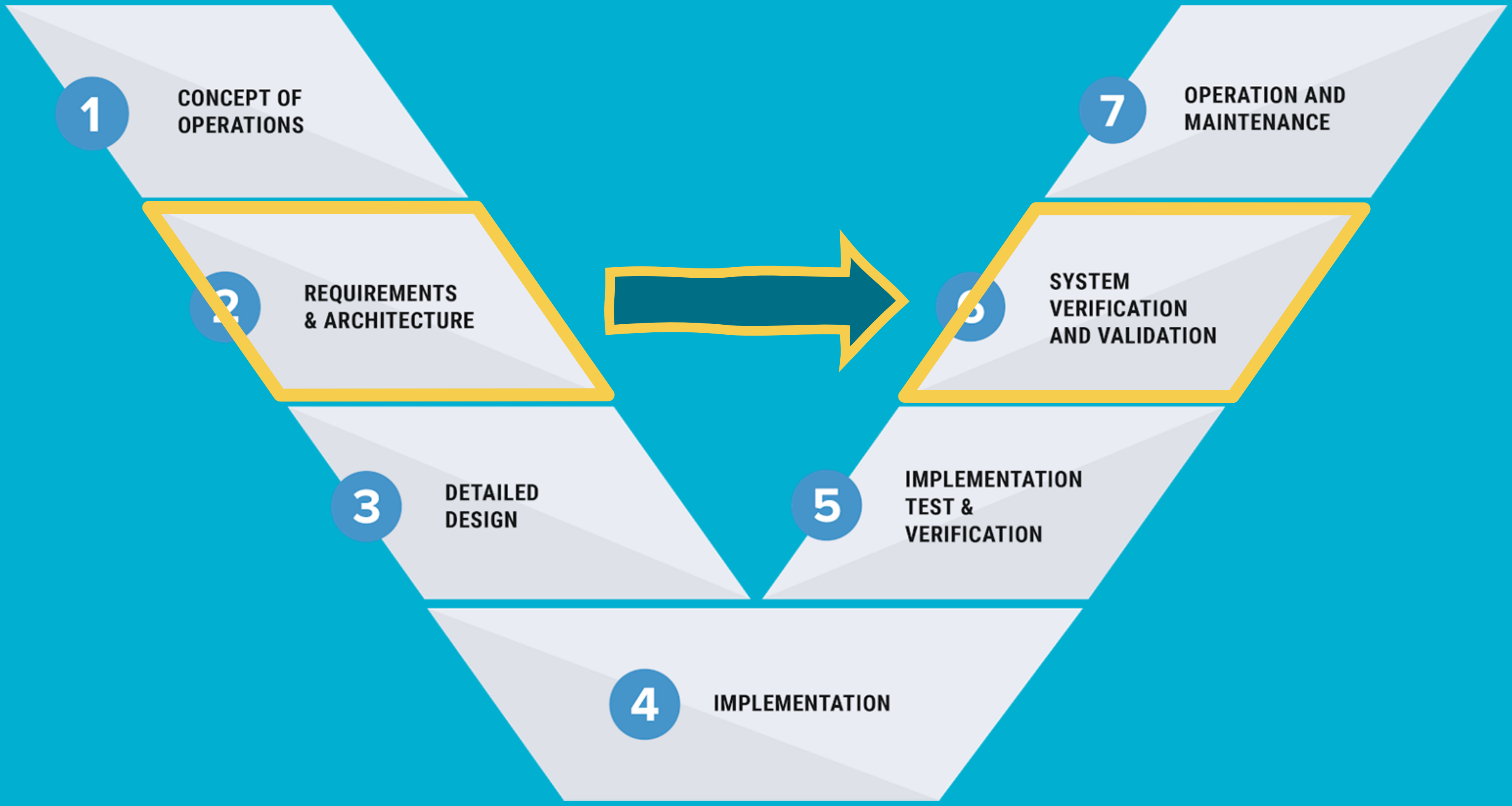
Ground vs. Space

- Atmosphere is (reasonably) transmissive in the millimeter
- Wants high sensitivity, low resolution (arcmin scale)
  - Difficult to observe sky to high sensitivity for decades in space

Where in the World?

- Need a high desert
  - Deserts tend to be at lats +/- 15 to 30deg around equator
    - Mexico, Chile, Australia
  - Other geographical conditions (like distance from the ocean)
    - South Pole, Tibet

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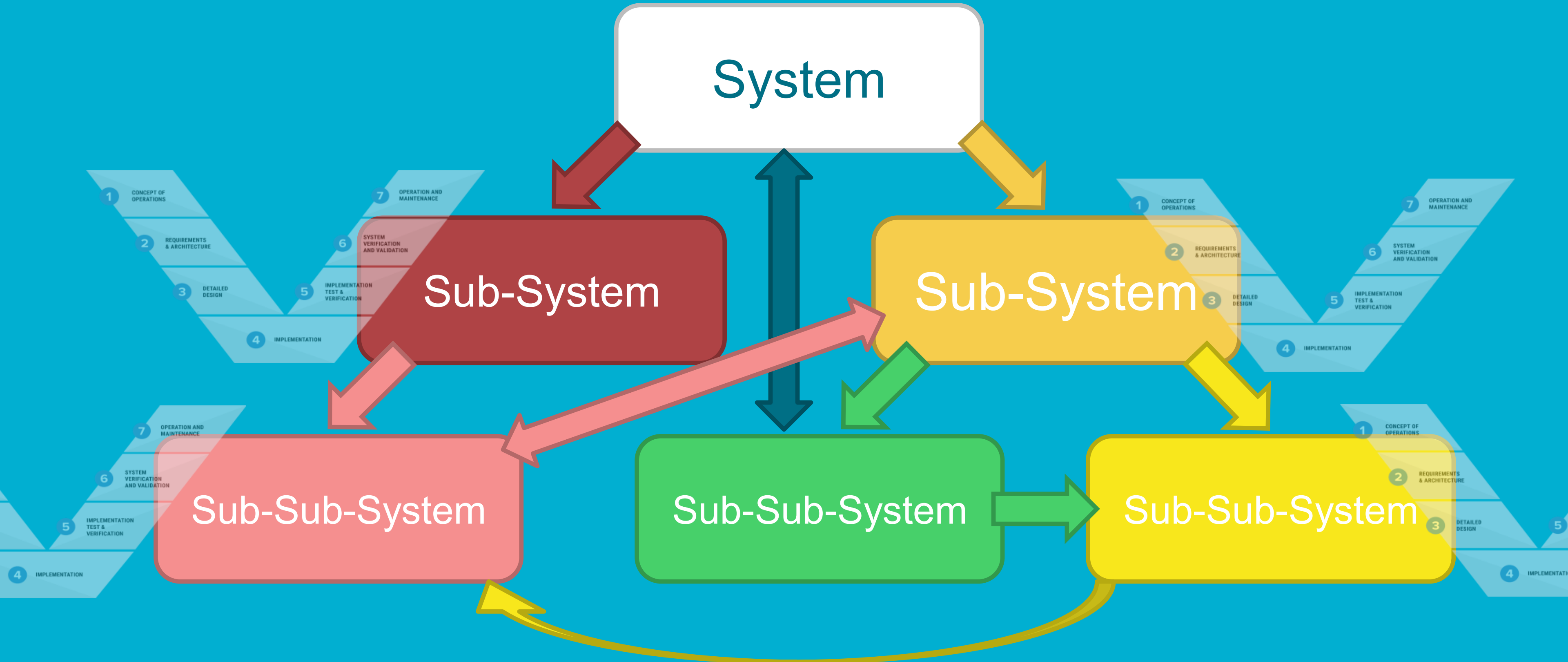
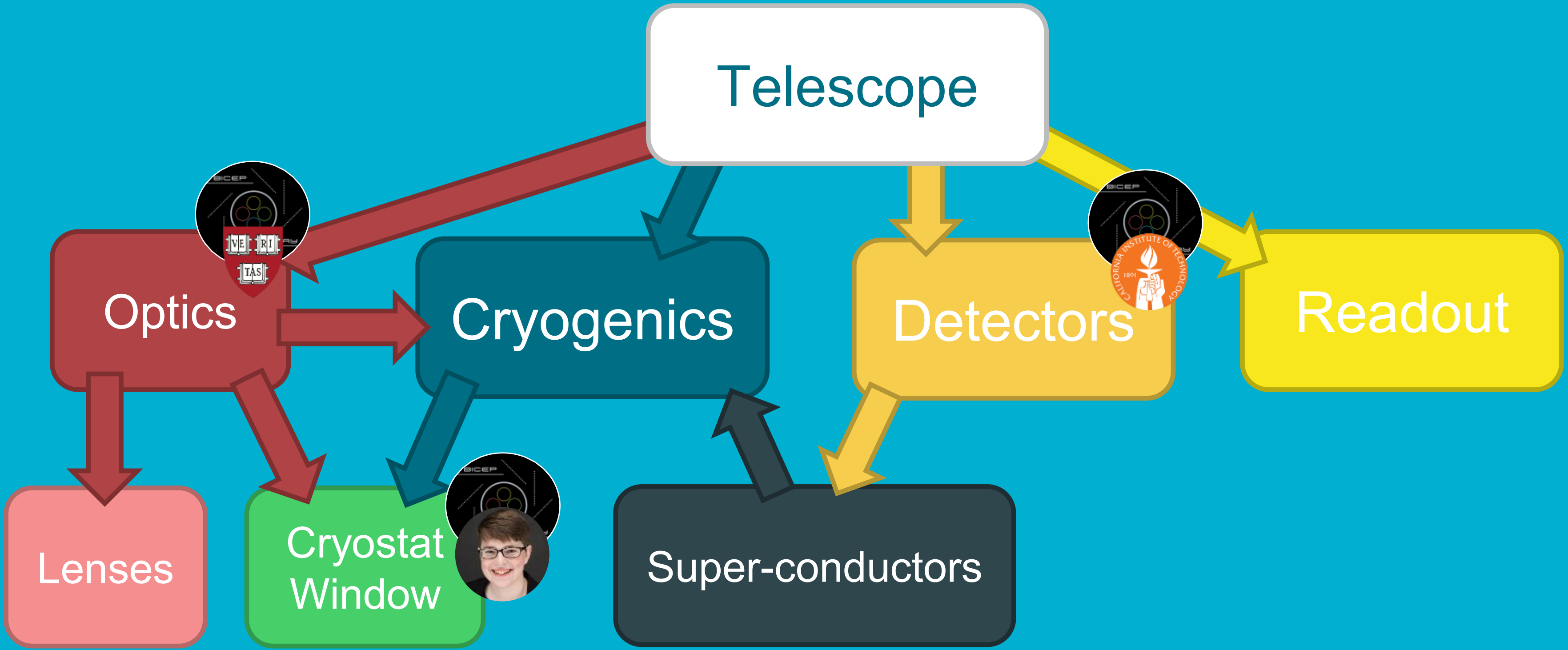
Architecture of a System



Architecture of a Millimeter Telescope



Example Requirements: Cryostat Window

Problem: Everything Emits Millimeter Radiation

Solution: Make Everything Cold

Problem: Heat Transfer

Solution: Eliminate Convection with a Vacuum

Problem: The Atmosphere is Heavy

Problem: Strong Materials Are Reflective/Absorptive

Solution: A transmissive window!

REQUIREMENT: The window must be strong enough to hold out the atmosphere.

REQUIREMENT: The window should not absorb more than X% radiation.

‘Current’ System

Table 4. Per-detector in-band optical load. The total loadings listed in **bold** are direct measurements from detector load curves, which are in good agreement with the individual modeled optical elements. A stack of 300 K metal-mesh filters used in the 2016 season were replaced by HD-30 foam filters for the 2017 season.

