MMA Project Book, Chapter 6.

CRYOGENICS

L. D'Addario
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1998-07-10: First version
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See also:

- MMA Memo No. 184, "Cryogenics options for the MMA, " 1997-09-20. General background information.
- MMA Memo No. 185, "Review of Gifford-McMahon refrigerators for 4K, " 1997-09-25.

SUMMARY

The cryogenics plan for the MMA includes spending the first half of the D&D phase (through about March 2000) on technology assessment and development, followed by detailed design and construction of a prototype refrigeration system. The latter will be delivered in time for integration with the prototype receiver. The cryogenic system includes not only a refrigerator but also the thermal design of the receiver package, and hence it interacts closely with the receiver design. After thorough testing and documentation, it is expected that volume production of refrigeration systems for the array will be handled by a build-to-print contract to industry.

The technology assessment and development is expected to yield improved performance and reliability compared with earlier designs. Very high reliability and low maintenance are important because of the large number of systems and the remote site of this array. The following investigations are being carried out: detailed performance evaluation of the NRAO J-T refrigerator and of commercial 4K Gifford-McMahon refrigerators; evaluation of new componets for J-T cryocoolers, including expanders, reactive gas cleaners, and oil-free pumps with non-contacting seals; evaluation of pulse tube refrigerators, possibly including purchase of a prototype; and experimental studies of infrared filtering materials and structures. In addition, the thermal design will be proved by construction of a thermal mockup of the MMA receiver. This will produce the same conduction, radiation, and dissipation loads as the final receiver (supporting all bands)and will include a cryocooler suitable for testing; it will contain no mm-wavelength electronics, but will be available long before the actual receiver.

Construction of the antenna evaluation receivers will include use of cryocooler hardware previously developed at the NRAO or available commercially, and is therefore not covered in this chapter. Nevertheless, some novel design and construction techniques worked out during cryogenics development may be incorporated into the evaluation receivers if time permits.

6.1 OVERVIEW

The MMA cryogenics design is presently only roughly determined because, first, the cooling requirements of the receivers are not yet accurately known; and, second, because we intend to use the MMA development phase to achieve substantial improvements relative to the cryocoolers that have heretofore been conventional in radio astronomy. The large number of antennas and the remote location of the MMA imply that two kinds of improvement are highly desirable: power consumption and reliability.

Existing NRAO systems capable of cooling 1W to 4K use about 9.7kW from the power line; this is an efficiency of about .01%, compared to the ideal theoretical (Carnot) efficiency of about 1.2% and practical efficiencies achieved in other (much larger) systems of up to 0.2% (20x better). An improvement by a factor of 2 to 4 (to .02% to .04%) should be feasible in our size range, as described below. In addition, careful design to minimize the cooling requirements of the receivers should keep the 4K load below 0.5W and the loads at other stages below 10W.

Most cryocoolers in radio astronomy now use Gifford-McMahon refrigerators. These are highly developed commercially and are fairly reliable, but they nevertheless have parts that wear out and require overhauls at intervals of 12 to 18 months. In addition, random failures occur from leaks in joints and flexible hoses, from helium contamination, and in compressors. As a result, use of the traditional technology can be expected to result in about 2 shutdowns per year per cryocooler for maintenance or repair. Even with one system per antenna, this is more than one per week. Technologies now exist (for compressors, expanders, and hoses) that should, in principle, result in a large improvement in reliability. But in most cases the performance we need has not yet been demonstrated, and some components are not yet commercially available. Detailed investigations are planned during the development phase before making a final choice.

6.2 REQUIREMENTS

The receiver plan (see chapter 5 of this book) calls for dual-polarization coverage of 30 GHz to 950 GHz in 10 bands, with the lowest three bands (30-116 GHz) using HFET amplifiers as the initial stages, and the remaining 7 bands using SIS mixers. It is desired to have the HFET amplifiers as cold as 15K; colder would not lead to significant improvement, and temperatures as warm as 50K might be acceptable. The SIS mixers (at least for Nb devices) must be kept below 4.5K in the worst case, and the nominal temperature should be 4.0K or less. Each receiver will have a cold feed horn at the same temperature as its first stage, and optical components outside the dewar are to be minimized. (As we shall see, eliminating all external optics after the subreflector implies large windows at the lower frequency bands, creating substantial heat load.)

