12-1-99

2nd MEETING OF THE ALMA JOINT RECEIVER DESIGN GROUP (JRDG)

IRAM, Grenoble

Thursday, 2 December 1999, 9:00 – 18:00, Open session

Chair - John Payne

09:00 Introduction (J. Payne)

09:10 Framework for the conceptual design studies (W. Wild)

09:30 Photonic development in Japan (M. Ishiguro)

09:40 Japanese receiver plans (Y. Sekimoto)

Presentation of conceptual design studies and discussion:

09:50 NRAO: Previous receiver design including evaluation receivers (G. Moorey)

10:30 *Coffee Break*

10:45 OVRO (J. Lamb)

11:45 IRAM (M. Carter, B. Lazareff)

12:45 *Lunch*

Chair - Wolfgang Wild

14:00 OSO (V. Belitsky)

15:00 RAL/ATC (R. Wade)

16:00 *Coffee break*

16:15 General discussion of presented receiver concepts. Some important issues could be: pro and cons of the different designs, optical layout, number of dewar windows, options for LO coupling, overall receiver system layout: mechanical configuration, size and location of LO and electronics modules, modular design: ease of exchanging modules, size and location of modules and components inside the dewar, required interfaces, LO coupling possibilities, thermal calculation, ease of maintenance and refurbishing of receivers, weight estimate of the receiver system.

18:00 Adjourn

20:00 *Dinner*

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09:00 Science requirements and receivers (W. Wild, S. Guilloteau)

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10:45 Evaluation of conceptual design studies, conclusions (all)

12:00 *Lunch*

Chair – W. Wild

The Joint receiver work program

13:00 Reactions from the AEC and ACC (R. Kurz, R. Brown)

Duplication of development work (all)

Refining the work program: milestones, deliverables, WBS (R. Brown)

General discussion

16:00 *Coffee break*

16:30 Next steps, action points, unresolved questions

17:00 Adjourn

JRDG meeting — Grenoble

Payne: today, presentation of concepts — tomorrow, discussion/resolution

Wild: conceptual design sent out: Optics, bands, LO coupling, modes, cryogenics, modular design, mechanical — all fairly general

Ishiguro: photonic developments in Japan

NTT photodiode expect 1 mW at 200, 100 μW at 900 GHz (goal) 1.55 μm λ

ISAS photomixer 0.1 μW @ 800 GHz 0.85 μm λ

Continuing to work with NTT - contract for faster photodiode

Have not tested with highly stable lasers, but plan to

Sekimoto: receiver plans. Mt. Fuji 600K DSB @ 810 GHz, 300K SSB @ 492, 120K DSB @ 350

Quasi-optical sideband sep at 500 GHz. IF 2.0-2.5 GHz (expect 4-8 with development)

now need 200 μW LO - hope to improve

797-828 GHz 600-650K — strong fn. of T

Some redesign for 10m in Chile - install late 2001

Daikin GM with He pot 1W @ 4K, 20W @ 40K (7kW) MTBF ~ 10 yr

ΔT ~ 30mK at 4K

ALMA-packaged design - looking at new possibilities

Moorey: NRAO status. Reviewed MMA development plans.

Contentious: bandwidth; switch time within band

→ What is time scale for warm-up?

— BREAK —

Lamb: preliminary study

Assumed OMT and waveguide LO to 370 GHz

Concentrates on optics. Optimize for each band.

Dominated by low frequency considerations.

Lamb, cont.

Details of fundamentals considered.

Considered: 1. horn, 2. horn + cooled lens, 3. horn + ambient mirrors

1. find minimum length $R = 2\pi w_0^2/\lambda$ $a = \sqrt{2}\, w_0$

at $\lambda = 4.5$mm, horn is 1m long, 84mm diameter!

2. Worries about uniformity – need large windows also

99% efficient at $5 w_0$

e.g. 67-90 ⇒ 133mm (Memo 213) for <1% loss

3. Ambient mirrors  images primary

Reduces window area

about X7

But: losses, distortion, polarization X, machining, alignment

Optimized for each band separately

Vacuum windows: material: quartz, rigid plastic, thin sheets

Mylar: could use 2 layers separated by $\lambda/4$

IR block: solid, multilayer, foams for absorption

Reflection: black coating; blazed grating (cold stops?)

micro-corner-cubes would be truly retro

Interference filter? Could be big development.

Si substrate could work, but high ϵ requires etching

could get 2:1 freq. ratio passed

Corrugated horn of SS with thermal gradient?

Layout: ambient rotating mirror for band selection, different ellipsoidal mirrors for each band

for high frequencies, 2 additional internal mirrors

WVR in center, room temp lens + prism (rotatable for measurement of anomalous refraction)

Have to change focus with band

Lamb, cont.

Dewar diameter ~600 mm, top 

Calibration? Tilt rotator?

Is there room for the receiver inserts?

IRAM concepts: Bernard Lazareff

Modules include mixers, LO injection, cold IF, etc. serviced from top

~like NRAO design 

Control: I2C bus – Philips and >10 other suppliers

4 wires daisy-chained, 100 kHz clock (400 kHz soon), >10m length

Functions & interfaces widely available

IRAM has specific modules: bias (done), others in development

use opto-isolator and buffer to I2C bus

Image rejection

MPI or backshort: can it do 4-12 GHz?

MPI: Calculate loss <1% within ±1 GHz of center freq

average loss 5.2% over 8 GHz (T_{sys} ≈ 1.18 at 4 & 12)

Plambeck: what if cold load is hotter than sky?

Adjustable backshort for image rejection:

lose 13% for full 8 GHz – but little in center of band

Carter: new receivers for PdB

85-115, 130-180, 200-275, 275-365

SSB

hot/cold cal

LO by waveguide

dual pol, single freq

IF 3.8-4.8

Carter, cont. 3 mm system:

610mm dewar, Oxikin refrig

20 dB waveguide couplers in series – works OK up to 3 SIS mixers

pol. split by grids. Big IF amps.

200-275: pol mirror + grid, box is ~80 mm cube

series 4-port couplers. Backshort tuning for SSB.

Offset feeds from optical axis 150mm = 5' arc

Disk rotator outside dewar for hot/cold load cal

For ALMA receivers:

OMT design adapted from FIRST (U. Florence)

Split arms out – put DSB on each with right path lengths to get SSB – but how to inject LO?

Offset on diagonal, sidewall couplers to do 90° LO phase shift

Think this could work to ~500 GHz

Higher freqs: MPI, lots of pieces, dump image (-10dB) to 4K plate

may need only one actuator

Put rcvrs on 170mm ring, rotator for hot/cold cal

150mm square for high bands

WVR beam in center, pick-off mirror to off-axis feed, 3' arc from other beams

Payne: can you keep λ/4 with sidewall couplers over the whole band? Reply – no worse than Kerr's

Backshort reliability? In ~1/3 height waveguide, 10μm layer of Teflon-like coating – no sticking in 6 years of operation of 18 rcvrs. Drivers are another question. Normal failures are the IF amplifiers.

Wild: problems at 30-m. Reply: old cryostat had poorly designed backshort drivers. Have had motor failures outside dewar at PdB.

Lamb: cold motor for driver? Looking into it. Edinburgh using steppers inside dewar.

Blanbeck: reproducibility of backshort tuning? OK but must compensate for backlash.

Payne: what is the LO? Haven't worked on it in detail. Would prefer multipliers outside dewar for maintainability. Have been using whisker contacted multipliers.

— LUNCH —

DSO: Belitsky: work with Torchinsky

Central mirror, optical pol. sep. and LO injection

Modularity is not by frequency, but by function; optics separated from SIS mixers separated from LO, IF etc.

Flat + 2 elliptical mirrors, LO couplers

Requires dewar diameter of 1.5m – can be compressed some

Also requires large windows – would mask unused windows

RAL: Wade: Will show ~10% of their design work

Edinborough cryo stepper reliable but large

Overall design uses only current technology

Critical role of WVR 3' from others

Guillotean: 3' is very conservative – could be much wider

Wade, cont. — Ellison:

Separate 30 GHz recvr — separate dewar.

Use 6 windows total; 5 beams centered around WVR

3 & 5 are coincident, 4 & 6 etc. with MPIs at 77K

Use wideband, single-ended SIS mixers in pairs

Multiple double relay/refocus mirrors outside dewar

Windows ~45mm. No IR blocking filters.

Freq. multiplexing — different lobes of MPI

Requires a lot of LO power

Adjusted freq. bands to accommodate freq. multiplexing

Assuming PTFE and Mylar windows

Calculated losses from all the mirrors etc. & added noise

e.g. + 22K for 850 GHz at band edge from everything

SIS mixers: single ended, fixed tuned backshort, non-integrated LNA

LO multipliers HBV's or varactors @ 77K, injected via dielectric beamsplitter

WVR: suggest cooled subharmonic Schottky mixer — suggest it is reliable and goes in the main dewar

Hot/cold cal not fully worked out

Works SSB for narrow band, DSB for continuum (tune MPI)

Bradshaw: Cryogenics

Have done J-T for spacecraft — fixed-orifice on top of GM

Demonstrator 4K for Planck using Stirling cycle refrig

Careful attention to contamination issues

Might use a pulse tube — come in at a 45° angle

Hot reactive gas purger — hot vanadium wire

Modules mount from the bottom.

Dewar 800 mm, teapot cooler

Bradshaw, cont.

Service MPIs from top

Thermal contact to modules: nylon ring compresses Be-Cu fingers

Expect 5.7W load at 70K — 20 layers of superinsulation

2.8 — 15K — CFRP between 15K/70K

0.1 — 4K

Anna Orlowska

Looked at GM, pulse tube, Stirling alternatives

Stirling is too expensive for ALMA

2-stage GM can provide 4K but is inefficient

2-stage GM + JT is most efficient, easy to distribute 4K

Weighing all factors, opted for a JT system

Would prefer 15K pulse tube to GM, but can't buy commercially

Expect 2-3kW for GM, 400W for JT stage

Intend to reach 3.80-3.85K at JT stage

Wade: circular pol. is a question

Plambeck: BIMA rcvrs inject LO external to dewar,

simple double lens system (antennas f/4.5)

anti-reflection machining: circular grooves have different ε with angle; have gone to multiple milled holes (20 mil holes @ 100 GHz)

beware extruded plastic; measure patterns

OMTs: sees difficulties with waveguide versions

probes in a round waveguide? 180° hybrid on substrate (5 mil quartz) with slotline stubs terminating microstrip — plan to try at 100 GHz

Welch cal scheme — now have some data on one antenna

General Discussion

Windows: no one wants a single wideband channel

General dissatisfaction with Mylar windows

Specs on Rx temps, SSB, 30 GHz? No agreed specs.

SSB mixers – at 50k and 8 GHz, = backshort at 40k and 4 GHz

LO power & tuning range

Discussion of merits of MMIC SSB vs. MPI

Discussion of modularity – double channel design makes it harder

Belitsky: mistake to separate by freq. rather than function

– End 6 pm

JRDG meeting – day 2

Guilloteau: requirements – first, spectroscopy

SSB, low noise – mostly relevant up to 350 GHz

do what you can > 350 GHz

2nd priority: continuum sensitivity → largest reasonable bandwidth

⇒ ≳ 10 dB image rejection

≲ 6 $\frac{h\nu}{k}$ T_{rec} at ν < 370 GHz over <u>most</u> of band

4 GHz/polarization (more if possible)

Forward efficiency > 0.95

Operation constraints:

cold load (match T_{sky}) – may not need hot load

100 GHz – always operating? permanent LO?

WVR: acceptable angular distance ∝ λ
≈ 3′ at ~300 GHz should be OK
can something be made to fit?
} discussion, conclusion that more work and some flexibility needed

Retuning: 1.5 sec between bands – just to 90 GHz?

5-10 sec within band – is this the right number?

Reliability: MTBF 1 year + 5 days cooling

⇒ always >1 ~~antenna~~ receiver out of service

avoid devices at subreflector if possible

locate single point failures outside dewar

Experience: main failure modes:

IRAM: amplifiers

NRAO, BIMA: connectors

IRAM: motors outside dewar

cold switches, cold motors?

Construction time: alignment? modularity?

I raised: saturation? how accurately calibratable?
need a spec - affects Sun (with attn.) + planets
stability for total power? need more data

Payne: questions raised in Tucson at last JRDG meeting
1. Circular pol? Spot freqs? Needs more study to turn specific science requirements into engineering requirements
→ D'Addario + Crutcher (delegated by Payne & Emerson)
2. Freq. bands (RAL adjusted) - specific questions to be generated (Wild)
3. 30-45 GHz? Need written memo. → Brown to organize
4. Initial bands - 90, 230, 650 or 90, 345, 650? → Guilloteau
5. 183 GHz WVR → Hills (Wade to press)
6. Total power stability. IRAM gets 2×10^{-4} in one minute (SIS)
1×10^{-7} at 230 GHz would not be good enough
Should be communicated to scientists. Needs study to determine HFET/SIS for <116 GHz.
7. Nutators? Have to wait for prototype antennas.
— BREAK —

Payne: where do we go from here?

Suggestions: external optics for band selection, window sizes
MMIC SSB mixers to 275 GHz, MPIs above
do 86, 230, 345, 650 as baseline plan
one cartridge / freq band
→ Payne: NRAO does 86, 230; OSO does 345; SRON does 650 by 15 Jan
Lamb's optics, RAL dewar concept
→ LO range restriction initially? Gets rid of one MPI?
Get numbers from Neal Erickson

— LUNCH —

Organization of work:

Change work packages / work program to reflect reality?

There is no work package for diplexers used for sideband sep.

Discussion of how designs of different pieces interrelate.

Boundary of SSB MPI vs. other? Belitsky's SSB plan will take about 2 years. Will do 100 GHz first.

Could lay out DSB/MPI version to test for fit.

Role of IRAM?

Proposal: NRAO: 90 & 230 module layouts

Lamb: warm optics

Ellison: whole package (collaborate with Lamb) (IRAM optics lead?)

OSO: 345 GHz module layout

SRON: 650 GHz module layout

IRAM: diplexers? need to have a role!

Guilloteau: noise performance at 100 GHz is very important — carefully consider SIS rather than HFET — use Belitsky development at 100?

Who does widgets? (1/4λ plates, solar atten)

Issue of hot/cold loads, cal in subreflector?

— BREAK —

Brown: Eval rcvr: CDR soon; deliver 2001-5, 2001-12 — Ellison: move up

Proto rcvr: CoDR 2000-03; PDR 2001-01; CDR 2001-07

deliver 2002-11

ALMA rcvr: design mods 2002-11 → 2003-03

pre-production review 2003-03

release for fab 2003-04

Deliver Rx #1 2004-10

Total ALMA cost → ECC end of 2000-03

Brown, cont.

Would like to see more deliverables — e.g. devices — with dates attached (ACC to track progress)

If you run into trouble: change schedule? Plow ahead with what's available? Plow ahead! Deliver rcvrs!

Wild: revise Joint Work Program to reflect reality, including specifics on tasks & milestones

Wade: review assignments & dates for immediate work

Plambeck & others: proposed refrigerator is underpowered — would like to see 1W capacity at 4K station. Need better estimate of thermal loads. This is part of Bradshaw's work package.

→ Date ~~&~~/place for next meeting? Charlottesville March 20-21

12-2-99

Minutes of the second
Joint Receiver Design Group (JRDG) Meeting

Meeting dates: 2 December 1999, 9:00 – 18:00, and 3 December 1999, 9:00 – 17:00
Meeting place: IRAM Grenoble

Present: **The Joint Receiver Design Group:**
John Payne (NRAO) – chair
Wolfgang Wild (NOVA/SRON) – chair
Victor Belitsky (OSO)
Charles Cunningham (HIA)
Brian Ellison (RAL)
James Lamb (OVRO)
Bernard Lazareff (IRAM)
Dick Plambeck (BIMA)
John Webber (NRAO)
Peter van der Wal (MPIfR, representing Rolf Guesten)

Richard Kurz (ESO)
Stephane Guilloteau (ESO)
Jaap Baars (ESO)
Bob Brown (NRAO)
Darrel Emerson (NRAO)
Graham Moorey (NRAO)
Richard Wade (RAL)
Masato Ishiguro (NRO)
Yutaro Sekimoto (NRO)
Ryohei Kawabe (NRO)
Takashi Noguchi (NRO)
additional attendees during the first day from IRAM, RAL, MPIfR, and OSO.

Minutes : Wolfgang Wild and John Payne

Agenda: (see Appendix)

The "Joint Receiver Design Group" (JRDG) met for two days to discuss conceptual designs for ALMA receivers. These minutes will not reproduce all the discussions, but rather summarize the results and decisions.

The first day opened with an outline of the framework for the conceptual design studies. This presentation was a shortened version of the document "ALMA Receiver Conceptual Design: Guidelines for Receiver Configuration Meeting" (available at the ESO shared workspace ALMA – receivers) which was sent to the groups working on ALMA conceptual receiver designs. The following two talks by Masato Ishiguro and Yutaro Sekimoto informed about photonic development in Japan and Japanese receiver plans. The main part of the day was dedicated to presentations of design ideas and concepts by NRAO, OVRO, IRAM, OSO, RAL/ATC, and BIMA and discussions. This was an open session and was attended by approximately 35 engineers and scientists from 11 institutions.

On the second day the JRDG discussed the science requirements and its implications on receiver design, evaluated the presented conceptual design studies, identified the next steps, and discussed the Joint US/European receiver work program.

S. Guilloteau presented his view of the ALMA science requirements and specifications (an agreed set of scientific requirements and receiver specifications between the U.S. and European partners is pending). The contents of his viewgraphs is given here (with comments in square brackets):

Main goal

- Optimal spectral line sensitivity: → Single sideband tuning
  → 4 hν/k
- Band priority for sensitivity: 80 – 115 GHz, 220 – 280 GHz, ~ 350 GHz (continuum)

[The U.S. and European SAC earlier recommended 3 mm, 1.2 mm, 650 GHz, and 3 mm, 350 GHz, 650 GHz, respectively. The JRDG favours the initial installation of four receiver bands: 89 to 116 GHz, 211 to 275 GHz, 275 to 370 GHz, and 602 to 720 GHz.]

- Good continuum sensitivity: → largest reasonable bandwidth

Specifications

- ≥ 10 dB sideband rejection
- ≤ 6 hν/k T_{rec} below 370 GHz (over <u>most</u> of the band)
- 4 GHz per polarization (more if possible) [discussion revealed that 4 GHz per sideband was meant]
- Forward efficiency > 0.95 [difficult to achieve at higher frequencies]

Operation constraints
Calibration scheme

- cold load required (match T_{sky})
- permanent operation of the 100 GHz channel → permanent LO on that channel ?