Source	Load [pW]	T_{RJ} [K]
4K lenses & elements	0.15	1.0
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Total (2016)	**3.13**	**27**
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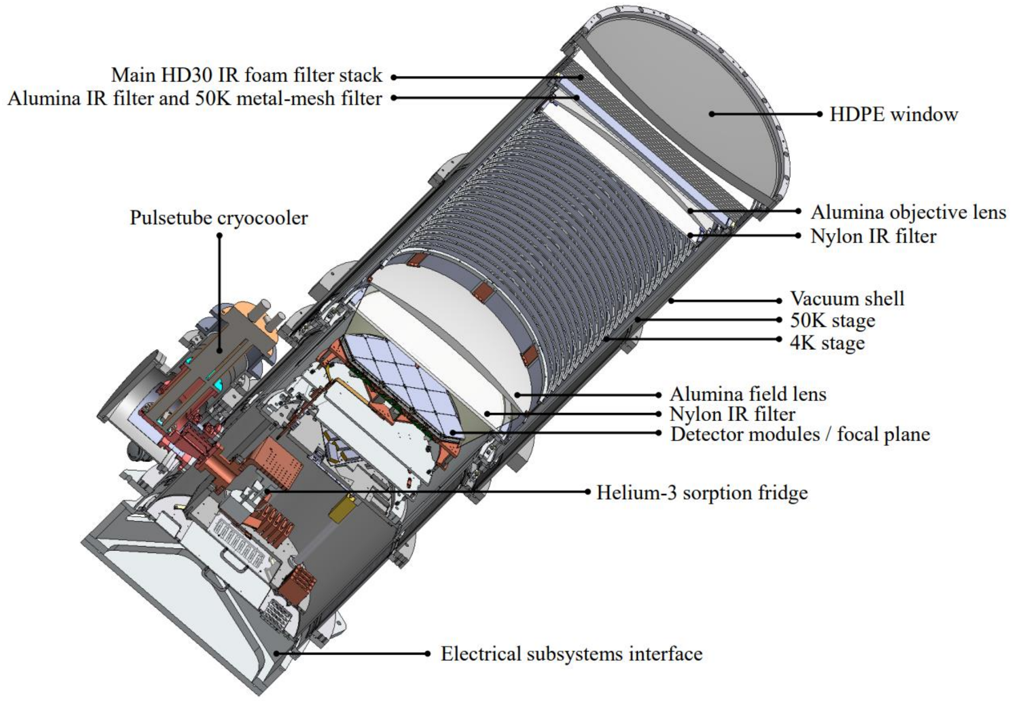

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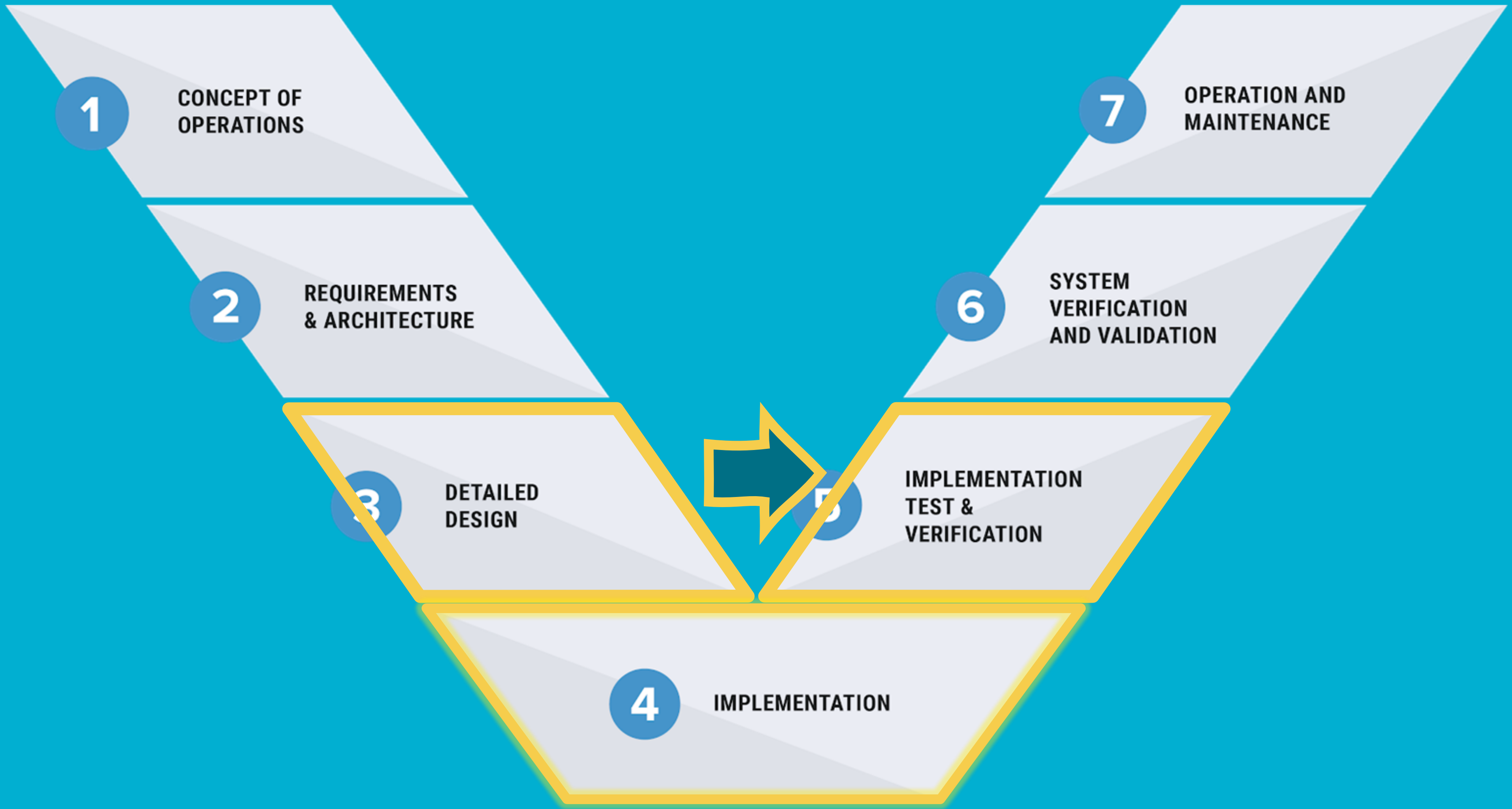
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You’re in a hallway.

You’re in a hallway.

Ahead of you is a T-intersection.

You’re in a hallway.

Ahead of you is a T-intersection.

To the LEFT you feel a strange heat emanating

You’re in a hallway.

Ahead of you is a T-intersection.

To the LEFT you feel a strange heat emanating

and something glints.

You’re in a hallway.

Ahead of you is a T-intersection.

To the LEFT you feel a strange heat emanating

and something glints.

To the RIGHT you hear water (or is it air?)

You’re in a hallway.

Ahead of you is a T-intersection.

To the LEFT you feel a strange heat emanating

and something glints.

To the RIGHT you hear water (or is it air?)

and there is the occasional heavy thump.

You’re in a hallway.

Ahead of you is a T-intersection.

To the LEFT you feel a strange heat emanating

and something glints.

To the RIGHT you hear water (or is it air?)

and there is the occasional heavy thump.

What do you do?

What do you do?

LEFT

What do you do?

LEFT

Ahead are two doors.

What do you do?

LEFT

Ahead are two doors.

The one to the LEFT is mirrored, but you

What do you do?

LEFT

Ahead are two doors.

The one to the LEFT is mirrored, but you can’t see your reflection in it.

What do you do?

LEFT

Ahead are two doors.

The one to the LEFT is mirrored, but you can’t see your reflection in it.

The one to the RIGHT is a fathomless void,

What do you do?

LEFT

Ahead are two doors.

The one to the LEFT is mirrored, but you can’t see your reflection in it.

The one to the RIGHT is a fathomless void, with a radiant heat emerging from it.

What do you do?

LEFT

Ahead are two doors.

The one to the LEFT is mirrored, but you can’t see your reflection in it.

The one to the RIGHT is a fathomless void, with a radiant heat emerging from it.

What do you do?

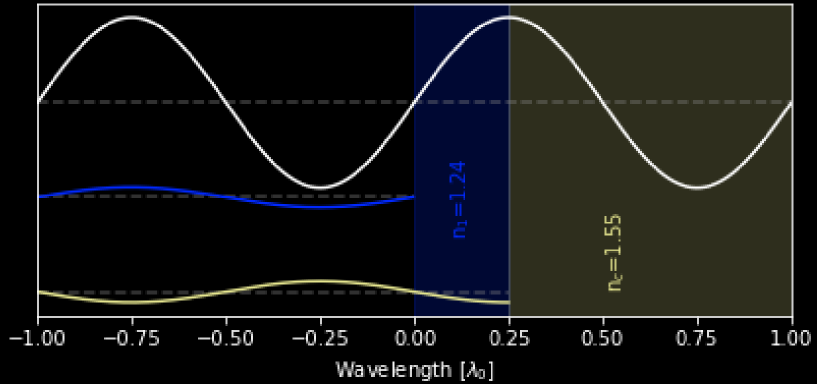
You’ve chosen:

Optics Tests: Anti-Reflection

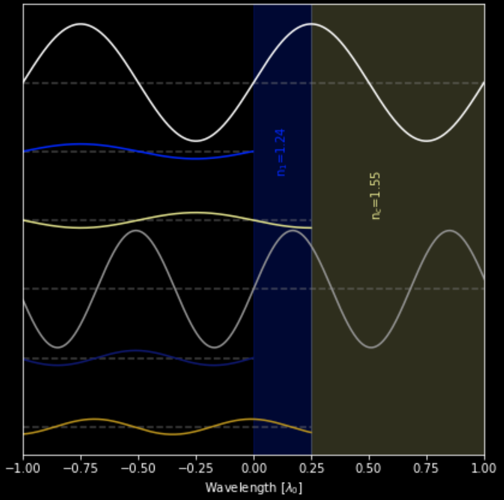
Problem: Impedance changes into a material will cause lost optical power

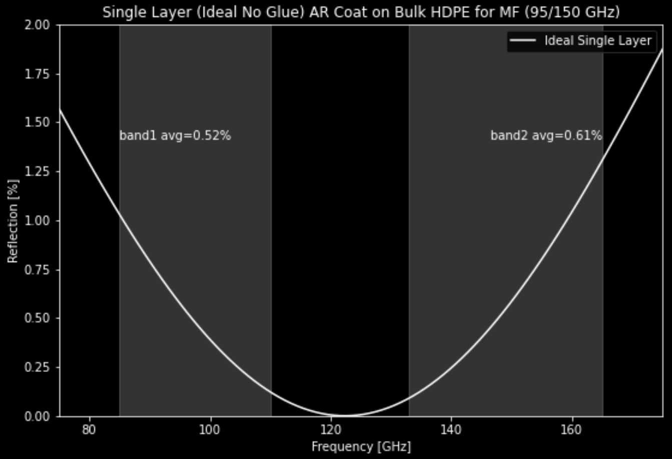
Problem: Reflections off the window could cause problematic internal reflections, such as “buddy beams”

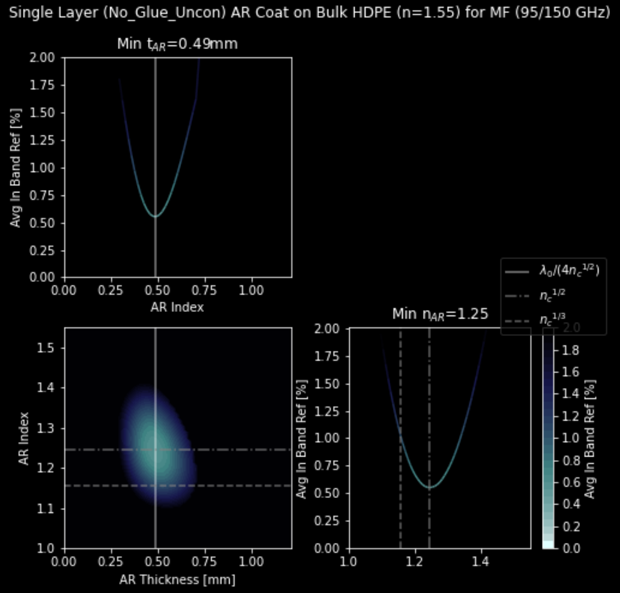
Solution: An anti-reflection coat!