(The receiver plan might change, but the cryogenics plan given here is based on the receiver configuration just described.)

With the goal of keeping the cryogenic system as simple and hence as reliable as possible, configurations with heat sinks at only two cryogenic temperatures are being considered (as opposed to the three stages that are traditionally used to reach 4K). The coldest stage would then have to be at 4K, and the other stage might be at about 40K. Some commercially available Gifford-McMahon refrigerators achieve these temperatures. Table 6.1 shows the likely distribution of cooled components for the 2-stage and 3-stage cases.

Table 6.1: Temperatures of Cooled Components

Three-Stage Case	Two-Stage Case
Stage 1, 70K	**Stage 1, 40K**
Radiation shields	Radiation shields
IR filters at windows	IR filters at windows
Cable and WG heat sinks	Cable and WG heat sinks
LO multipliers or photodiodes	HFET amplifiers, RF and IF, stages 3--5 (34 ea.)
	LO multipliers or photodiodes
Stage 2, 20K	**Stage 2, 4K**
Cable and WG heat sinks	All feedhorns (10 ea.)
HFET receiver feed horns (3 ea.)	SIS mixers (14 ea.)
HFET amplifiers, RF, bands 1-3 5 stages (x6)	HFET amplifiers, RF and IF, stages 1 and 2 only (34 ea.)
Stage 3, 4K	
SIS mixers (7 ea.)	
SIS receiver feed horns (7 ea.)	
HFET amplifiers, IF, stages 1 and 2 only (28 ea.)	

For the three-stage case, an attempt has been made to estimate all contributions to the heat load for the 10-receiver system. The result is given in Appendix A. The calculation assumes that all receivers are in the same dewar and can use a common refrigerator, but splitting them into separate dewars would affect only the radiation shields, which contribute a relatively small amount. The radiation through each window is assumed to be mostly sunk to the first stage by a fairly thick (several mm) PTFE infrared filter. The filter performance assumed is based on the measurements reported in [1]. A separate window is assumed for each band, with the sizes taken from [2]. The thermal properties of coax cables and waveguides are taken from [3]. The photonic and multiplier LO options (see chapter 7) are treated separately, but each is assumed to include 100 mW of RF dissipation; the multiplier option has slightly more load on the first stage due to its input waveguides.

It is apparent from Appendix A that the dominant load on every cooling stage is from the 300K radiation incident on the windows. This is true for each receiver separately as well as for the grand total. (This depends on using a large number of layers of multi-layer insulation ["superinsulation"] to keep the radiation from opaque surfaces low.) Therefore, minimizing the window area is one of the best things we can do to minimize the load.

Without any special effort, the calculated loads are about 36W, 1.4W, and 0.7W on the three stages. Appendix A also shows some ways to reduce this. A great deal of the first stage load (22W) and second stage load (1.2W) can be eliminated if the large windows of the three HFET receivers could be reduced to 2.2in diameter (from 9.0, 4.5, and 3.2in, respectively) by using external optics to reduce the beam waist diameter. Slightly more could be saved by eliminating the 33-50 GHz band entirely. The calculation assumes that all SIS receiver windows are 2.2 in diameter, which is what’s needed for the lowest frequency band; actually, smaller windows can be used at the higher frequencies. After taking these steps, the largest remaining loads are from HFET amplifier dissipation and from conduction through coax cables. If only one SIS receiver is in use at one time, and if the bias is turned off for the other IF stages, significant saving results. (Note that the HFET receivers remain on, and could be used simultaneously.) If the IF coax from 4K to 20K is lengthened to 20cm (at some sacrifice in loss), further savings occur at 4K. With all of these measures, the loads become 6.5W, 0.27W, and 0.37W, respectively.

It should be emphasized that these are theoretical results, and are very preliminary. Whether they represent reality remains to be seen.