WVR

- Acceptable angular distance ∝ λ [not so clear after discussion]
- ≈ 3' / 300 GHz ? Do we have a concept ? Can that fit into the main dewar ?

[The JRDG considered 3' as maximum angular distance between observing channel and wvr as adequate for working on conceptual receiver designs.]

Retuning

- Switching between # bands: 1.5 sec [this refers to switching between pretuned frequencies in two different bands, not to tuning time]
- Within a band: 5 sec, perhaps 10 sec, ?? discuss [some discussion about implications].

Reliability:

- MTBF 1 year + 5 days cooling ⇔ always more than 1 receiver out of order

[Some misunderstanding here. The guideline for the conceptual receiver design was a *maximum* of 5 days *cycle* time, i.e. warming up, opening, working inside dewar, closing, pumping, cooling down. There was some discussion and concern about a 5 day cycle time. The actual cycle time can be assessed once the overall receiver design is more advanced, and may be much shorter.]

- Avoid devices in subreflector if possible (difficult access)
- Locate single point failures out of dewar

Experience: main failure modes - amplifiers (IRAM)
- connectors (NRAO – BIMA)
- motors outside dewar (IRAM)

Cold switches ?
Cold motors ?

[end of S. Guilloteau's viewgraphs]

The questions from the JRDG to the Science & System group formulated by the JRDG during its 30 September meeting (see minutes of that meeting) were discussed.

During the evaluation of the conceptual design presented the previous day, the JRDG came to the following opinions and conclusions:

- Agreed scientific requirements and their translation into engineering specs are needed. This includes issues like specs for the water vapour radiometer, supported observing modes, calibration accuracy, polarization requirements, confirmation of frequency bands, the 30 – 40 GHz channel, and others.
- One module pre frequency channel is preferred.
- One RF cryostat window per frequency channel is preferred.
- A maximum angular separation of 3' between any frequency channel and the 183 GHz water vapout monitor was considered adequate for working on conceptual receiver designs. More detailed specs for the wvr are needed (see action points).
- The JRDG favours the initial equipment of ALMA with four frequency channels (if resources are available): 89 to 116 GHz, 211 to 275 GHz, 275 to 370 GHz, and 602 to 720 GHz.
- Given the rather short schedule for ALMA, sideband separating mixers may be the choice up to 370 GHz. Above 370 GHz, single-ended mixers with a SSB filter (Martin-Puplett diplexer) may be the choice.
- It is most likely that the last frequency multiplier for each channel needs to be cooled.
- The JRDG should have monthly telecons (see action points).

The following decisions on action points, the next meeting and next steps were taken.

Action points:

- S. Guilloteau will contact R. Hills to get more detailed specs on the 183 GHz water vapour radiometer. In particular, required sensitivity and stability, max. angular separation of the wvr to the observing channels, calibration requirements, and backend requirements are important.
- J. Payne, D. Emerson and L. D'Addario will look into requirements for polarization measurements. They will also contact D. Crutcher.
- R. Brown will get a scientific justification for the 30 to 40 GHz channel.
- W. Wild will formulate and circulate detailed questions about the ALMA frequency bands.
- J. Payne and D. Emerson will look into the required amplitude stability for ALMA receivers.
- J. Payne and W. Wild will set up monthly telecons for the JRDG. Details will be e-mailed.

Next meeting:

- The next JRDG meeting and a "Conceptual design review" for the ALMA overall receiver design will be held on March 20 and 21, 2000, at NRAO Charlottesville.

Next steps:

The following table indicates the next steps before the conceptual design review.

What	By whom	When available
Overall optics layout/design	Carter, Lamb, Ellison (coordinated by IRAM)	1 Feb 2000
Diplexer specs and design	IRAM (D. Maier)	1 Feb 2000
Cryostat design incl cooler and thermal model	RAL/ATC	15 Feb 2000

Receiver channels (outline drawings)		
3 mm / 1.2 mm	NRAO	15 Jan 2000
350 GHz	OSO (Belitsky)	15 Jan 2000
650 GHz	SRON (Wild)	15 Jan 2000
Polarimetry analysis	Emerson/Payne/D'Addario	15 Jan 2000

As part of a discussion about the Joint US/European receiver work program (starting later than foreseen due to extended discussions about the receiver design and next steps), R. Brown presented the schedule for ALMA receivers. In summary:

- Evaluation receivers:
  - CDR soon !
  - deliver rx #1 by May 2001
  - deliver rx #2 by Dec 2001

- Prototype receivers:

Conceptual design review (CoDR):	Mar 2000
PDR	Jan 2001
CDR	Jul 2001
deliver prototype receiver	Nov 2002
design modifications	Nov 2001 to Mar 2003
pre-production review	Apr 2003
deliver ALMA receiver #1	Oct 2004

After a general discussion about milestones, deliverables, parallel development, and the joint work program, the meeting concluded at 17:00.

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General discussion

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12-2-99
Webber

ALMA Front-End Conceptual Design

Victor Belitsky † and Steve Torchinsky ‡

†Onsala Space Observatory, Chalmers University of Technology, Sweden, belitsky@oso.chalmers.se
‡Dept. of Physics and Astronomy, University of Calgary, Canada, sat@iras.ucalgary.ca

The ALMA conceptual design we present here is based on ideas earlier outlined in ALMA Memo 242, by V. Belitsky. Compare to the version presented in Memo 242 the optical layout was revised, as well we added 183 GHz water vapor monitor (WVM) channel. We also present 3D Gaussian beam tracing for two channels, channel #2 lowest frequency, the center frequency 79 GHz, and channel #10 highest frequency, the center frequency 869 GHz.

Objectives

- **Optical layout:** Simple, with minimum number of optical components, using only mirrors:
  - Individual optics for each channel => avoiding aberrations due to different curvature of mirrors required for different frequencies;
  - Using optical switch with central beam at the axis of the telescope focal plane => no offset aberrations and polarization distortion;
  - Gaussian Beam Telescope (GBT) as re-imaging tool => frequency independent waist positions and the telescope beam coupling;
  - Grids as polarization splitter in front of the mixers;
  - 183 GHz WVM beam @ 3 arc min from any of the mixer beams;
  - One LO feed for both polarization mixers.

- **Modular and integrated design: 5 subsystems**
  - Input optics, including the switch;
  - 183 GHz WVM with its associated optic and cryogenic;
  - Dewar with SIS mixer modules (8/9 channels) with their respective optics and LO injection interface; The dewar has integrated cold calibration load; Dewar has mechanical interface to cryocooler;
  - LO subsystem mounted onto the dewar bottom plate, consisting of multiplier modules, photonic reference source, etc.; IF, DC bias and control integrated onto LO subsystem platform with interface to the dewar from the bottom;
  - Cryocooler with mechanical interface to the dewar;

- **Miscellanies**
  - EMI problem with many openings in the dewar wall => idle windows should be blinded; The window blinding improves thermal isolation;
  - Cooling power to be oversized => lower ultimate temperature + reserves in the lift power due to future cryogenic multipliers and photonic LOs;
  - Flexibility of the entire system with enough room for upgrades and/or alternatives.

ALMA Front-End Conceptual Design

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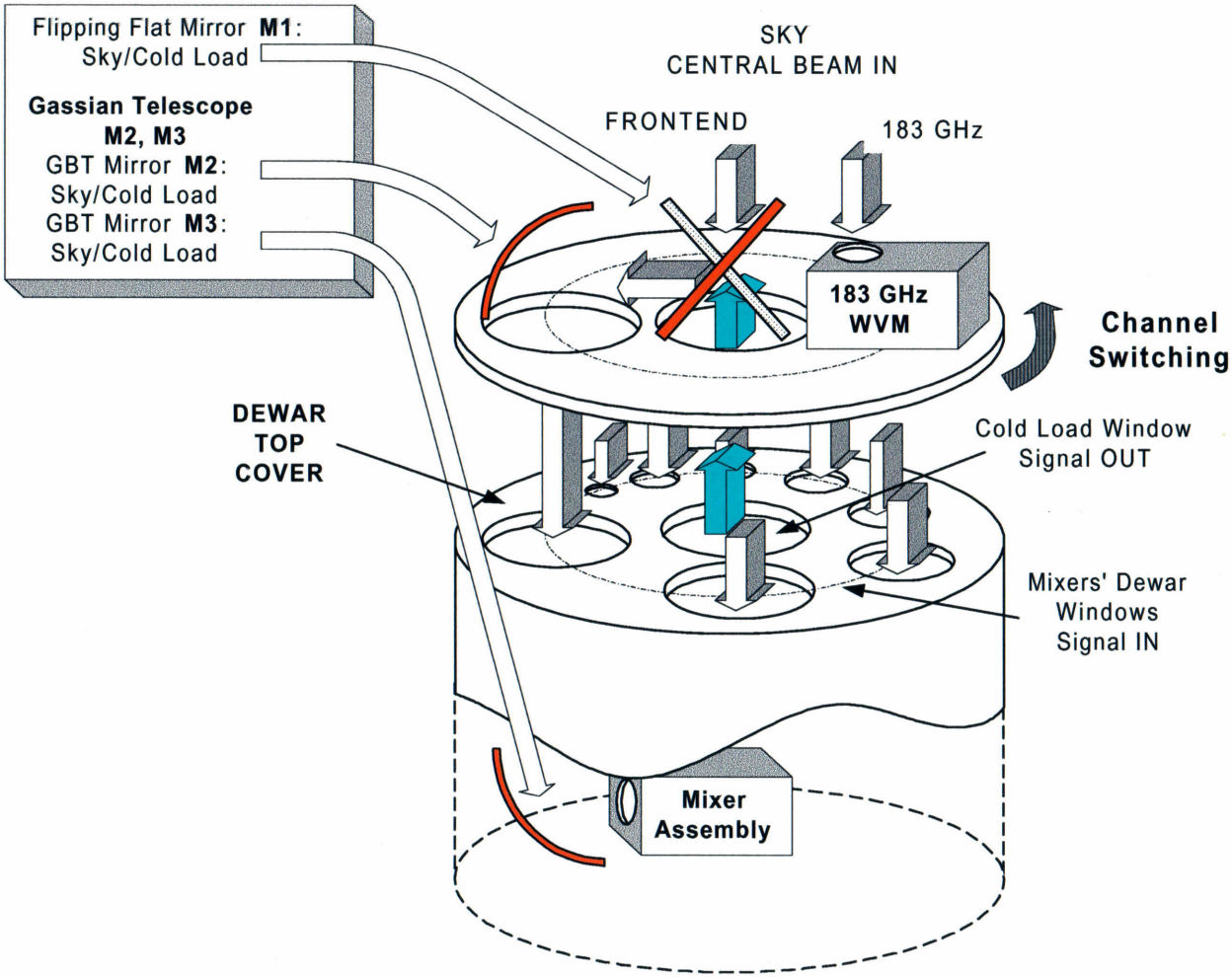

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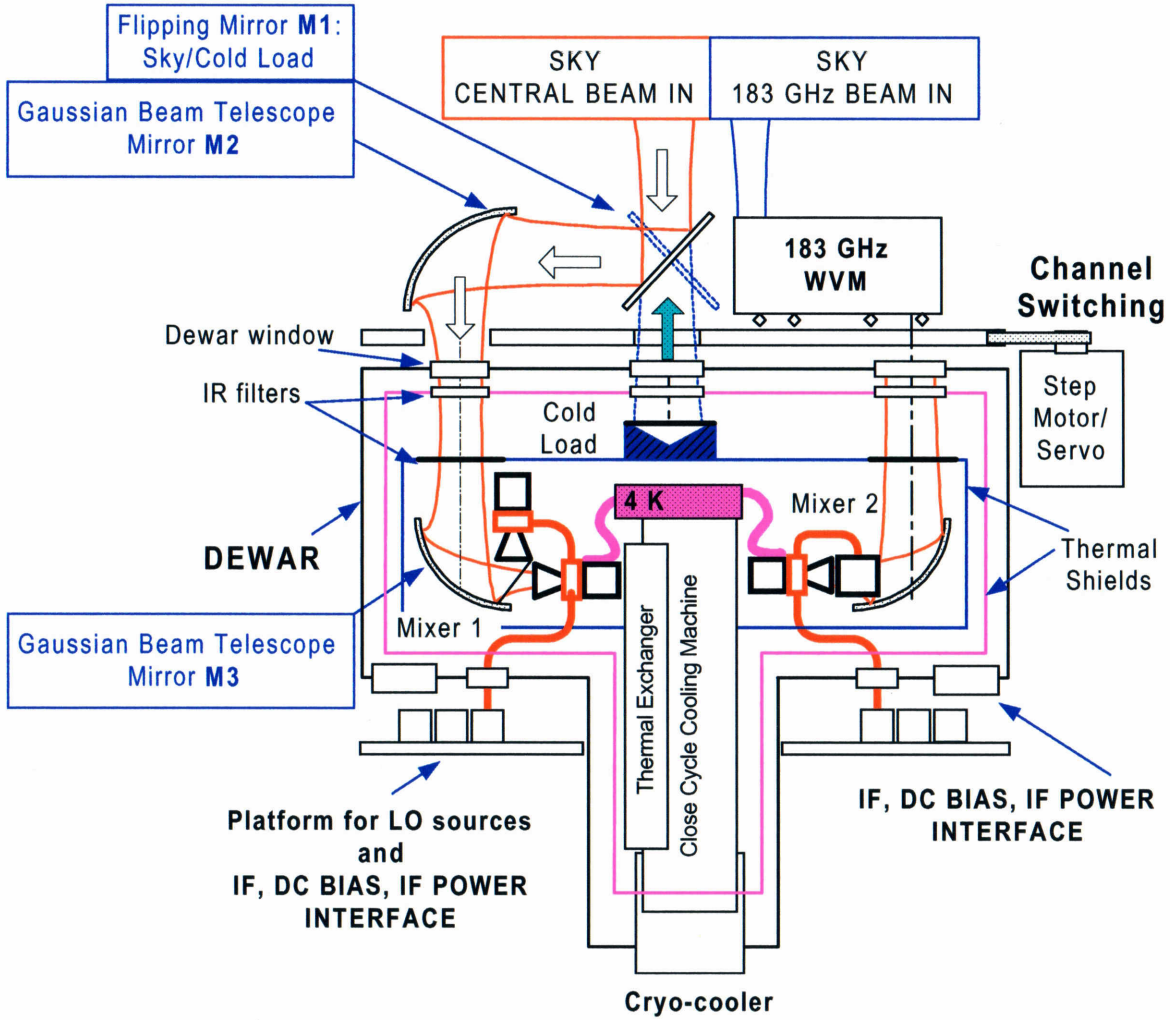

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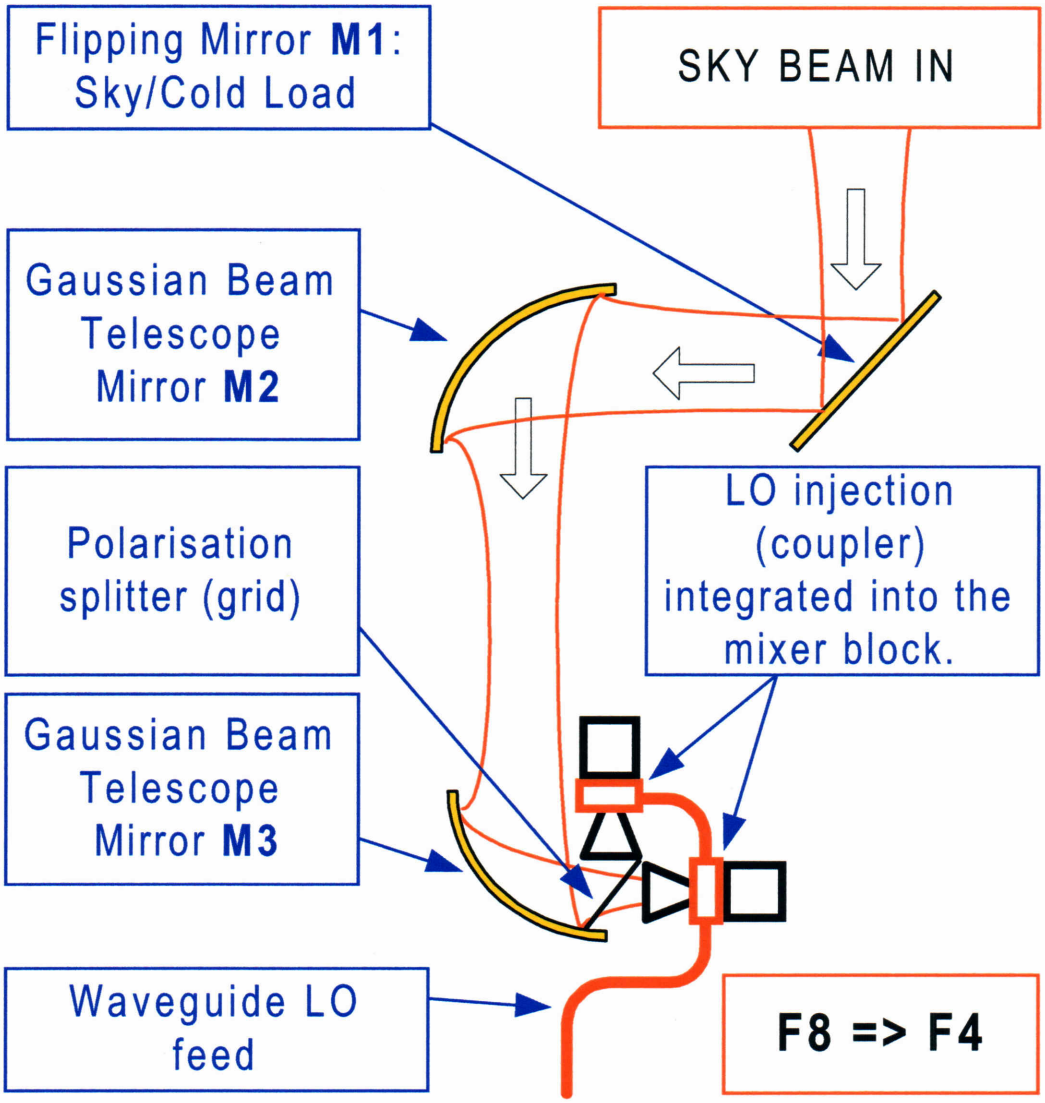
Mixer Assembly
LO Injection Waveguide

