Herschel/Planck

HFI Bolometer Detectors
Programmatic CDR

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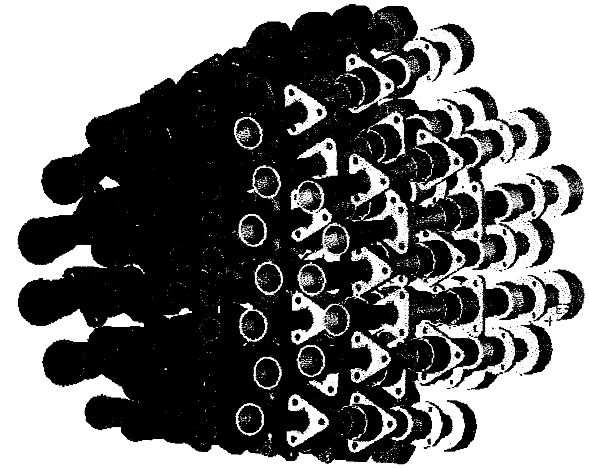
2001

Andrew Lange, PI
Timothy Koch, PEM

JPL

Overview: Scientific Requirements and Goals

- **HFI contains 9 types of bolometric detector**
  - 6 photometric bands
    (100, 143, 217, 345, 545, 850 GHz)
  - 3 polarization-sensitive bands
    (143, 217, 354 GHz)

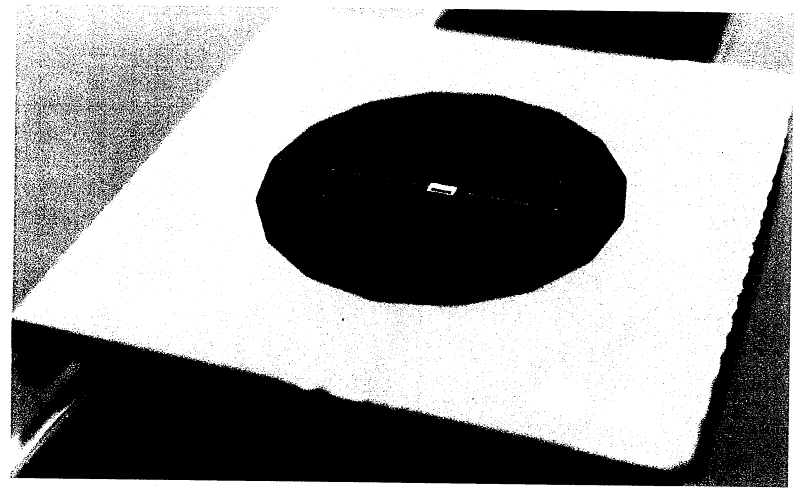


- **Ultimate Scientific Requirement is NET (ΔT_{cmb} sec $^{1/2}$) on-orbit**
  - Function of bolometer properties + (photon background + optical efficiency + amplifier noise + other sources of system noise)

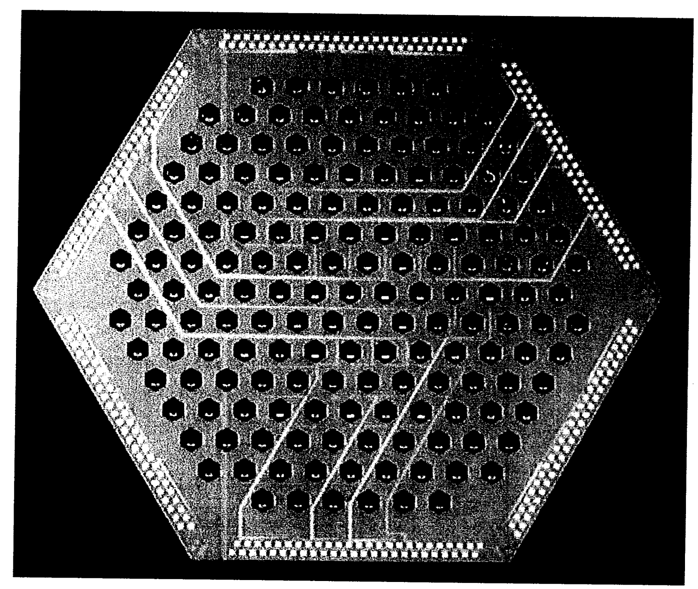
- **Philosophy:**
  - Well-defined budget for each contribution to noise
  - Well-defined specifications on specific, easily measured bolometer properties (dark electrical NEP, tau, G) that ensure that bolometer contribution to noise not exceed budget
  - Well-defined Requirements and Goals, with large margins to meet Requirements
    - Required performance ensures that precision of CMB power spectrum is limited by fundamental confusion by astrophysical foregrounds. Goal performance enhances secondary scientific goals.

