T. Matsumura (ISAS/JAXA)

CMB telescope and the design consideration toward a next generation satellite mission

Introduction

- Design of the optical system
- Heritage of the past CMB telescopes
- Design consideration toward the next space mission

Design of the optical system

The list of the requirements and constraints to design the optical system to the next generation CMB telescope.

Requirements from science

- Beam size
- Field-of-view
- Observing band
- Beam qualities
    - Main lobe
    - Near-sidelobe
    - Far-sidelobe
- Beam calibration capability
- Temperature

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Potential constraints

- Size (mirror/lens/filters/HWP…)
- Telecentric focal plane
- Available mount
- Cooling capability
- Where to define the aperture
- Mass
- Power
- Budget

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Design parameters

- Aperture size
- F/#
- The # of optical elements and its shapes
- Feed
- …

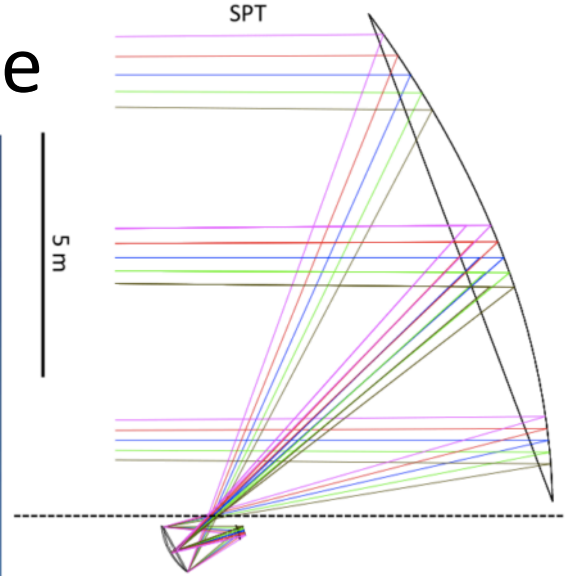
Examples of the optical system

Experiment	Type[a]	N_{feeds}[b]	N_{det}[c]	Optical Design	Plat.[d]	Reference
Isotropometer	Dicke-switched	2	1	Feed	Gnd	Wilkinson & Partridge (1967)
Stanford	Dicke-switched	2	2	Parabola	Gnd	Conklin & Bracewell (1967)
Crawford Hill	Maser	1	1	Horn/reflector	Gnd	Wilson & Penzias (1967)
Aerospace	Coherent	2	2	4.6 m telescope	Gnd	Epstein (1967)
White Mountain	Coherent	2	2	Dicke-switch 2 feeds	Gnd	Conklin (1969b)
Ratan	Coherent	1	1	Parabolic	Gnd	Pariiskii & Pyatunina (1971)
KaDip	Dicke-switched	2	2	Feeds	Gnd	Boughn et al. (1971)
XBal	Dicke-switched	2	2	Feeds	Bal	Henry (1971)
NRAO-P	Parametric amp	2	2	140ft Greenbank Centered Cass.	Gnd	Parijskij (1973)
Goldstone	Maser	1	1	64m Goldstone Centered Cass.	Gnd	Carpenter et al. (1973)
Parkes	Correlation	2	2	64m Parkes Centered Cass.	Gnd	Stankevich (1974)
U2	Dicke-switched	2	2	Two corrugated feeds	Plane	Smoot et al. (1977)
Testa-Griga	Bolometers	1	1	Cass	Gnd	Caderni et al. (1977)
Greenbank-R	Parametric amp	2	2	Cass	Gnd	Rudnick (1978)
MIT	Bolometers	2	2	Two 0.4m sph refl + flat + lightpipe	Bal	Muehlner (1977)
KKaQBal	Dicke-switched	2	2	Feeds	Bal	Cheng et al. (1979)
PolCMB	Coherent (P)	1	1	First pol	Gnd	Nanos (1979)
KPRO	Coherent	1	2	11m Cas	Gnd	Partridge (1980)
Convair	Bolometer	1	1	lens/feed on FTS with chopper	Plane	Fabbri et al. (1980b)
DBal	Bolometer	1	1	Lens/feed	Bal	Fabbri et al. (1980a)
NRAO91	Coherent	2	2	91m NRAO	Gnd	Ledden et al. (1980)
OVRO40	Coherent	2	2	OVRO 40m	Gnd	Seielstad et al. (1981)
GBank-UW	Coherent	1	1	140ft GB	Gnd	Uson & Wilkinson (1982)
MaserBal	Maser	2	1	Dicke switch	Bal	Fixsen et al. (1983)
WBal	Mixer	1	1	Dicke-switched chopper	Bal	Lubin et al. (1983)
JodrellBank	Coherent	2	2	Prime focus of 100ft MkII telescope	Gnd	Lasenby & Davies (1983)
Relikt	Parametric amp	2	2	Two feeds	Sat	Strukov & Skulachev (1984)
NCP	Coherent	2	2	Dicke switch w/ feed-fed parabolas	Gnd	Mandolesi et al. (1986)
Tenerife	Coherent	2	2	Two feeds with chopping plate	Gnd	Davies et al. (1987)
IAB-I	Bolometer	1	1	1m parabola	Ant	dall'Oglio & de Bernardis (1988)
MITBal2	Bolometer	2	4	Horns and chopper	Bal	Halpern et al. (1988)
OVRO	Maser	2	1	OVRO 40 m	Gnd	Readhead et al. (1989)
SKInt	Mixer	2	2	2 feeds	Int	Timbie & Wilkinson (1990)
FIRS	Bolometer	1	4	Single cryogenic horn/lens	Bal	Page et al. (1990)
ARGO	Bolometer	1	4	1.2 m Centered Casegrain	Bal	de Bernardis et al. (1990)
SP/ACME	SIS Mixer	1	1	1m Decentered Gregorian	Ant	Meinhold & Lubin (1991)
COBE	Coherent	10	12	Feeds	Sat	Smoot et al. (1991)
SP/ACME	HEMT	1	1	1m Decentered Gregorian	Ant	Gaier et al. (1992)
19GHz	Maser	1	1	Feed plus lens	Bal	Boughn et al. (1992)
MAX	Bolometer	3	3	Same as SP/ACME	Bal	Alsop et al. (1992)
IAB-II	Bolometer	1	1	0.45 m Decentered Cassegrain	Ant	Piccirillo & Calisse (1993)
White Dish	Bolometer	1	1	1.2 m Centered Cassegrain	Ant	Tucker et al. (1993)
SASK	HEMT	1	1	1.2 m Off-axis parabola	Gnd	Wollack et al. (1993)
MSAM	Bolometers	1	4	1.4m Decentered Cassegrain	Bal	Cheng et al. (1994)
PYTHON	Bolometers	4	4	Off-axis parabola	Ant	Dragovan et al. (1994)
CAT	Coherent	3	6	Int	Gnd	O'Sullivan et al. (1995)
BAM	Bolometer	2	2	FTS with Off-axis parabola	Bal	Tucker et al. (1997)
SuZIE	Bolometer	6	6	CSO	Gnd	Ganga et al. (1997)
IAC-BAR	Bolometer	4	4	0.45m Decentered Para/hyper	Gnd	Piccirillo et al. (1997)
QMAP	HEMT	3	6	Feed + parabolic reflector	Bal	de Oliveira-Costa et al. (1998)
Toco	HEMT/SIS	5	8	Feed + parabolic reflector	Gnd	Miller et al. (1999)
JB-IAC	HEMTs	2	2	Feed plus reflector	Int	Dicker et al. (1999)
HACME	HEMT	1	1	Decentered Greg.	Bal	Staren et al. (2000)
Viper	HEMT	2	2	Decentered Aplanatic Greg. with chopper	Ant	Peterson et al. (2000)
RING5M	HEMT	2	1	5.5m/40m OVRO Centered Cass.	Gnd	Leitch et al. (2000)
BOOMERANG	Bolometers	16	16	Decentered Greg., w/tert.+lenses	Bal	de Bernardis et al. (2000)
MAXIMA	Bolometers	16	16	Decentered Greg.	Bal	Hanany et al. (2000)
PIQUE	HEMT (P)	1	2	1.2m Off-axis parabola	Gnd	Hedman et al. (2001)
POLAR	HEMT (P)	1	2	Cryo feed	Gnd	Keating et al. (2001)
CBI	HEMTs	13	13	Centered Cass.	Int	Padin et al. (2001)
DASI	HEMTs	13	13	Feeds	Int	Halverson et al. (2002)
Archeops	Bolometers	21	21	Decentered Greg.	Bal	Benoît et al. (2003)
COMPASS	HEMT (P)	1	2	2.6m Centered Cass.	Gnd	Farese et al. (2003)
VSA	HEMTs	14	14	Feeds+ Off-axis parabolas	Int	Grainge et al. (2003)
WMAP	HEMTs	20	40	Decentered Greg.	Sat	Bennett et al. (2003)
Acbar	Bolometers	16	16	Decentered Aplan. Greg. w/ chopper	Ant	Kuo et al. (2004)
BEAST	HEMT	8	8	2 m Decentered Greg.	Bal	Meinhold et al. (2005)
CAPMAP	HEMT (P)	16	32	7m Decentered Cassegrain	Gnd	Barkats et al. (2005)
MINT	Mixers	4	4	30 cm Cass.	Int	Fowler et al. (2005)
MAXIPOL	Bolometer (P)	16	16	Decentered Greg.	Bal	Johnson et al. (2007)
QUAD	Bolometer (P)	31	62	Centered Cass. w/lenses	Ant	Ade et al. (2008)
WMPol	HEMT (P)	4	3	2.2 m Decentered Greg.	Ant	Levy et al. (2008)
SPT	TES Bolometer	966	966	Decentered Greg. w/lens	Gnd	Staniszewski et al. (2009)
BICEP	Bolometer (P)	49	98	Centered refractive	Ant	Chiang et al. (2010)
ACT	TES Bolometer	Planar	3072	Decentered Greg. w/lenses	Gnd	Fowler et al. (2010)
QUIET	HEMTs (P)	110	110	Cross-Dragone	Gnd	QUIET Collaboration et al. (2011)
Planck	HEMT/Bol (P)	47	74	1.6m aplanatic Gregorian	Sat	Tauber et al. (2010a)

[a] Detector technology. (P) indicated a design specifically for polarization.
[b] Number of feeds
[c] Number of independent detectors
[d] Platform. Gnd = ground; Bal = balloon; Sat = satellite; plane = airplane; Ant = Antarctica; Int = interferometer

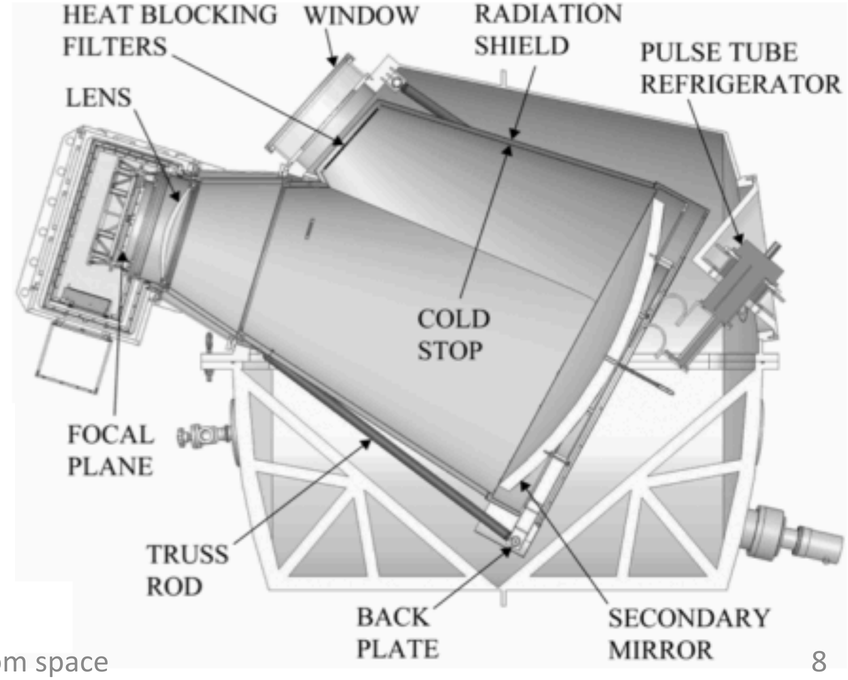
Table 5: CMB polarization and anisotropy experiments with comments on their optical and detector configurations. Much of the information about experiments prior to 2000 is adapted from "Finding the Big Bang" (Peebles et al., 2009). We include only instruments with astrophysical results as this indicates some level of the maturity of the design. Except for Planck, the citations are for the first astrophysical result from the instrument.