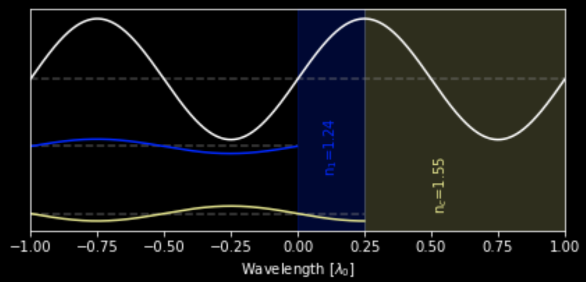
Visualizing the Parameter Space

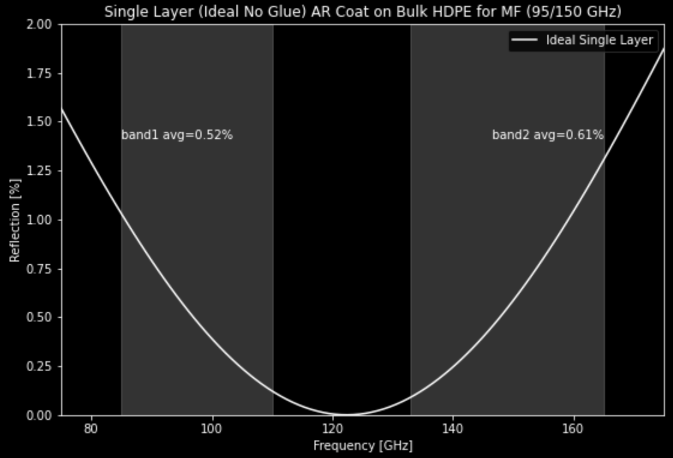


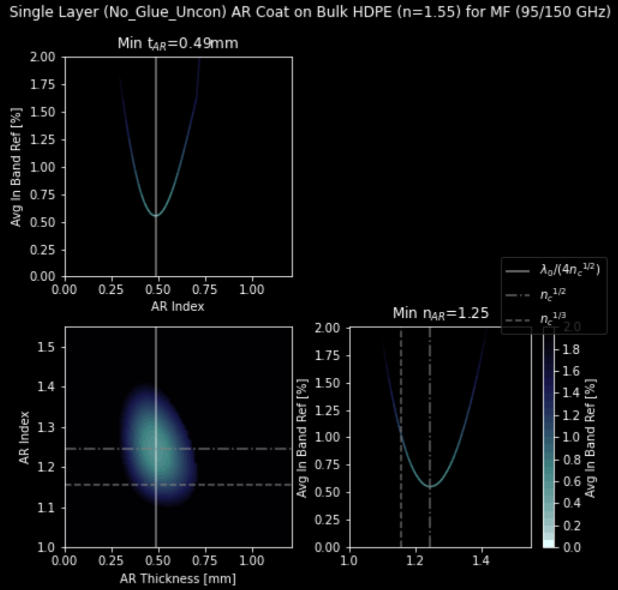




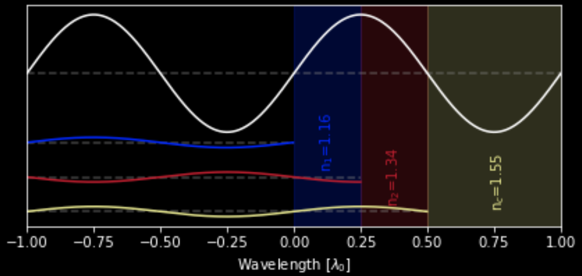
Single Layer

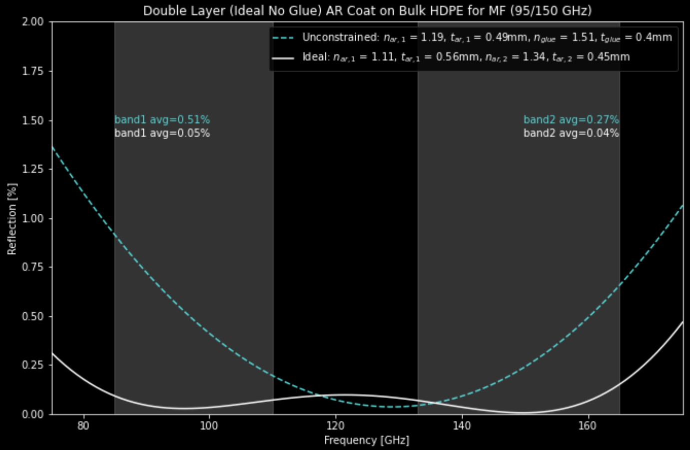


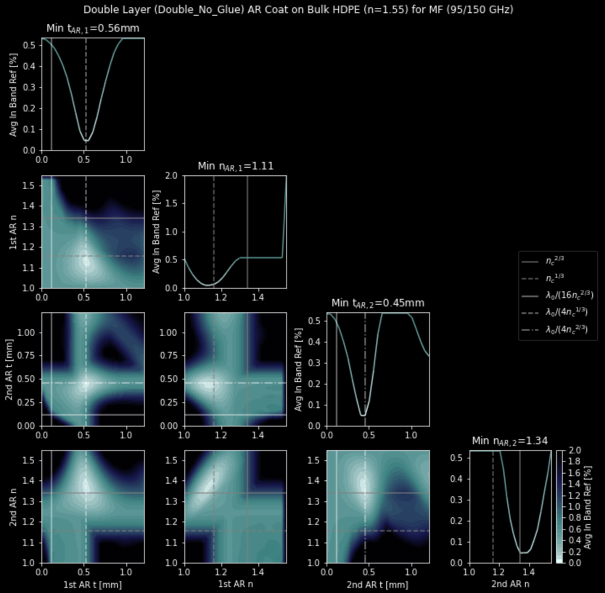




Double Layer

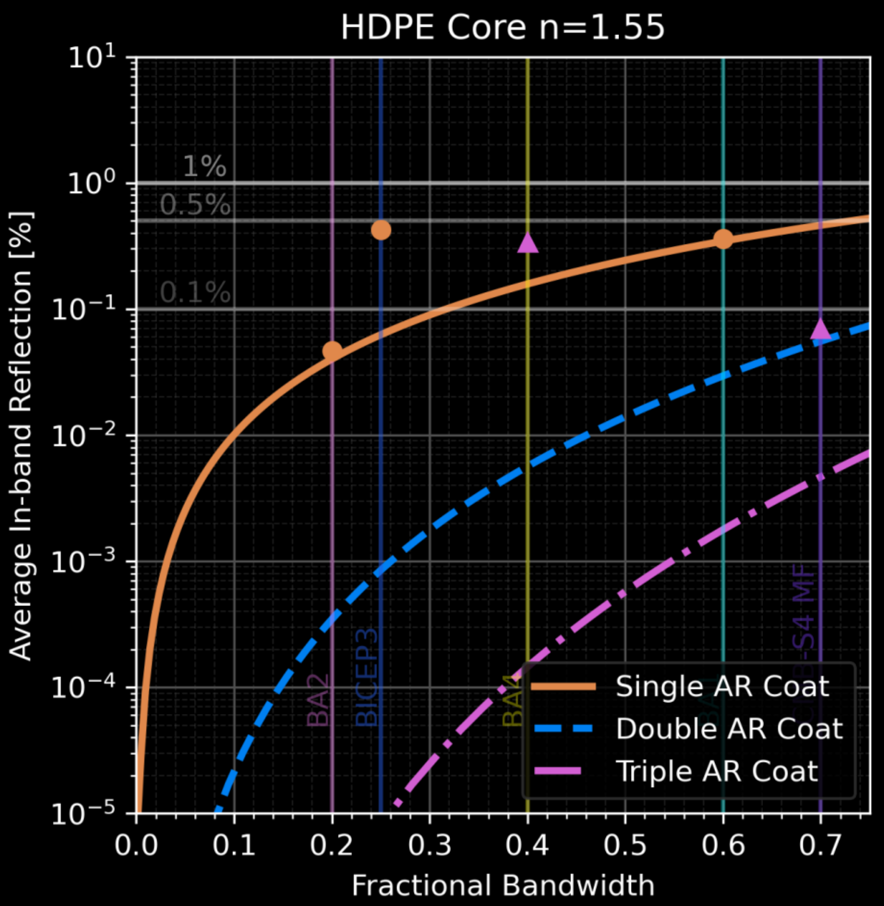






Idealized AR coats using Chebyshev polynomials over different fractional bandwidths with comparison to achieved AR coats

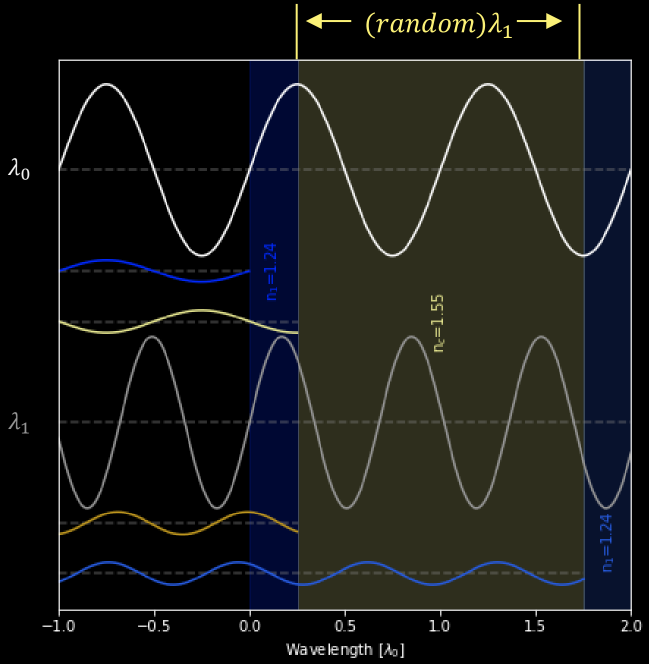
- Idealized AR coats are ¼ λ layers
- Infinite cores (only one reflection surface)

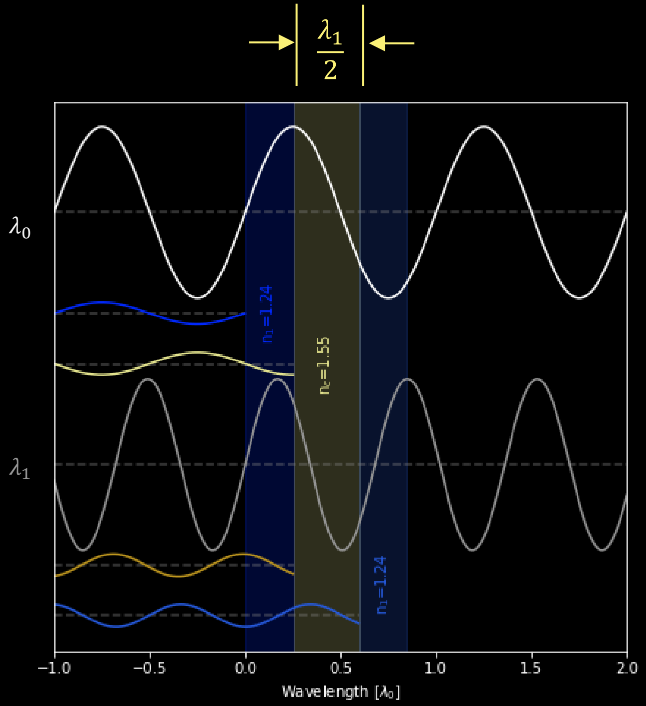


Anti-Reflection Coating with Thin Window

Thick windows are arbitrary number of wavelengths thick

Can use thickness of HMPE laminate to supplement anti-reflection





Anti-reflection Coat Requirements

- Can't do better than a Chebyshev solution for a given integer layer with infinite core for a given bandwidth
- Can use the thinness of the window to our advantage with further interference from window
- Can look to previous 'acceptable' solutions, and set that as an upper limit goal
  - We want to do at least this good or better

REQUIREMENT: Reflections off the window should be at most 1% or lower.

You’ve chosen:

Optics Tests: Noise Equivalent Temperature

Problem: Strong Materials Are Reflective/Absorptive

Problem: Emission in band and absorption are directly linked.

Photon noise $\propto$ absorption of component

Optical load goes like $\epsilon \approx e^{-\alpha t}$

Where:

α is the absorption coefficient

t is the thickness of the material

Table 4. Per-detector in-band optical load. The total loadings listed in **bold** are direct measurements from detector load curves, which are in good agreement with the individual modeled optical elements. A stack of 300 K metal-mesh filters used in the 2016 season were replaced by HD-30 foam filters for the 2017 season.