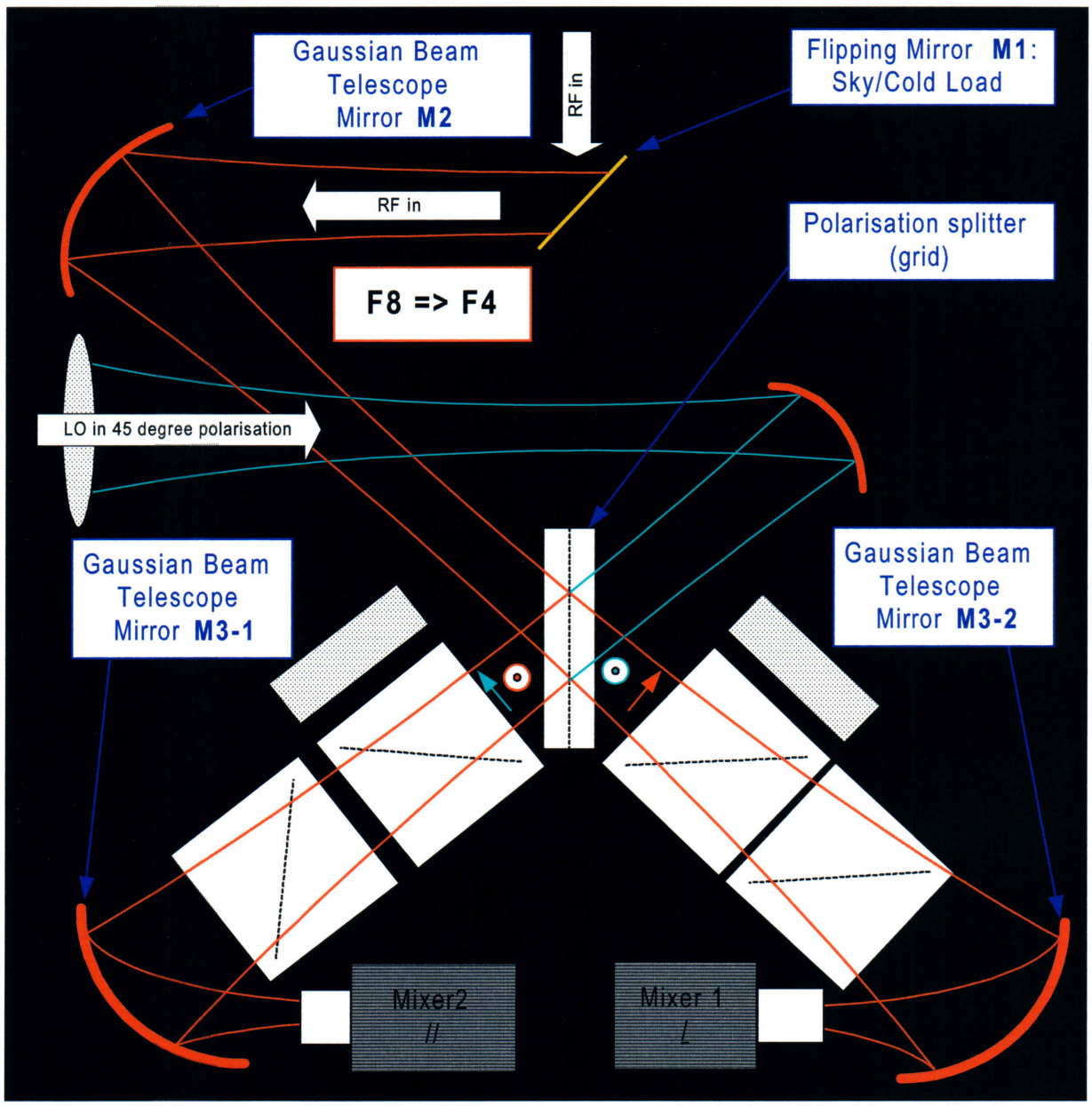


ALMA Front-End Conceptual Design

Victor Belitsky † and Steve Torchinsky ‡

†Onsala Space Observatory, Chalmers University of Technology, Sweden, belitsky@oso.chalmers.se
‡Dept. of Physics and Astronomy, University of Calgary, Canada, sat@iras.ucalgary.ca

Mixer Assembly
LO Injection Quasioptical



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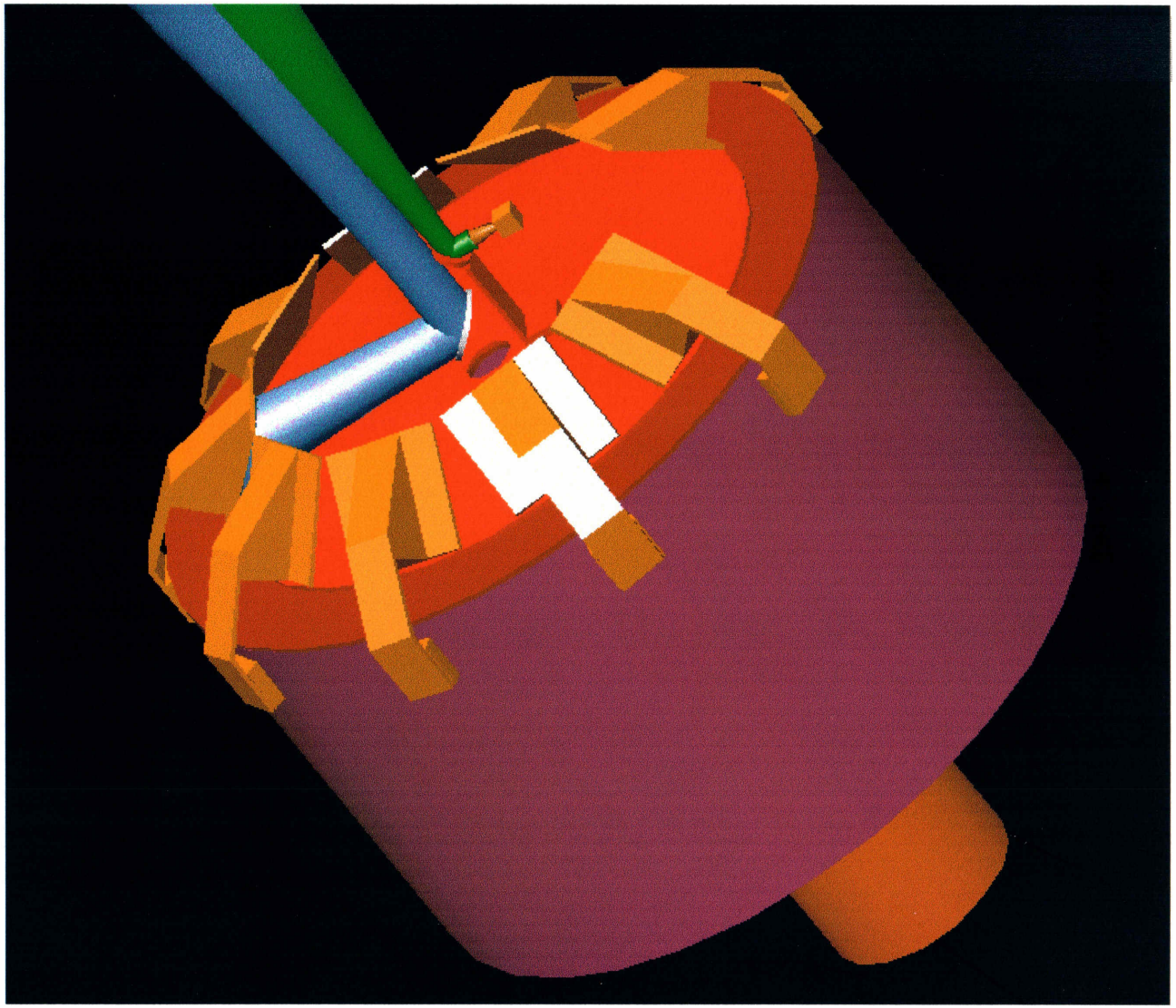
Top View: 3-D Gaussian Beam tracing: 79 GHz, 869 GHz and 183 GHz beams



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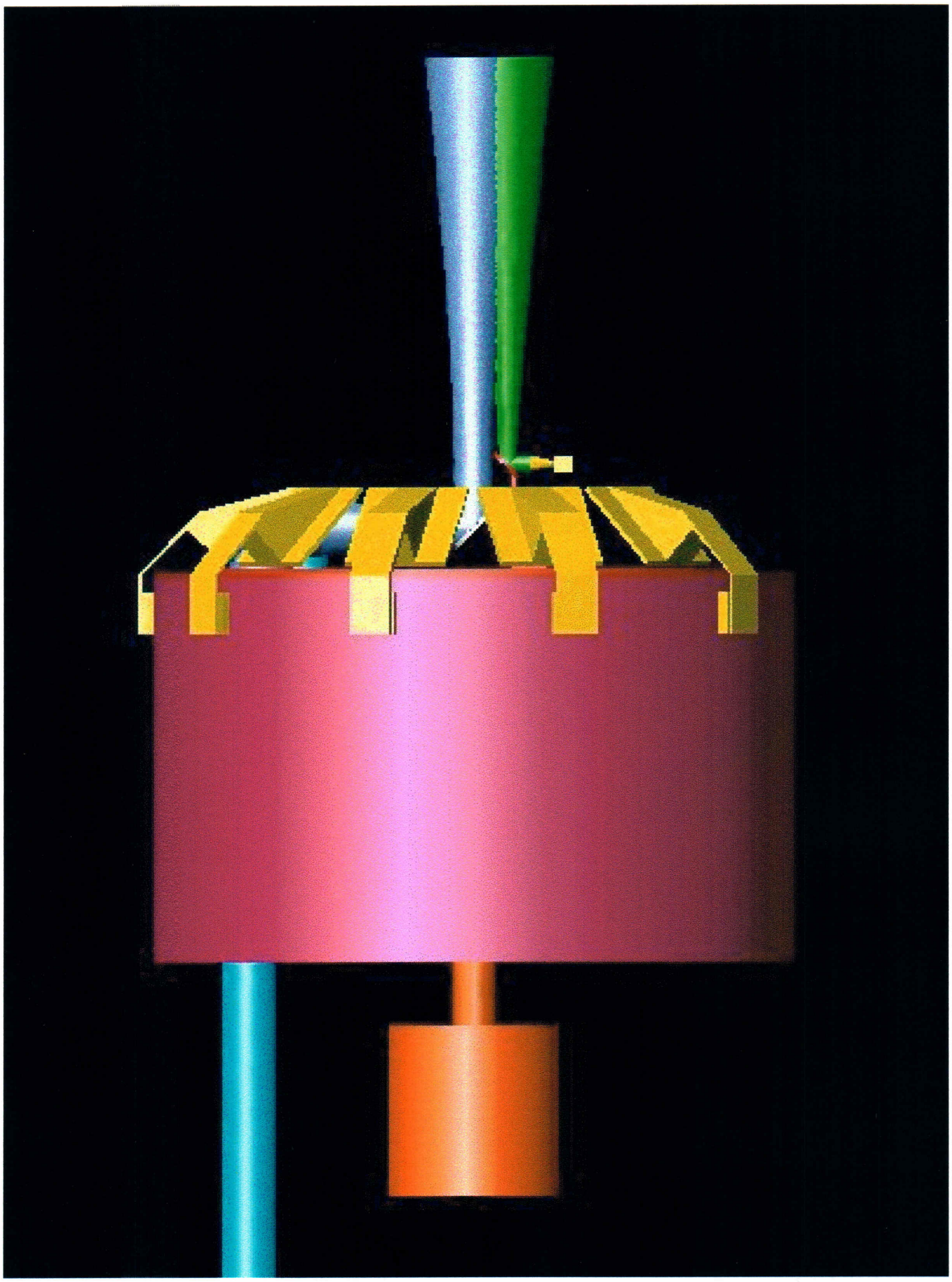
3-D Gaussian Beam tracing: 79 GHz and 183 GHz beams



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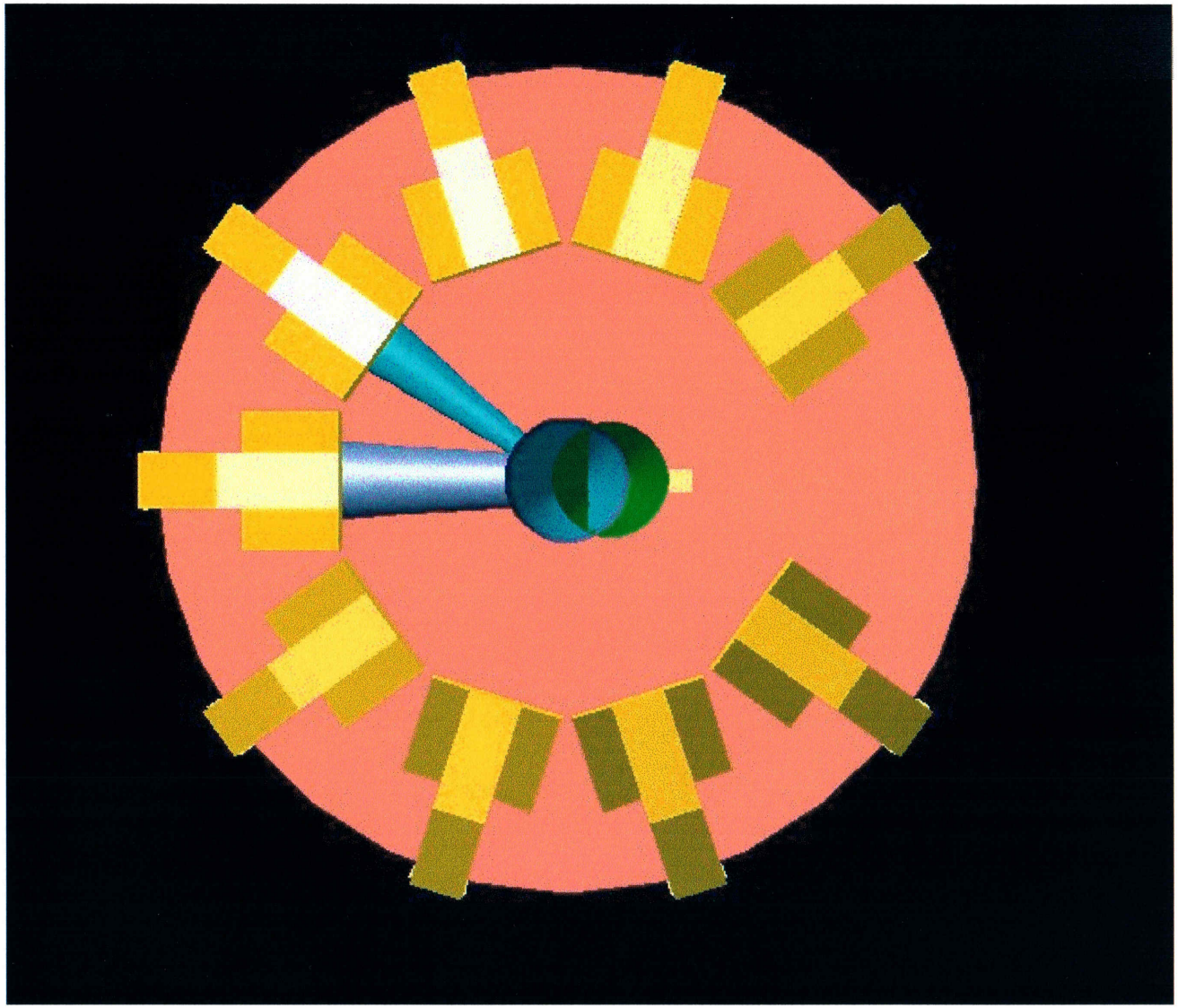
Top View: 3-D Gaussian Beam tracing: 79 GHz, 869 GHz and 183 GHz beams



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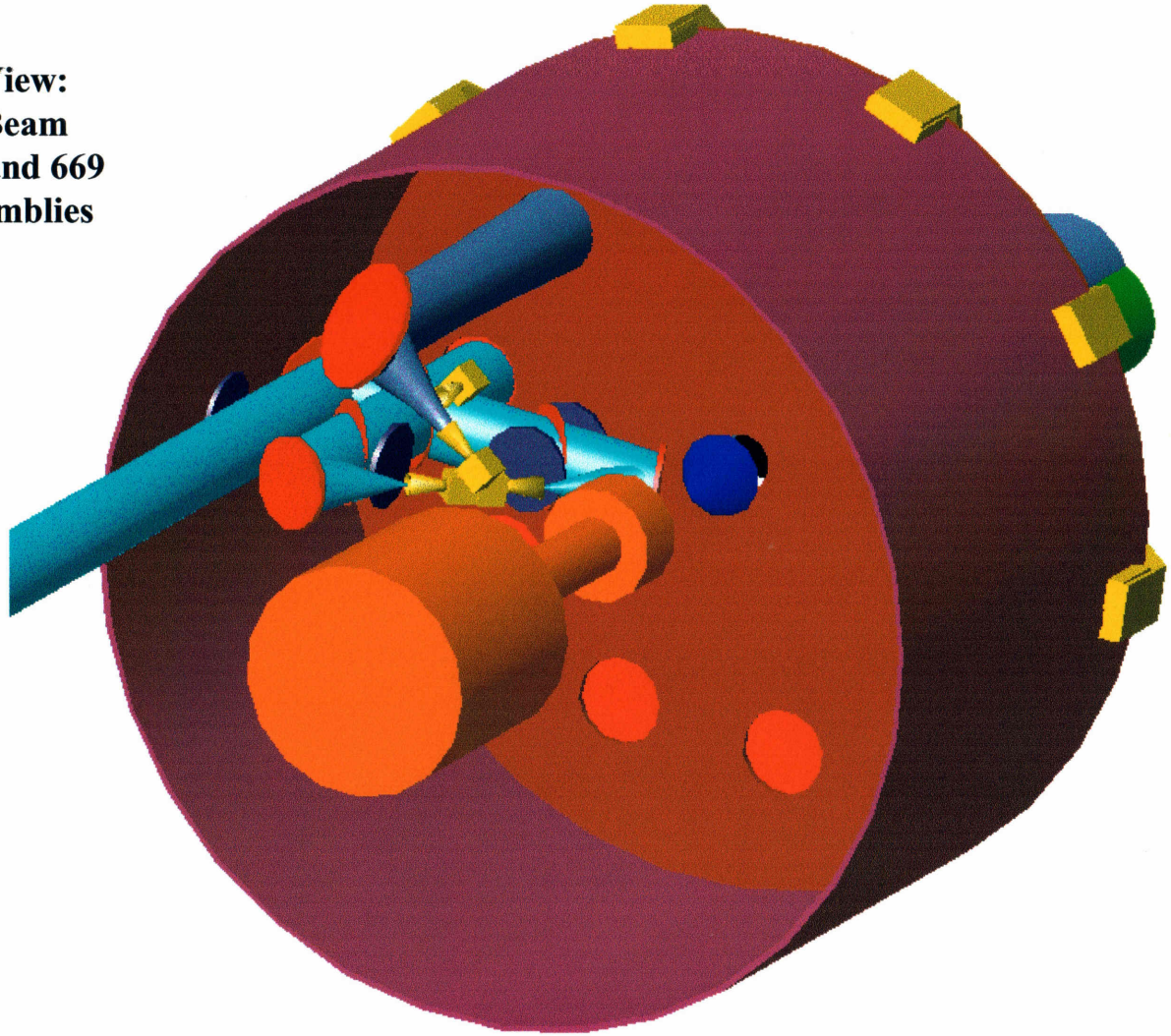
Inside Dewar View: 3-D Gaussian Beam tracing: 79 GHz and 669 GHz Mixer Assemblies