South Pole Telescope



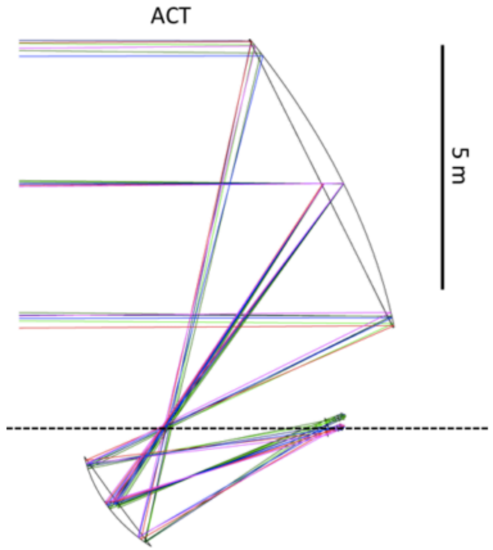
	ACT	SPT
D_p (m)	6	10
D_i (m)	5.6	7.5
D_s (m)	2	1
F_G	2.5	1.3
Temperature Receivers		
F_{temp}	0.9	1.3
$F\lambda_{150}$	0.5	1.7
$A\Omega_{R_{temp}}$ (cm^2 sr)	40	105
$A\Omega_{D_{eff}}$ (relative)	$\sim$2.5	1
Min. Strehl$_{150}$	0.97	0.89
FWHM$_{150}$ (arcmin)	1.37	1.15
Polarization Receivers		
F_{pol}	1.4	1.3
$F\lambda_{150}$	1.4	1.6
$A\Omega_{R_{pol}}$ (cm^2 sr)	180	140

SPT Receiver Overview



	ACT	SPT
Primary shape	Ellipsoid	Paraboloid
Easily reconfigurable	No	Yes
Stop type	Primary image	Secondary reflector
Cold stop Temperature	1 Kelvin	10 Kelvin
Refractive optics	3 Silicon lenses per array	HDPE lens
Temp. array coupling	Filled focal plane	Conical feedhorns
Pol. array coupling	Corrugated feedhorns	Corrugated & profiled feedhorns

Atacama Cosmology Telescope (ACT)



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Min. Strehl$_{150}$	0.97	0.89
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F_{pol}	1.4	1.3
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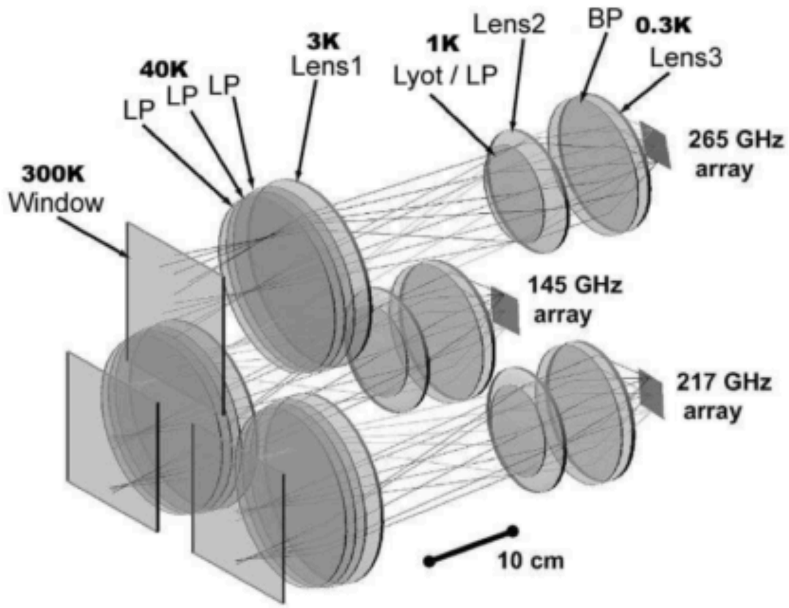
ACT Receiver Optics



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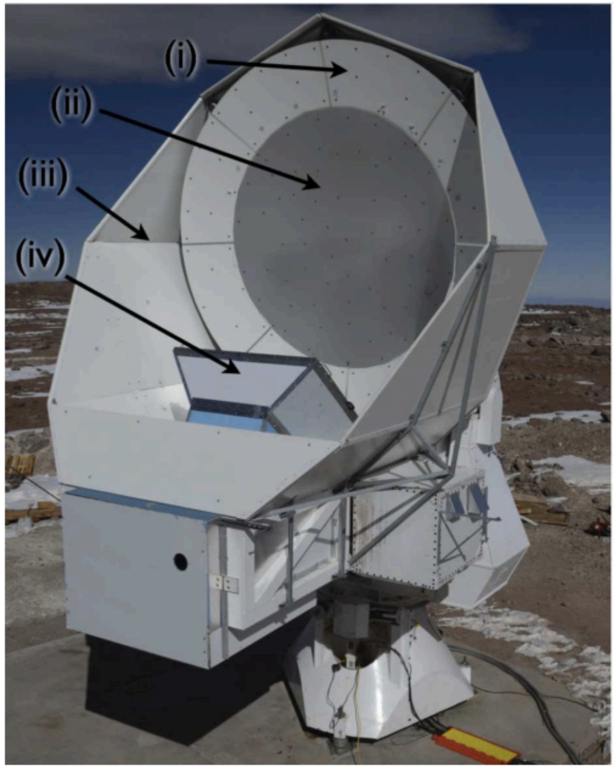
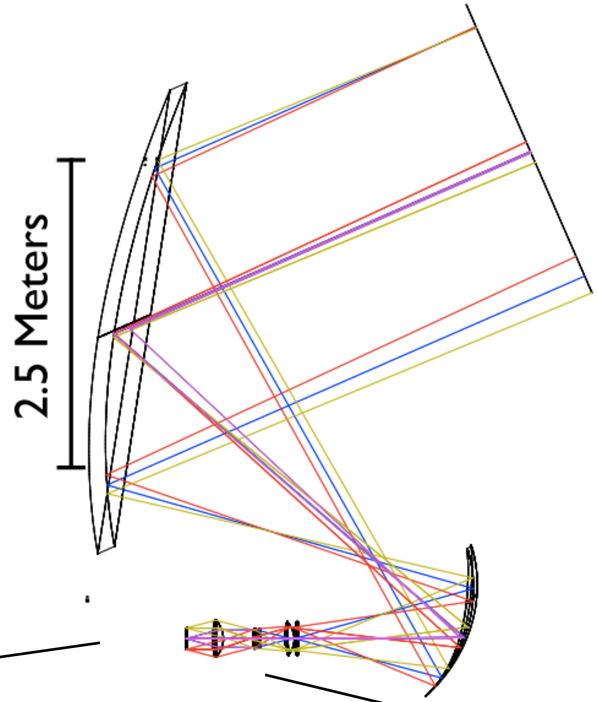
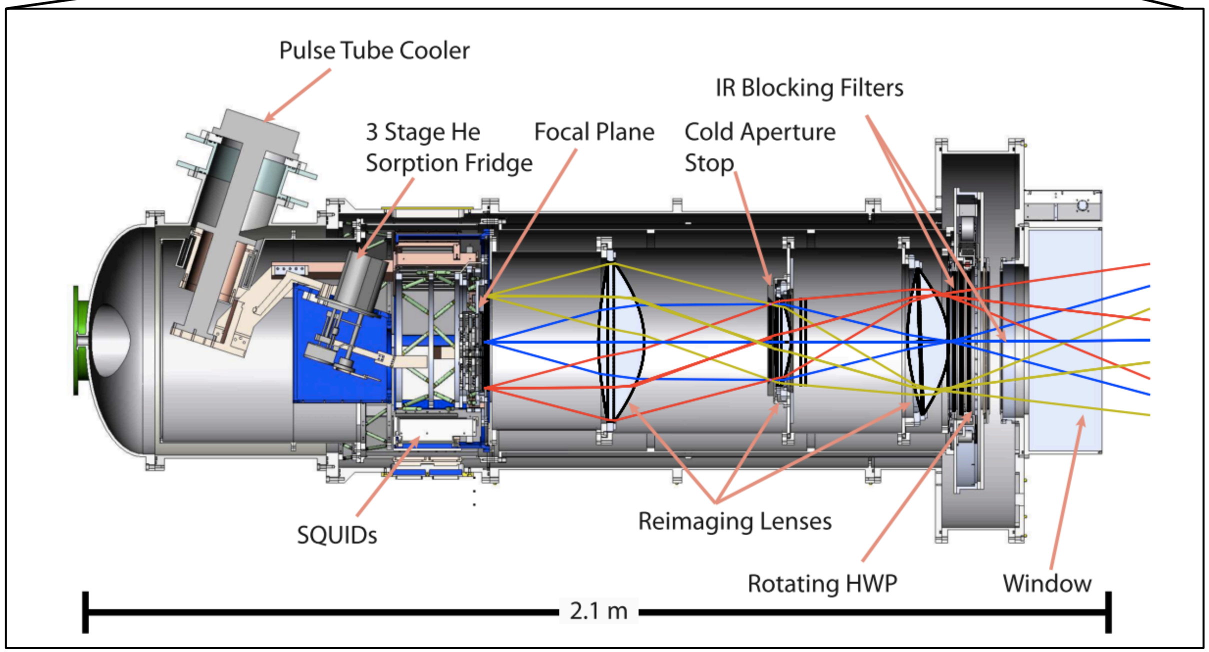
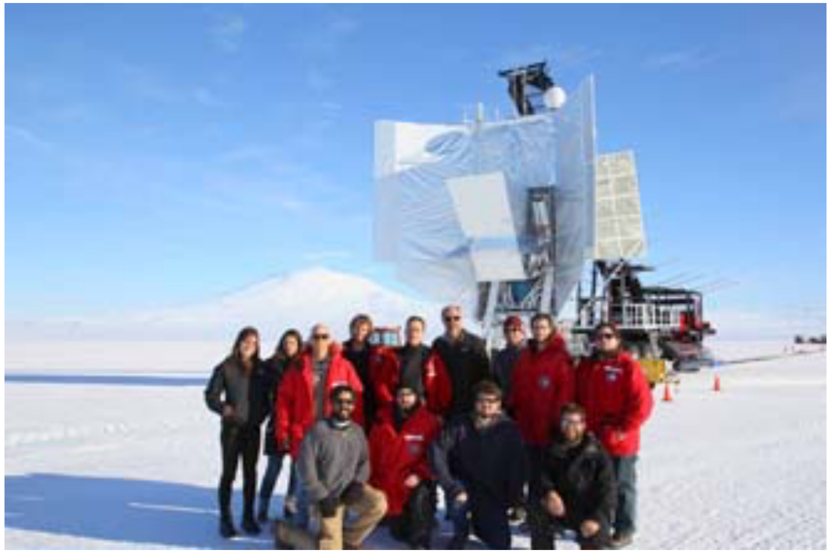
POLARBEAR Huan Tran Telescope