6.3 OFF-THE-SHELF TECHNOLOGIES

6.3.1 Two-stage Gifford-McMahon. (See MMA Memo #185.)

Table 6.2: Commercial Two-Stage GM Refrigerators for 4K

Mfgr	Model	Load@4.2K	MinTemp	System Price	Input Power
Daikin[1]	CSW210	0.8 W	3.0 K	$35k	6.7 kW
Sumitomo[2]	SRDK415	1.5	3.2	41k	7.5
Sumitomo[2]	SRDK408	1.0	3.1	39k	7.5
Sumitomo[2]	SRDK205	0.5	3.1	24k	3.4
Leybold	4.2GM	0.5	3.4	37.5k	6.5
Boreas[3]	B100	0.9	3.1	38.5k	3.0

Model	1stStg Q@T	P1,atm	P2,atm	He flow	Eff/Carnot[4]	
CSW210	35W @41K	21.8	7.1	85 Nm^3/h	.041	.0084
SRDK415	30W @40K	?	?	?	.040	.0141
SRDK408	37W @40K	23.4	6.8	80	.041	.0094
SRDK205	4W @40K	?	?	30	.018	.0104
4.2GM	50W @50K	22.1	7.5	88	.044	.0054
B100	2.5W@80K	21	1.0	20	.023	.0211

Notes:
[1] Represented in U.S. by APD Cryogenics, Inc.
[2] Represented in U.S. by Janis. SRDK405 is new, promised in 4Q97.
[3] Not GM, but a proprietary hybrid cycle, partially recuperative.
[4] Efficiencies relative to Carnot, first with specified loads on both stages, then with zero 1st stage load but same power consumption.

6.3.2 Hybrid three-stage: 2GM + JT. This is the configuration that has been traditionally used in radio astronomy when refrigeration near 4K is required. Specific designs were developed for cooling the superconducting magnets of microwave maser amplifiers in the 1960s, both for radio astronomy and for spacecraft tracking, and essentially the same designs are in use today.

6.4 ADVANCED TECHNOLOGIES

6.4.1 Pulse Tube Refrigerators. [to be written; some notes:]

- Generally not commercially available (but 1-stage 10W@77K now avail from Iwatani)
- Orientation dependence may require tilted installation
- Cyclic, producing temperature fluctuations

- See refs [5--7] and other works cited therein.

6.4.2 Sterling-Style Compressors.

- Produces cyclic pressure variation without valves, suitable for pulse tube or Sterling coolers
- Requires compressor close to cooler, but can be tipped
- Compressor cycle must be synchronized to refrigerator cycle for Sterling; compressor drives cycle for pulse tube
- Much more efficient than remote compressor with valves, as in GM, because of work recovery during expansion
- Until recently, these devices were very expensive and had relatively short lifetimes, with mainly military applications. But this is now changing. New compressors have clearance seals and flex bearings, with nothing subject to wear; low cost production methods under development by several companies. Further investigation needed.

6.4.3 Flexible Hoses. This is a simple one, and not really a matter of "advanced technology." A common cause of failures on NRAO's existing telescopes is the development of leaks in flexible hoses carrying high-pressure helium around the rotating axes of the antenna. These are corrugated metal hoses of stainless steel or brass. No manufacturer specifies the flex life of such hoses, yet it is well known (e.g., [4]) that the fatigue failure rate drops sharply to zero at a known value of peak stress for each material. By design, we should keep the stress below this level. This can be done by increasing the bend radius and/or decreasing the pitch of the hose corrugations (both at increased initial cost) as much as necessary. During the development phase, we will confirm this design approach experimentally. It should be possible to design for a flex life of >1e6 cycles, which should exceed the life of the array.

6.5 PRELIMINARY DESIGN

- Single dewar and cryocooler for all receivers.
- Maximum window diameter 2.2 inches; smaller for receivers above 245 GHz.
- Other thermal design choices (component placement, wire and transmission line types and lengths, etc.) consistent with Table 1 and Appendix A of this chapter.
- Three stage cryocooler with performance:
    - Stage 1 <=80K at 12W
    - Stage 2 <=20K at 1W
    - Stage 3 <=4.0K at 0.5W
- Cryocooler is hybrid, with stages 1 and 2 using pulse tubes and stage 3 using a J-T expander. No moving parts at cryogenic temperatures.
- Compressor is conventional oil-filled rotary for PT stages, special dry rotary for JT stage.
- Predicted power consumption: 2.5 kW.