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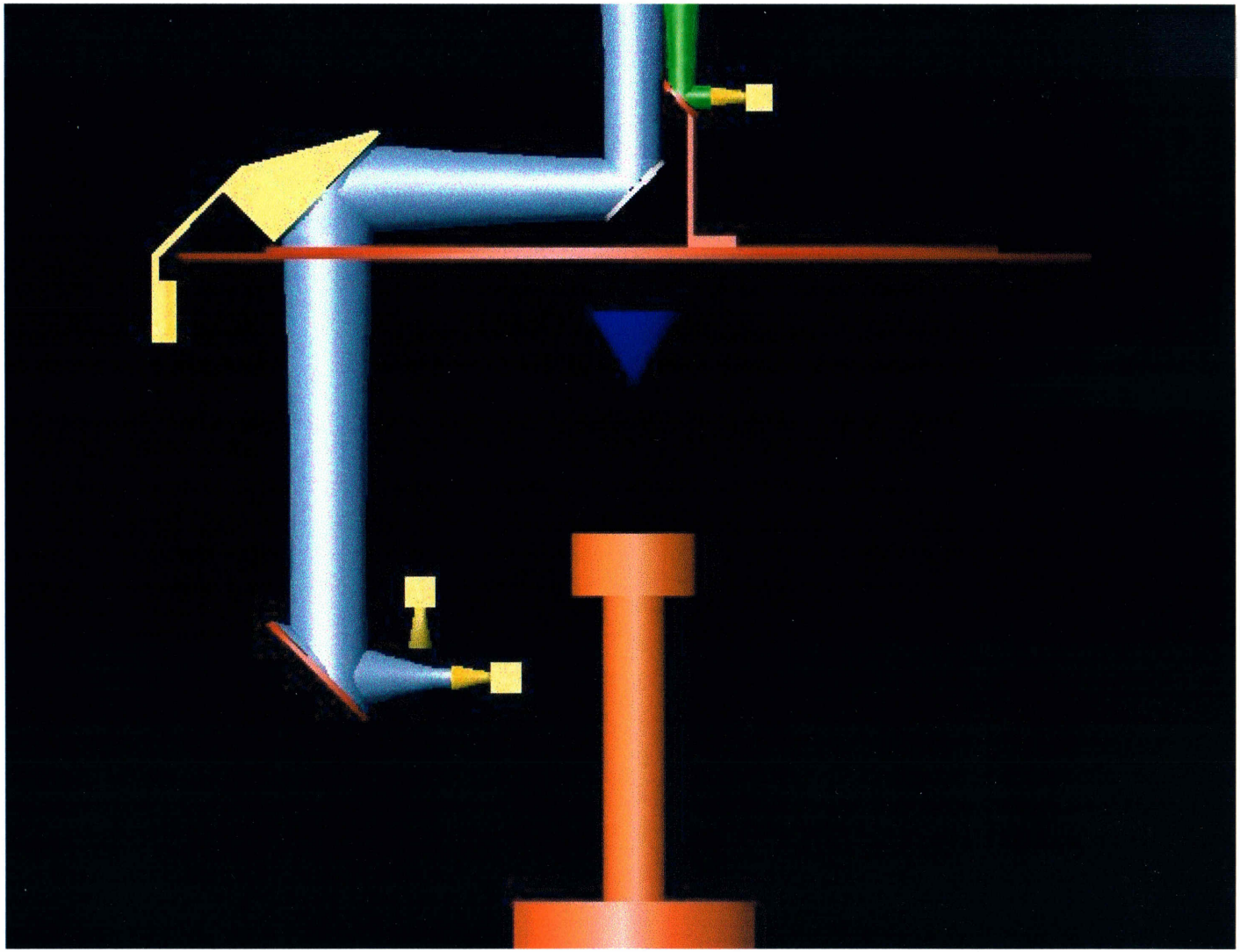
3-D Gaussian Beam tracing: 79 GHz Mixer Assembly

183 GHz WVM



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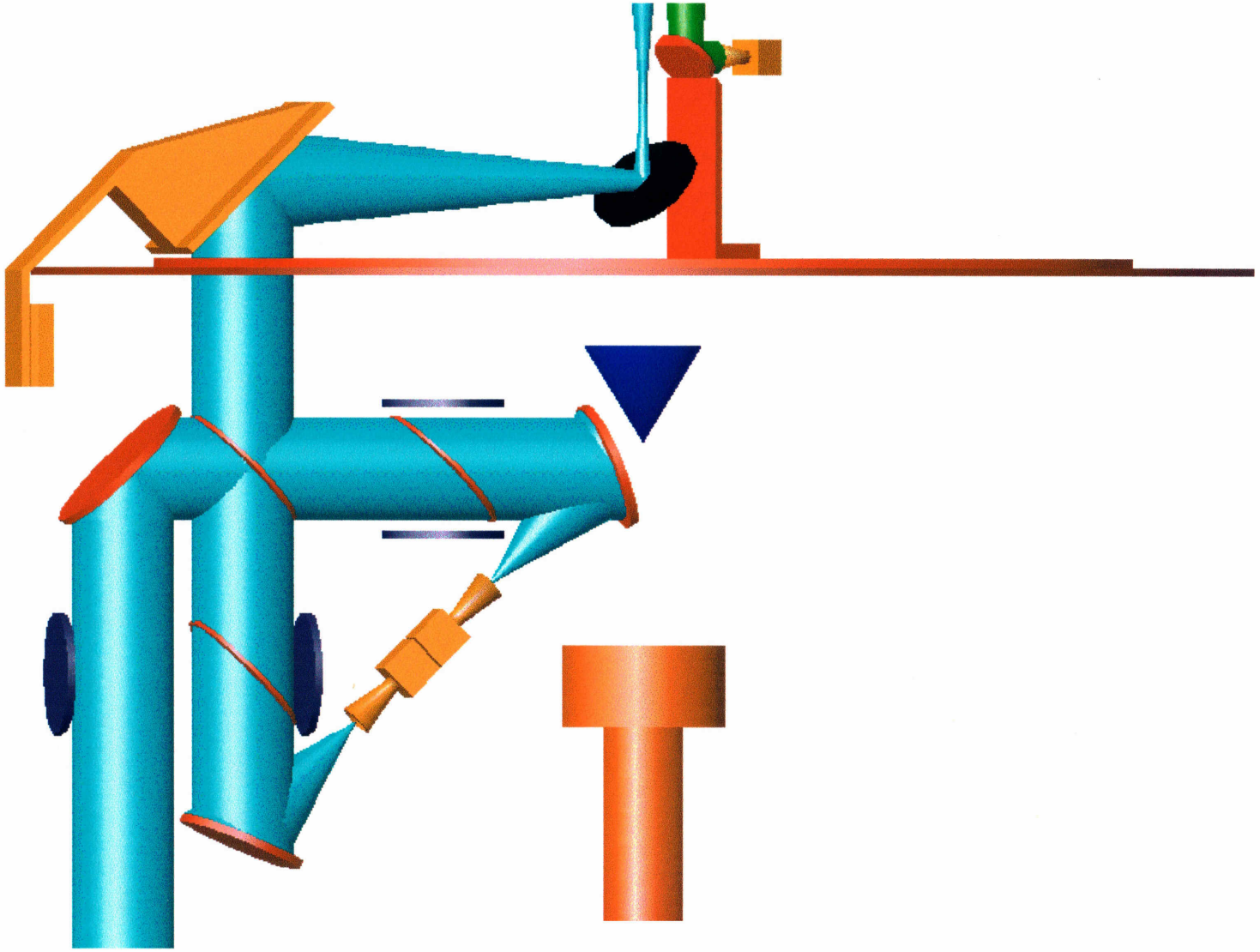
3-D Gaussian Beam tracing: 869 GHz Mixer Assembly

183 GHz WVM beam



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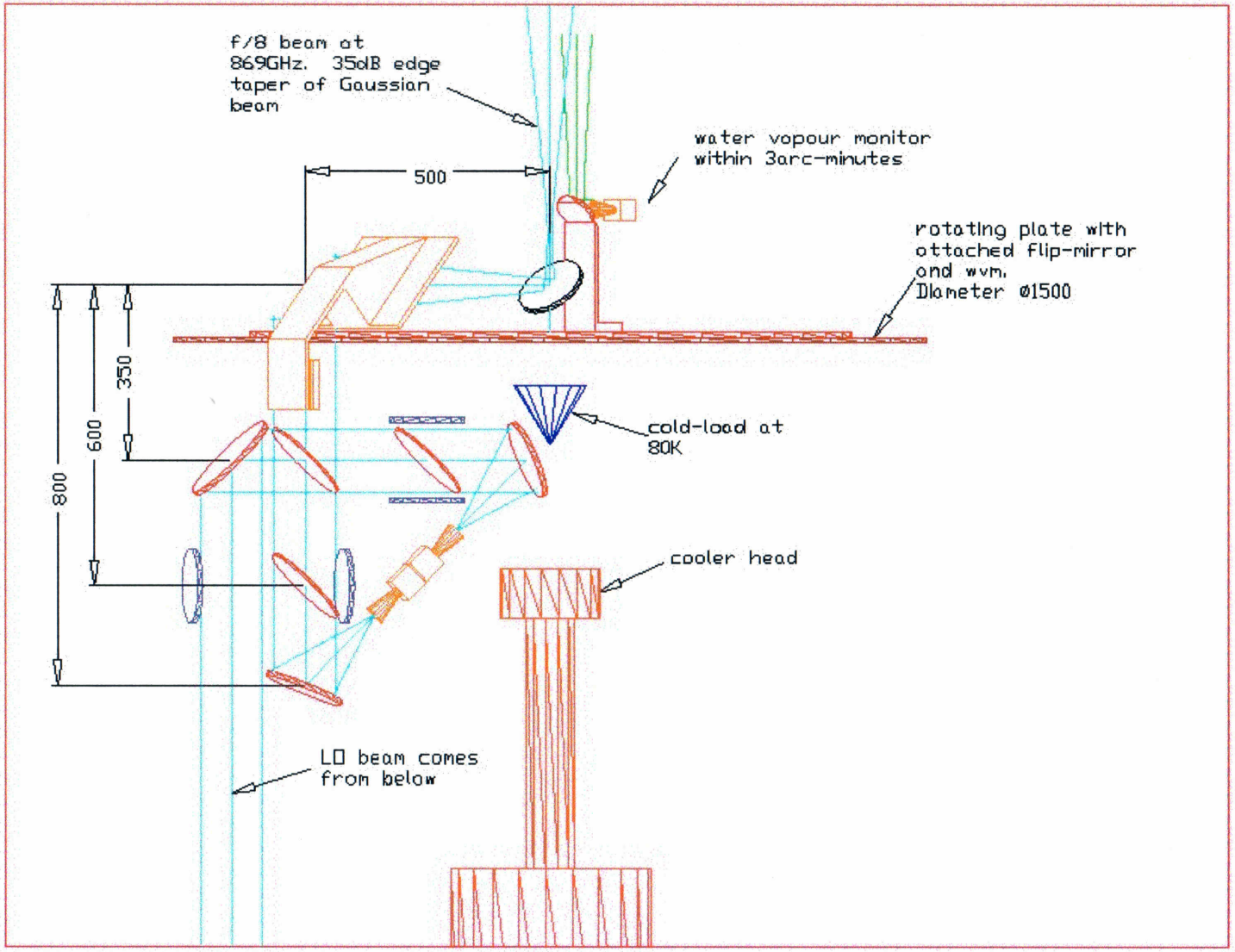


ALMA Receiver Configuration Study: Preliminary Results

James Lamb

Owens Valley Radio Observatory

California institute of technology

12-2[illegible]-99

Webber

Starting Point

Assumptions

- Band 1 (30 GHz) in separate dewar
  - Not considered further here
- Only one frequency to be observed at a time
- Circular polarization capability required
- May require scanning WVR for anomalous refraction
- All bands above 67 GHz may be SIS
- Corrugated horns, orthomode transducers, waveguide LO to at least 370 GHz
- Planar antennas or horns above 370 GHz
- Optical SSB, LO Injection above 370 GHz

Design drivers

- Minimize optics losses
- Minimize dewar dimensions
- Minimize moving parts
- Keep observing beams close to WVR beam

Optics Issues

Functionality

- How much functionality required?
  - Calibration
  - Polarization
  - Receiver selection

Effects on sensitivity

- Spillover
  - Warm, cold
- Dielectric and ohmic losses
  - Warm, cold
- Aberrations
- Cross-polarization
- Distortion

Cost

- 1% efficiency ≈ $2M!

General Approach

Minimize optics

- System temperatures expected to be very low -- go for raw sensitivity
- Allow calibration devices (choppers, grids) which may be removed during observations

Optimize for each band

- Beam sizes, receiver temperatures, atmosphere different
- Difficult to make extremely broadband vacuum windows
- Trade-off window thickness and diameter
- May use corrugated horns in low bands, quasioptical feeds in high bands

Driven By Low Frequencies

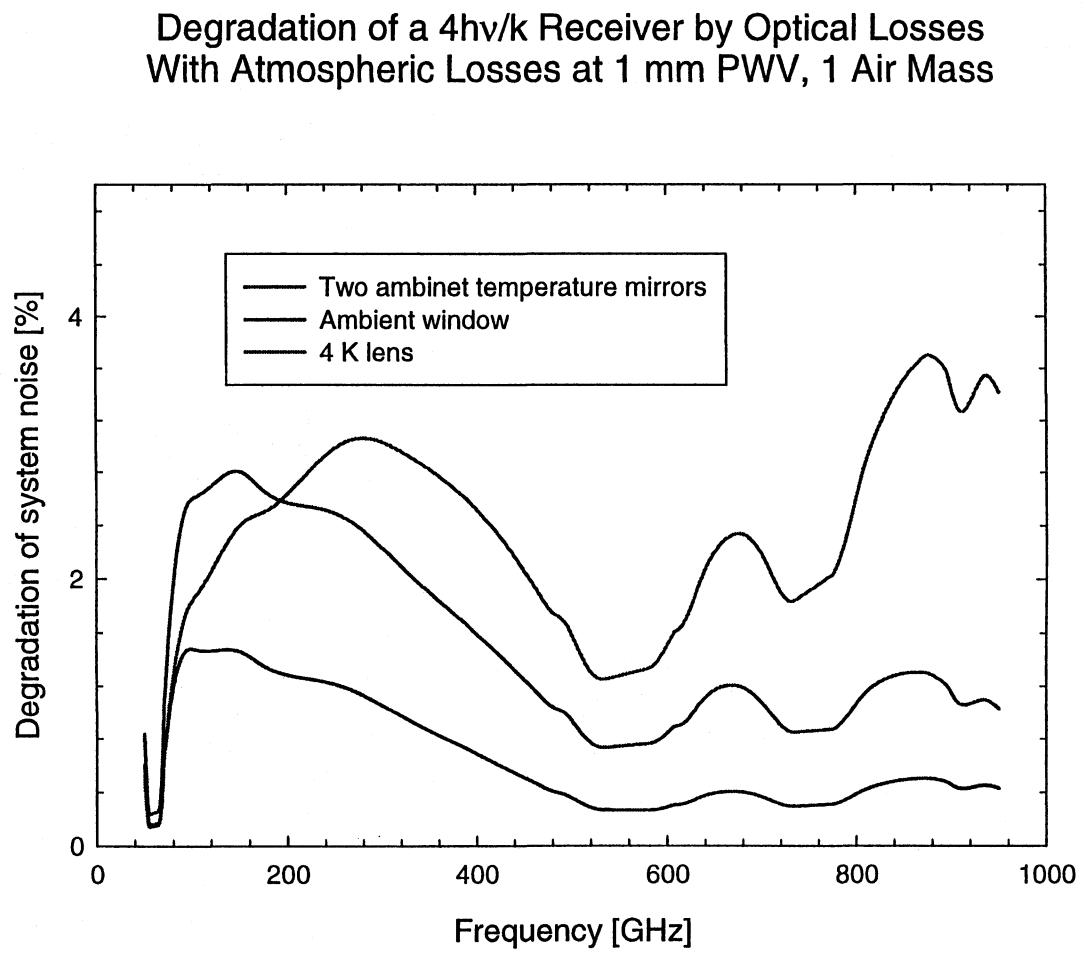
System temperatures

- Receiver noise limit $\propto$ hf/kt
- Ohmic losses $\propto \sqrt{f}$
- Dielectric losses (tan δ) may increase with f
- Atmosphere worse at higher frequencies

Beam sizes

- Airy spot width $\propto$ 1/f
- Optimum optics will give images of primary which are smaller at high frequencies