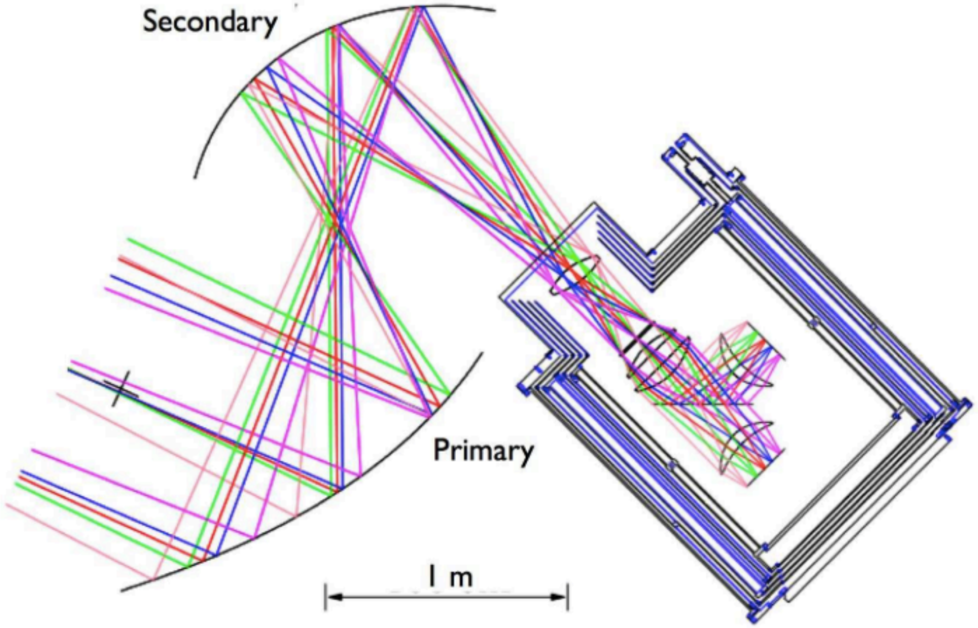




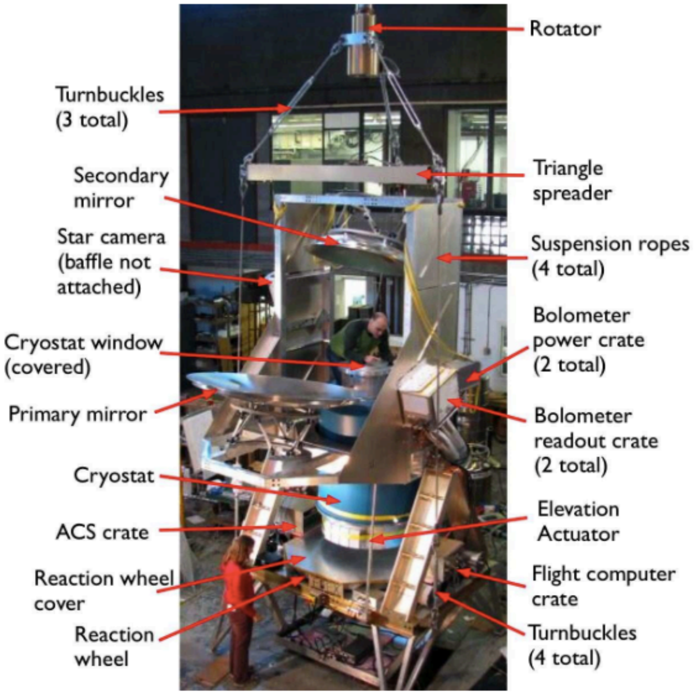


EBEX

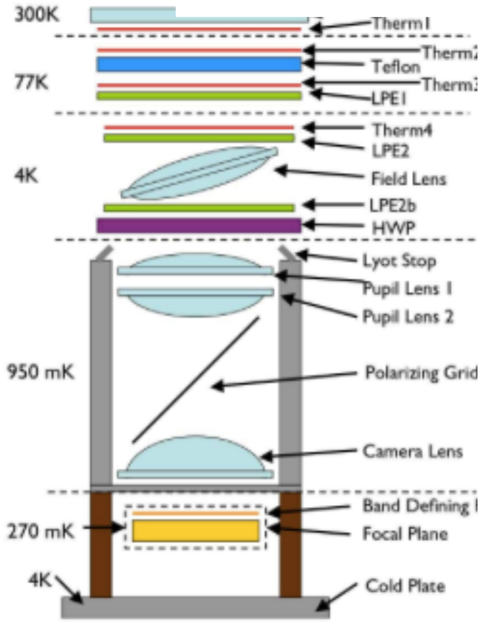




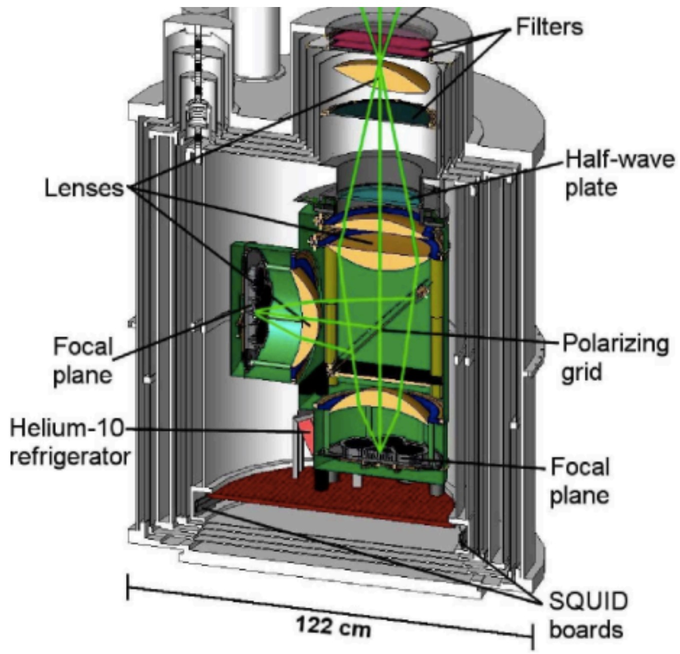
Secondary
Primary
1 m



Rotator
Turnbuckles (3 total)
Triangle spreader
Secondary mirror
Suspension ropes (4 total)
Star camera (baffle not attached)
Bolometer power crate (2 total)
Cryostat window (covered)
Primary mirror
Bolometer readout crate (2 total)
Cryostat
Elevation Actuator
ACS crate
Reaction wheel cover
Flight computer crate
Reaction wheel
Turnbuckles (4 total)

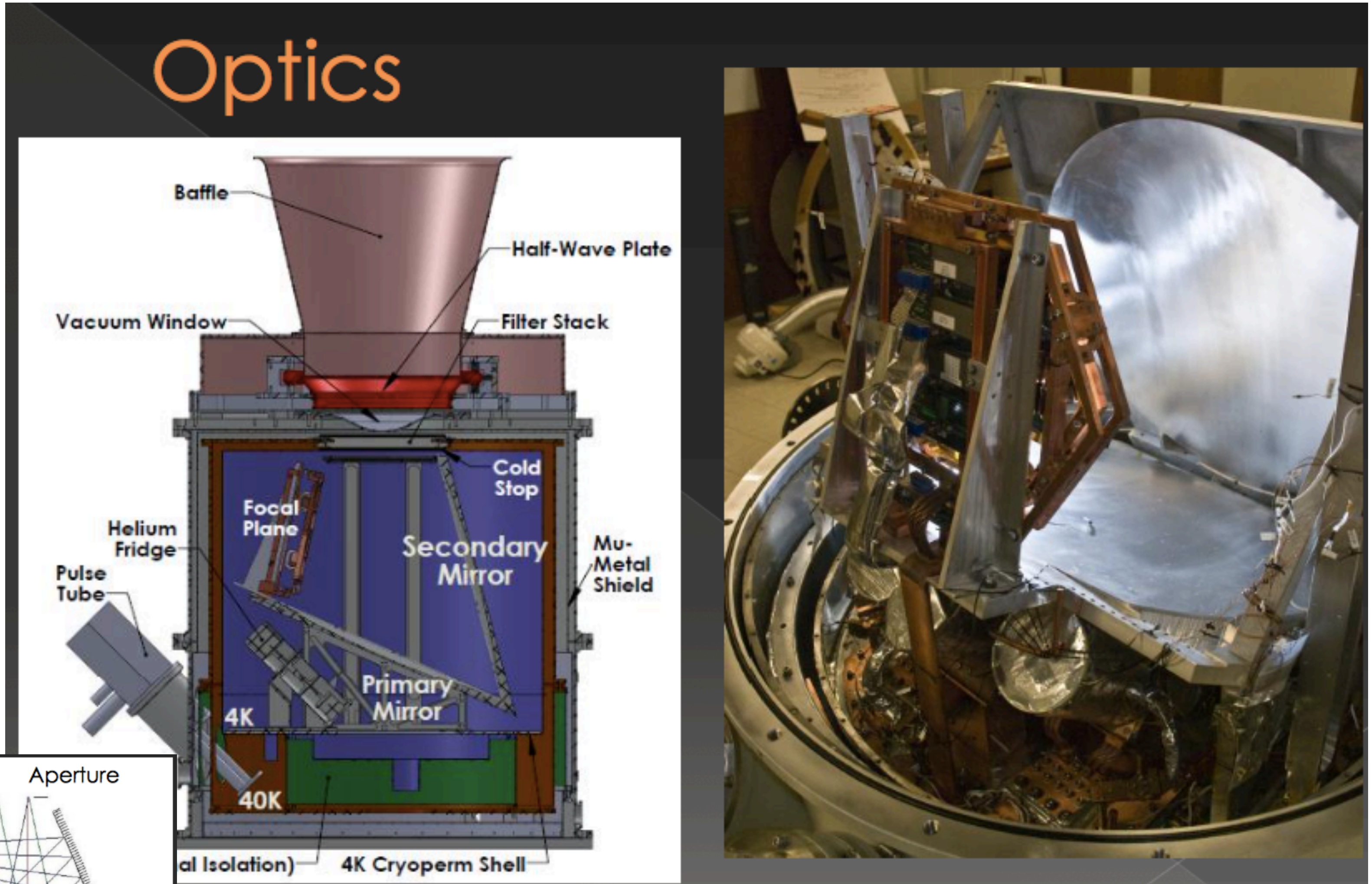


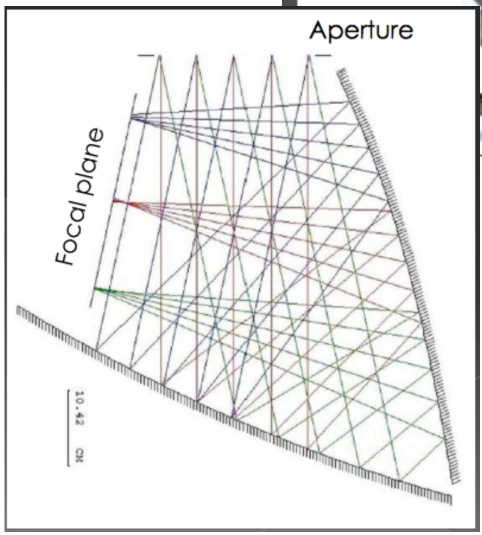
300K
Therm1
77K
Teflon
LPE1
4K
Therm4
LPE2
Field Lens
LPE2b
HWP
Lyot Stop
Pupil Lens 1
Pupil Lens 2
950 mK
Polarizing Grid
Camera Lens
270 mK
Focal Plane
4K
Cold Plate