6.6 DEVELOPMENT PLAN

The following is an outline of the current plan for development of the cryocoolers for the production receivers of the MMA; see also Table 6.3, below. In summary, the plan consists of about 1.75yr of technology evaluation and development (from now until mid-2000), by which time a choice should be made for the size and type of system to be used on the array. In the last few months of this period, a design will be developed on paper and a design review (PDR) will be held. This is followed by a period of re-design and refinement, further testing, and integration with receiver components, with a goal of having the final array design ready by 6/2001. The schedule to this point includes about 9 months of slack, in case of difficulties. After a critical review of the final design (CDR), we will concentrate on building a prototype, fully documenting it, and selecting a contractor to carry out the production fabrication. The post-CDR work then becomes part of MMA construction.

There are three main thrusts to the development effort:

a) Thorough evaluation of two kinds of existing systems -- 3 stage, 2GM+1JT; and 2 stage GM.
b) Refinements and improvements to JT refrigerator technology, including expansion valves, gas cleaning, and compressors.
c) Development of a pulse tube refrigerator for 70K and 15K, with appropriate capacity.

All three will proceed in parallel, with (c) depending on an outside contract. Another important effort, also done in parallel, is to determine accurately the cooling load of the MMA receivers. For this purpose, a "thermal mockup" will be built to duplicate the thermal characteristics of the full set of receivers; it will not contain any millimeter wave electronics, but will have the same radiation, conduction, and dissipation loads as the actual receiver assembly. It will be possible to vary the loads for test purposes. In particular, various options for IR filters between the vacuum windows and the feeds will be carefully evaluated.

It should be noted that this whole plan is subject to change in mid-stream, depending of the results achieved and the design choices made.

Table 6.3: Outline of Development Plan

Basic Experimental Studies

- Thermometry: measure thermal resistance from leads to mounting surface for Si diode temperature sensors. [Mostly done]
- Measure practical load on radiation shield at 50-80K vs. layers of MLI applied. Compare with theoretical. [In process now]
- Measure practical load on radiation shield due to window.
- Measure thermal resistances of practical waveguides, SR coax, and wire at 300-70K, 70-4K, 70-20K, 20-4K. Compare with theoretical.
- Measure heat capacity of bulk SS, ErNi, etc. at 4K for use as thermal capacitor. [maybe not necessary]

Technology Evaluation

- NRAO JT system (existing): measure heat exchanger efficiencies, loads on 1st & 2nd stages due to JT circuit
- Commercial systems--
  - 2GM refrigerators: Sumitomo, small
  - Pulse tube refrigerator: Iwatani (70K only)
  - Sterling comressor, ~2kW size

Technology Development

- Contract for 2-stage PTR, 12W and 1.3W
- JT circuit improvements:
    - Use of sintered metal expansion orifice, rather than needle
    - Use of reactive getters for gas cleaning
    - Single-stage compressors, rotary and reciprocating
- Experimental study of windows and IR filters.

Construction

- Thermal mockup of MMA receiver dewar: duplicate shield area, window area, conduction load, dissipation load.

REFERENCES

[1] J. Lamb, "Infrared filters for cryogenic receivers," EDIR #290, 23 Apr 1992 (NRAO, Green Bank).

[2] J. Lugten and J. Welch, "A suggested receiver layout for the MMA antenna," MMA Memo #183, 15 Sep 1997.

[3] S. Weinreb, "Cryogenic performance of microwave terminations, attenuators, absorbers, and coaxial cable," EDIR #223, Jan 1982 (NRAO, Green Bank).

[4] T. Baumeister, ed., *Marks' Standard Handbook For Mechanical Engineers*, eighth edition, chapter 5. New York:McGraw-Hill, 1978.

[5] C. Wang et al., "A two-stage pulse tube cooler operating below 4K." {\it Cryogenics}, vol 37, pp 159--164, 1997.

[6] G. Thummes et al., "Convective heat losses in pulse tube coolers: effect of pulse tube inclination." *Cryocoolers 9*, R. Ross, ed. NY:Plenum Press, 1997.