System Degradation Due To Optical Components



Optics Fundamentals

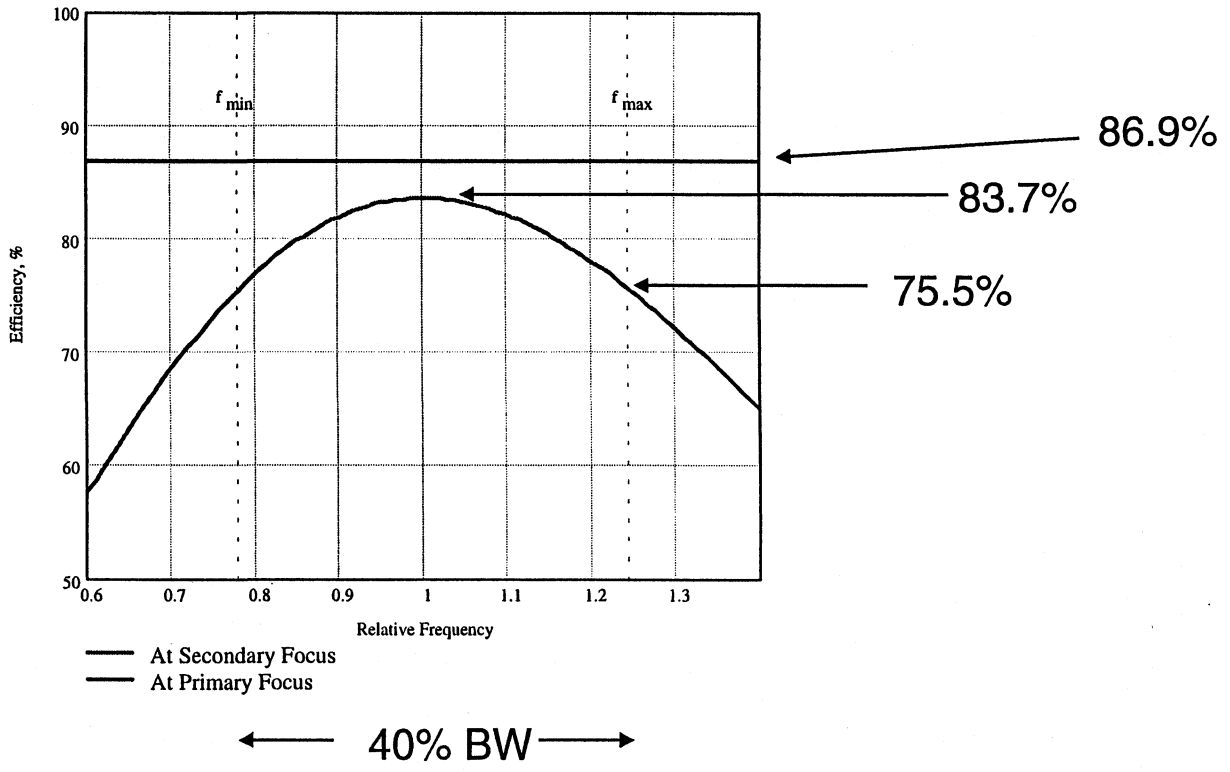
Imaging System

- Assume all lenses, etc are ideal phase transformers
- Feed may be placed:
  - at an image of primary aperture
  - at an image secondary focus (Airy disc)
  - at an intermediate point

Gaussian Beams

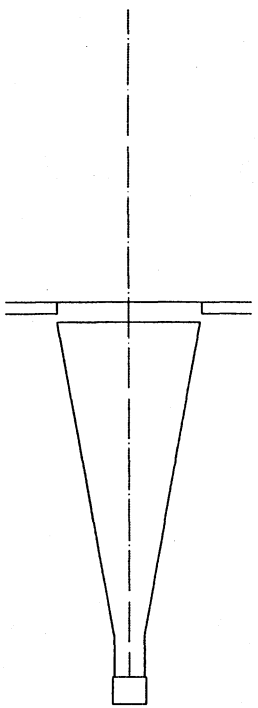
- Fundamental mode not sufficient for analysis
  - Does not give correct efficiency
  - Does not give truncation levels
- Propagation equations apply to all modes
  - Can use Gaussian beams as a basis for analysis
  - Use many modes or, alternative analysis

Comparison of Horn At Secondary and Tertiary Focus

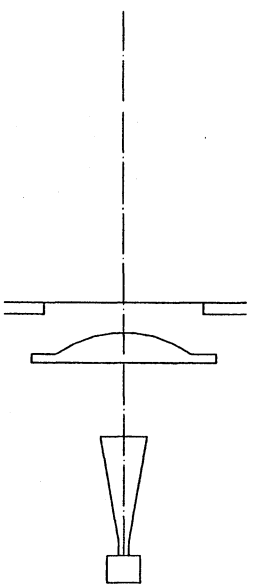


Three Options

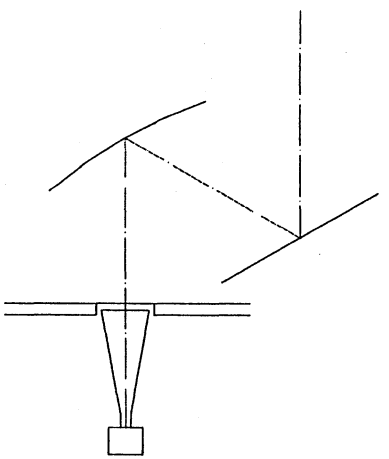
- Single Band



Corrugated Horn
Illuminating Secondary



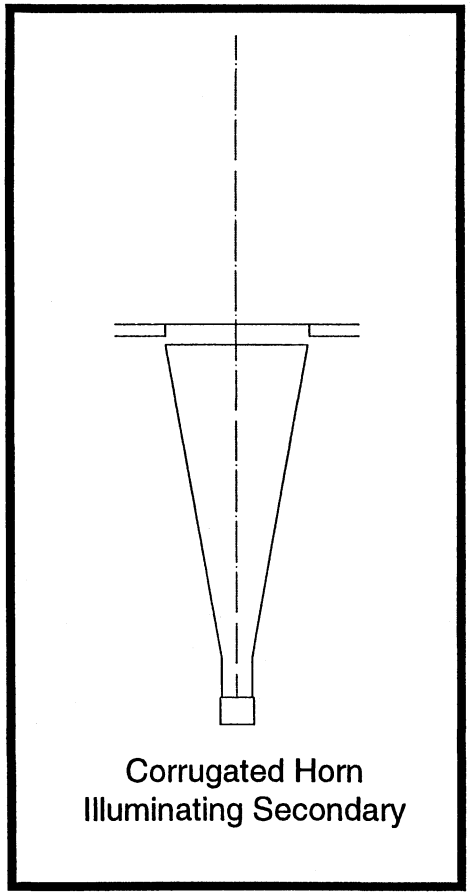
Corrugated horn
and cooled
dielectric lens

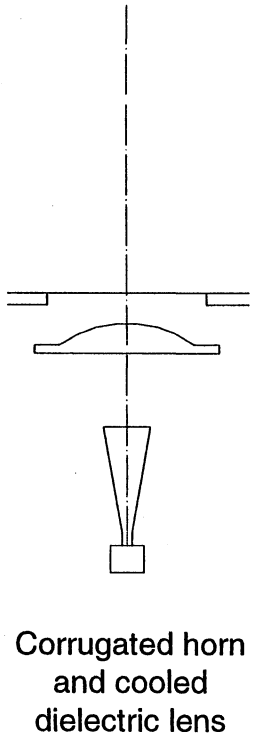


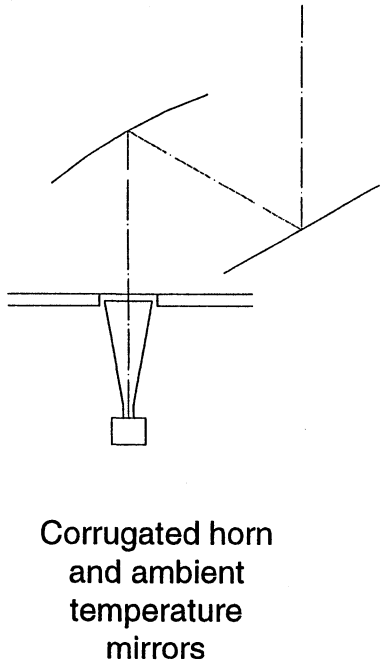
Corrugated horn
and ambient
temperature
mirrors

First Option

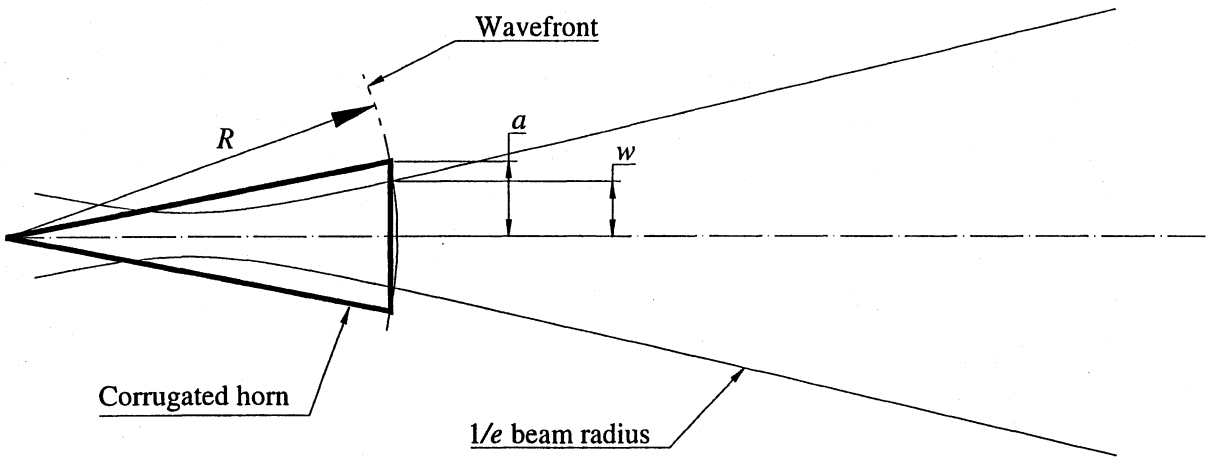
- Single Band







Optimum Gain Horn Concept



- Gaussian beam uniquely defined for given edge taper at secondary
- Optimum Gain Horn: Minimum length
- Minimum radius of curvature, R, when aperture at confocal distance from waist.

$$R = 2\frac{\pi w_0^2}{\lambda} \qquad a = \sqrt{2}w_0$$

"Minimum Design" Trade-offs

Feed at Secondary Focus

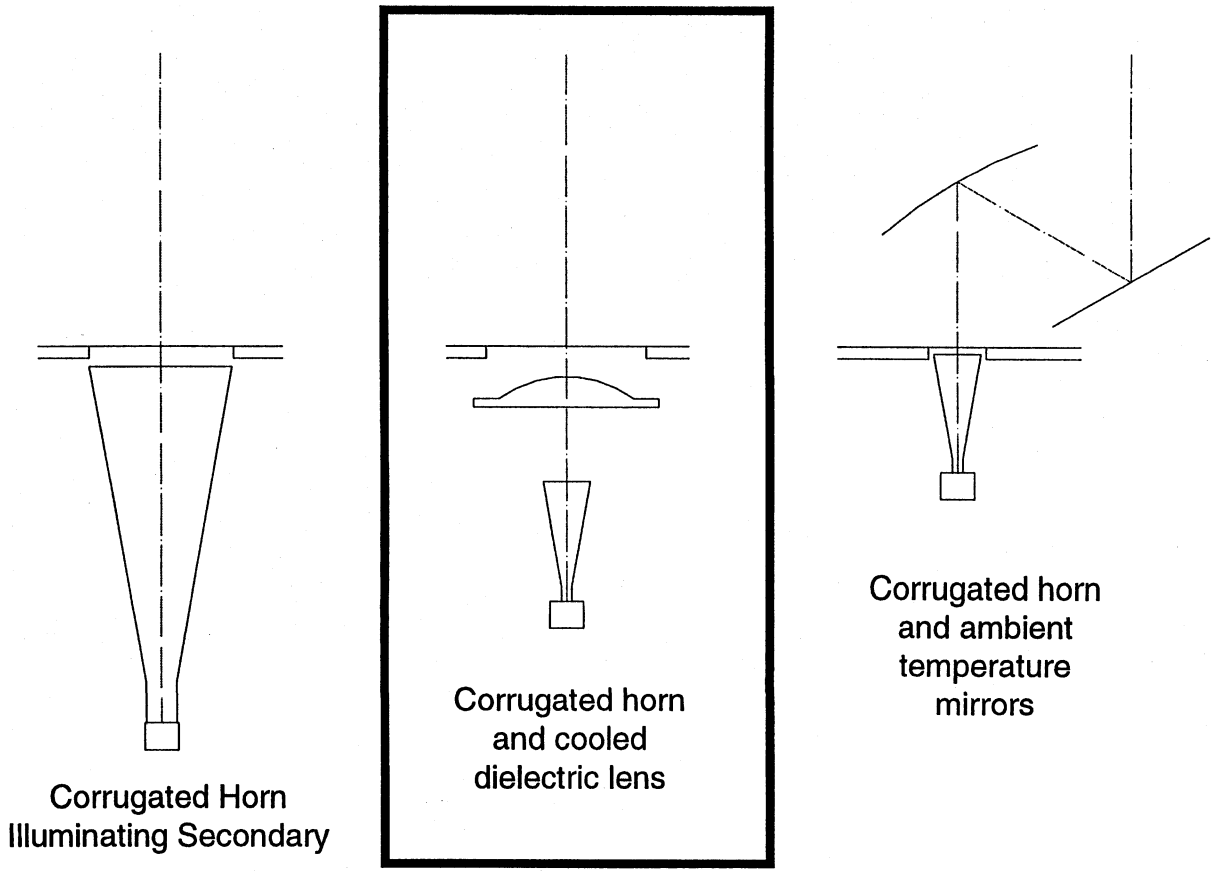
- Advantages
  - No lens, reflector, spillover losses
  - Simple
- Disadvantages
  - Frequency dependent
  - Sub-optimal efficiency
  - Large

Size

- Optimum gain horn
  - Aperture at confocal point of Gaussian beam
  - 1 m long, 84 mm diameter @ $\lambda = 4.5$ mm

Second Option

- Single Band



Horn + Lens

Advantages

- Simple
- High efficiency
- Optical axis is not folded

Disadvantages

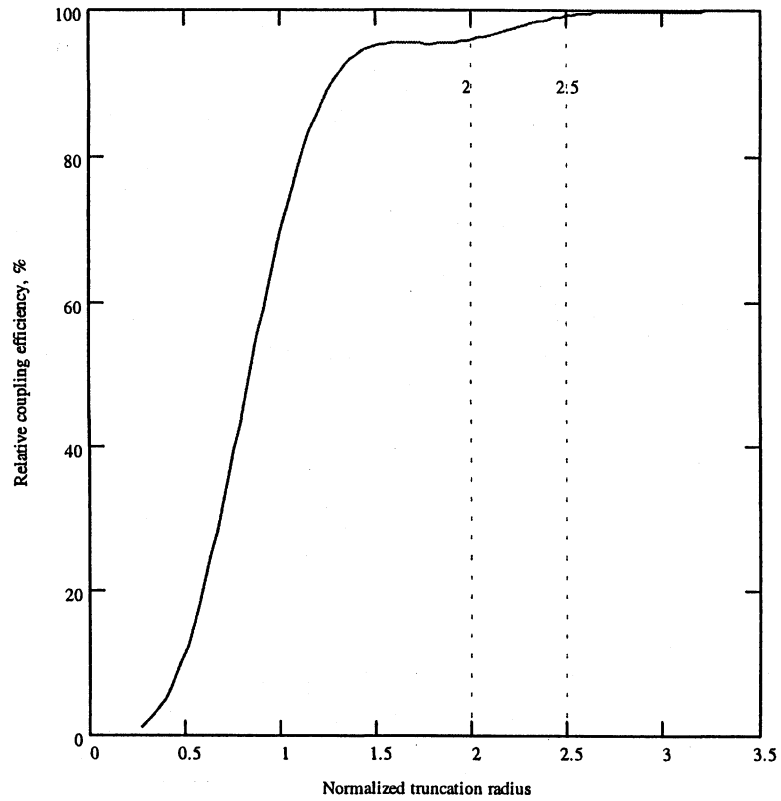
- Large window required
- Dielectric losses
- Anti-reflection coating needed
- Material issues: Uniformity, cooling stresses
- Doubts about performance at 1 % level (scattering, edge effects, ...)