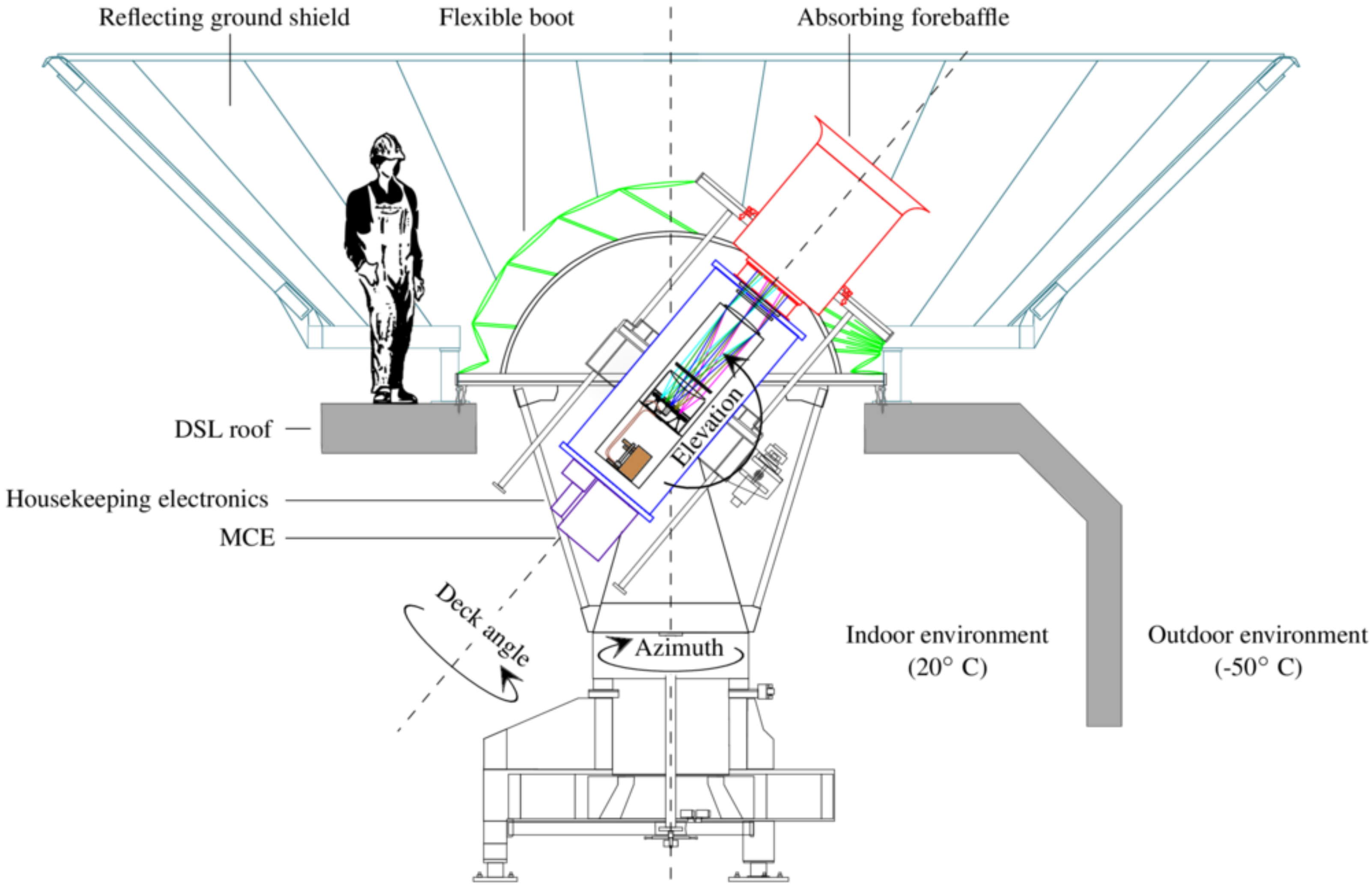
Filters
Lenses
Half-wave plate
Focal plane
Polarizing grid
Helium-10 refrigerator
Focal plane
SQUID boards
122 cm

ABS


Optics
Baffle
Half-Wave Plate
Vacuum Window
Filter Stack
Cold Stop
Focal Plane
Helium Fridge
Secondary Mirror
Mu-Metal Shield
Pulse Tube
Primary Mirror
4K
40K
al Isolation)
4K Cryoperm Shell

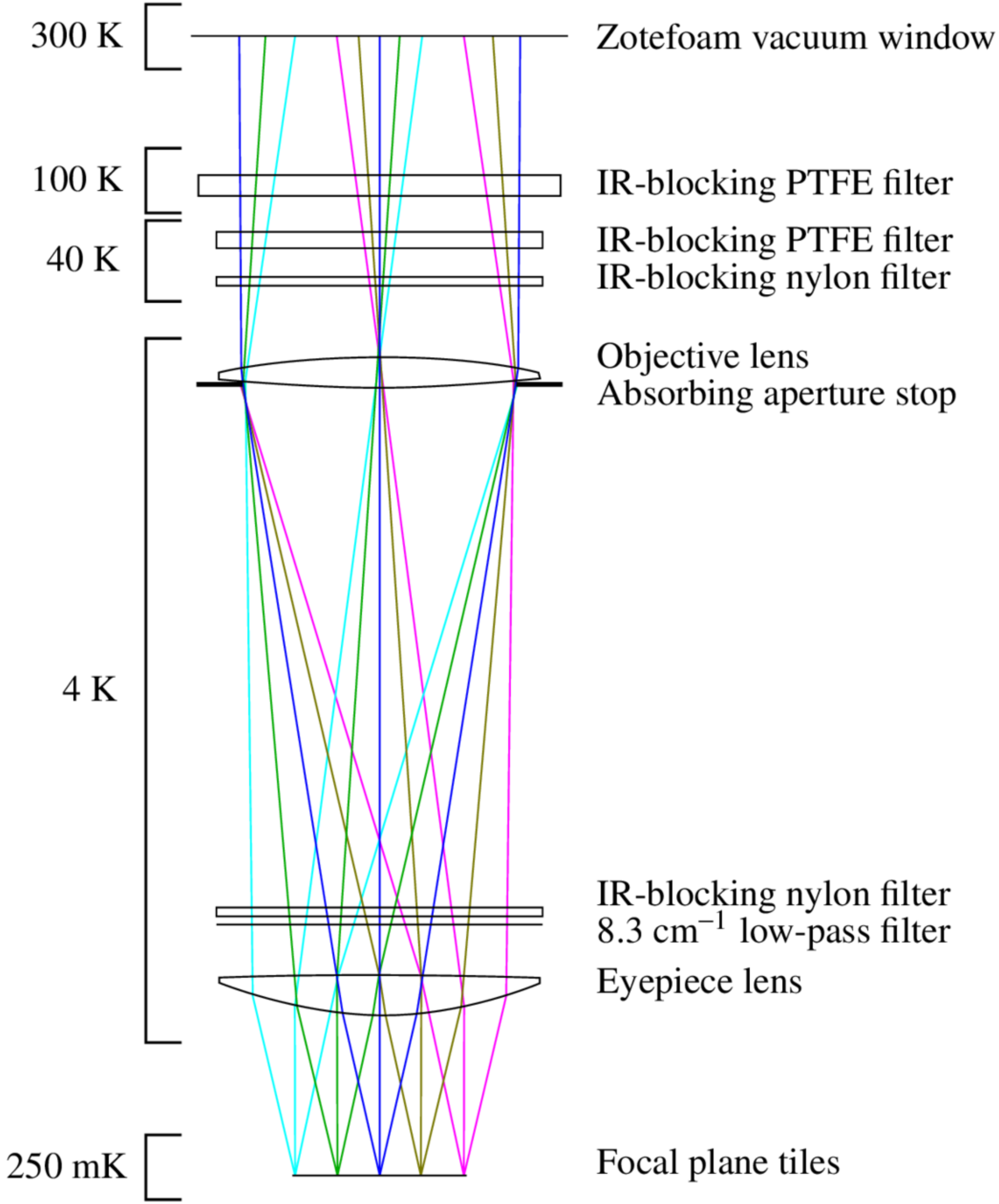

Aperture
Focal plane

BICEP

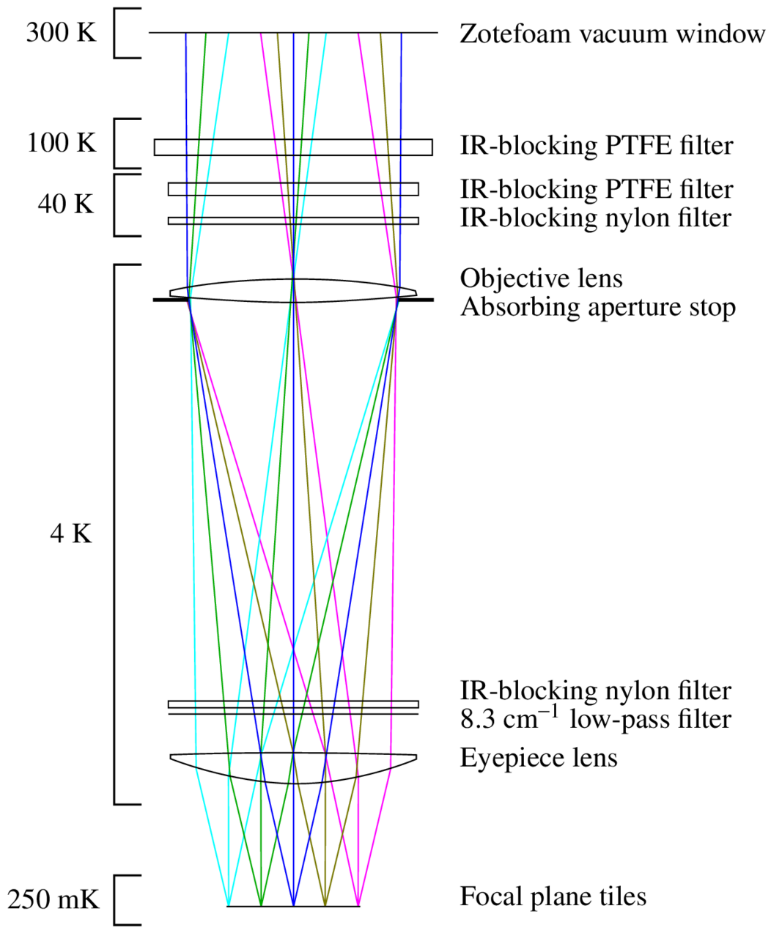


Reflecting ground shield
Flexible boot
Absorbing forebaffle
DSL roof
Housekeeping electronics
MCE
Elevation
Deck angle
Azimuth
Indoor environment
(20° C)
Outdoor environment
(-50° C)

BICEP/KECK


300 K
Zotefoam vacuum window
100 K
IR-blocking PTFE filter
40 K
IR-blocking PTFE filter
IR-blocking nylon filter
Objective lens
Absorbing aperture stop
4 K
IR-blocking nylon filter
8.3 cm^{-1} low-pass filter
Eyepiece lens
250 mK
Focal plane tiles