Silicon Nitride Micromesh 'Spider-web' Bolometers

Spider-web architecture provides
- low absorber heat capacity
- minimal suspended mass
- low-cosmic ray cross-section
- low thermal conductivity = high sensitivity



Sensitivities and heat capacities achieved to date:
- NEP = 1.5 x 10^{-17} W/√Hz, C = 1pJ/K at 300 mK
- NEP = 1.5 x 10^{-18} W/√Hz, C = 0.4 pJ/K at 100mK

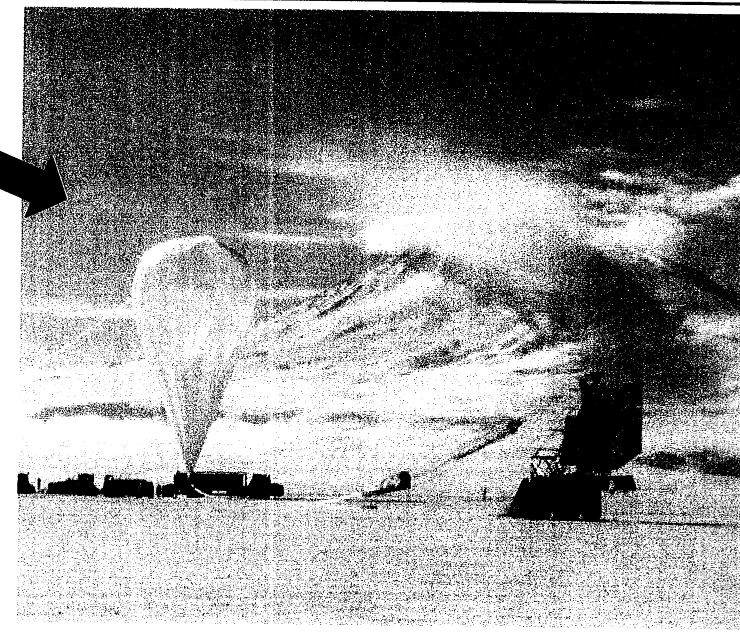


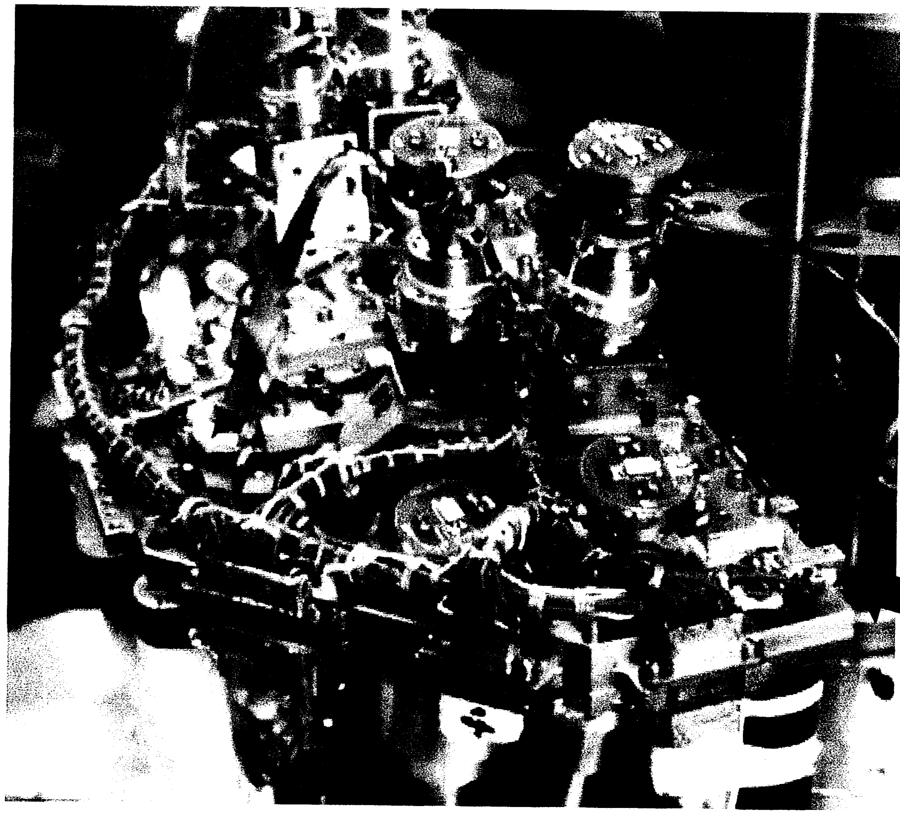
Operating in numerous sub-orbital experiments:

BOOMERANG	Caltech	Antarctic balloon CMB instrument
SuZIE	Stanford	S-Z instrument for the CSO
MAXIMA	UC Berkeley	North America ballon CMB instrument
BOLOCAM	UMass	Bolometer camera for the CSO
ACBAR	UC Berkeley	Antartic S-Z survey instrument
MAT	UPenn	CMB experiment for Chile
POLATRON	Caltech	CMB polarimeter for OVRO
Archeops	CNRS, France	CMB balloon experiment
PRONAOS	IAS, France	Submillimeter balloon experiment

Sub-Orbital Heritage: BOOMERANG

High cosmic ray flux
High and time-varying temperature gradients
Challenging EMI / RFI environment