Required Window Size

- Loss in aperture efficiency from truncation at secondary focus

- First Airy null -> 95%
- Second null -> >99.5%

- Second null: ~6w
- 99% at ~5w



Truncation radius normalized to Gaussian beam radius

Window Sizes to Accommodate Beam at Secondary Focus

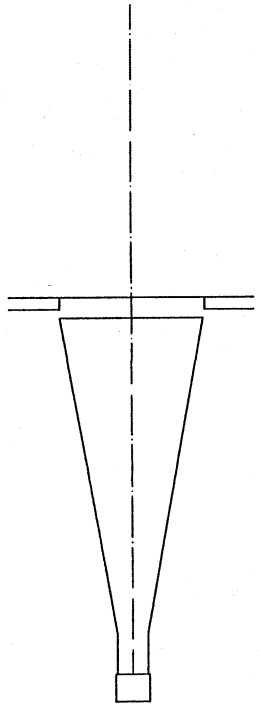
Band	Lowest frequency GHz	Highest Frequency GHz	Window Size mm
2	67	90	133
3	89	116	100
4	125	163	71
5	163	211	55
6	211	275	42
7	275	370	32
8	385	500	23
9	602	720	15
10	787	950	11

MMA Memo 213

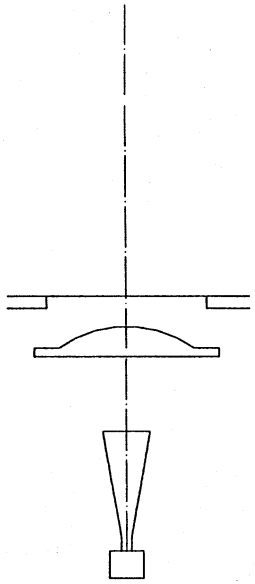
- Window is sized for < 1 % loss at lowest frequency in band
- Large windows
  - IR Loading a problem

Third Option

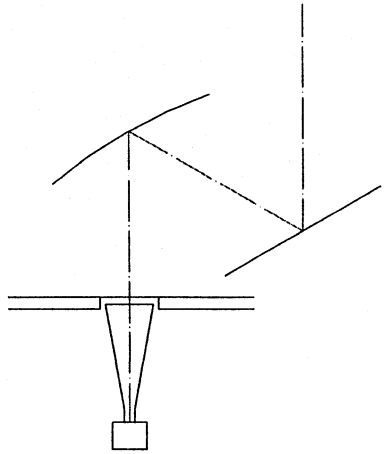
- Single Band



Corrugated Horn
Illuminating Secondary



Corrugated horn
and cooled
dielectric lens



Corrugated horn
and ambient
temperature
mirrors

Horn + Mirrors

Advantages

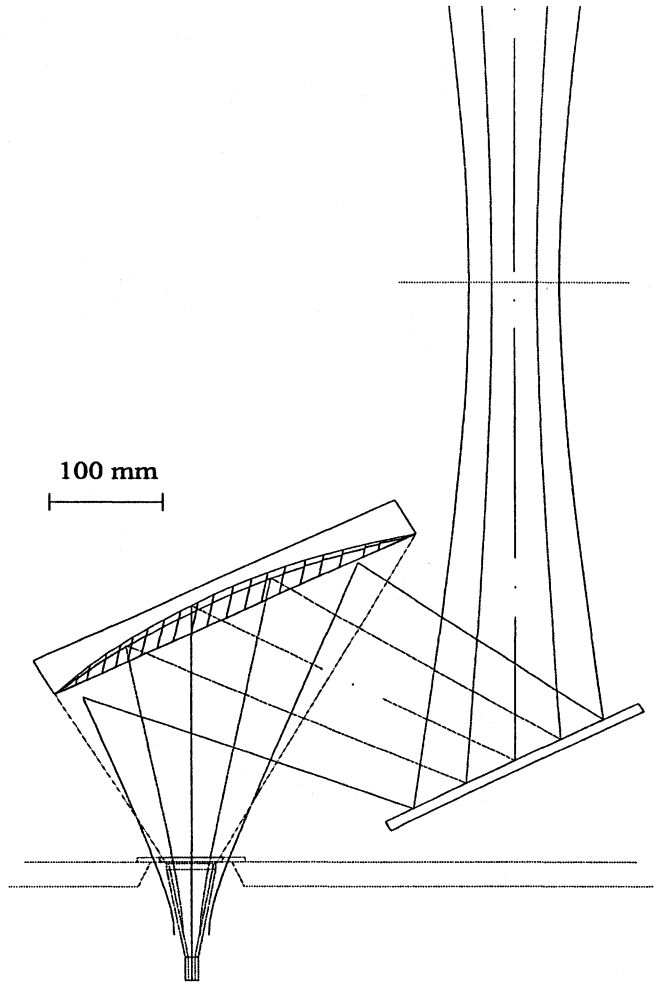
- "Clean" design
- Reduce size of window into dewar: area reduced by factor of ~7
- No need for anti-reflection treatment, low VSWR
- More flexibility in positioning elements in dewar

Disadvantages

- Ambient temperature losses
- Need two mirrors to get low angle of incidence
  - X-pol, distortion
- Mirror machining accuracy needs to be better than for lenses
- Alignment may be tricky
  - Elements inside and outside dewar

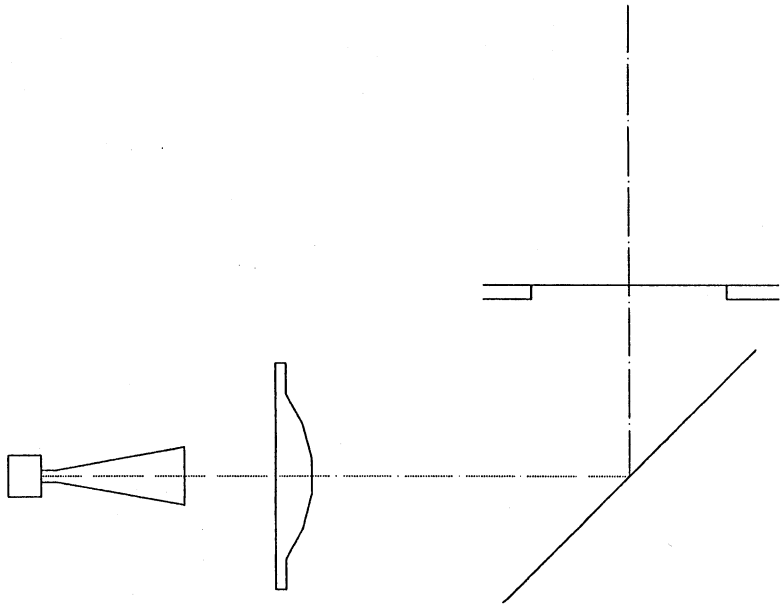
Single Band Design: Low-Frequency

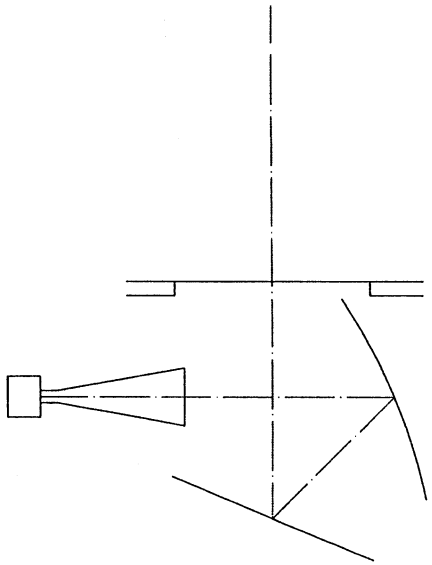
- Use optimum gain horn
  - Minimize size
- Frequency-independent optics
- Minimize offset angle
  - Amplitude distortion + X-pol < 1 %
- Mirror shape is different for each band
  - <0.1% aberration loss



Band Selection in Dewar

- Single window
- Cold optics





Vacuum Windows (1)

Material

- Losses
- Dielectric constant
  - Reflection loss
  - Antireflection coatings
  - Bandwidth
- Water permeability
- Strength

Vacuum Windows (2)

Rigid solid

- Quartz/Crystalline quartz
- High dielectric constant

  Need multilayer matching

  Bandwidth?

  Losses

Semi-rigid solids

- Plastics (HDPE, LDPE, PTFE)
  - Lower dielectric constant
  - Machine matching grooves

    triangular

    rectangular
  - Losses OK

Thin Sheets

- Mylar, Melinex
  - Low losses
  - Permeability issues

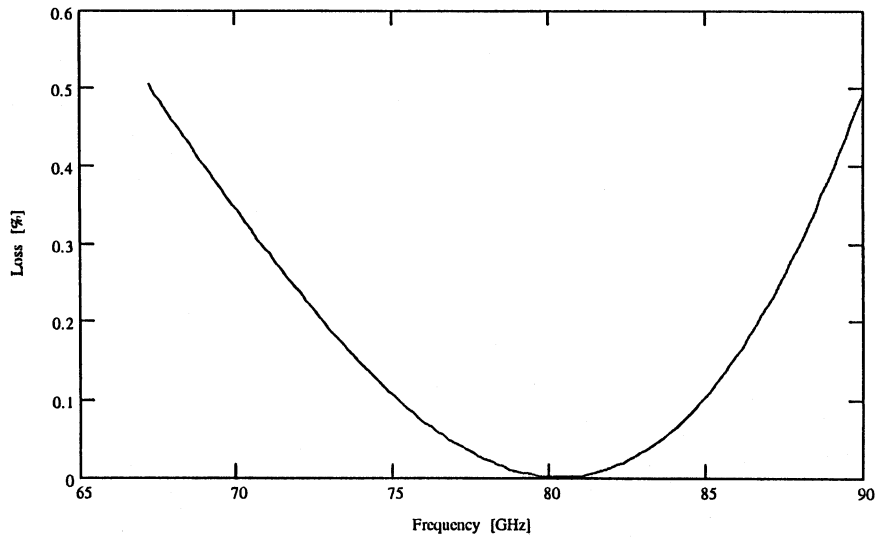
Mylar Window

Two layers separated by quarter wavelength

Example

Thickness: 100 µm

Separation: 0.736 mm



IR Blocking (1)

Dielectric

- Solid (PTFE, quartz) attached to cold station
  - Load transferred to refrigerator
  - Thermal gradient through radius
- Multilayer dielectric
  - Load on refrigerator reduced
- Foams
  - Essentially multilayer dielectric

Pros/Cons

- Pro
  - Known technology
- Con
  - Dielectric loss
  - Scattering loss

IR Blocking (2)

Reflector

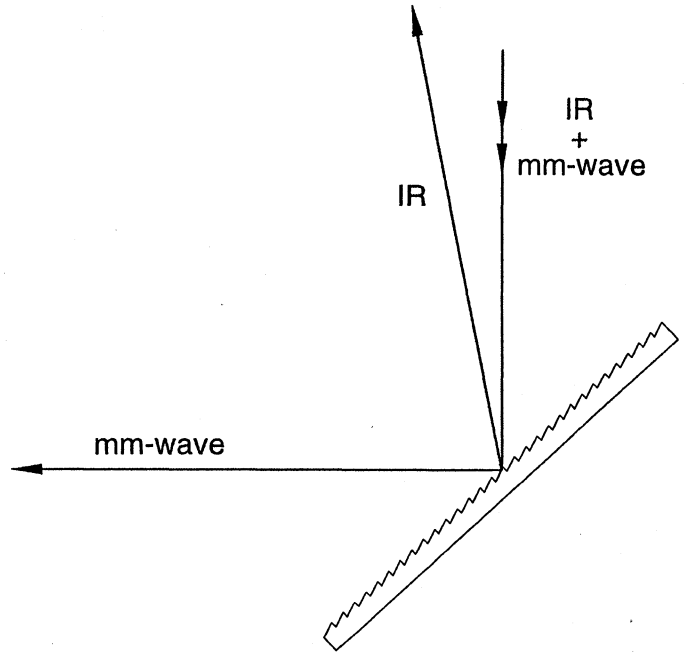
- IR Black coating
  - Load transferred to refrigerator / floating
- Reflection
  - Separate IR and mm/sub-mm by diffraction
  - Blazed grating
  - Micro-corner-cubes

Pros/Cons

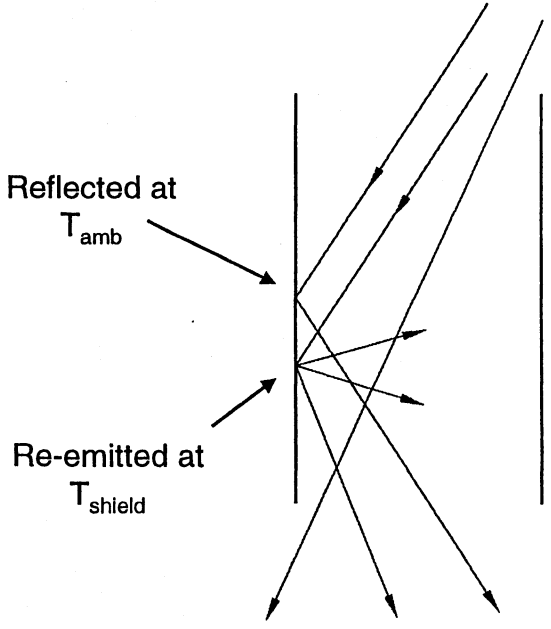
- Pros
  - Potentially low loss in mm/sub-mm
- Cons
  - Difficult to avoid stray light
    cold stops
  - May be difficult to fabricate diffraction structures

Blazed Grating

Principle

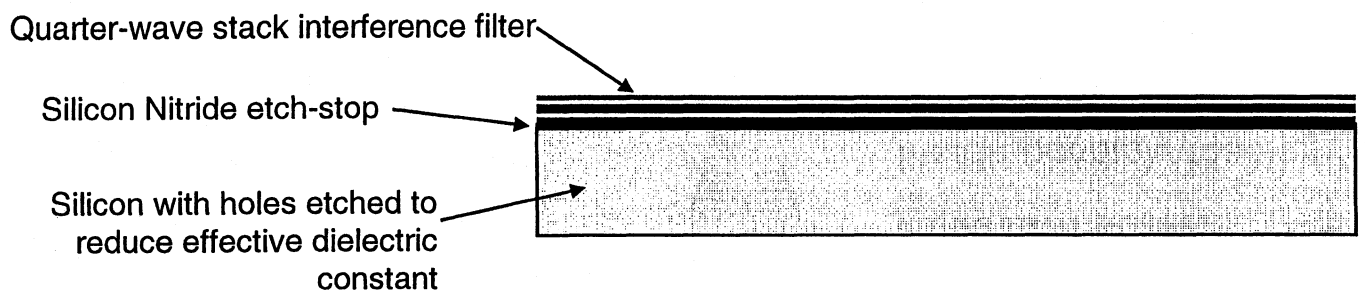


Problem



Interference filter

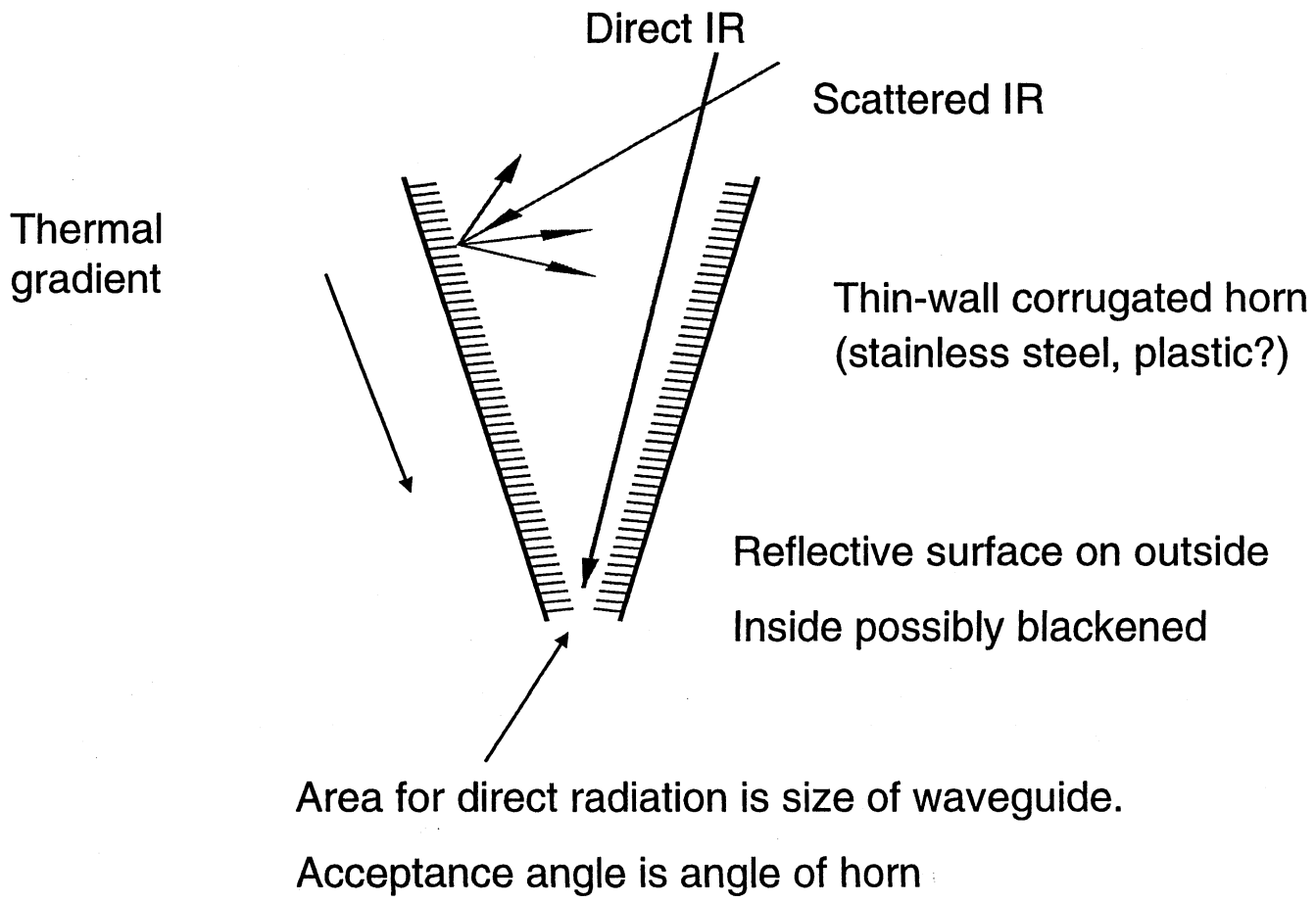
Construction



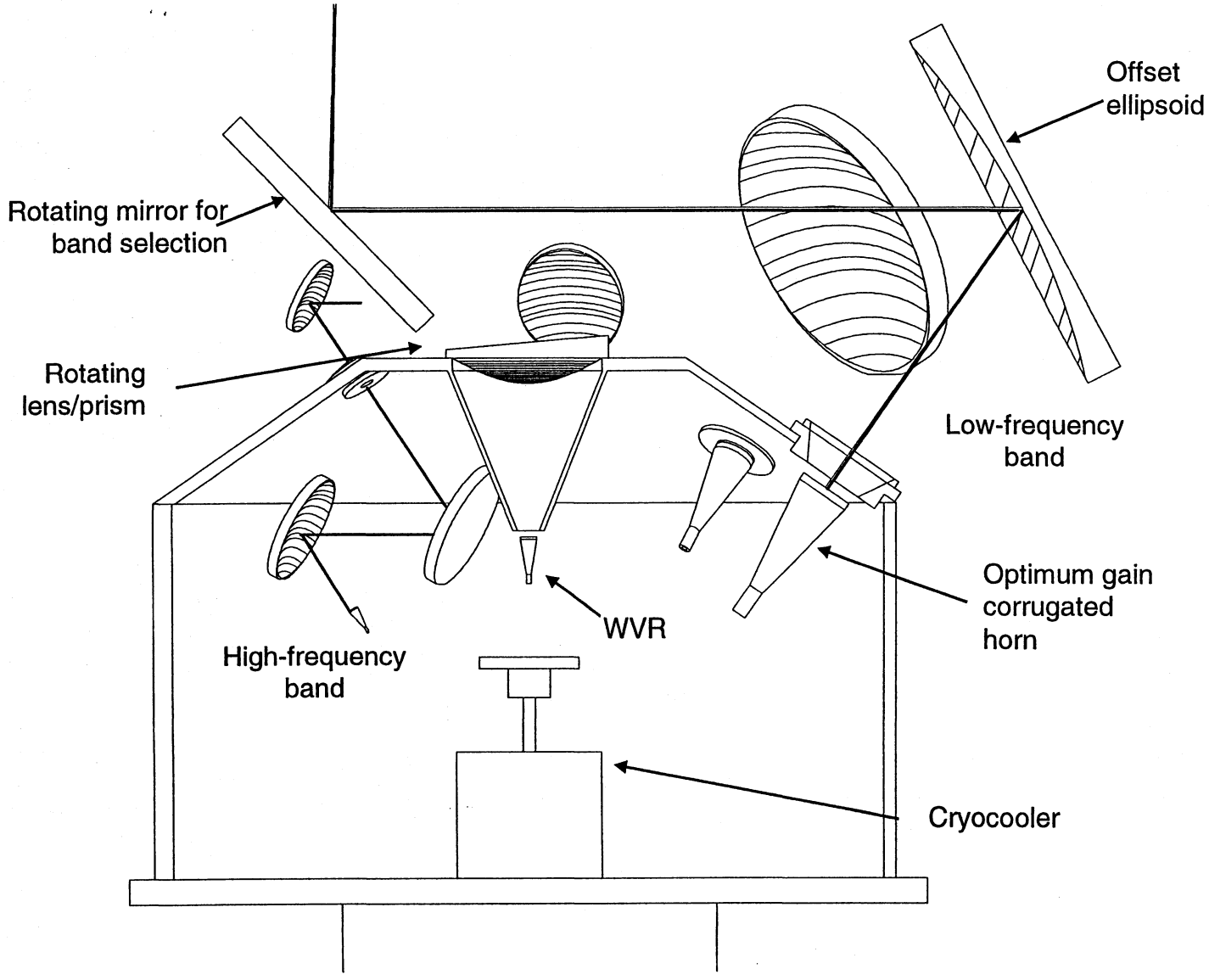
Notes

- No loading on refrigerator
- Thin
- Hard to get more than octave wavelength rejection
  - May use more than one filter
  - May use absorbing layers also
- Not fully investigated
  - Uniformity of silicon etch?
  - Silicon filling factor