SPIDER


300 K
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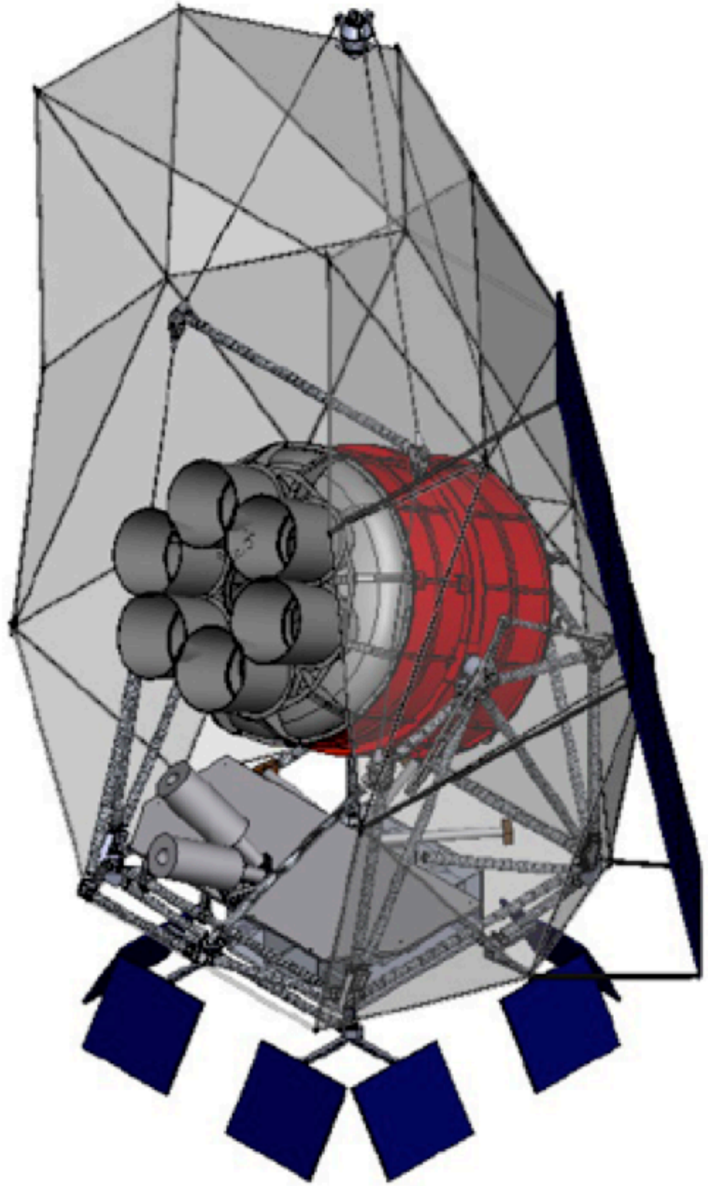
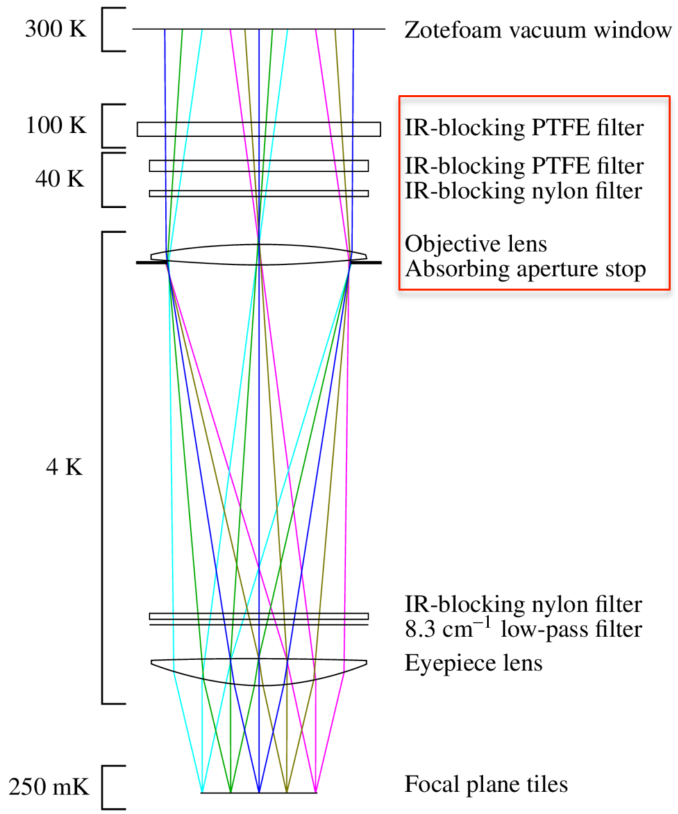
Focal plane tiles



BICEP3



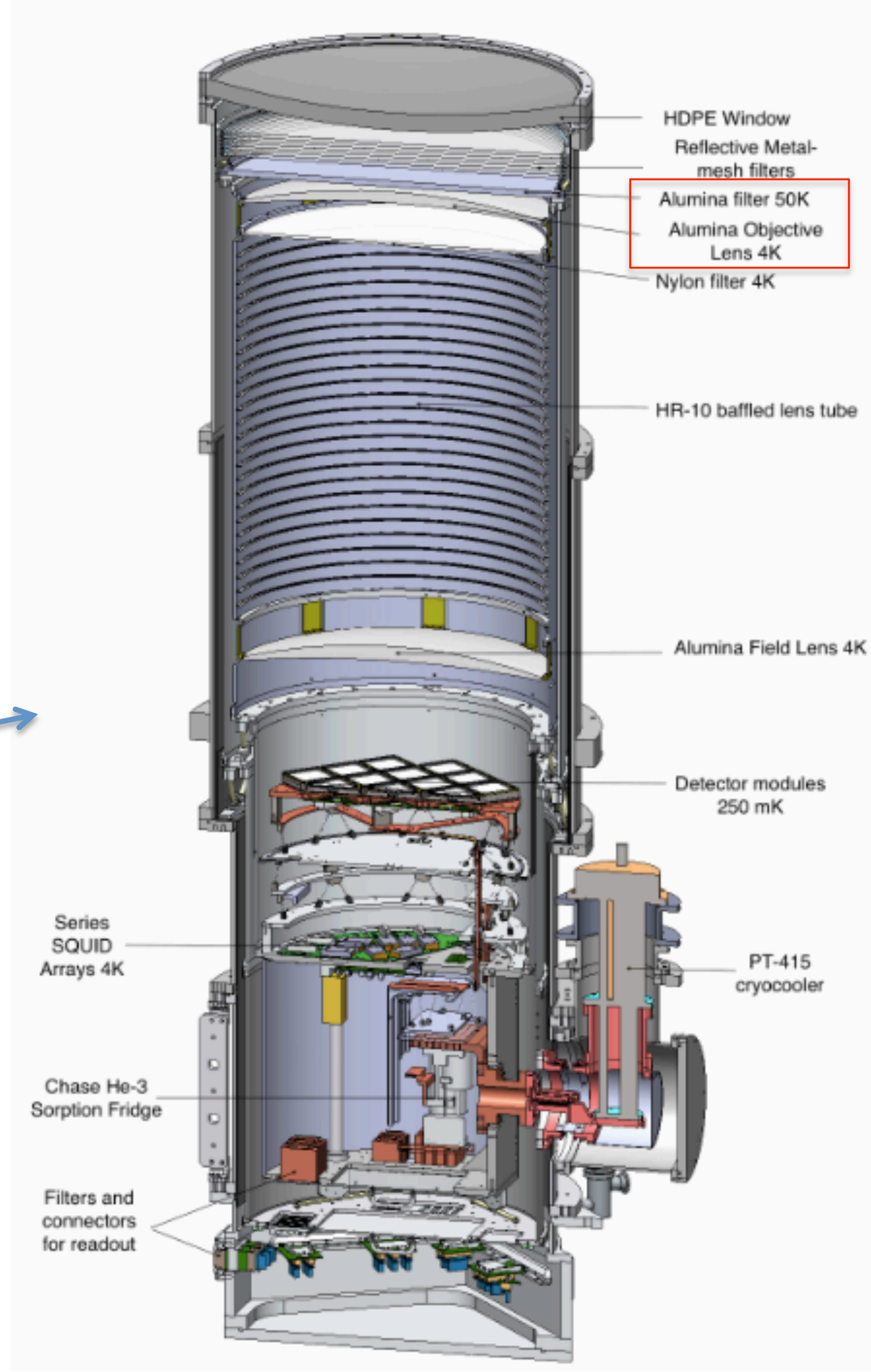
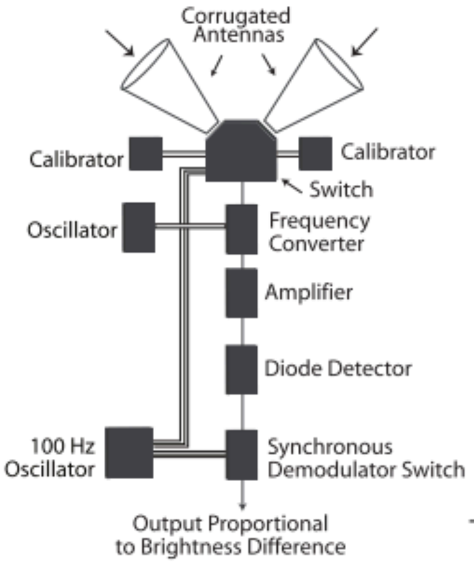
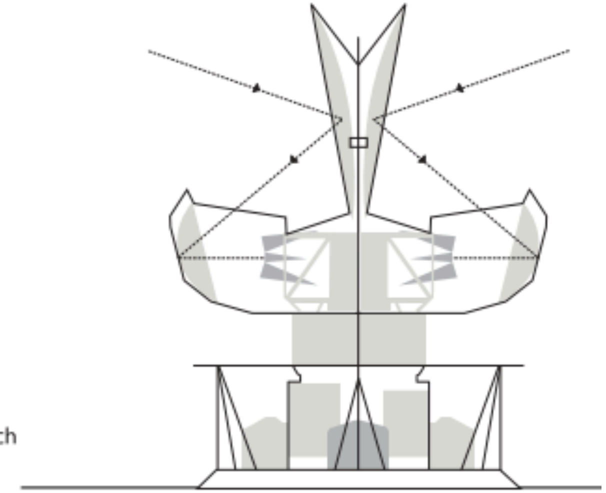


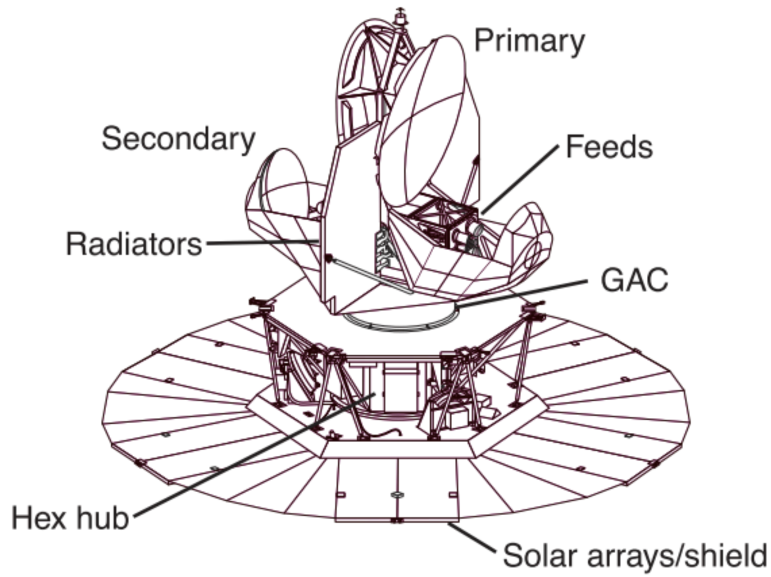
Figure 3. Cross section of BICEP3 receiver showing various components.