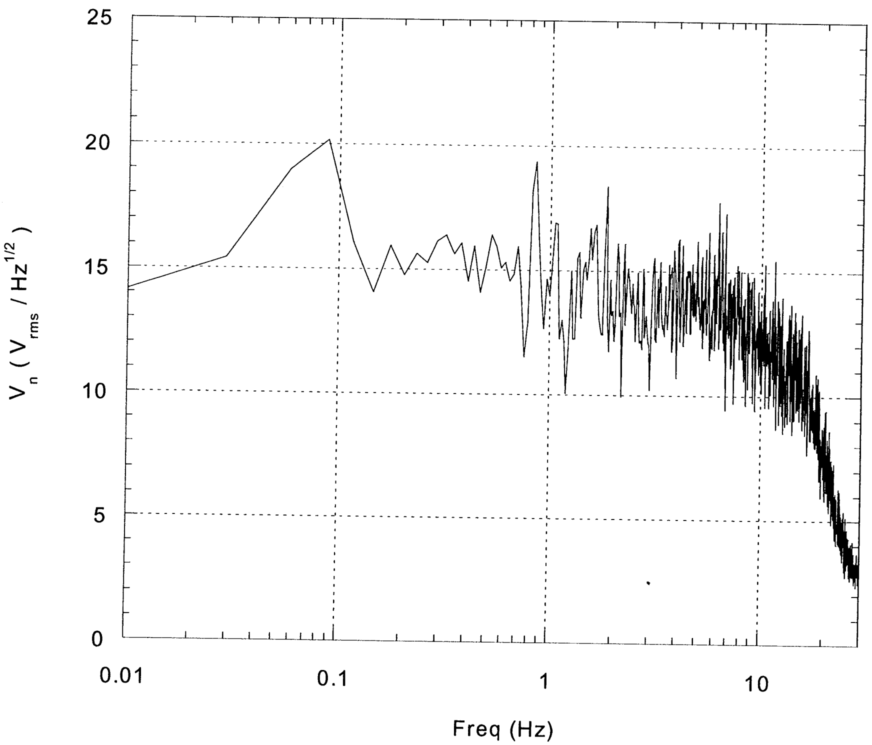




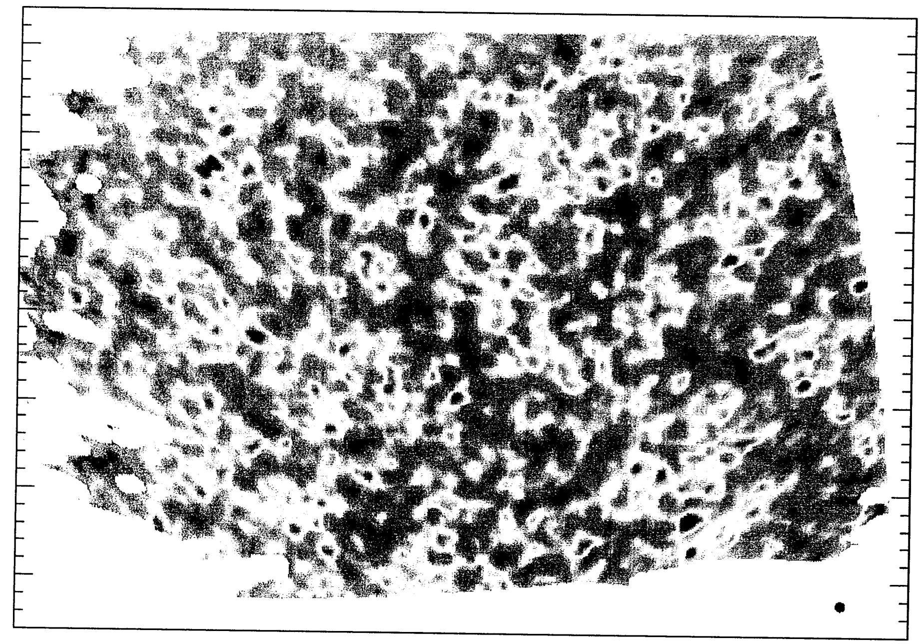
Boomerang 300 mK focal plane

- 18 detectors in focal plane
- NEPs ~ 2×10^{-17} W/Hz $^{-1/2}$ @ 300 mK
- Time constants $\tau \sim 10$ msec
- Feedhorn coupled
- AC-biased with 20 Hz post-demodulation bandwidth
- 1/f knee @ ~ 30 mHz

Noise stability demonstrated in BOOMERANG



Measured noise stability in lab without temperature control



BOOMERANG map of CMB anisotropy

Overview: Instrument Partners

- **CNES/IAS**
  - **Centre National d'Etudes Spatiales**
  - **Institut d'Astrophysique Spatiale, Orsay, France**
    - Jean-Loup Puget, HFI Principal Investigator
    - Jacques Charra, HFI Project Manager
    - Jean-Michel Lamarre, HFI Instrument Scientist
- **PPARC/Cardiff**
  - **Particle Physics and Astronomy Research Council**
    - Ray Carvell, UK HFI Project Manager
  - **University of Wales, Cardiff (QMC group), UK**
    - Peter A.R. Ade, UK HFI PI and Local Project Element Manager
- **NASA/Caltech/JPL**
  - **Jet Propulsion Laboratory, Pasadena, USA**
    - Gary Parks, US Herschel/Planck Project Manager
  - **California Institute of Technology , Pasadena, USA**
    - Andrew E. Lange, US HFI Principal Investigator