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CMB	0.12	1.1
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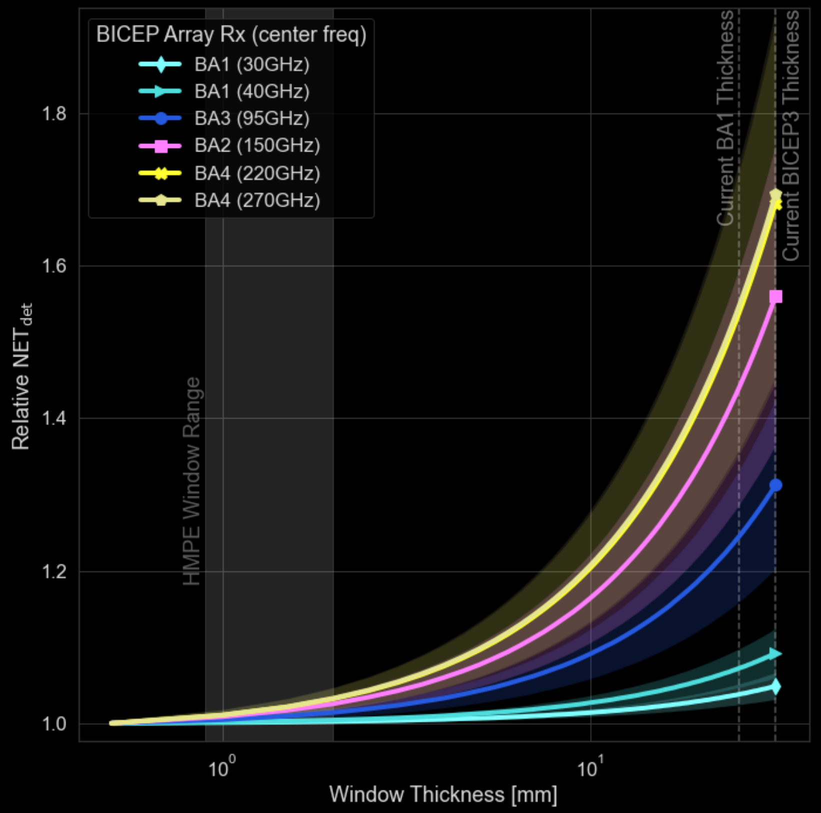
Some integrals and some conversions



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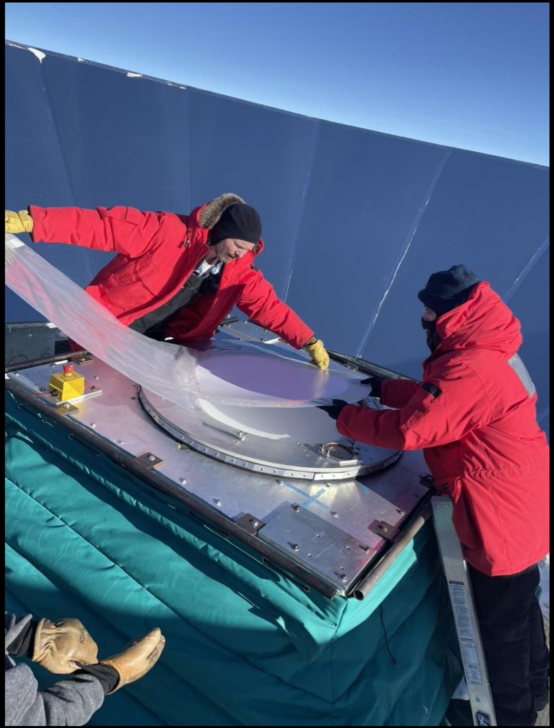
What can we measure?

Optical Load

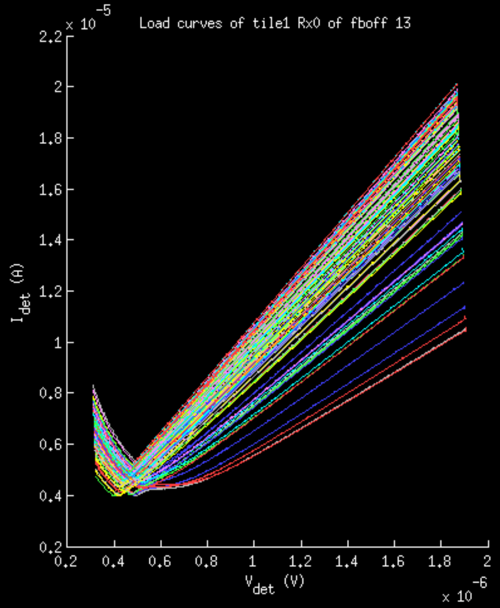
Noise

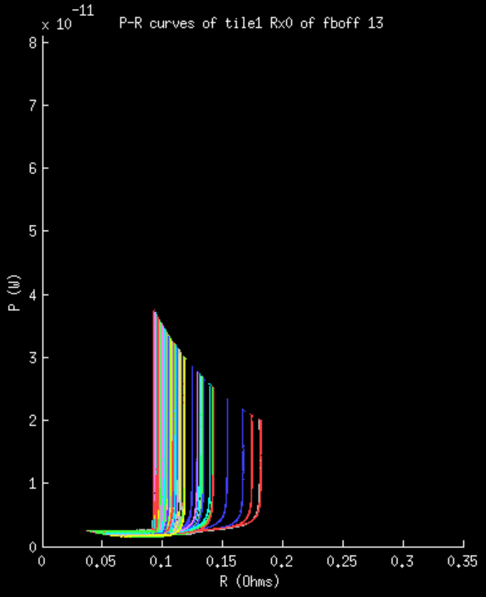
What can we measure?

Optical Load



Radiometric measurements made by Jamie Cheshire, John Kovac, and Thomas Leps

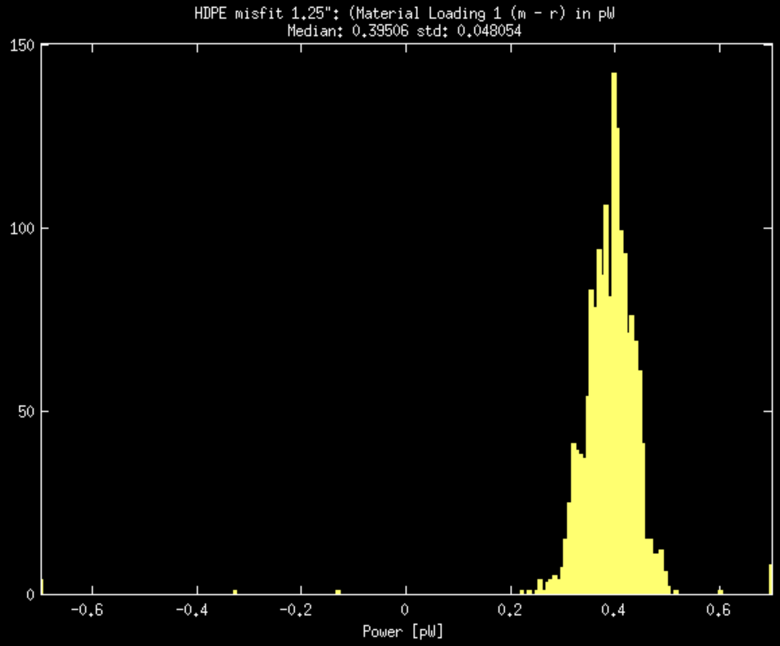




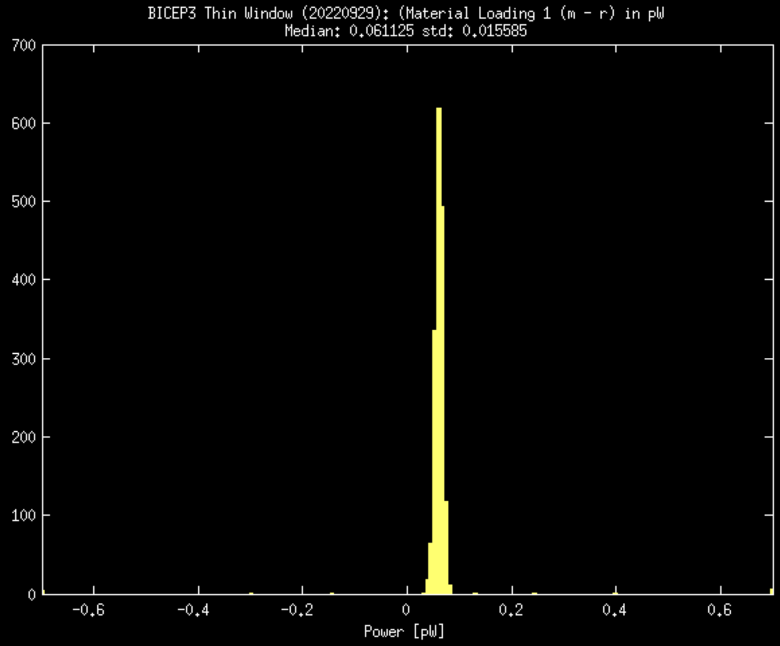
What can we measure?

Optical Load

Spare Slab HDPE Window

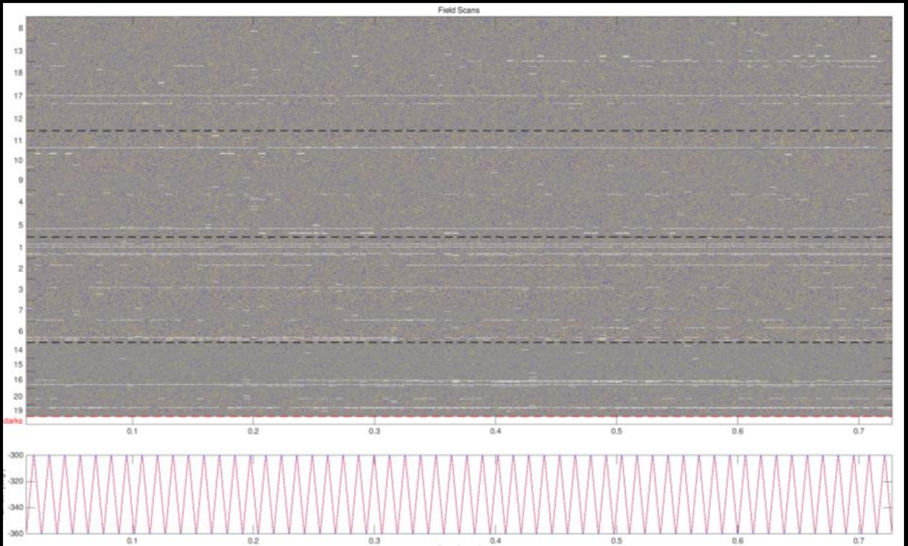


Replacement Thin Window

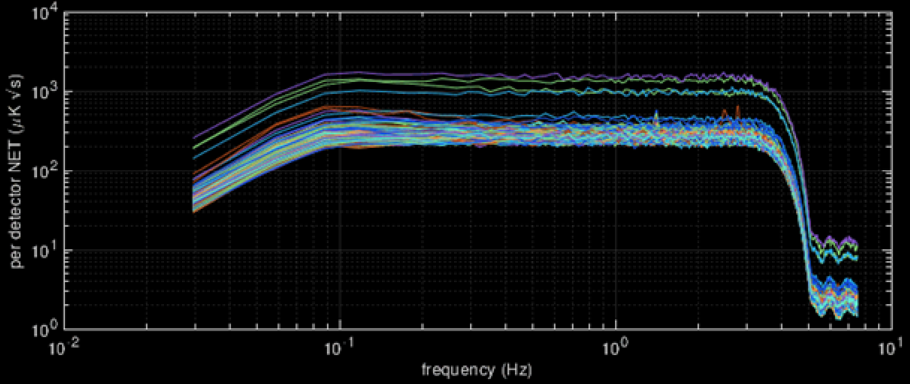


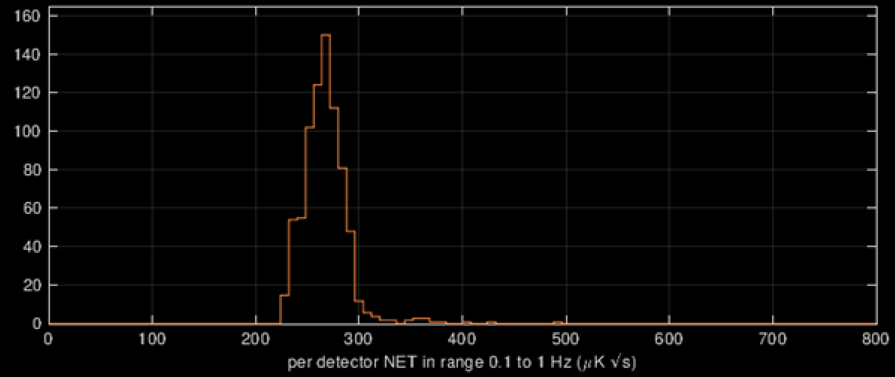
What can we measure?