DMR

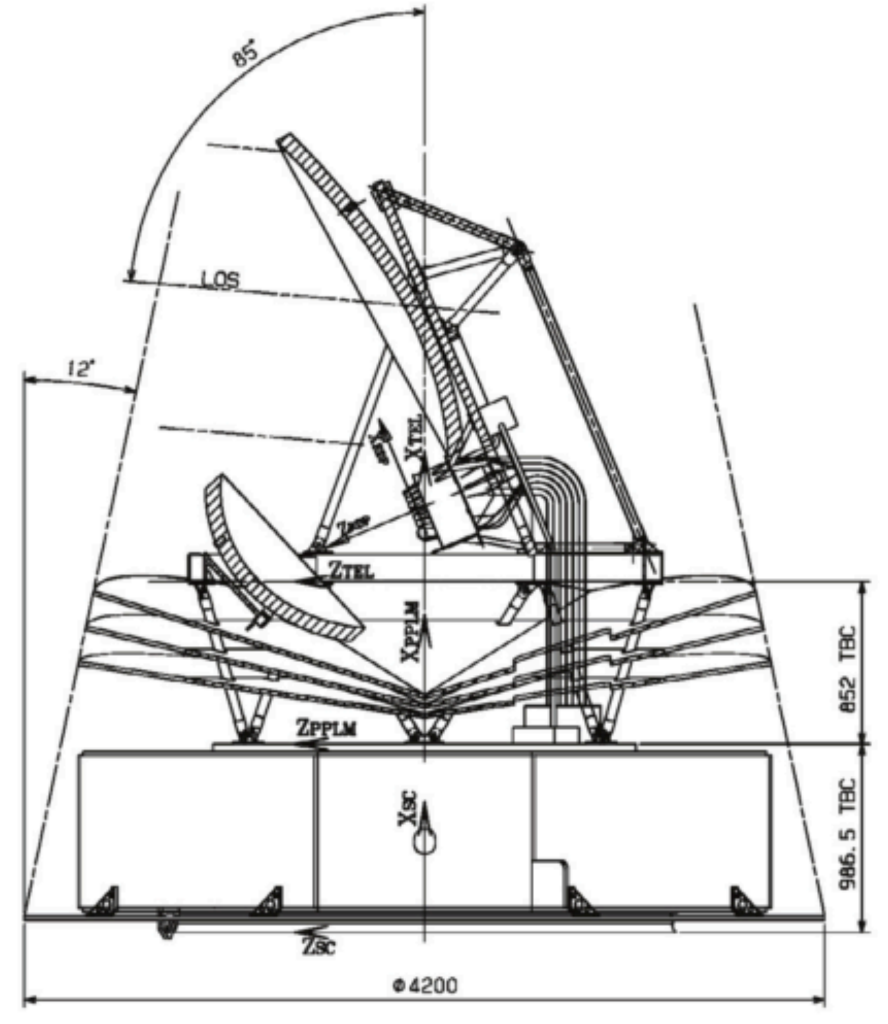


WMAP



Relikt (1983)				COBE (1989)				WMAP (2001)				Planck (2009)			
Freq GHz	N	S $mKs^{1/2}$	$\theta_{1/2}$ deg	Freq GHz	N	S $mKs^{1/2}$	$\theta_{1/2}$ deg	Freq GHz	N	S $mKs^{1/2}$	$\theta_{1/2}$ deg	Freq GHz	N	S $mKs^{1/2}$	$\theta_{1/2}$ deg
								22.7	2	0.49	0.82°				
												28.5	4	0.15	0.54°
				31.5	2	30	7°								
								33.0	2	0.51	0.62°				
37.5	1	25	5.8°												
								40.7	4	0.47	0.49°				
												44.1	6	0.16	0.47°
				53	2	11	7°								
								60.6	4	0.54	0.33°				
												70.3	12	0.13	0.22°
				90	2	16	7°								
								93.4	8	0.58	0.21°				
												100	8/4P	0.0173	0.16°
												143	12/4P	0.0084	0.12°
												217	12/4P	0.0068	0.078°
												353	12/4P	0.0055	0.074°
												545	4	0.0045	0.063°
												857	4	0.0019	0.061°

Planck: See the next talk



What's the path forward to the future B-mode telescope design and some considerations?

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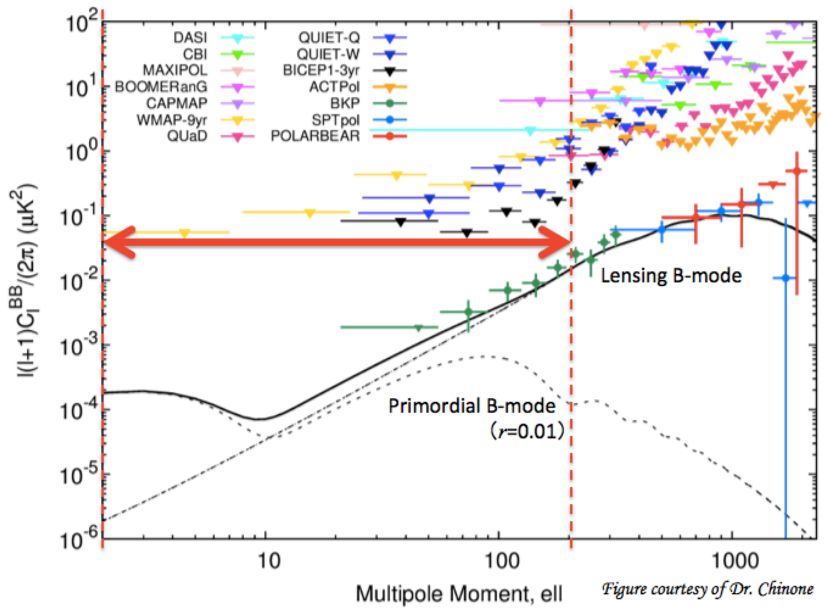

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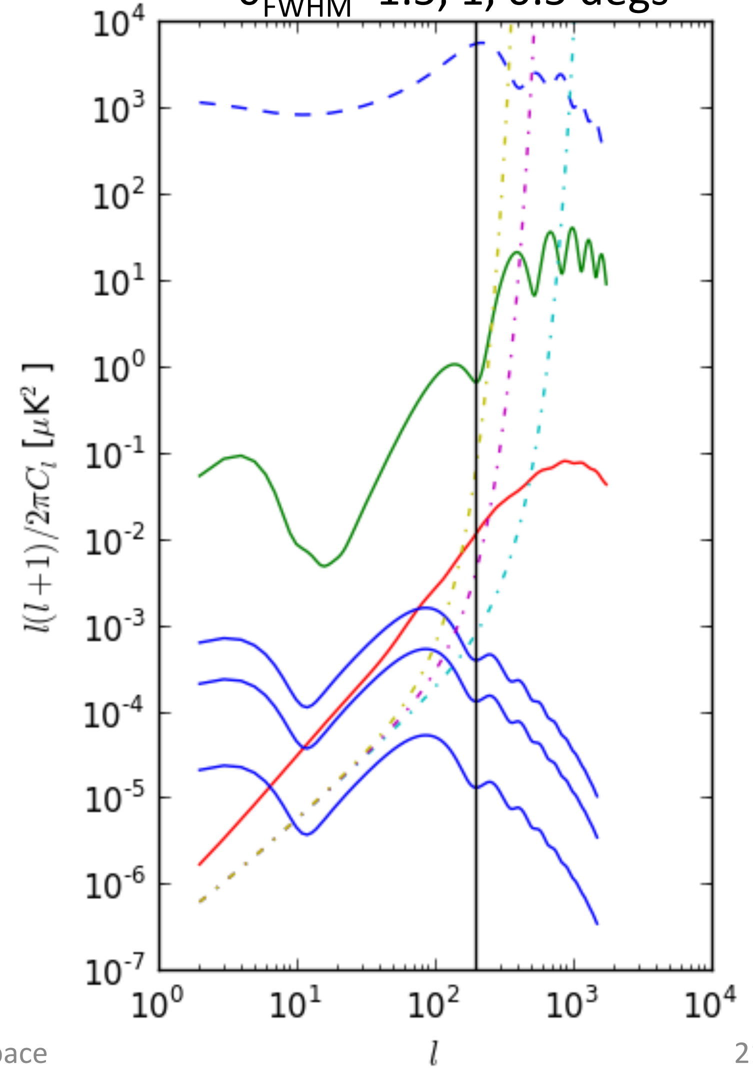
θ_{FWHM}=1.5, 1, 0.5 degs



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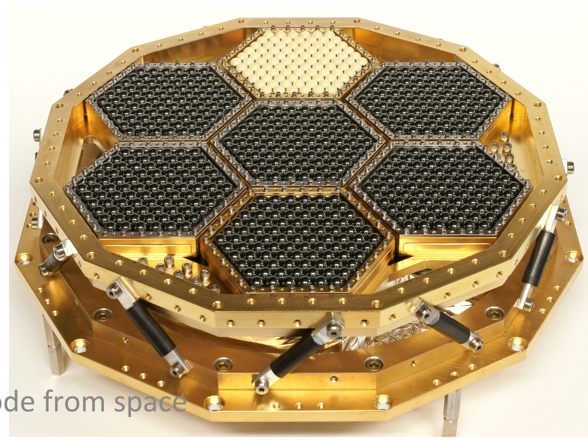
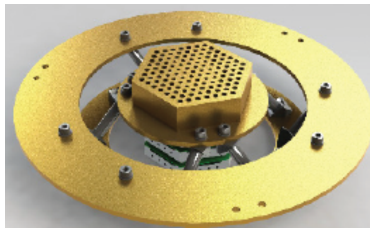
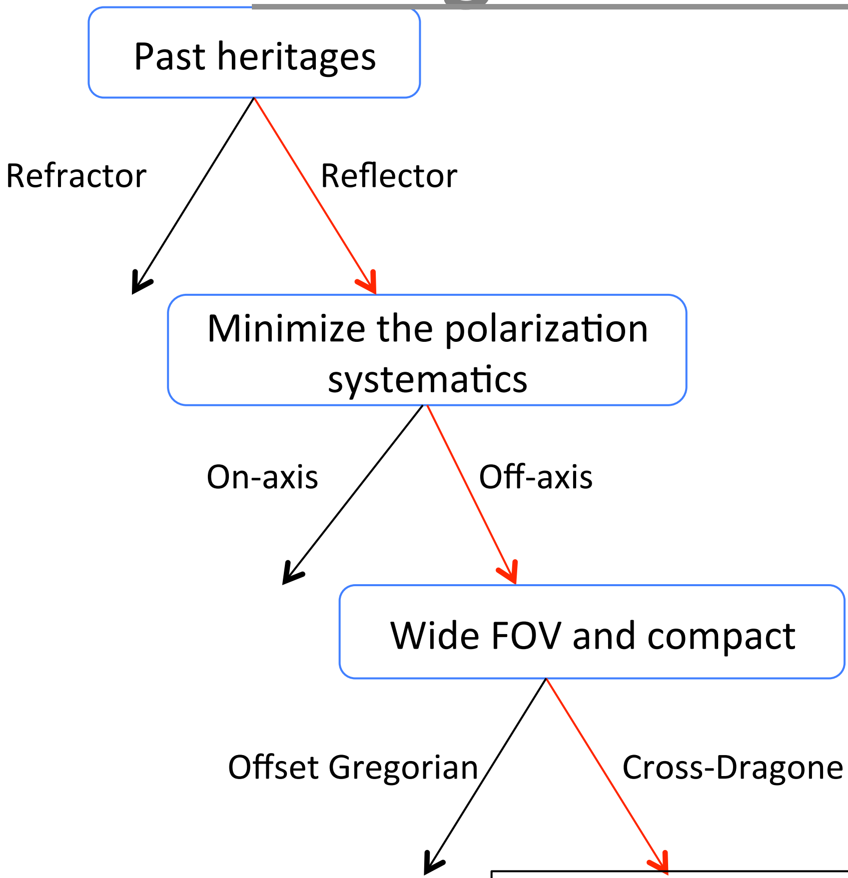
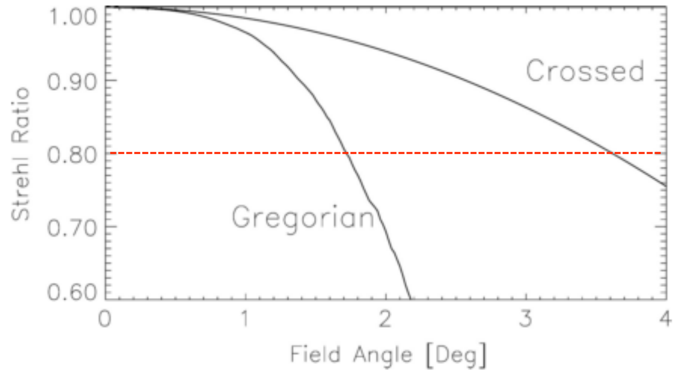
- Power
- Budget