Overview:
Bolometer Environment on Planck/HFI

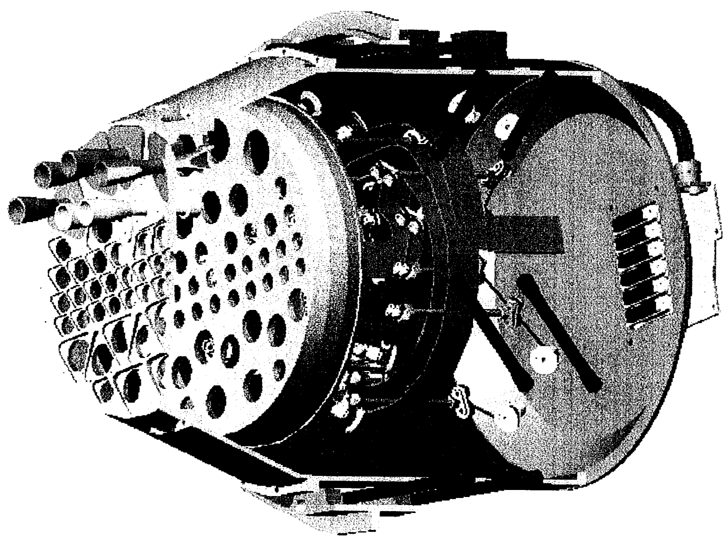
100 mK heat sink provided by 4 stages of cooling:

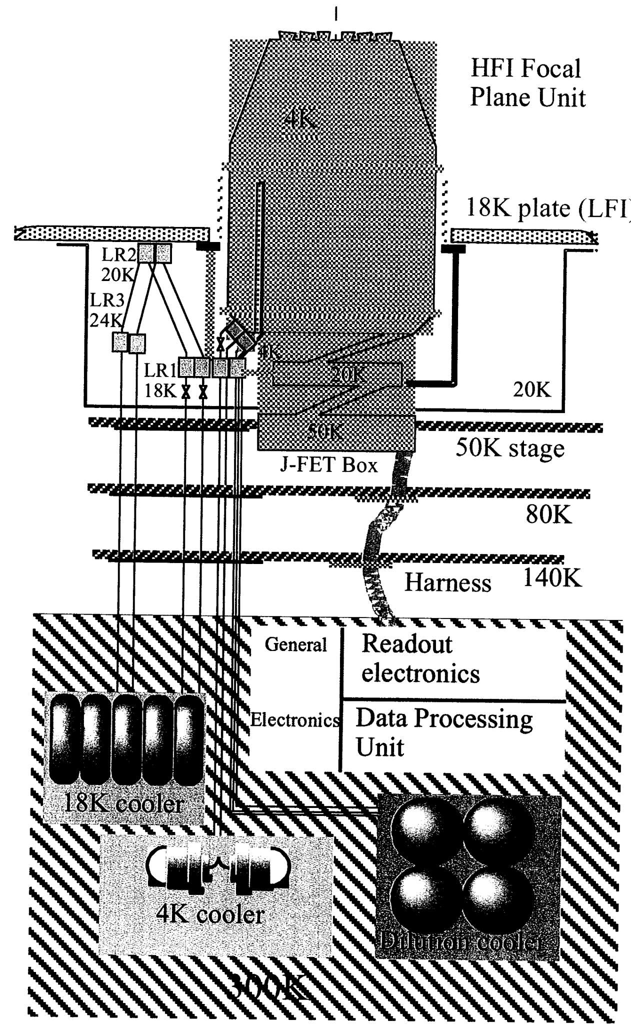
passive cooling to 50 K

H sorption cooling to 18K

JT cooling to 4K

3He/4He dilution to 0.1K



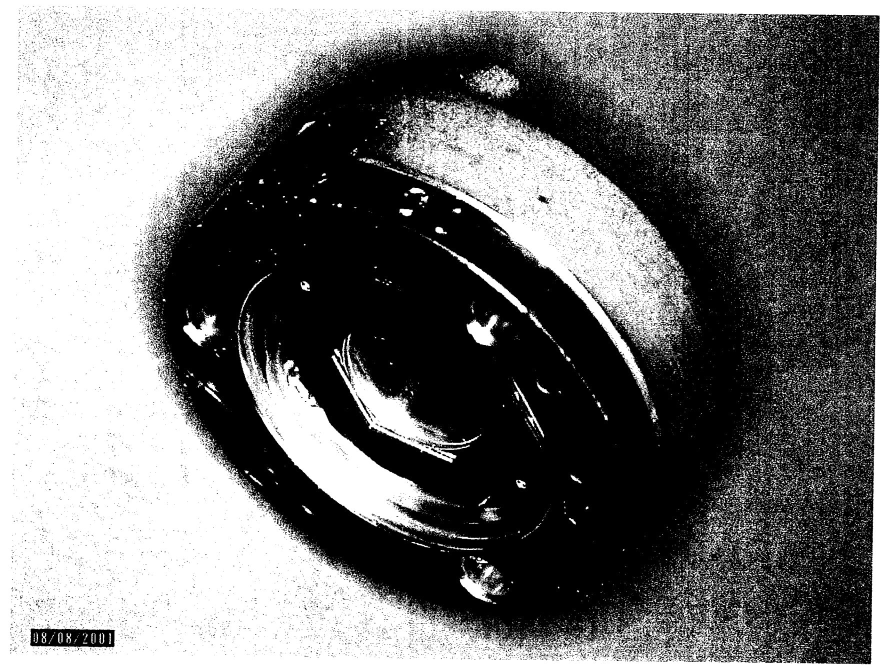


Optical backgrounds dominated by loading from instrument

Signal band of 0.016 to 90 Hz determined by 1 rpm rotation of satellite

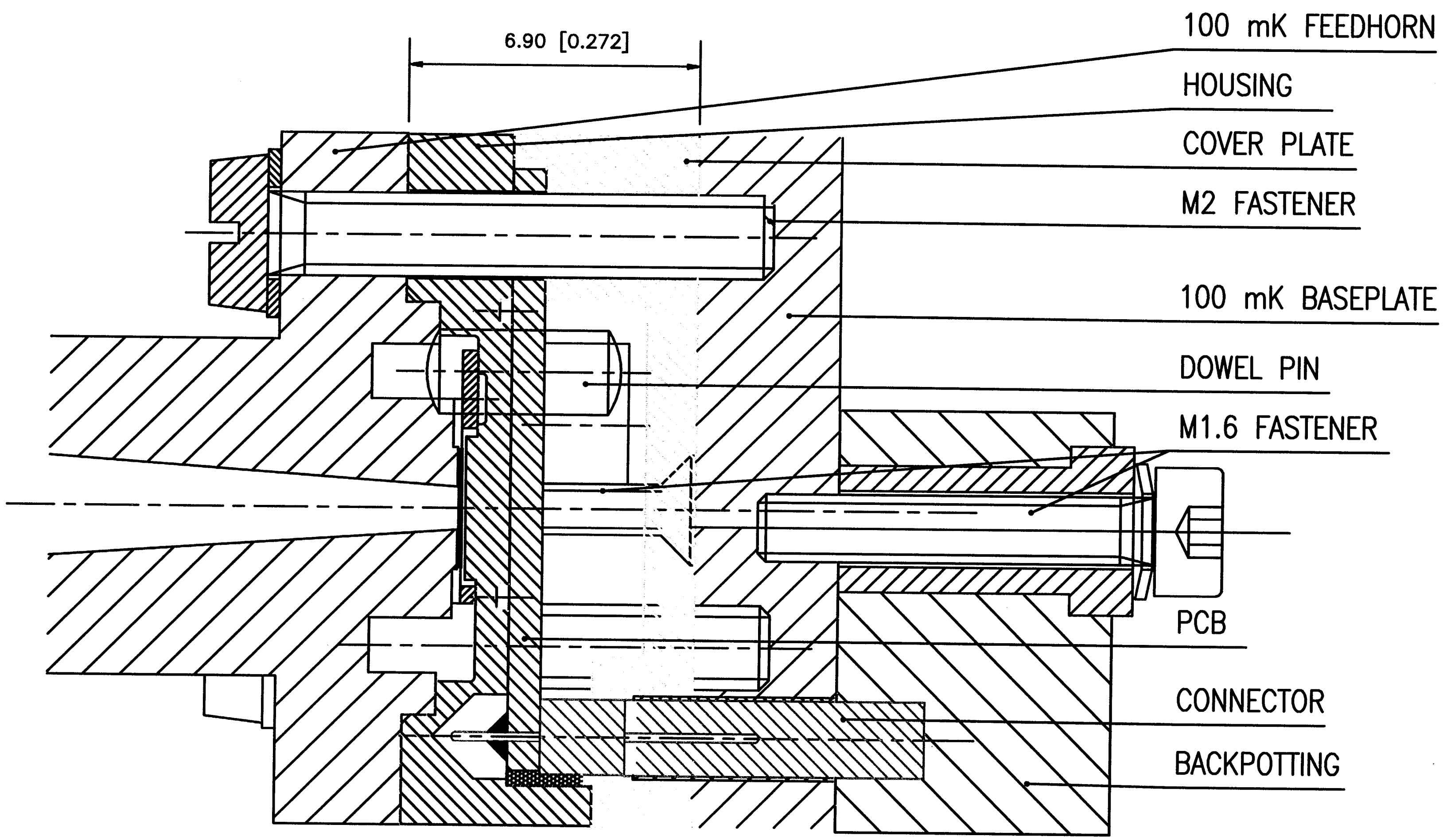
Bolometer Modules

- Define interface
- Control all aspects of bolometer environment :
  - Optical
    - Stray light
    - Tuned backshort
  - Electrical
    - Electrical connection
    - RFI/EMI filter
  - Thermal
    - Heat sink via cover plate
  - Mechanical
    - Close packing in focal plane
    - XYZ and rotational position
- EM Modules deployed on ARCHEOPS: 0/24 failures



Mechanical Interface

857 GHz Detector Module Layout (side view)



HFI Scientific Requirements and Goals:

Current Performance Estimates Meet Requirements in All Bands

Detector Chain	Requirement	Goal	Current Estimate*
[GHz]	[T_{cmb} sec ^{½} uK]		
100	99	47	70
143	123	51	77
217	182	74	112
354	553	231	350
545	4,000	900	1400
850	180,000	33,000	50,000
143P	161	72	110
217P	266	105	159
354P	810	326	492