Fourier Transform and calibration



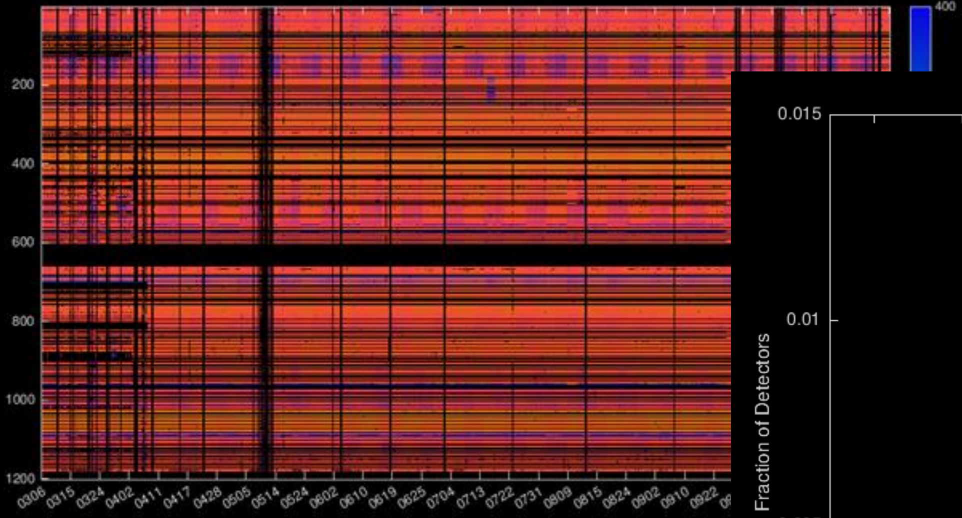
Noise



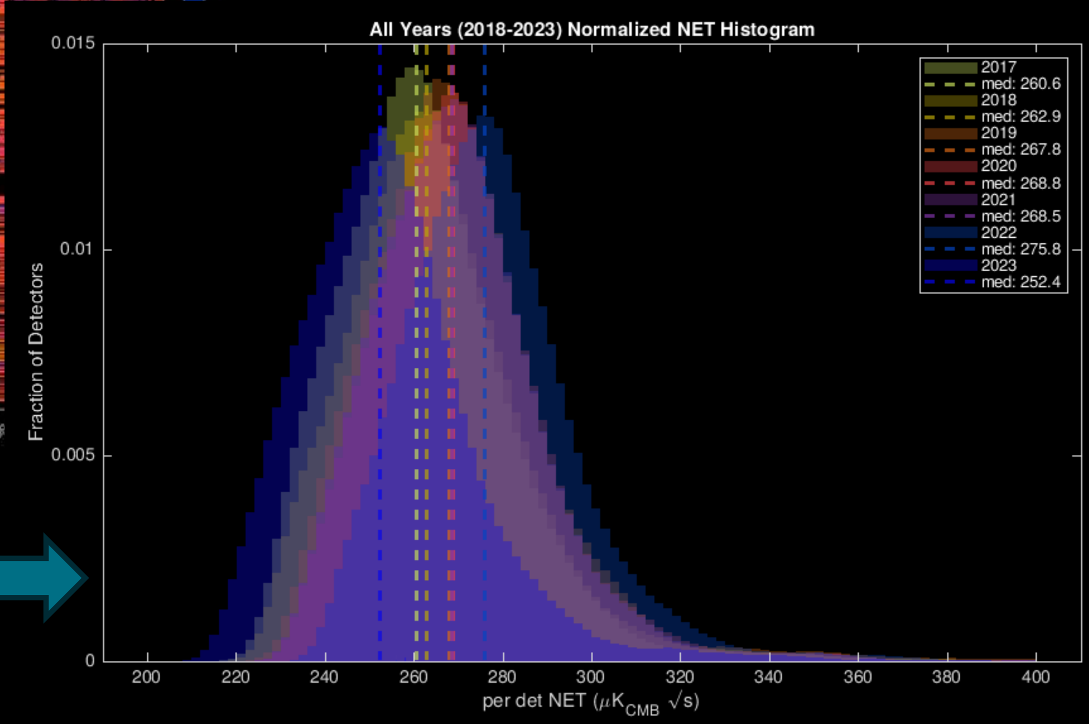


What can we measure?

Noise



Take a median over the year and compare years



Noise Requirements

- We expect that the in band optical loading and noise should lower, but we are unsure how much
  - If we approach characterization of the effect from multiple angles (independent measurements) we can gain confidence in our understanding of the physics, and our predictive abilities of similar changes in the future

REQUIREMENT: Take multiple independent characterization measurements

What do you do?

RIGHT

What do you do?

RIGHT

Ahead are two doors.

What do you do?

RIGHT

Ahead are two doors.

The one to the LEFT is semi-transparent,

What do you do?

RIGHT

Ahead are two doors.

The one to the LEFT is semi-transparent,

and water is slowly filling behind it.

What do you do?

RIGHT

Ahead are two doors.

The one to the LEFT is semi-transparent,

and water is slowly filling behind it.

The one to the RIGHT is slowly bending out

What do you do?

RIGHT

Ahead are two doors.

The one to the LEFT is semi-transparent,

and water is slowly filling behind it.

The one to the RIGHT is slowly bending out

and occasionally something slams into it.

What do you do?

RIGHT

Ahead are two doors.

The one to the LEFT is semi-transparent,

and water is slowly filling behind it.

The one to the RIGHT is slowly bending out

and occasionally something slams into it.

What do you do?

You’ve chosen:

Mechanical Tests: Strength

Problem: The Atmosphere is Heavy

Problem: Specifically, the atmosphere is ~15 psi, the window is large and the combined force is: **9.5e3 lbs=4.2e4 N**

Problem: How can we be sure that we are never going to exceed the max force the window can take?

$$\text{Force} = P_{ATM}\pi r^2$$
P_{ATM} = atmospheric pressure
r = radius of window

REQUIREMENT: The window must have a strength safety factor of at least 3.

Can we model the safety factor?

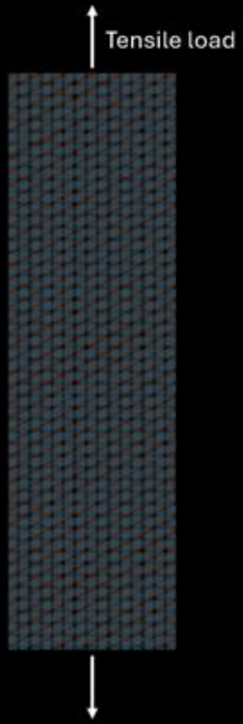
$$\delta = K\left(\frac{\Delta P\, R^4}{E\, t}\right)^{(1/3)}$$

$$\sigma_{max} = Z\left(\frac{E\, \Delta P^2\, R^2}{t^2}\right)^{(1/3)}$$

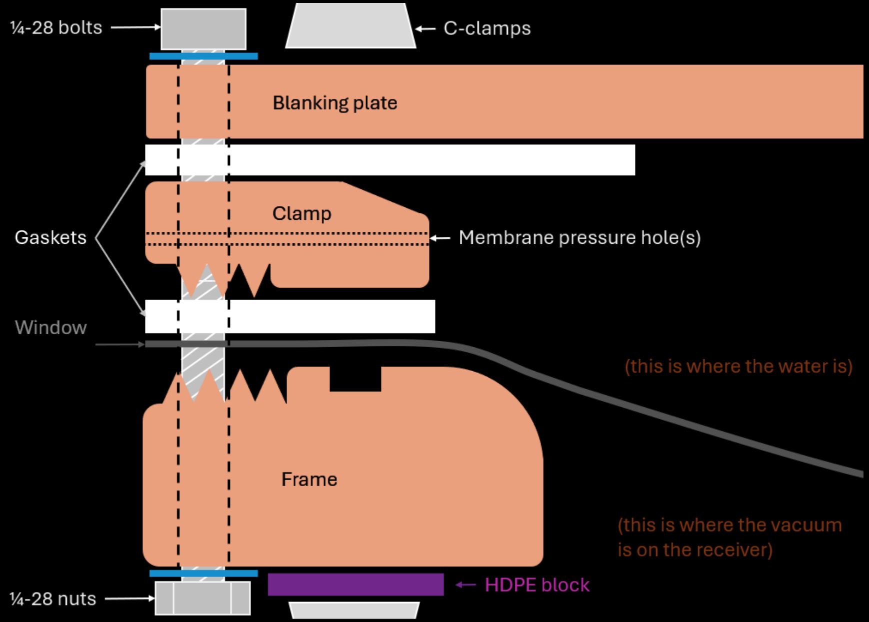
Recipe	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)	Expected Elastic Center Deflection (cm)	Safety Factor
HDPE	17.5 - 21	0.8 - 1.10	(failure)	0.54 - 0.65
UHMWPE	27.6 - 40	1.25	(failure)-6.045	0.73 - 1.06
8hrs 10atm 120C [a]	97 - 99	0.831 - 0.856	6.86-6.93	2.95 - 2.98
8hrs 10atm 130C	115 - 119	1.303 - 1.329	5.92 - 5.96	2.99 - 3.12
8hrs 10atm 135°C	120 - 135	1.139 - 1.275	6.01 - 6.24	3.17 - 3.67
8hrs 10atm 150°C [b]	60 - 85	0.663 - 0.820	6.96 - 7.47	1.97 - 2.62
16hrs 10atm 137°C [c]	110 - 144	1.562 - 1.770	5.38 - 5.75	2.71 - 3.64
24hrs 10atm 137°C [c]	114 - 140	1.455 - 1.648	5.51 - 5.75	2.76 - 3.54
32hrs 10atm 137°C	138 - 144	1.368 - 1.430	5.78 - 5.87	3.53 - 3.66

Can we model the safety factor?