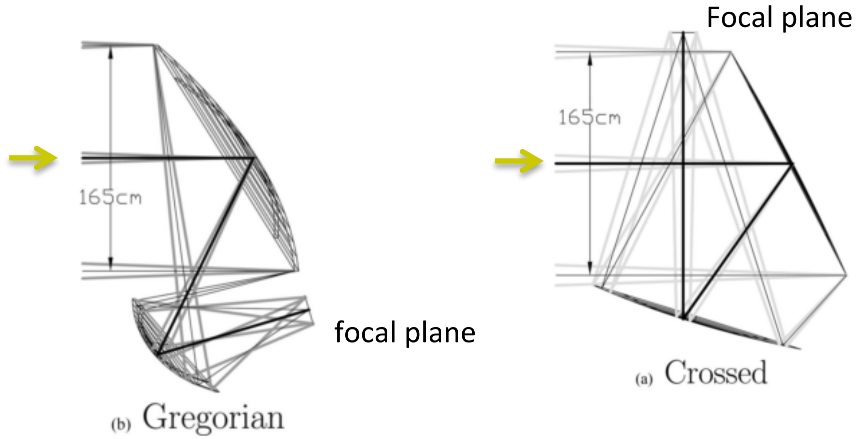




Design decision tree: example1



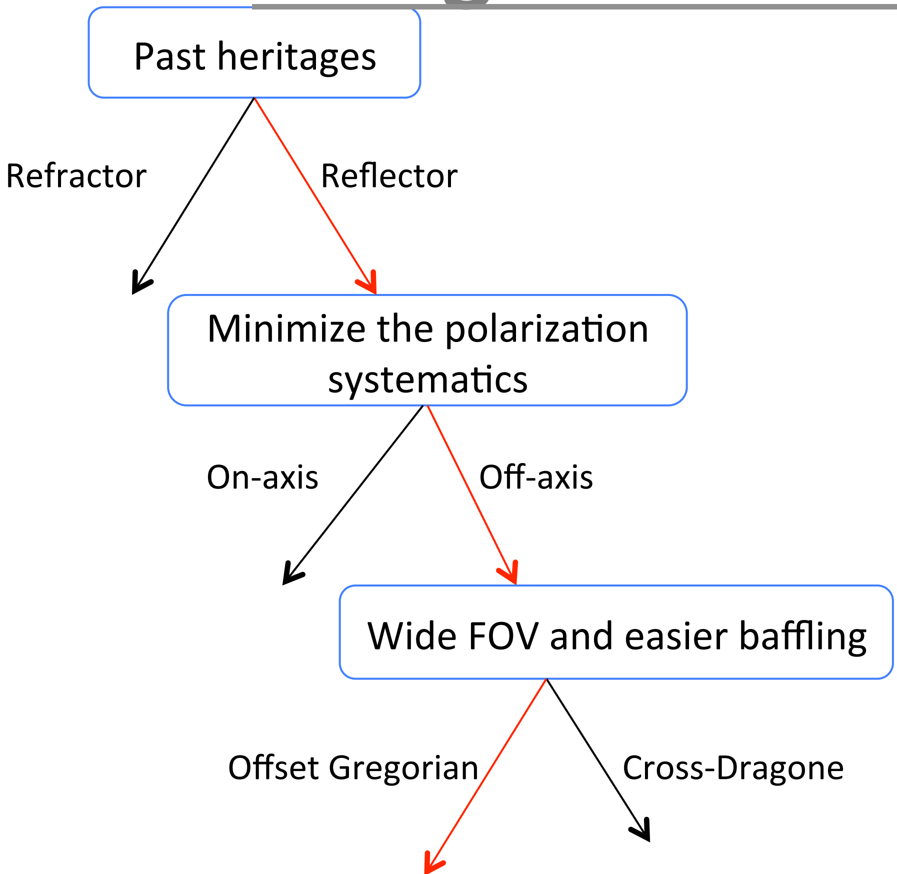


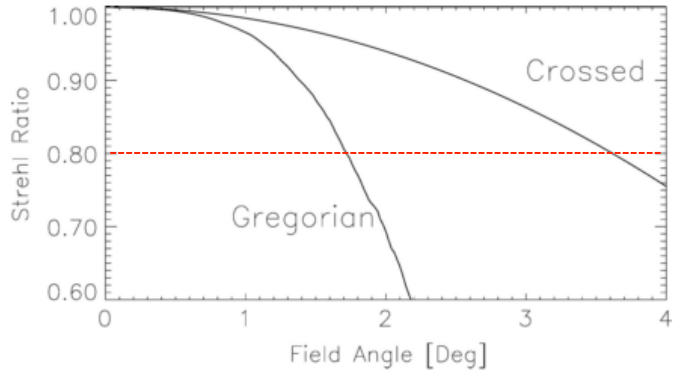


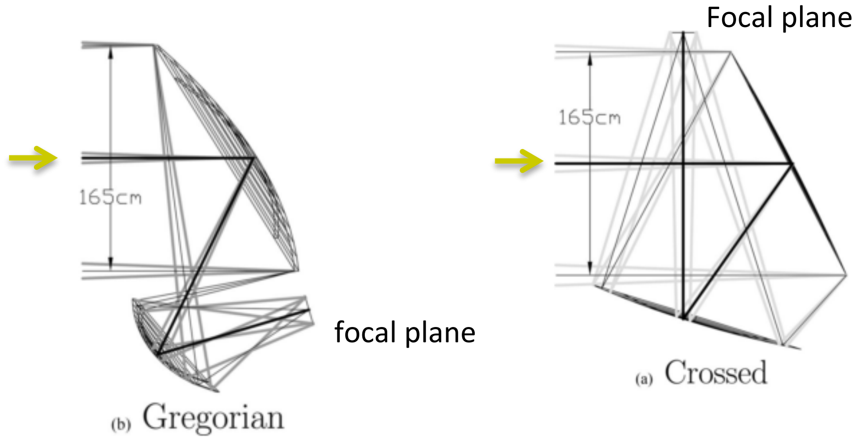
Remaining challenges

1. Optical design
2. Cross-Dragone configuration is known to be susceptible to the stray light, and thus the optical design should include the baffle design. Verification by GRASP and beam map type measurements.
3. Make the optical element broadband
4. Thermal and structural design and fabrication feasibility study

Design decision tree: example2



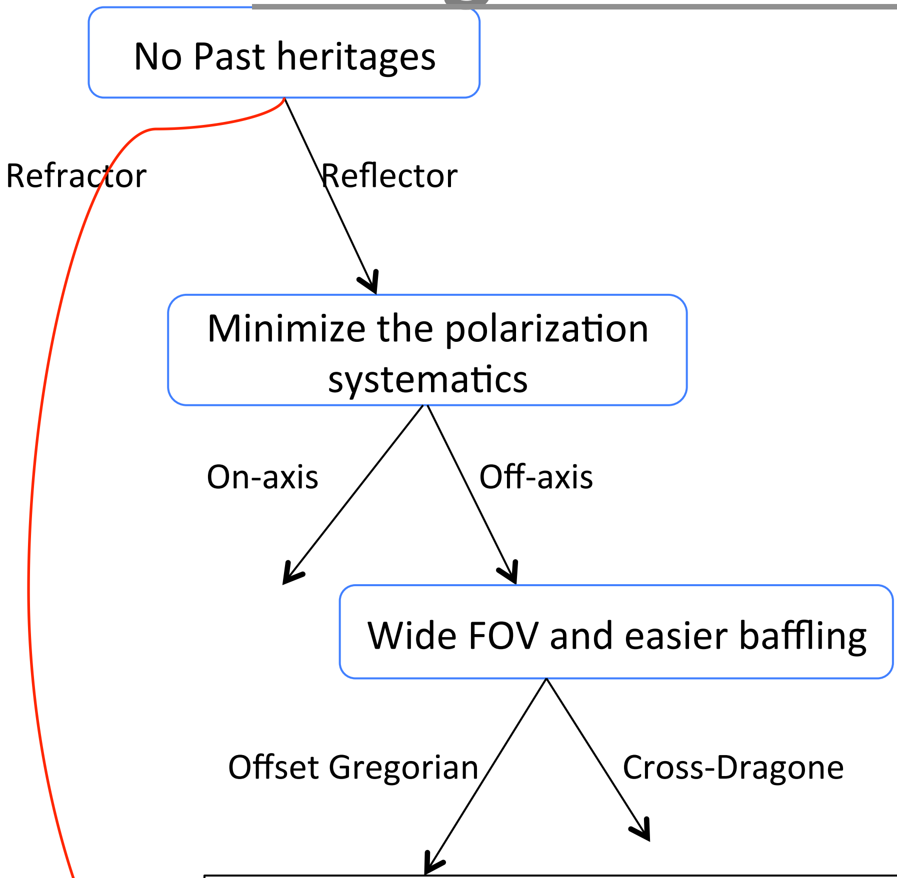


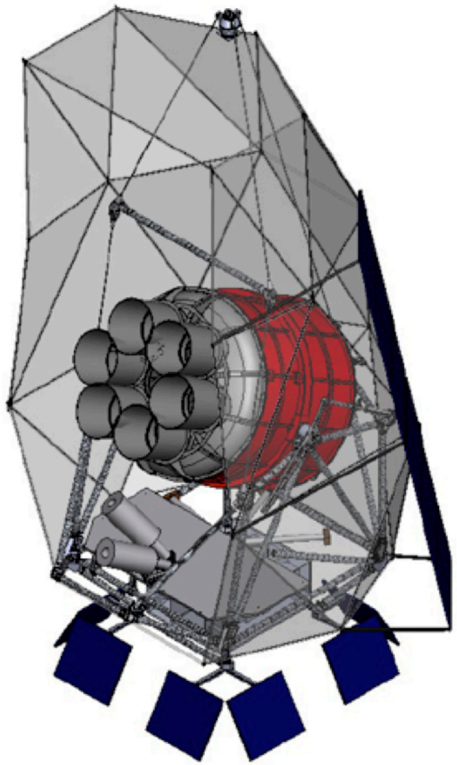


Remaining challenges

1. Optical design
2. Offset-Gregorian is known to have a non-telecentric prime focus and introduce the reimaging cold optics to achieve the wide telecentric FOV.
3. Broadband AR on lens(es) and assess the impact of a (probably) bigger envelop.
4. Maybe the HWP won't be the first element? Reflective metal-mesh HWP with even bigger envelop?
5. Thermal and structural design and fabrication feasibility study

Design decision tree: example3



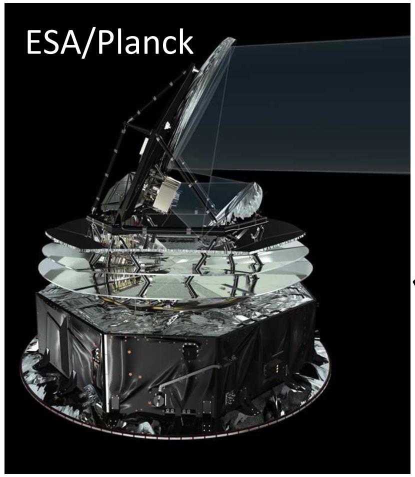


SPIDER Fraisse et al. (2013)