* includes contributions from photon noise, bolometer noise, amplifier noise, and 10 identified sources of additional system noise

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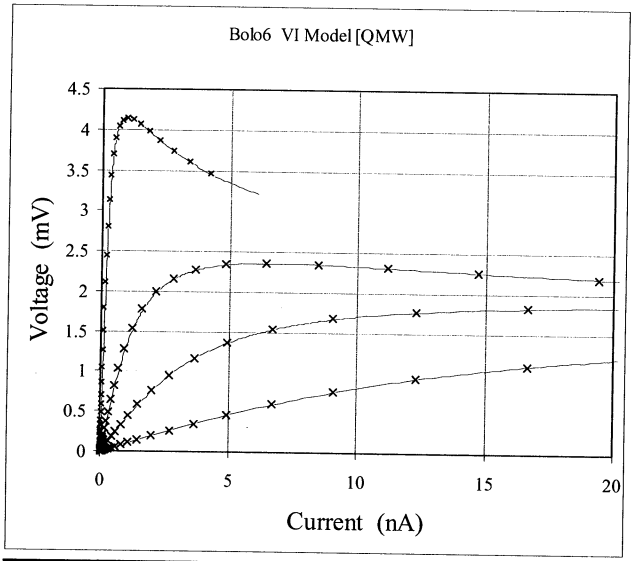
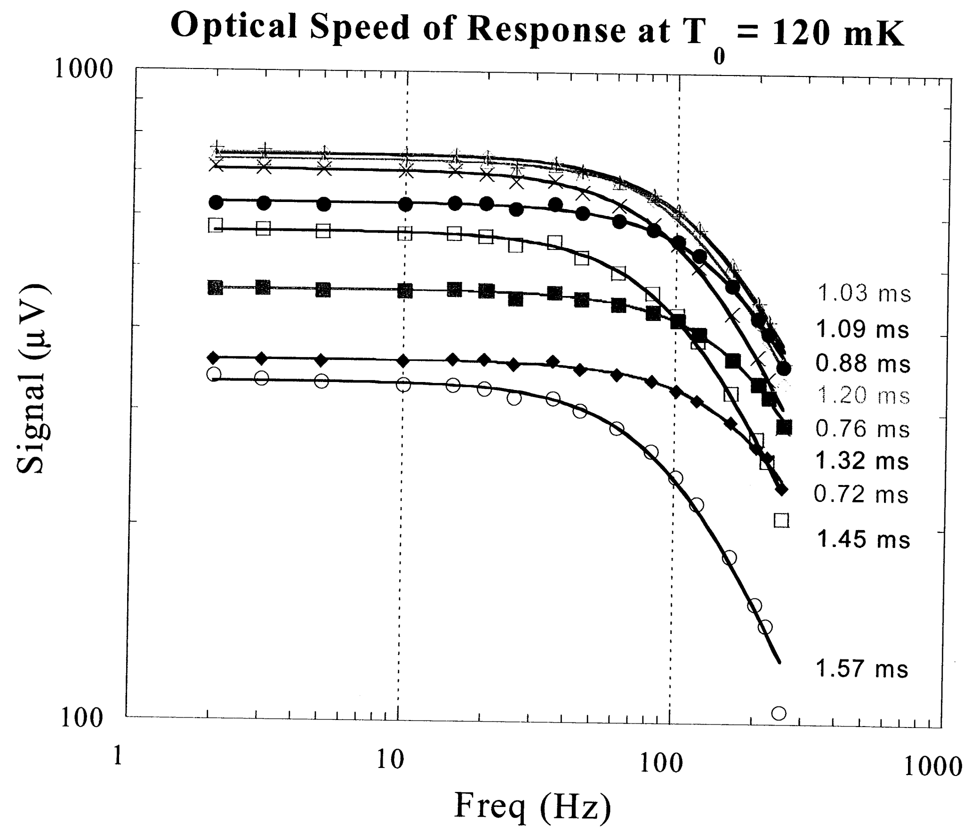
Requirement Traceability

- **All Requirements Explicitly Stated in Business Agreement:**
  - **Requirements on Bolometers:**
    - Dark electrical $NEP_{bolo} < 0.88\ NEP_{BLIP}$
    - Dark optical time constant $\tau_{bolo} < t_{beam}/\pi$
    - Responsivity under assumed optical load adequate to give $V_n > 7\ nV/Hz^{1/2}$ load
    - Thermal conductivity adequate to maintain BLIP limited performance under 2 x higher than expected loading
    - Optical efficiency > 25% end-to-end, including all filters and focal plane feeds
  - **Requirements on System**
    - Amplifier noise < 7 $nV/Hz^{1/2}$
    - Heat sink < 110 mK
    - Limits on following sources of excess noise:
      - Amplifier chain and CR deglitch
      - Straylight from payload
      - Straylight from sidelobe responcse to astrophysical sources
      - Temperature fluctuations of 4K, 1.6K and 0.1K stage
      - EMI
      - Microphonics
      - Data compression