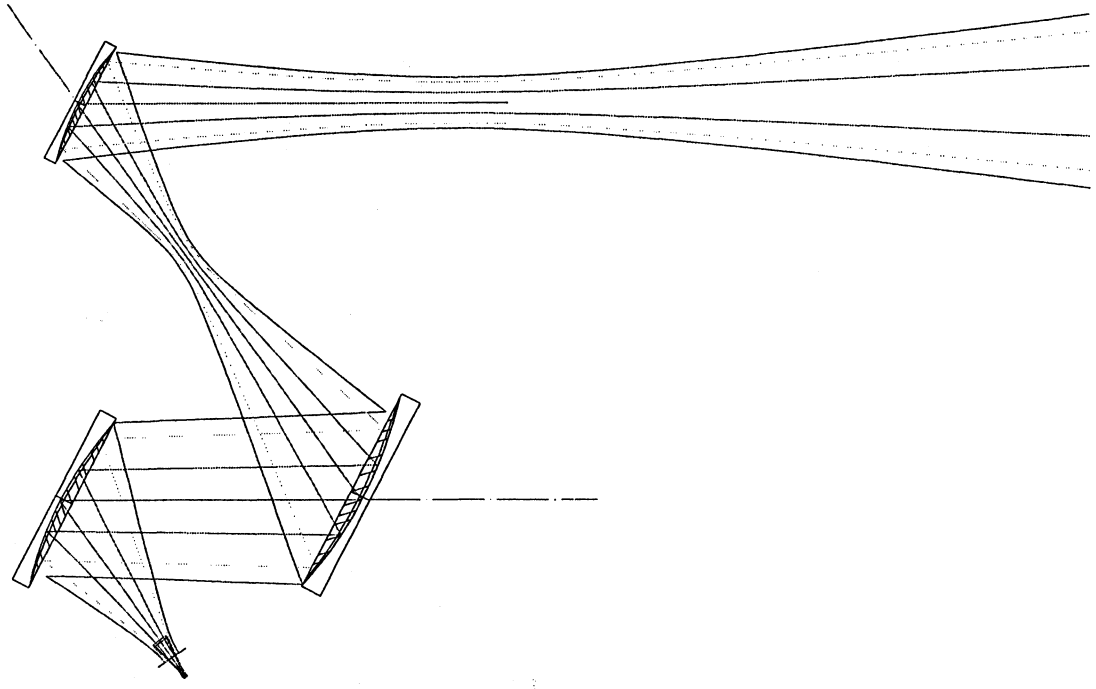
Corrugated Horn as IR Filter



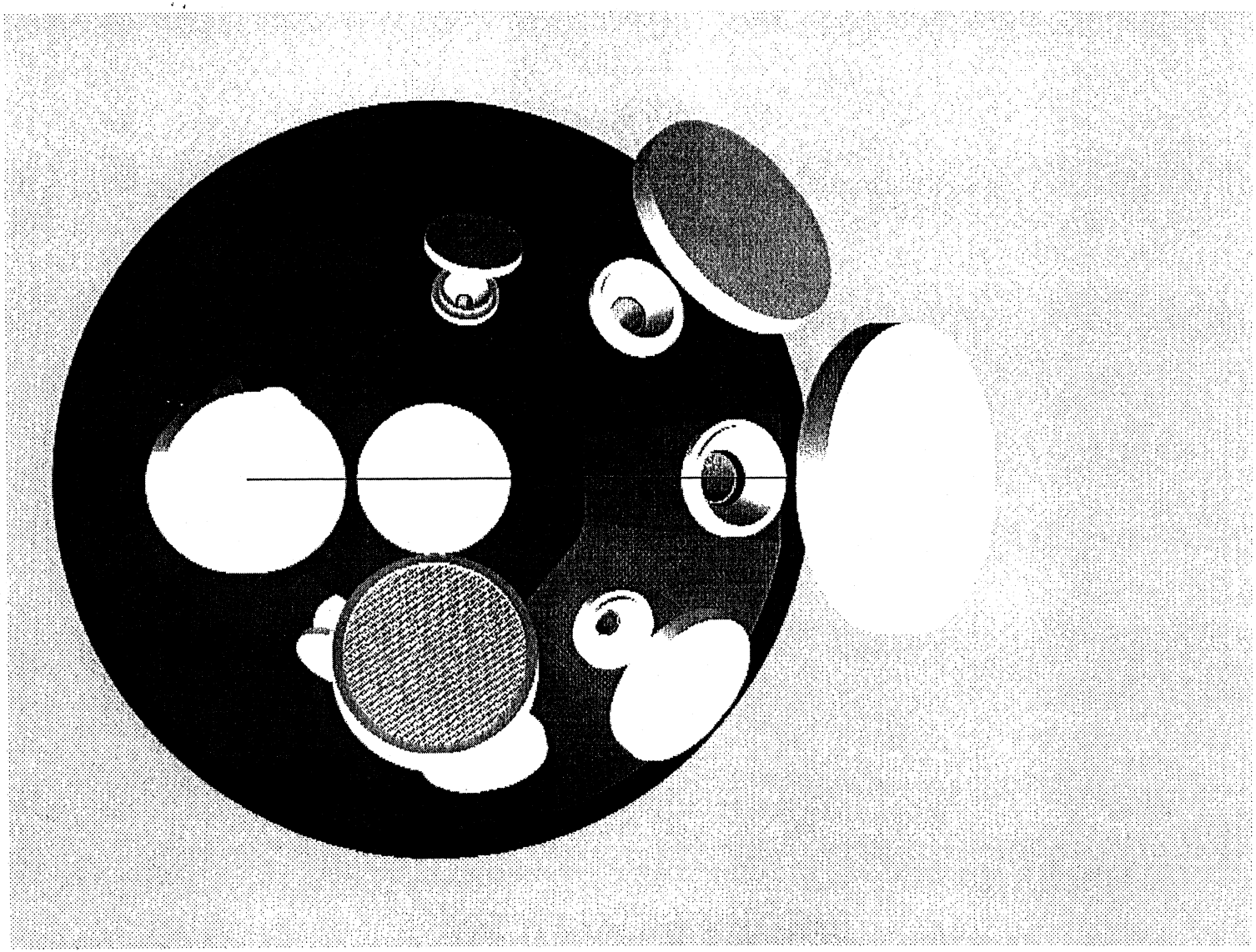
Optical Layout



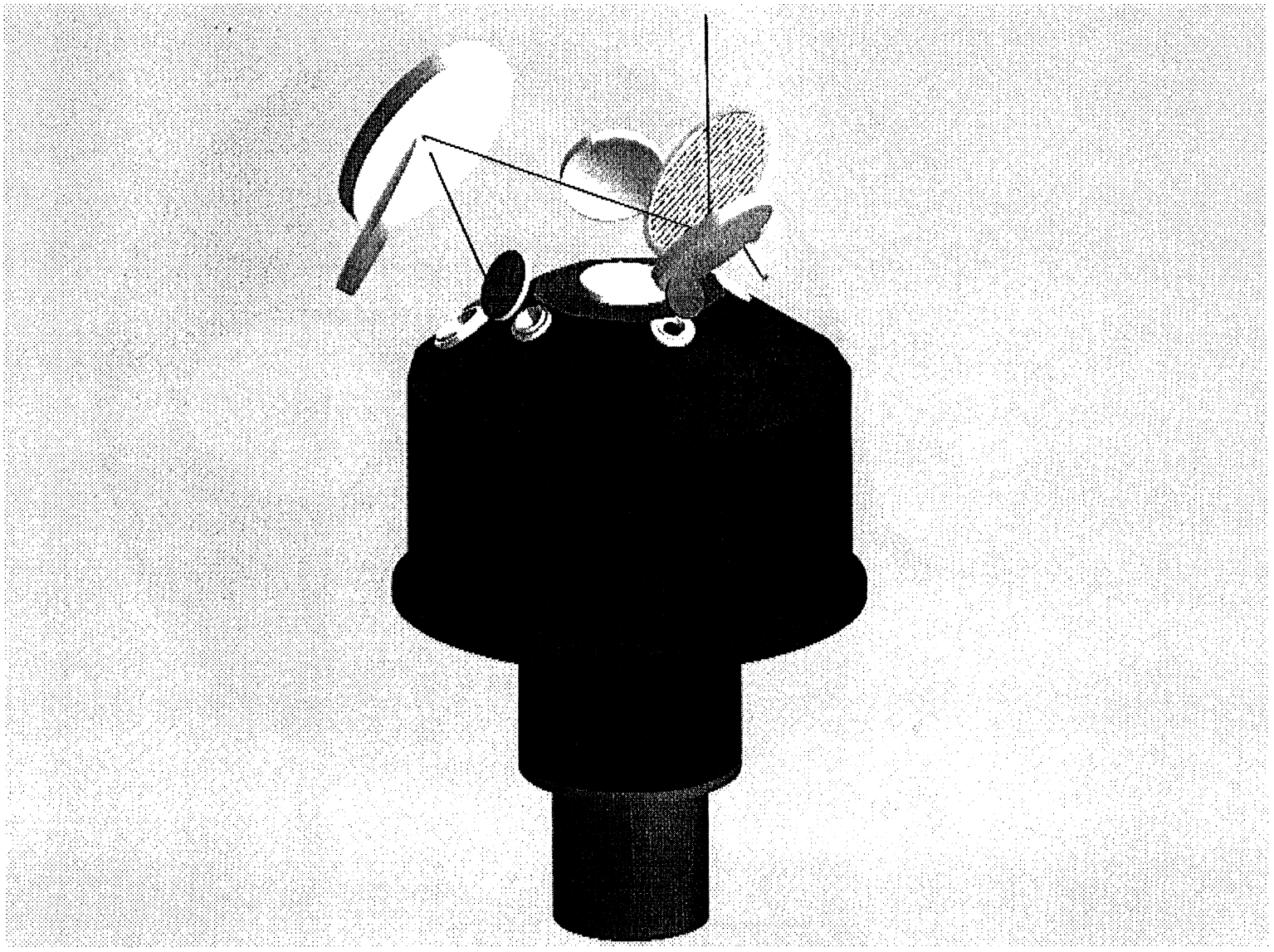
High-Frequency Bands



Top View of Dewar



Side View of Dewar



Design Features

Optics

- Optimized for each band
- Corrugated feeds to 370 GHz
- Planar antennas possible above 370 GHz
- High efficiency
  - Truncation losses < 1%
  - Aberrations < 1%
  - X-Pol < 1%
  - Distortion < 1%
- Low loss windows
- Frequency independent within band
- Circular polarization at any frequency
- Beams close to WVR beam (< 6 arcmin)
- ± 200 mm refocus required (5 μm surface rms)
- Thin IR filters

Water Vapor Radiometer

- On optical axis
- Can have scanning for anomalous refraction correction

Dewar

- Small window area
- Compact
- Strong design
- Easy access

Dimensions

- Dewar
  - Diameter: 600 mm
  - Height: 450 mm
  - Plus cryocooler: 500 mm
- Optics
  - Diameter: 750 mm
  - Height above dewar: 400 mm

Conclusions/Questions

- Driven by low frequency bands
- Need separate windows for each band
- Avoid dielectrics if possible
- Use one plane and one focusing reflector per band
- Use optimum gain horns
- High-frequency bands may have re-imaging optics, LO injection, *etc.*, inside dewar
- IR blocking options to be investigated
- What other components required in the beam (choppers, *etc.*)

Webber 12-2-99/A

ALMA Receiver System
UK Design Concept

- Rutherford Appleton Laboratory
  - Richard Wade, Brian Ellison, Tom Bradshaw, Anna Orlowska, Mark Harman
- UK Astronomy Technology Centre
  - Peter Hastings, Bill Dent, Colin Cunningham

Cryogenics Section Past Developments

4K system

Now proposed for Planck. Licensed to MMS and is being space qualified as part of that programme. Included a study on contamination effects and gas purity. Verified models for design purposes are available.

Pulse tubes

Subject of a joint study with SBT - Original RAL PT with diaphragm spring suspension compressor achieved 90K ten years ago.....

Low vibration drive systems

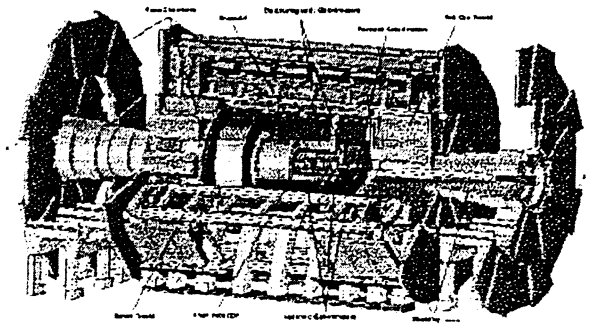
Now being used on demonstrator for Planck - consists of computer controlled active vibration feedback control.

Regenerator work

We have studied and manufactured rare earth regenerators for low temperature operation.

Cryogenics Section Current Projects

Atlas Common cryogenics - Aim is to provide a common cryogenic system for both the End Cap Toroids and Barrel toroid. Includes transfer lines, valve boxes, pumps and ancillary equipment. Helium flow 1.5kg/s !..



Cryogenics Section Current Projects

Planck - An ESA instrument to measure the cosmic microwave background. RAL is supplying the 4K part of the cooling system. Working with IAS (Paris) on a 100mK demonstrator.

ISIS Methane moderator - An investigation into the polymerisation of liquid methane under the influence of neutron irradiation.

Closed cycle coolers - Investigation into the heat transfer at the cold end of Stirling coolers - 0.3K systems.

Pulse tube coolers - Working with CEA (Grenoble) and MMS (Stevenage) on the development of small pulse tube refrigerators.

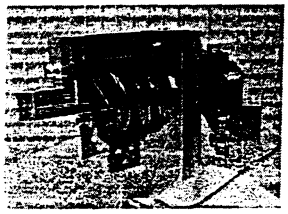
Support to MMS Space Systems - Engaged in work on the Integral gamma ray observatory and various cooler developments.

Cryogenics Section Projects

Thermal links - To connect the cryocooler cold finger to the instrument with high conductivity low stiffness. Integral, MIPAS ...

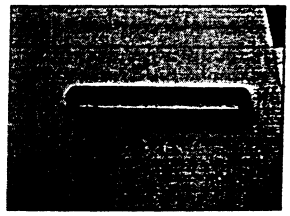
Mechanical Heat Switch - High performance mechanical heat switch using cold stepper motors and clamped mechanical contacts.

Materials - Investigation into cryostat supports including thermal conductance measurements and fatigue testing.



MIPAS Thermal Link

Carbon-Fibre support loop



ROE / ATC cryomechanisms heritage

external motors and insulating drive shafts

1985 UKT14 photometer (300mK bolometer)
filter wheel (4K)

1987 IRCAMs (64x56 InSb array)
filter wheels (77K)
focus mechanism (77K)

1990 CGS4 (1-5um spectrograph)
image rotator (80K)
filter wheels (80K)
slit rotation (80K)
grating tilt (80K)
array focus (80K)
array translation (80K)

1990 ISOCAM optical test facility
entrance wheel (4K)
filter wheel (4K)
focus mechanism (4K)

1996 SCUBA (100mK bolometer array)
filter drum (4K)

1998 UFTI (IR camera 1028x1028 HgCdTe)
filter wheels (60K)
shutter (60K)

internal stepping motors modified for cryogenic use

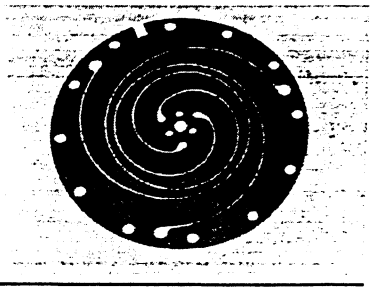
Cryogenics Section Background

The cryogenics section has been working on the development of closed cycle refrigerators for space use for many years.

Original development of closed cycle refrigerators utilising diaphragm spring suspension was done at Oxford University and Rutherford Appleton Laboratory.

Design licensed to MMS (UK) and Ball Aerospace (UK). Many copies and imitations of this technology abound.....

Original coolers were for ISAMS, ATSR, life test coolers; seven years and stripped down; another seven years and still going (at 40Hz). Mechanism at 80K - 10^{10} cycles



Coolers in Space:

ATSR1	Launch June '91 run until June '96 still OK.
ATSR2	April '95 - still running
ISAMS (2 coolers)	Launch Sep '91 15,500 hrs each
NRL HTSSE1	Sea ?
NRL HTSSE2	Spring '97 No failures
IMG, MIPAS ODIN, MOPPITT etc.. Two stage & 4K Coolers	MMS have manufactured and sold 40 coolers Being space qualified for FIRST

Life tests:

ESA 80K - 8.1 years, report available

(RAL prototype cooler)

-springs 1 x 10^{10} cycles !