Remaining challenges

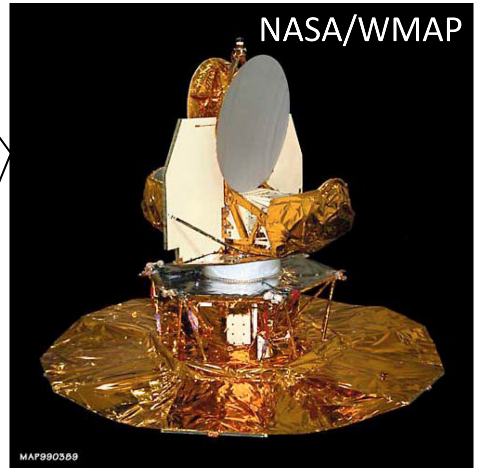
1. Optical design
2. Broadband AR on lens(es)
3. Mass, alignment and vibration tolerance
4. Thermal and structural design and fabrication feasibility study

mm ～ THz space telescope



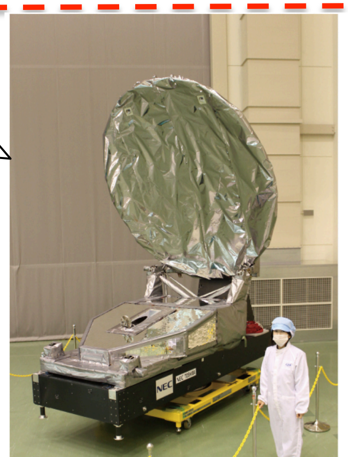
Planck(ESA) Obs. end
Obs. Freq.: 24-857 GHz
Aperture dia.: 1.5×1.9m
Temp.: 45 K (passive cooling)
Material: CFRP

WMAP (NASA) Obs. end
Obs. Freq.: 20-100 GHz
Aperture dia.: 0.7m
Temp.: 70 K (passive cooling)
Material: CFRP (XN70)

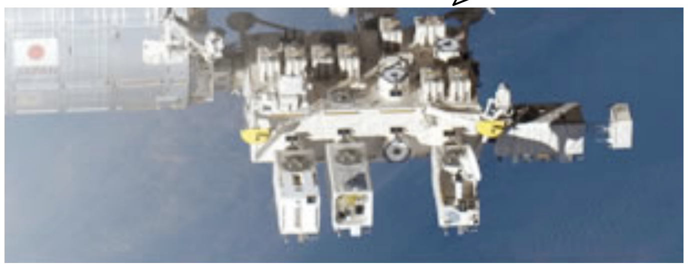


AKARI (JAXA) Obs. end
Obs. Freq.: 1.7-180μm
Aperture dia.: 0.7m
Temp.: 6 K (Liquid ^{4}He)
Material: SiC

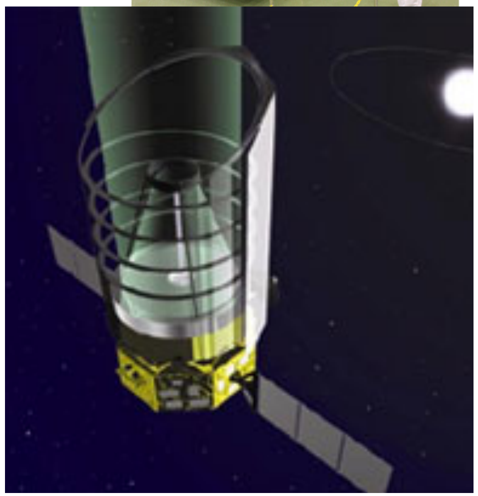
Earthcare (JAXA) in Prep.
Obs. Freq.: 94GHz (W-band)
Aperture dia.: 2.5 m
Temp.: room
Material: CFRP



SMILES(JAXA) Obs. end
Obs. Freq.: 625−650 GHz
Aperture dia.: 40cmx20cm
Temp.: Warm and 4K
Material: aluminum



SPICA (JAXA) Future sate.
Obs. Freq.: IR
Aperture dia.: >2m ?
Temp.: 6 K ? (actively cooled)
Material: C/SiC



ISS Ongoing
1-2 years of exposure of CFRP mirror experiment at ISS

Material choices

- Mirror
  - The material choice of the mirror body will be the interesting parameters. The choices may be
    - Aluminum
    - CFRP
    - SiC
    - C/SiC
    - Zero-expansion ceramic type material
- Lens
  - The choice would be tightly coupled to the AR coating methods
    - UHMWPE/HDPE
    - Si
    - Alumina
    - Meta-material-based lens
- Absorber choice
  - The current generation experiment is fan of coating with a cold black body material in order to absorb the stray light to mitigate the instrumentally induced polarization.
  - The aperture is one critical place on its choice.
  - Inner shell of the optics envelop
  - Mass is always an important metric for space mission

FOM:

- Mass
- Thermal expansion
- AR

Systematics and Calibration

From “Planck pre-launch status: HFI ground calibration” (2010)

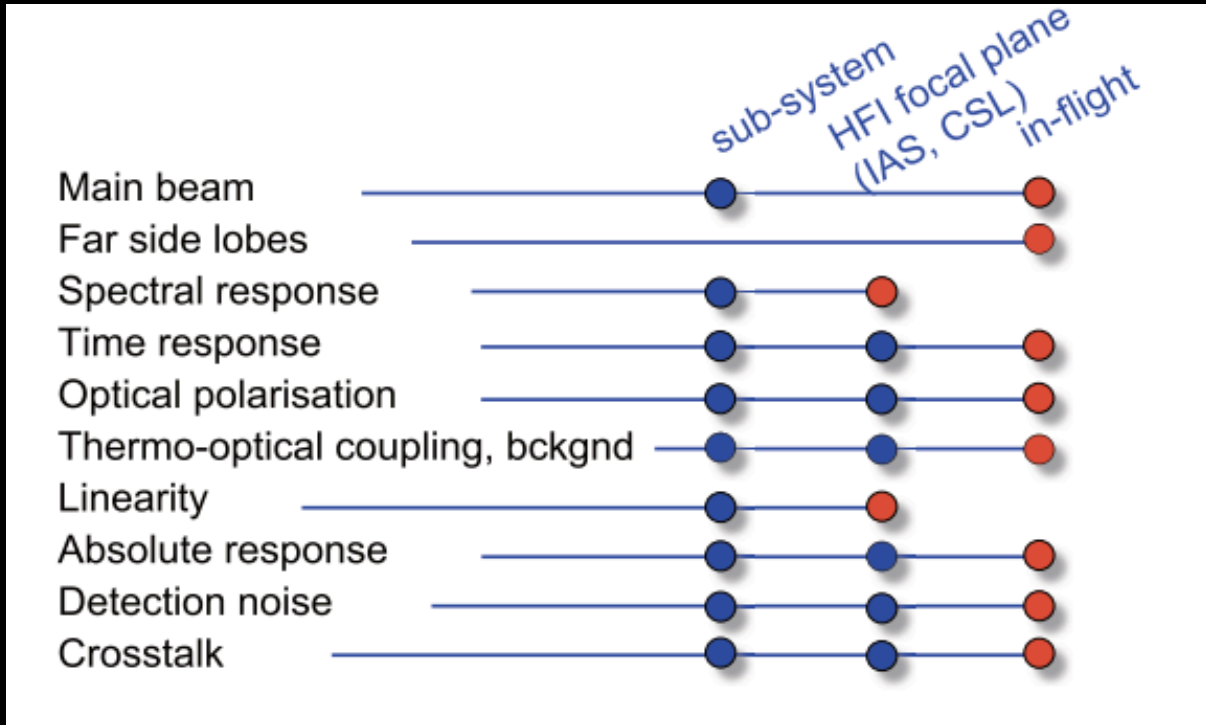


Fig. 1. Calibration philosophy. Blue dots indicate preliminary determinations, red dots indicate final determination.

Systematics and Calibration

From "Planck pre-launch status: HFI ground calibration" (2010)

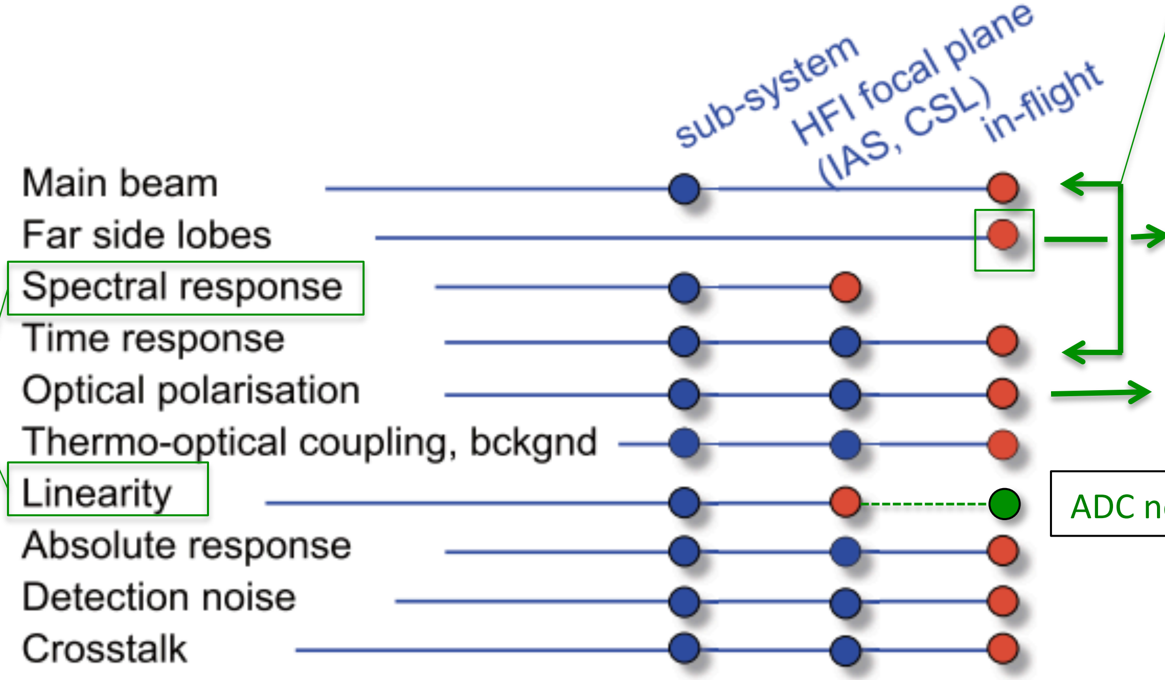


Fig. 1. Calibration philosophy. Blue dots indicate preliminary determinations, red dots indicate final determination.

Must tighter requirements for things that cannot be calibrated by the post launch.

Ideally decouple these two as much as one can at the design stage.

Potential pre-launch measurement in the flight like condition?

Polarized sky source enough?

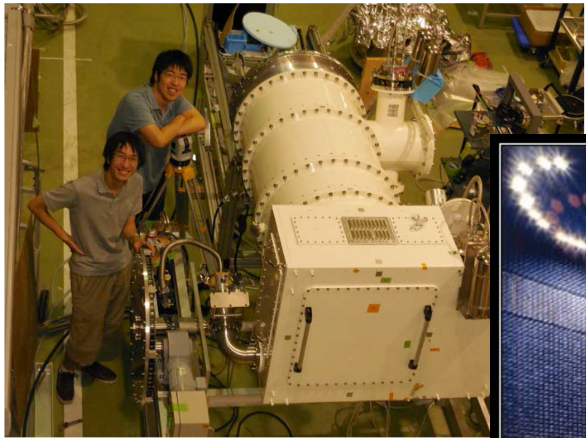
ADC non-linearity at warm

Things that are not listed and could have listed are

- Cosmic ray susceptibility of the system including the detector
- Anything else?

Testing and integrations

POLARBEAR2 integration is ongoing at KEK with sub-K cryogenic system and UC Berkeley TES bolometers.



JAXA Antenna test facility

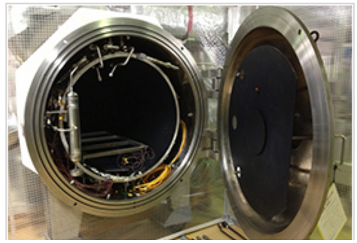
JAXA 13-m diameter space chamber

Astro-H test is done here.

More comes from the optics calibration session tomorrow.

How much do we rely on the simulation? Computational time is non-negligible with GRASP type software.

JAXA 6-m diameter space chamber



JAXA 1-m diameter space chamber