Problem: This isn't exactly the stress conditions that angled layers relative to one another undergo in a circular aperture



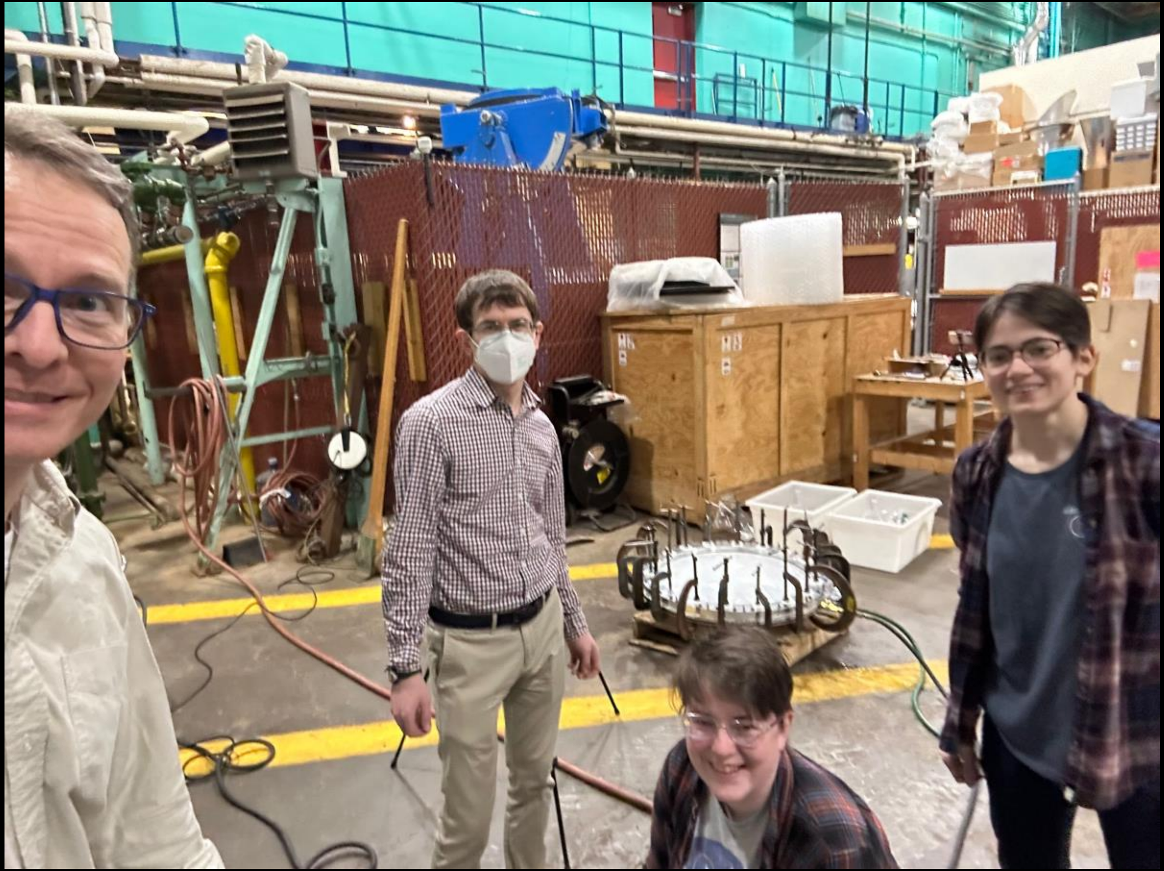
Can we measure the safety factor?



Problem: Unique boundary conditions around the edge of the window

Solution: We set up a system that can hold water above the window in the cryostat frame/clamp.

Can we measure the safety factor?



Can we measure the safety factor?

We got to ***85 pounds per square inch***

Strength Requirements

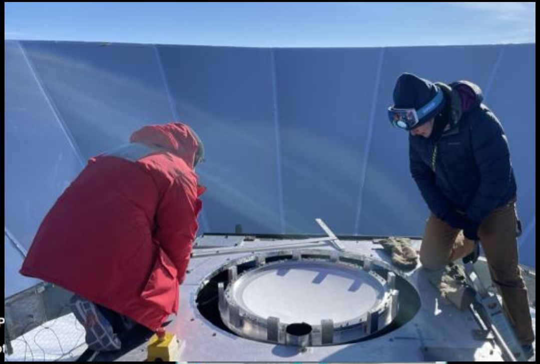
- Can model using mechanical constants derived from small scale tests
  - Doesn’t fully capture the stress conditions of the actual window
- Can measure using an empirical test (hydrostatic failure)
  - Got to 85 psi! Equivalent safety factor of 5.7 at sea level and 8.2 at South Pole

REQUIREMENT: The window must have a strength safety factor of at least 3.

You’ve chosen:

Mechanical Tests: Creep, Impact, Permeation

Jamie Cheshire [left] and Marion Dierickx [right]

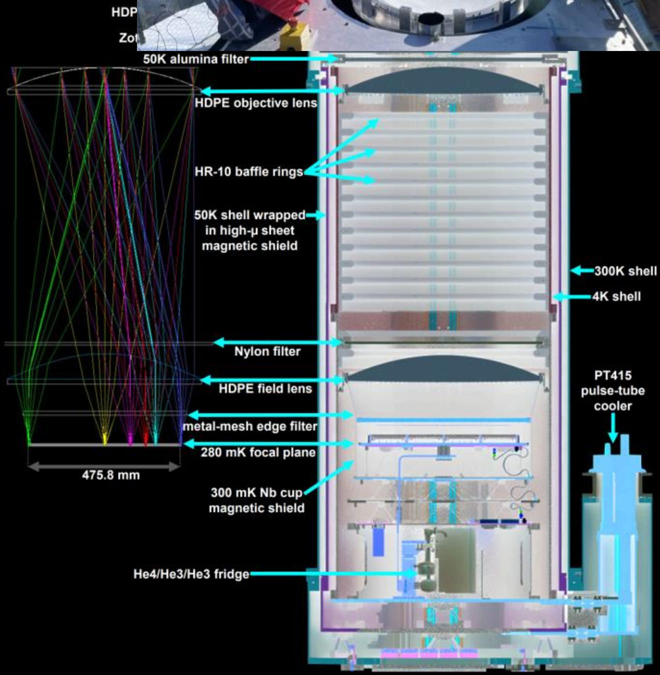


Problem: The Atmosphere is Heavy

Problem: And plastics under continuous load will slowly deform (creep)

Problem: There's other stuff just below the window

Solution: Characterize the Creep!



Moncelsi, et al. *Receiver development for BICEP Array, a next-generation CMB polarimeter at the South Pole* (2020)

Problem: People are clumsy

Problem: People may drop tools or other equipment onto the window, when it's under vacuum

Solution: Make sure impacts don't break the window!

Table 3. Objects dropped on a full scale window under vacuum, with estimated impact area, max impact stress, and outcome of failure testing.

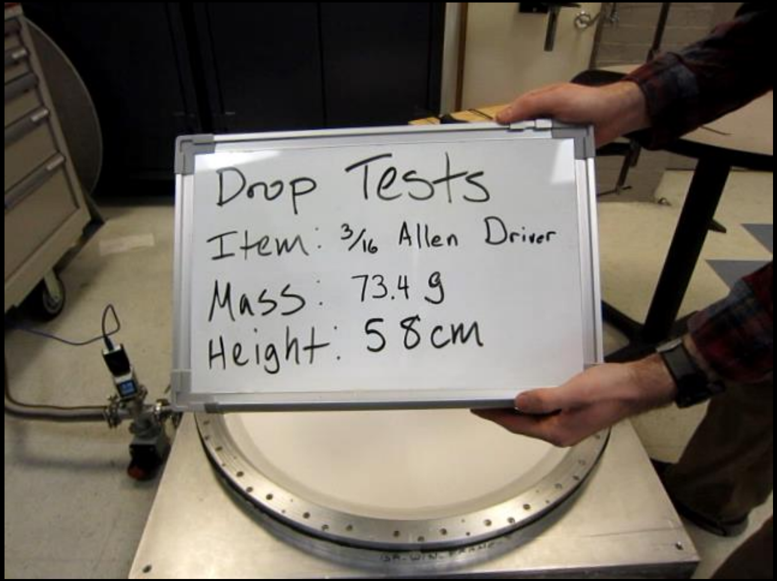
Object	Mass [g]	Estimated Impact Area [mm^2]	Estimated Max Impact Stress [MPa]	Failure? [Y/N]
1/4-20 Washer	1.5	3.0	5.7	N
1/4-20 1" Bolt	7.4	5.1	16.6	N
1/4-20 1.5" Bolt	10.1	5.1	22.7	N
1/4-20 2" Bolt	13.4	5.1	30.1	N
1/4-20 2.5" Bolt	16.5	5.1	37.1	N
3/16" Hex Key	21	22.5	10.6	N
3/16" Hex Screwdrive	73.4	25	33.4	N

Drop Tests

- Dropped 7 different commonly dropped objects from 58cm
  - 58cm is the height of the table I was dropping from
  - Estimated impact area from the dents AR coating

$$\sigma_{\text{impact}} = \frac{mgh}{dA_{\text{impact}}}$$

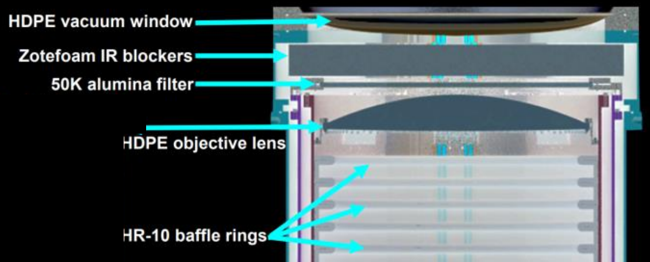
- Pressure behind window never rose higher than 5 mbar (0.5% atm)
- No drops caused a failure
- Also: left about 2lbs of dry ice on it
  - Inducing a thermal gradient of ~100C
  - Thermal gradient did not cause a failure

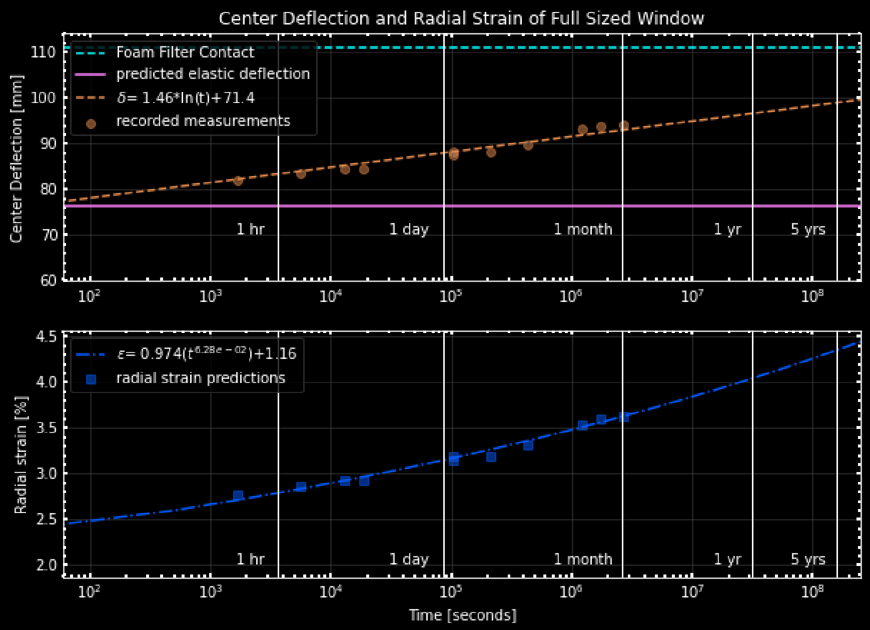


Video taken with help from David Goldfinger

Creep Tests

- To anticipate physical margin required between window and IR filters below it
  - We expect creep to decrease at lower temperatures
- Initial elastic deformation is consistent with prediction
  - $\delta = K\left(\frac{\Delta P\, R^4}{E\, t}\right)^{(1/3)}$
- Plastic deformation due to creep is consistent with a fit logarithmic function
  - Behavior also consistent with previous measurements



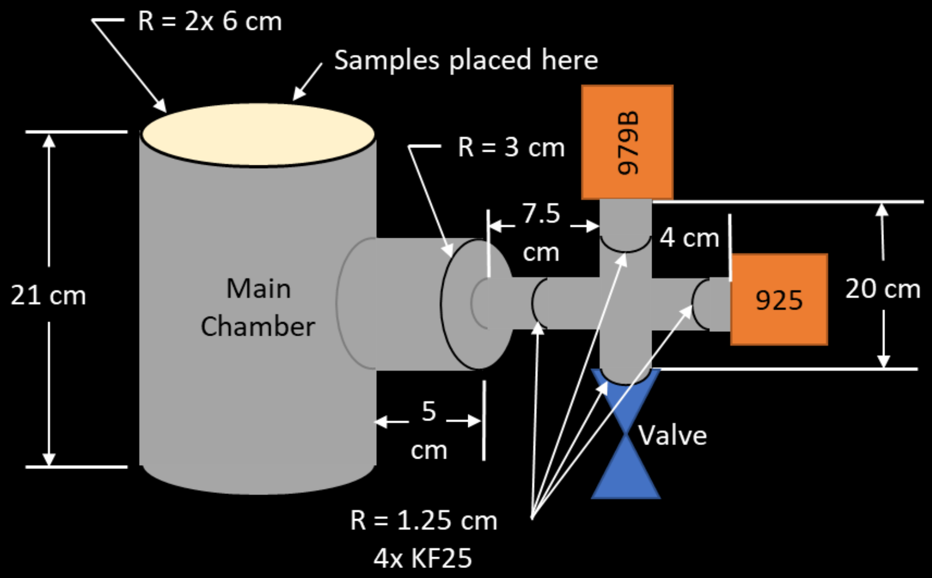


Measurement and modeling by Sage Crystian

Problem: Wait, doesn't gas permeate through plastics?