Summary of Performance of P04 Engineering Prototype



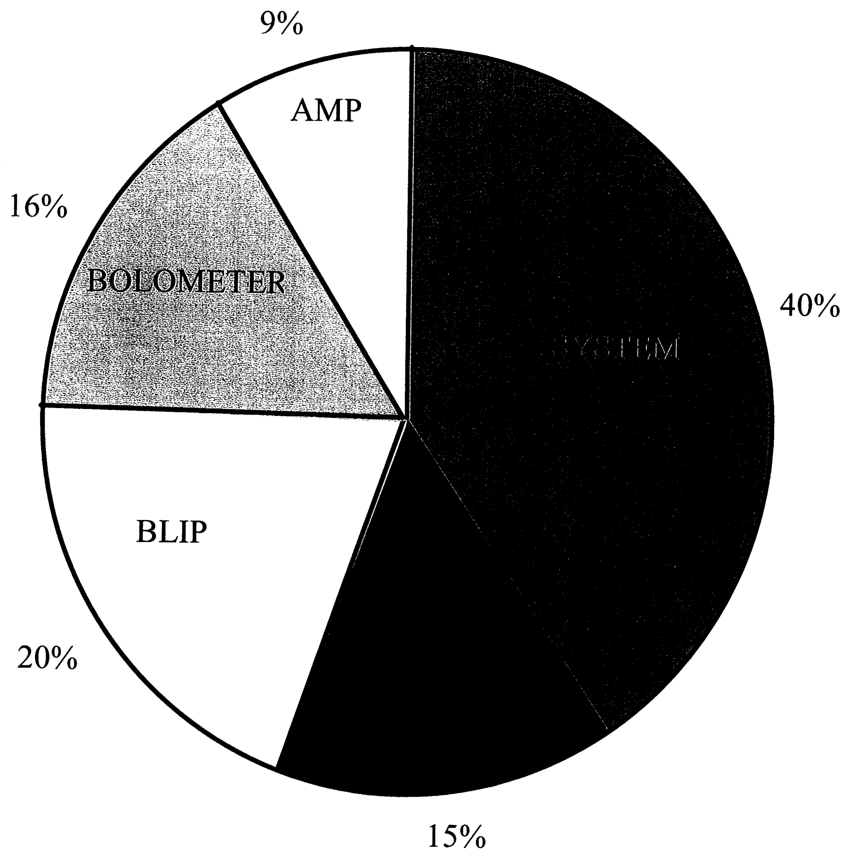


Measured P04 Parameters		
G	$122(T/0.1)^{1.34}$	pW/K
C	$0.17(T/0.1)^{1.34}$	pJ/K
R_0	77	Ω
Δ	15	K
R_{op}(120 mK)	5	MΩ
V_{nop}(120 mK)	7.0	$nV/(Hz)^{1/2}$
τ	1.0	ms
$NEP_{e,bol}$	1.43	e-17 $W/(Hz)^{1/2}$

Satisfies speed and sensitivity goals for 143 GHz channel

Worst-Case (100 GHz) Detector Noise Budget:

TOTAL = (99 microK_CMB)^2 sec



- **Assumes 25% optical efficency**
- **Assumes conservative CBE for BLIP**
- **Assumes worst-case for amplifer noise**
- **"System" = maximum allowed contributions to NET from:**
  - Signal processing efficiency
  - Payload straylight
  - Sidelobes straylight
  - Temperature fluctuations of 0.1K, 1.6K, and 4K stages
  - EMI/RFI
  - Microphonics
  - Data compression

Summary of Contingency NET/ Bolometer NET:

100	143	217	353	545	857	143P	217P	353P
99%	162%	177%	162%	450%	580%	124%	192%	183%

Margins Analysis

- Analysis of worst-case 143 GHz polarized channel
- Choose bias point to satisfy goal criteria with R ≤ 10 MΩ
- Otherwise satisfy specification with R ≤ 10 MΩ

Parameter	Units	Nominal Value	Satisfies Goal	Satisfies Specification
G_0	pW/K	46	$33 < G_0 < 87$	$17 < G_0 < 87$
C_0	pJ/K	0.2	$C_0 < 0.27$	$C_0 < 0.55$
R_0	Ohms	155	$R_0 > 50$	
Q	pW	0.57	$Q < 1.25$ *	
V_n (amp)	nV/rtHz	5	$V_n < 9$	
T_0	mK	100	$T_0 < 113$	

* In order that $NEP_{det} < (2h\nu Q\_nom)^{1/2}$; $NEP_{det} < (2h\nu Q)^{1/2}$ for $0.33 < Q < 5$

- Large margins in G_0, R_0, V_n, and Q, small margins in C_0, T_0
- Decreasing V_n and/or increasing R_0 can provide more margin in T_0
- Need to include τ_{elec}(RC), V_n(RC) in this analysis!