[7] Zhu, Wu, and Chen, "Double inlet pulse tube refrigerators: an important improvement." *Cryogenics*, vol 30, pp 514--520, 1990.

APPENDIX A: HEAT LOAD CALCULATIONS

	4K ===== mW	20K ====== mW	80K ====== mW
Radiation Shields			
1st stage: 50cm H x 50cm D (1.18m^2)			
e=0.1 both sides, 10 layers MLI			1211
last stage: e=0.1 @ 80K, e=0.9 @ 4K, 900 cm^2			
5 layers MLI (0 layers => 21mW)	1.7		
(See Cryo Engr, Fig 7.23 p 404.)			

HFET Receivers -- 3 each

IR absorbing filters at 80K between windows and feeds (see EDIR 290).
Amplifiers and feeds at 20K.
Output at RF to 300K via waveguide; mixers at room temp.
Waveguide 10cm long to 80K, then 10cm to 300K.
Bias via #36 BeCu wires, 30cm to 80K or 20K, then 30cm to 300K:
1.267e-8m^2; 4-300K:190, 4-80K:20.3, 4-20K:1.21 uW-m.

90-116	6 stages, 1.2v*25mA total, 30mW/amp, x2 pol	60	
	WR10 WG, SS 10mil, Cu 100uin, x2 pol	40	75
	Bias wires, (2/stg+LED+com)*2pol=28ea	1.8	16
	Window 3.2in dia 5.1887e-3m^2	110	2354
70-90	4 stages 1.2 15mA x2 pol	36	
	WR12 WG	24	94
	Bias wires 20ea	1.3	11
	Window 4.5in dia .01026m^2	218	4654
33-50	4 1.2 15mA x2 pol	36	
	WR22 WG	24	166
	Bias wires 20ea	1.3	11
	Window 9in dia .04104m^2	872	18620
	SUBTOTALS, HFET RECEIVERS	1424.4	26001

SIS Receivers -- 7 each

IR absorbing filters at 80K.
Feeds and SIS mixers at 4.0K.
Single-stage HFET amplifier integrated with each balanced mixer (2 amplifiers per dual-sideband mixer), 4-12 GHz, 1.2V 5mA.
Additional 4-stage IF amp at 80K.
Photonic mixers at 80K, waveguide or quasi optical to SIS depending on band, separate optical fiber into each, one per polarization per band, level control via external optical attenuator; OR
Multiplier chain at 80K, waveguide in from 300K, one per polarization per band, level control via d.c. bias on last multiplier, outputs as above. 100mW drive, maximum of 4 operating simultaneously.

125-175 GHz

Window 2.2in	52	1113
1st IF stage x2sidebds x2pol @6mW	12	
Wires to 4K 2/SIS 2/HFET 2pol com spare = 26	1.76	14.7
LO waveguide WR8 SS 10mil Cu 0.1mil 10cm	6.7	
IF coax 4ch SS 10cm->80K, 20cm->300K	24	148
2nd IF amp x2sidebds x2pol @ 18mW		72
Photonic mixer dissipation		100
Multiplier		
Input WG WR12 10cm		94
Dissipation		100
Wires to 80K 10/ampl 2/photomix|mplr = 44ea		25
SUBTOTAL THIS BAND	96.5	1567[m]
		1473[p]

175-245 GHz			
245-320			
320-416			
416-510			
602-720			
787-950			
TOTAL SIS FOR 7 RECEIVERS ASSUMED IDENTICAL	675.2		10369[m] 9711[p]
GRAND TOTAL, shields + HFET + SIS	677	1424	36370[m] 35712[p]
POTENTIAL SAVINGS:			
Turn off bias to IF amplifiers in all but one SIS receiver	-72		-432
Windows for top 4 bands (>320 GHz) to 1.1in dia	-156		-5843
IF coax 4K->80K increase to 20cm long	-84		
Windows for all HFET receivers to 2.2in dia (requires use of ext lens or mirrors)		-1044	-22289
Delete 33-50 GHz band		-933	-18797
Both of the last two items		-1157	-23579
GRAND TOTALS WITH ALL THE ABOVE SAVINGS	365	267	6516[m] 5858[p]

[m] -> with multiplier LOs (only one driven)
[p] -> with photonic LOs (only one driven)