Problem: The vacuum could be pulled underneath the window for years

Problem: Permeation is inversely related with the thickness, and we could be significantly increasing the gas entry rate



$$Q_{\text{permeation, measured}} = \frac{\Delta PV}{A\Delta t}$$

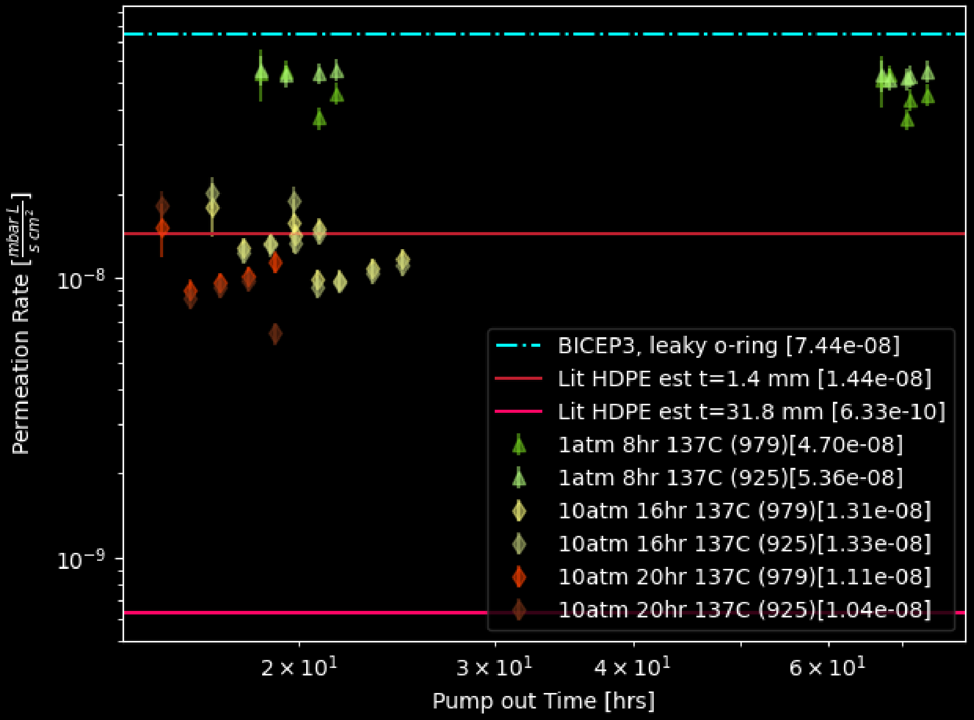
Permeation of Gas

- Measured rate similar to the literature value

$$K_{\text{HDPE, literature}} = \frac{1.6\times10^{-7}\frac{\text{Torr L}}{\text{s}}(3.2\text{mm})}{760\text{Torr }(34\text{cm}^2)} = 1.98\times10^{-9}\frac{\text{cm}^2}{\text{s}}$$

$$Q_{\text{permeation, calc}} = \frac{KP}{d}$$

- About 20x more gas through HMPE laminate than through the 31.8mm current window
  - As calculated from literature values
- About 7x less gas as in the year with a leaky o-ring in BICEP3
  - Permeation at Pole should be 30% less
- Will this adversely impact cryogenics?
  - We believe that the window permeation is not dominant over other sources of gas into the system



Creep, Impact, Permeation Requirements

- Most of these concerns are basically one offs
- Require testing, but not new tests and requirements for each window, necessarily
    - Still a good idea to take measurements of these properties when able, but once tested we don't expect it to be a problem

REQUIREMENT: Test to ensure that these are not and will not become problems in the future

What do you do?

BEHIND

What do you do?

BEHIND

You’ve chosen:

What do you do?

BEHIND

You’ve chosen:

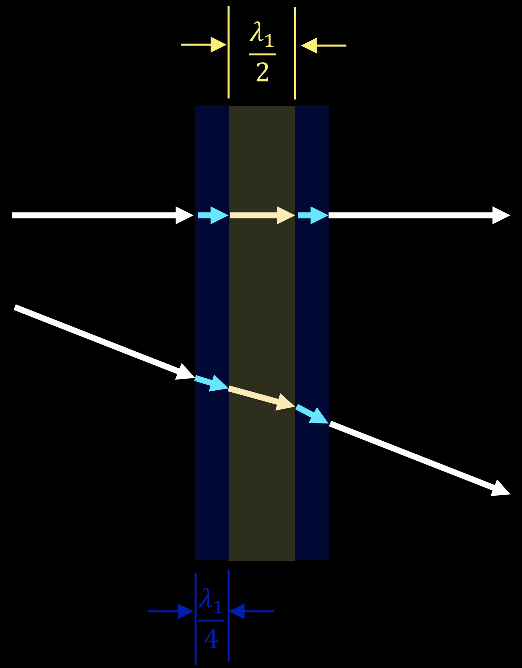
Miscellaneous Tests: Deflection & Reflection

Problem: The Atmosphere is Heavy

Problem: Strong Materials Are Reflective/Absorptive

Wait! The anti-reflection coats rely on the travel distance of the light, which changes at different angles, and the window deflects!

Problem: The deflection of the thin window may adversely affect the performance!



Fresnel polarized reflections

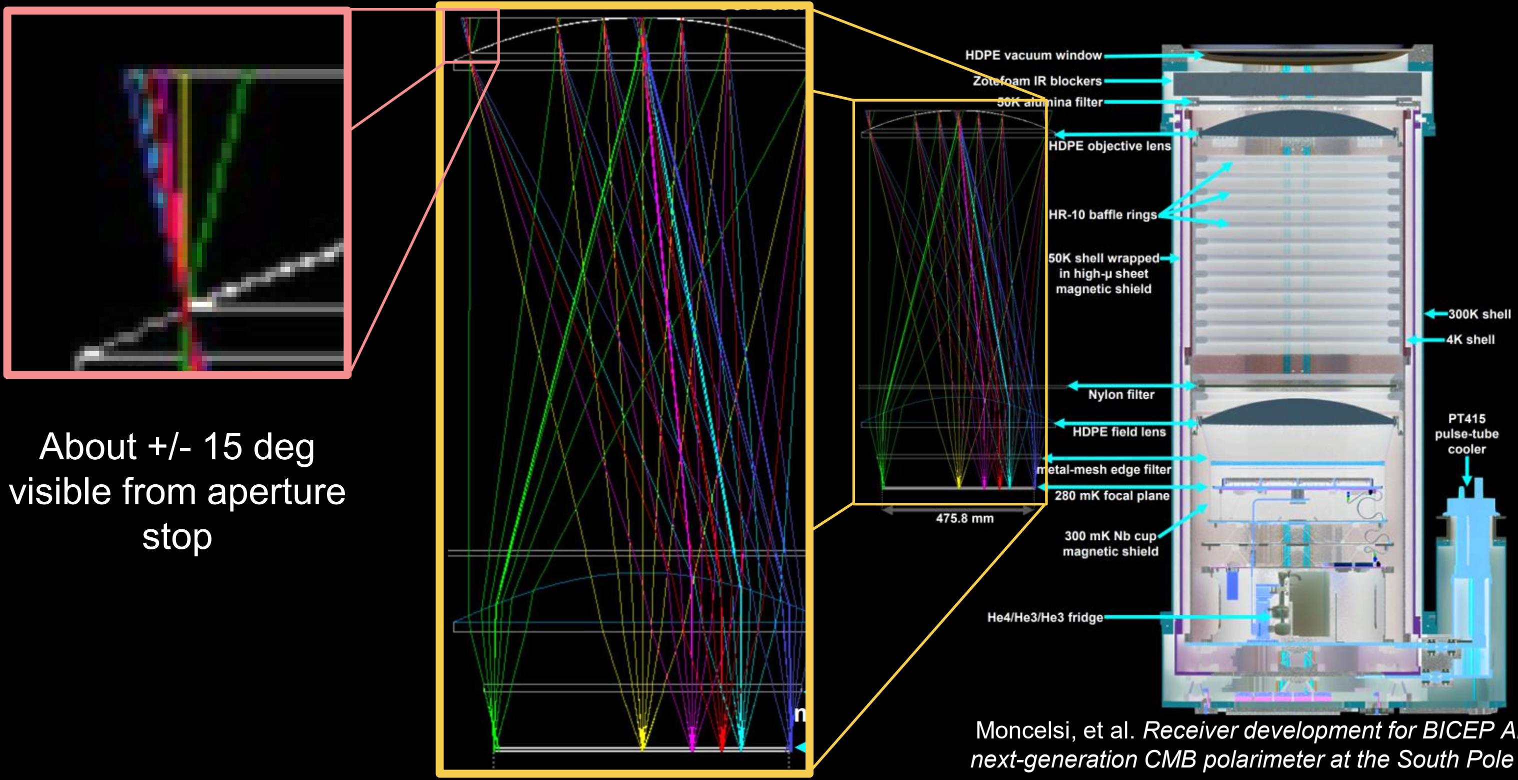
$$R_s = \left|\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t}\right|^2 = \left|\frac{n_1 \cos\theta_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2}}{n_1 \cos\theta_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2}}\right|^2,$$

$$R_p = \left|\frac{n_1 \cos\theta_t - n_2 \cos\theta_i}{n_1 \cos\theta_t + n_2 \cos\theta_i}\right|^2 = \left|\frac{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2} - n_2 \cos\theta_i}{n_1 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i\right)^2} + n_2 \cos\theta_i}\right|^2.$$

Problem:
Low incidence angle reflections are highly polarized!

Pictures from Fresnel Equations Wikipedia page

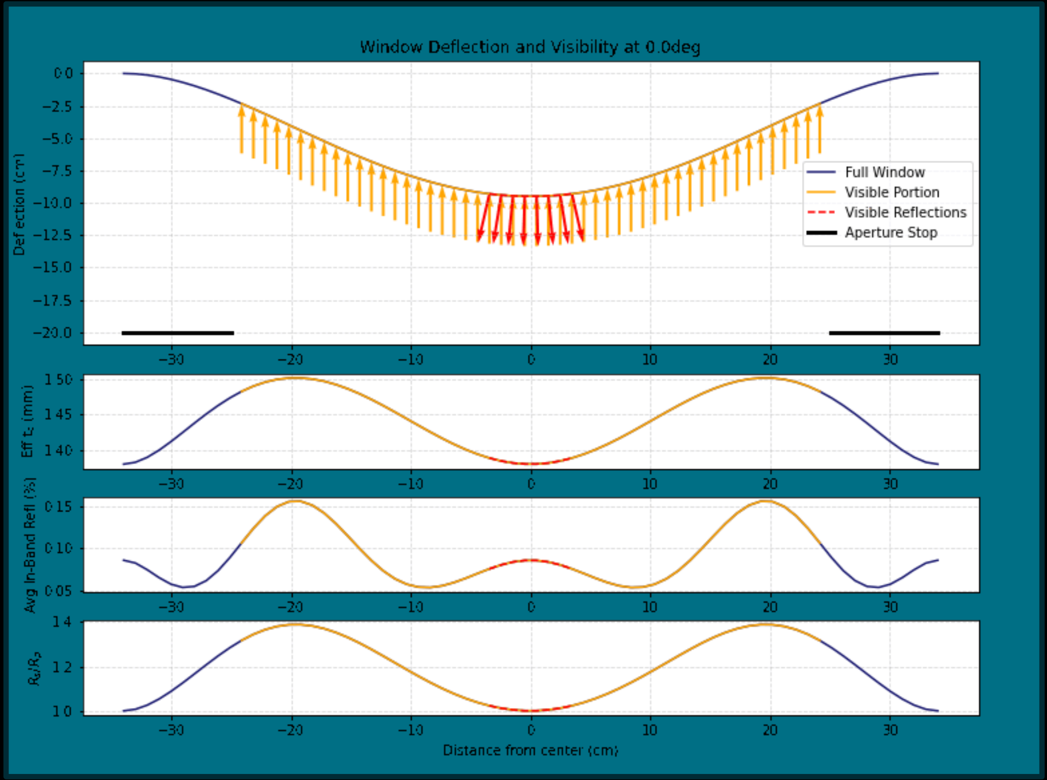
What can the detectors see?