Model Philosophy

- **Engineering Models**
  - **ARCHEOPS**
    - Full-up balloon-borne technical and scientific demonstrator
    - Telescope, Focal plane optics, 0.1K cooler, and readout electronics all mimic Planck HFI
    - 24 EM detectors delivered in November 2000
    - In-flight performance verifies that end-to-end system can meet HFI requirements (optical efficiency of 30% achieved)
  - **EBB**
    - Laboratory simulator: first test of cooler chain including 4K compressors
- **Flight Models**
  - **"Cryogenic Qualification Model"**
    - First chance to test full Planck HFI + LFI focal plane and cooler chain
  - **"Proto Flight Model"**
    - Flight model
- **JPL Qualification Models**
  - **Taken from CQM build**
    - Qualification tests on these detectors prove reliability of detectors, but invalidate them as flight deliverables

Deliverables

Total of 114 Bolometers to be delivered to HFI:

Frequency (GHz)	EBB	EBB Spare	CQM	CQM Spare	Flight Model	Flight Spares	Quantity Requirement
100	0	0	1	1	4	2	8
143	0	0	1	1	4	2	8
217	1	1	1	1	4	2	10
353	0	0	1	1	4	2	8
545	0	0	1	1	4	2	8
857	0	0	1	1	4	2	8
143P	*0*	*0*	*2*	*2*	*8*	*4*	*16*
217P	*0*	*0*	*2*	*2*	*8*	*4*	*16*
353P	*0*	*0*	*2*	*2*	*8*	*4*	*16*
217 Blanked	0	0	1	1	2	2	6
217 Resistor	0	0	1	1	1	1	4
217 Capacitor	0	0	1	1	2	2	6
						TOTAL	**114**

European Instrument: Test Plans

- Bolometers delivered to Cardiff, UK
  - Cardiff integrate detectors with horns and filters.
  - Cardiff test one detector from each wafer for conformance check of end-to-end performance
  - Cardiff maintain one set of horns and filters from each CQM channel as a performance standard
  - Cardiff integrate detectors horns and filters into focal plane support plates
  - Cardiff characterize focal plane units in dilution test facility
  - Cardiff vibrate focal plane units to qualification levels and retest
- Focal Plane Units delivered to IAS, France
  - IAS integrate focal plane units into HFI
  - IAS mount HFI into large 4K cryostat and characterize instrument
  - IAS vibrate HFI to qualification levels and retest

European Instrument Status

- Cardiff, UK
  - Cardiff have experience from characterising engineering devices and from integrating and testing of 22 channels flown in Archeops.
  - Dilution fridge installed and is being modified for focal plane unit testing.
  - Horn procurement in progress
  - Filter production in progress
- IAS, France
  - IAS have experience from flight dilution system testing and Pronaus experiment with bolometer instrument
  - IAS are modifying the ISO test cryostat to install HFI for instrument characterisation
- Alcatel, France
  - Late start but now being integrated into programme

Business Agreement Status: Requirements Documents

- "Requirements complete and stable" and "no changes in scope"
- Business Agreement updated in response to August 2001 Peer Review
  - Explicit Statement of Total System Noise Budget
  - Requirements on Optical Efficiency
  - Plan for Confirming Optical Efficiency
  - Requirement on Cross-Polarization of PSBs
  - Vibration Requirement
  - Agreed to by all parties, signed off
- Handling and Storage Requirements Document created in response to Peer Review includes:
  - Bakeout time and temperature
  - ESD, Cleaning, Venting, Thermal Cycling, Electrical
  - Shipping Containers and Receiving Inspection
  - Other handling requirements imposed on Instrument
  - Agreed to by all parties, sign off in process
- ICD updated
  - Mechanical and Electrical Interfaces
  - Agreed to by all parties, signed off

Rec / Del Plans and Status (With Europe)

- Deliverables (all detectors include data package with fabrication and test data):
  - EBB: 2 detectors
  - CQM: 24 detectors + 6 diagnostic loads
  - PFM: 72 detectors + 10 diagnostic loads
- Receivables
  - Test data on opt efficiencies of detectors (from Cardiff)
  - CQM detectors for refurbishment to flight spares (from IAS)

Design Status

- Spider Web detectors demonstrated to meet all requirements at 143, 217 GHz
  - Most difficult channels to meet specs -> high confidence in all channels
- New design tool (HFSS) allows optical and thermal performance of absorber geometry to be accurately modeled
  - Simulations show opportunity for significant (~ 15%) improvement in optical coupling
- Low yield of 100 GHz devices will be improved by better mechanical design of web and legs
- PSBs still in EM phase
  - Prototypes to date have failed to meet optical efficiency requirement
  - HFSS analysis confirmed that problem was in absorber impedance AND that high optical efficiency can be achieved with proper impedance match
  - EM/CQM wafer in fab now / optical tests complete before delta-CDR end of 11/01
- Design of PFM detector masks will be finalized in December
  - Anticipate modest evolution in detailed design parameters from CQM devices
  - Goal: increased mechanical and electrical yield to minimize program cost and maximize performance of FM detectors

Status of 100 mK Test Facility

- Cryogenics working reliably
- Measurement electronics characterized:
  - 20/24 channels of bolometer signal acquisition functional
  - Well characterized transfer function allows τ_{bolo} to be measured
  - Excess noise < detector noise but needs more work!
- Optical modulation implemented
  - Low level optical signal injection demonstrated - allows τ_{bolo} to be measured optically
- Thermal stabilization plan in implementation
  - electronics characterized
  - thermometry sensitivity sufficient for evaluation
- Additional signal collection electronics (in process) will improve throughput, enhance automation of data collection