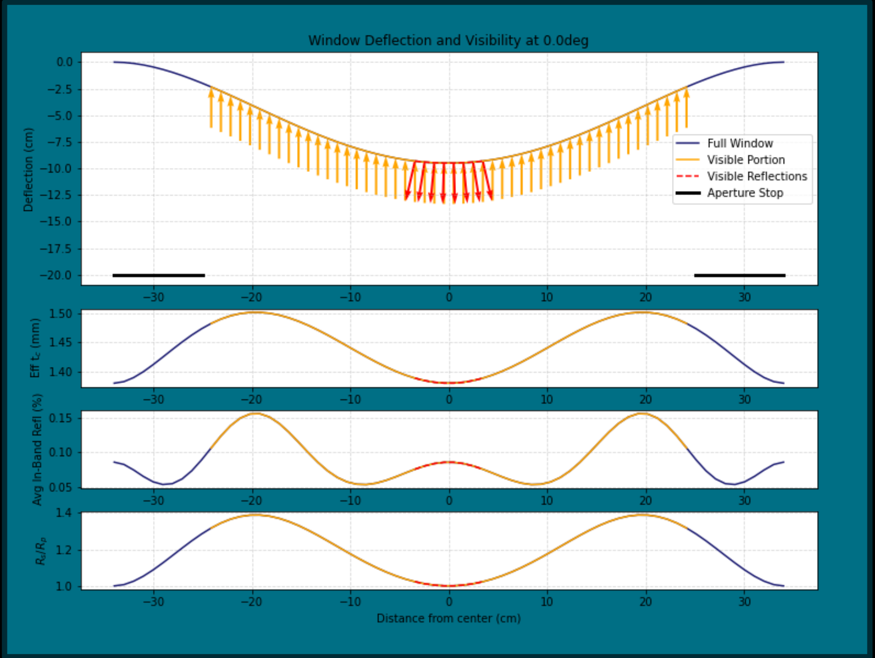
About +/- 15 deg
visible from aperture
stop

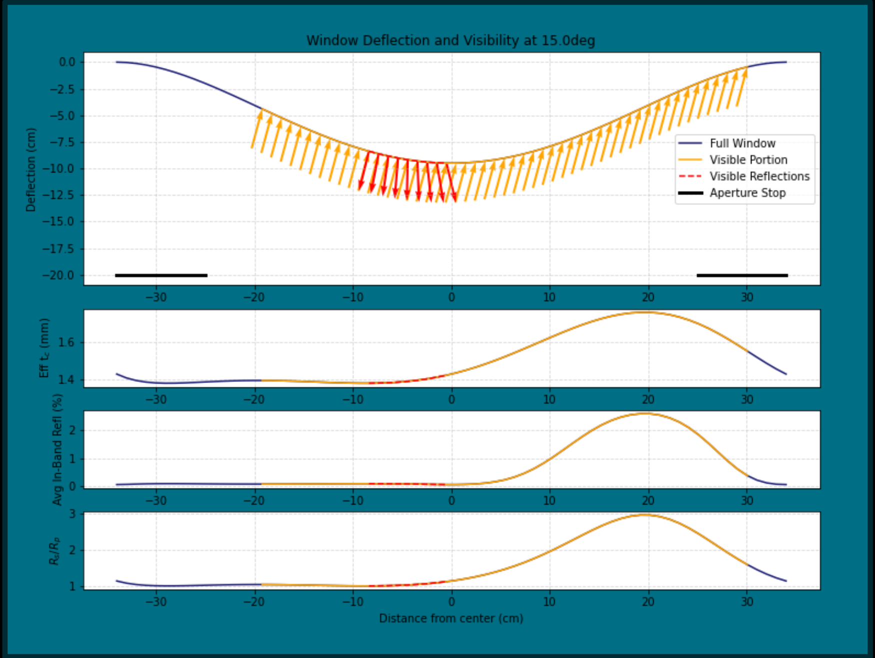
Moncelsi, et al. *Receiver development for BICEP Array, a next-generation CMB polarimeter at the South Pole* (2020)

How does the reflection change?

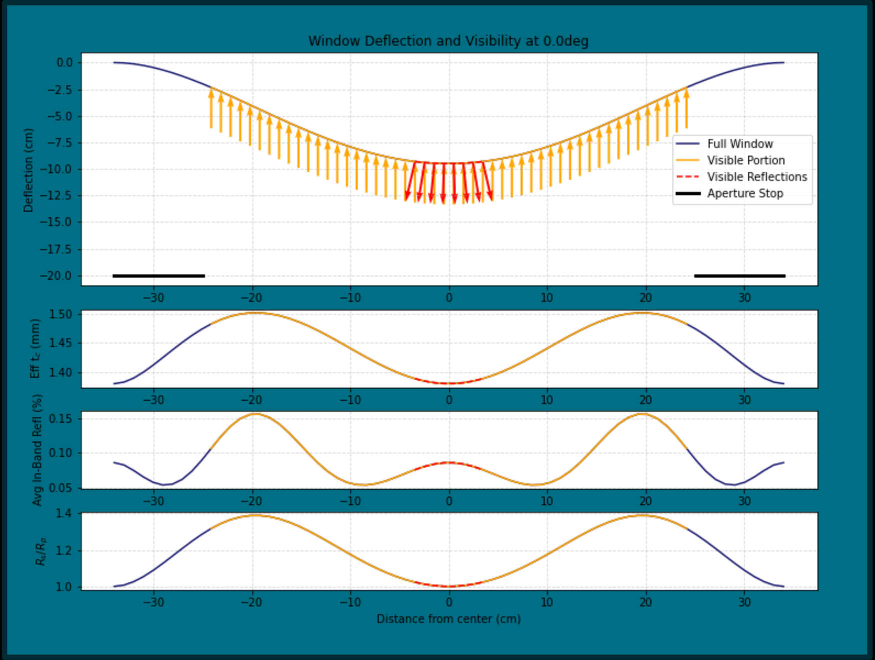


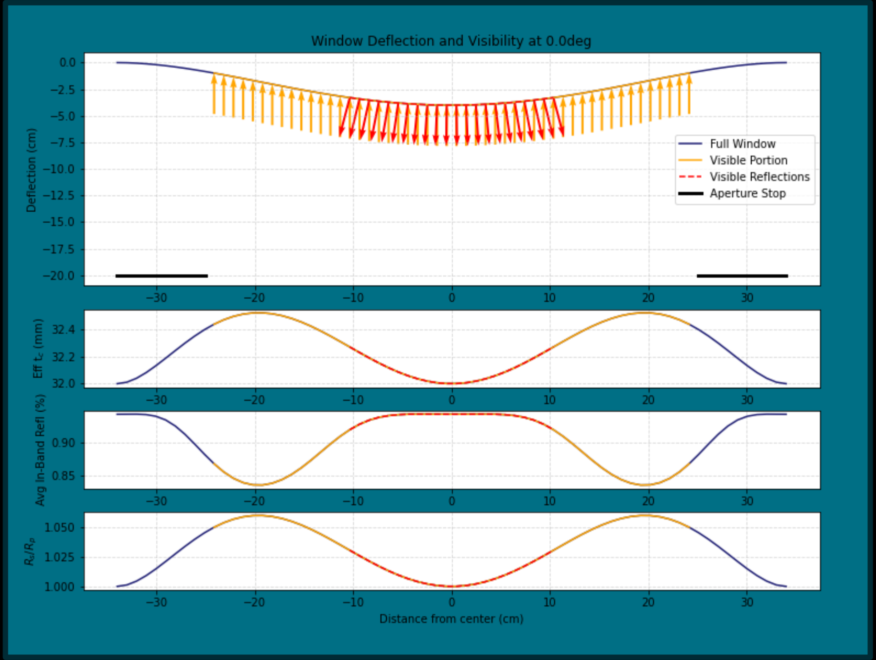
How does the reflection change?



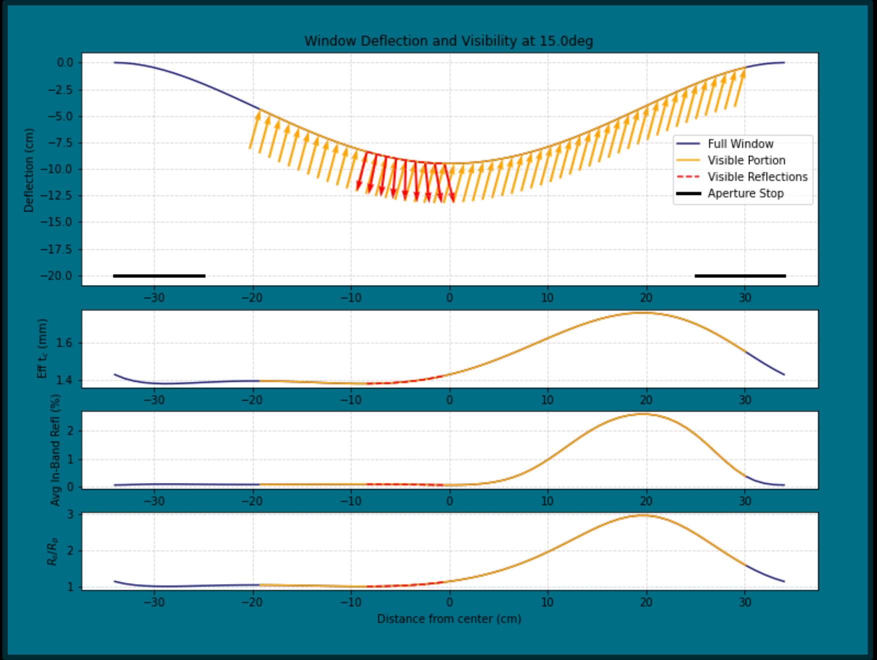


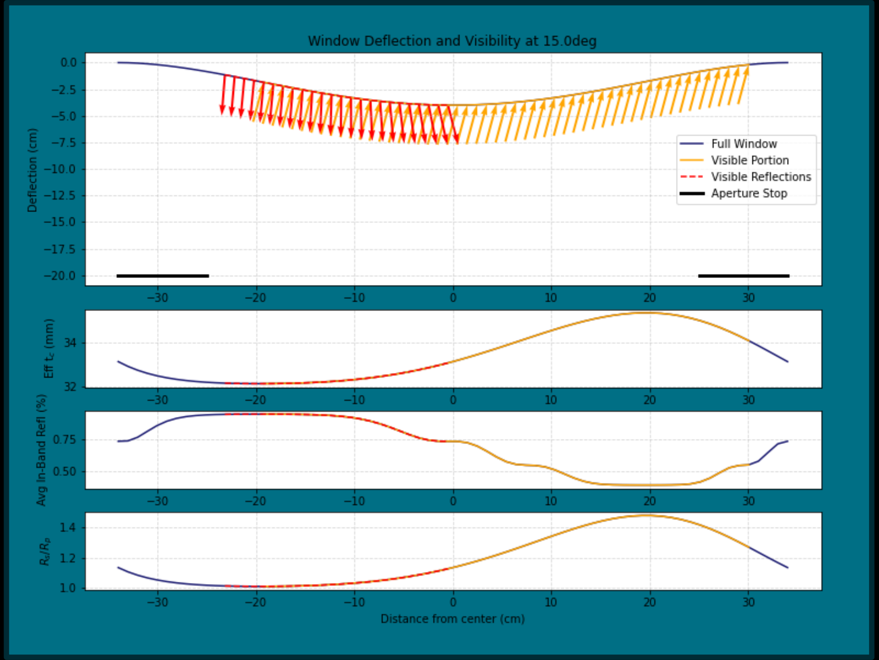
How does this compare to the last window?





How does this compare to the last window?





Deflection and Reflection Requirements

- This is mostly a thought exercise of ‘how bad does it get’?
  - The answer is ‘not that bad, honestly!’

REQUIREMENT: Model to check for problems

It takes a village to build a telescope!