RAL 80K - 6.7 years, still going

RAL Space Science and Technology Department
- Millimetre Technology Group -

Specific Role:

- Develop heterodyne receiver technology, including key components (mixers, local oscillators etc.) and complete systems, over the frequency range 100 to 3000 GHz (mm and sub-mm wavelength range).

Programme of Work:

- Development of appropriate device and system technology for use in ground, air and spaceborne astronomical and atmospheric remote sounding experiments. Work performed in support of UK Research Councils (e.g., PPARC and NERC) and HEI's.

- Provide support to UK industries and other national and international organisations e.g., UK Met. Office, ESA, EU, JPL, SAO, KIST(Korea), Academia Sinica (Taiwan) ....

MMT Group Facilities and Expertise

The MMT Group posses a range of facilities and expertise that support the development of heterodyne detection systems. These facilities include:

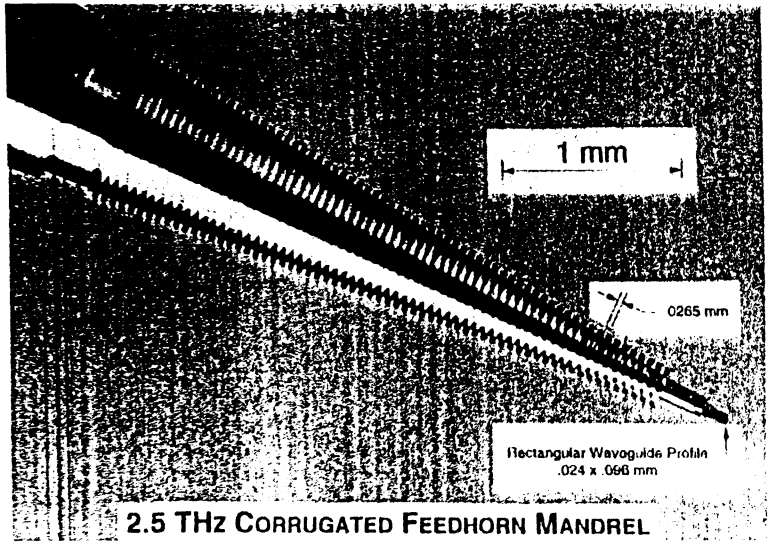
- World class high precision manufacturing.
- Component electroforming.
- Photolithgraphic and thin film deposition.
- Micro-machining.
- Substantial microwave/mm wave CAD design and test equipment.
- Cryogenic and vacuum.
- Clean room assembly areas.

Precision Manufacturing Facility

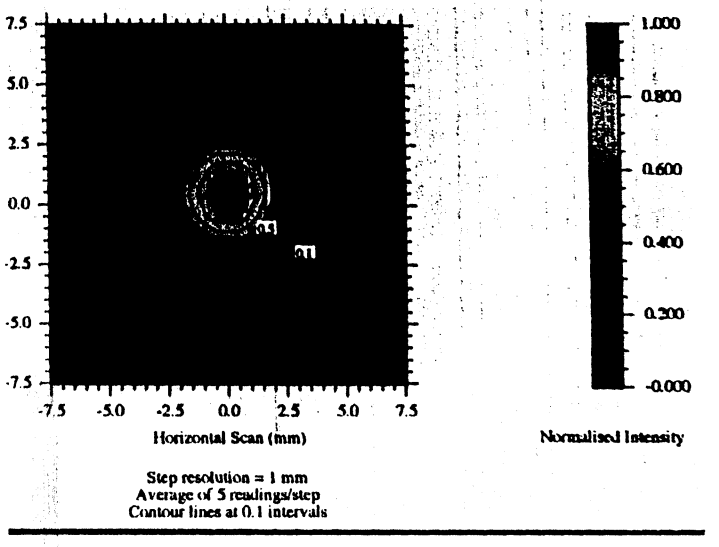
- Temperature controlled
- Two mini jig bores
- Micro-machining mill
- Three precision lathes
- Non-contact measuring
- Electroforming facility
- Grid winding facility
- Micro-machining facility

Precision Waveguide Fabrication

2.5 THz Feedhorn mandrel and antenna pattern

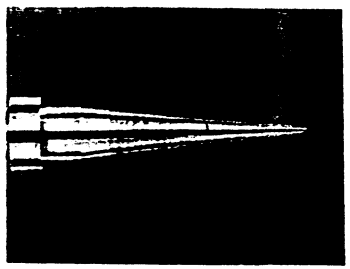


2.5 THz Corrugated Feedhorn Mandrel

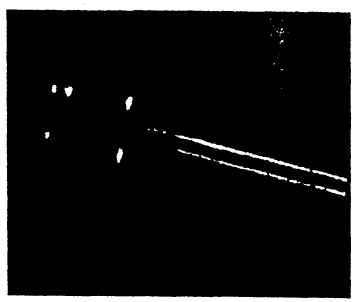


In-house Electroforming Facility

Mandrel

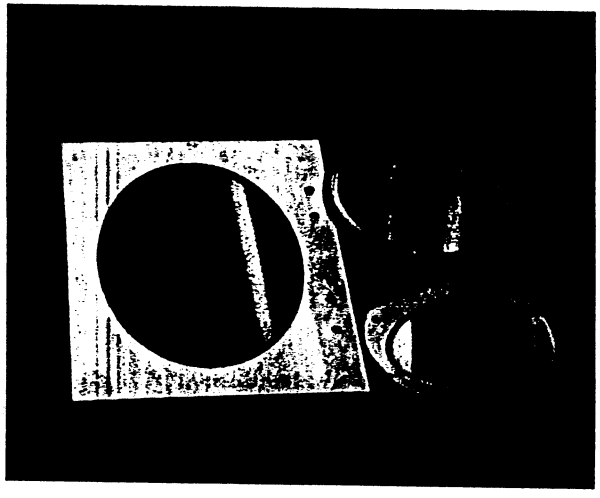


Electroform

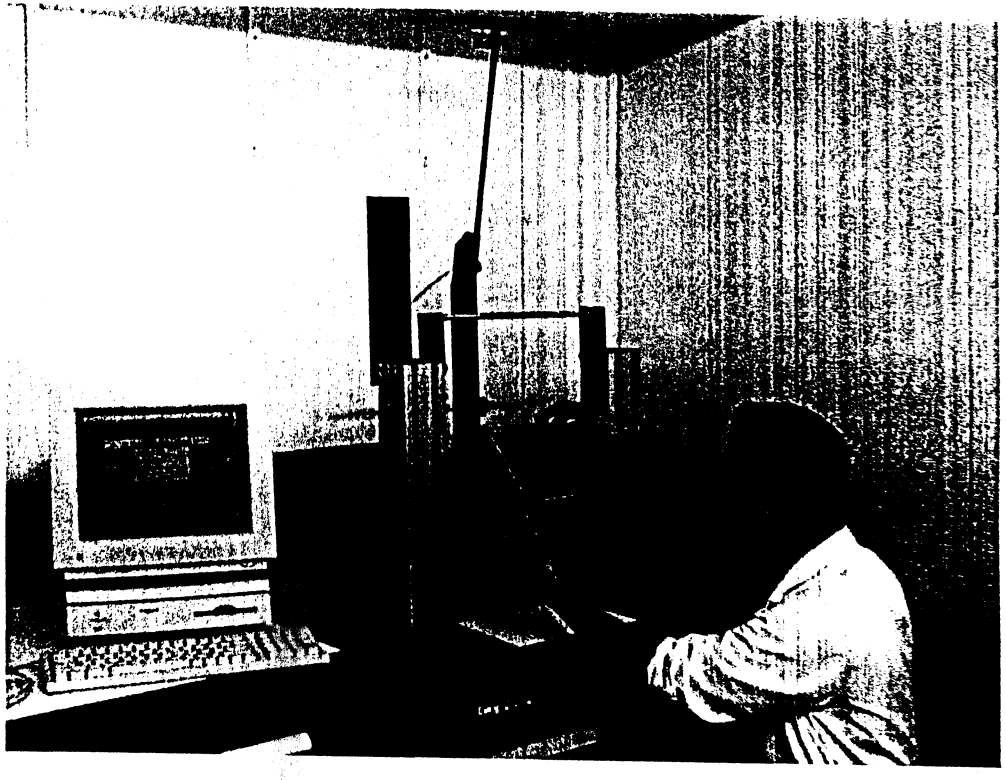


Feedhorn

Grid Winding Capability



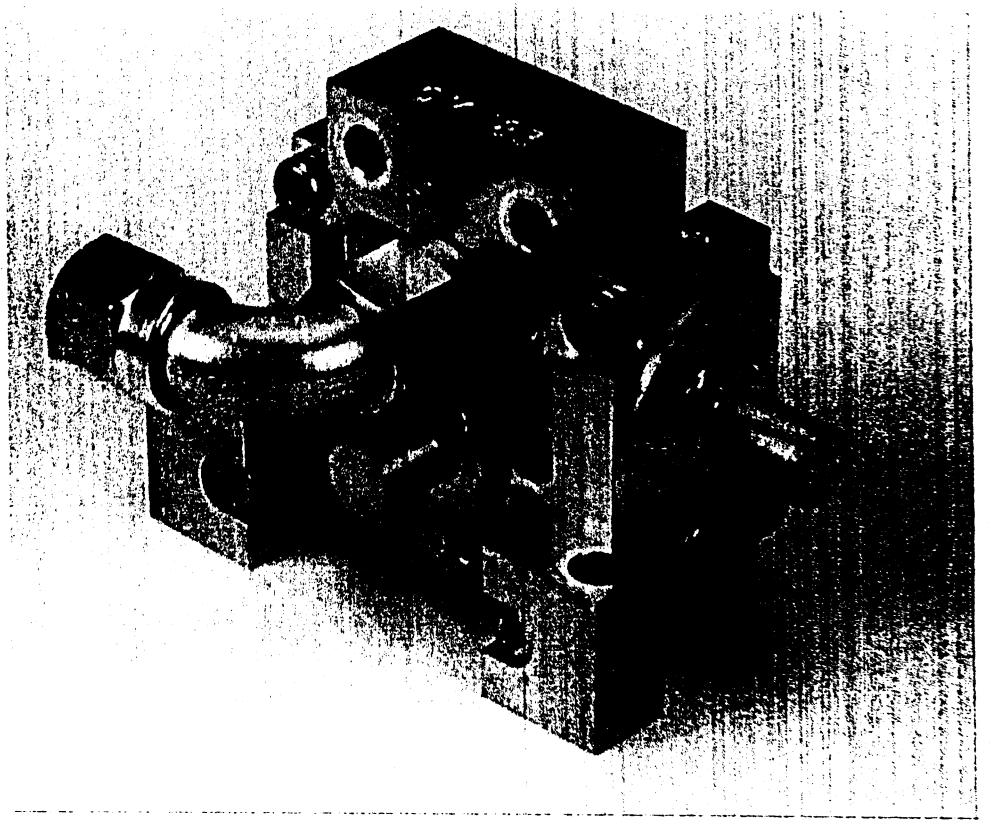
- Gold plated Tungsten wire
- 25 20 15 10 micron diameter
- Space Flight Q.A.



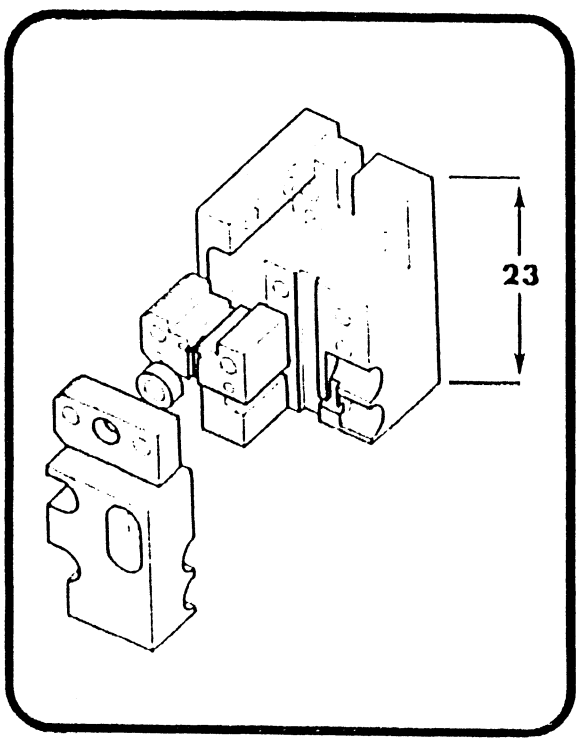
Fine Wire Interferometer Grid Winder

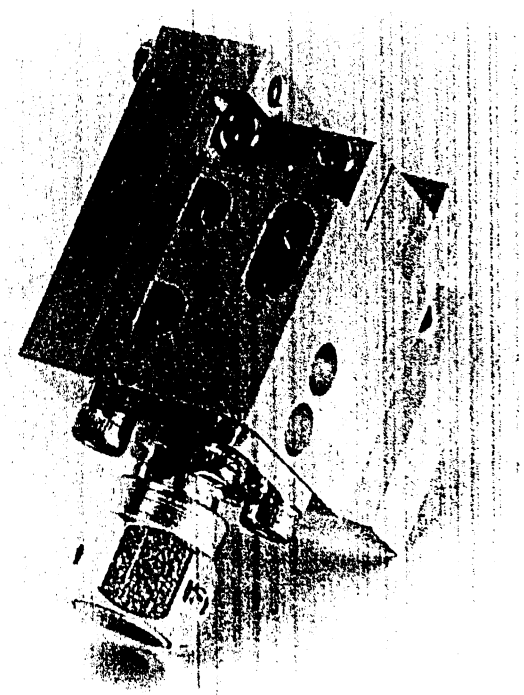
Subharmonic Schottky Diode Mixers

- **Humidity Sounder Brazil.**
- **150 & 183 GHz mixers.**
- **2 prototypes 4 flight**
- **Space Fight Q.A.**
- **State of the art performance.**



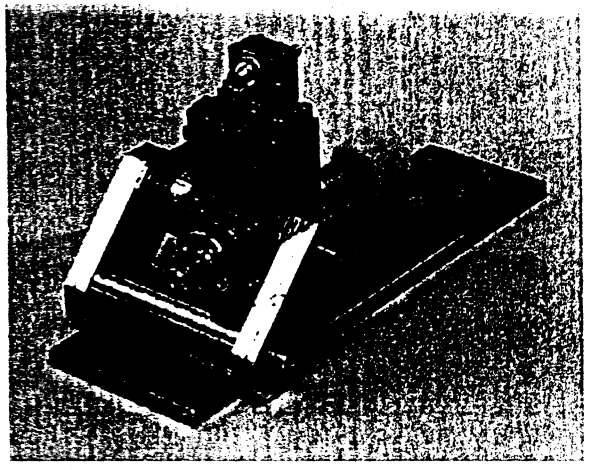
Terahertz Mixer Technology



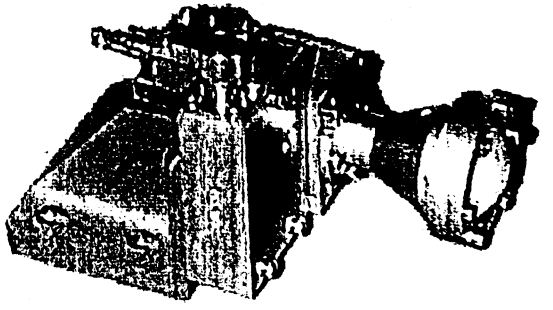


2.5 THz Space Qualified Mixers Developed for the Jet Propulsion Laboratory, USA

SIS Mixer Technology

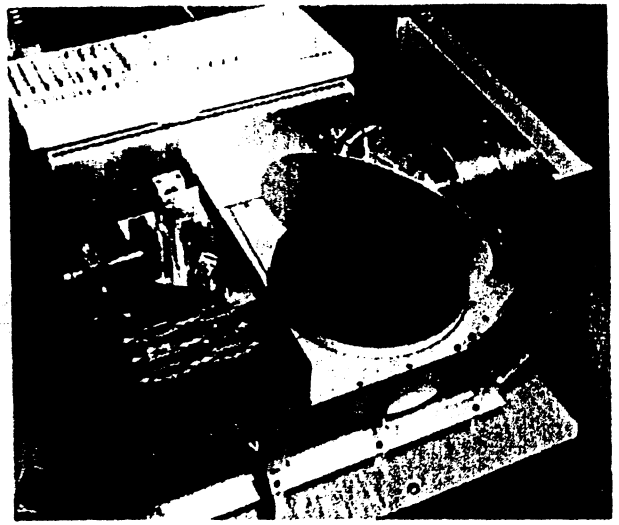


EMCOR 230 GHz SIS waveguide mixer

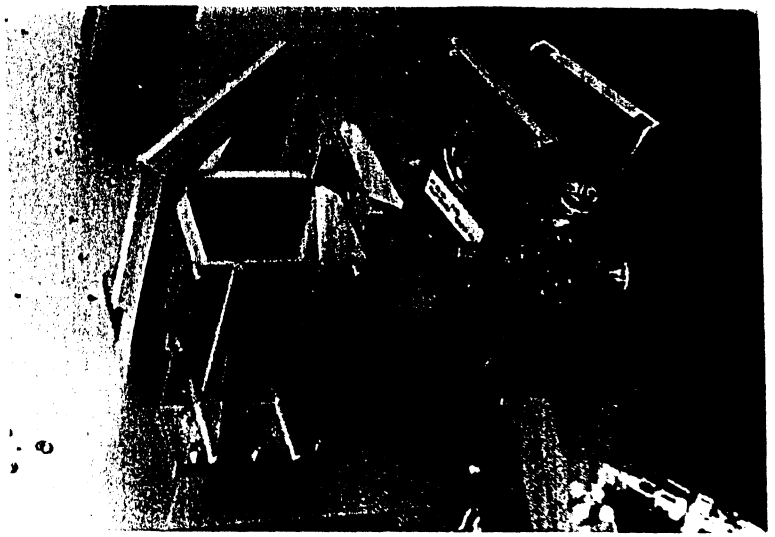


700 GHz SIS waveguide mixer

RAL Schottky Based Systems

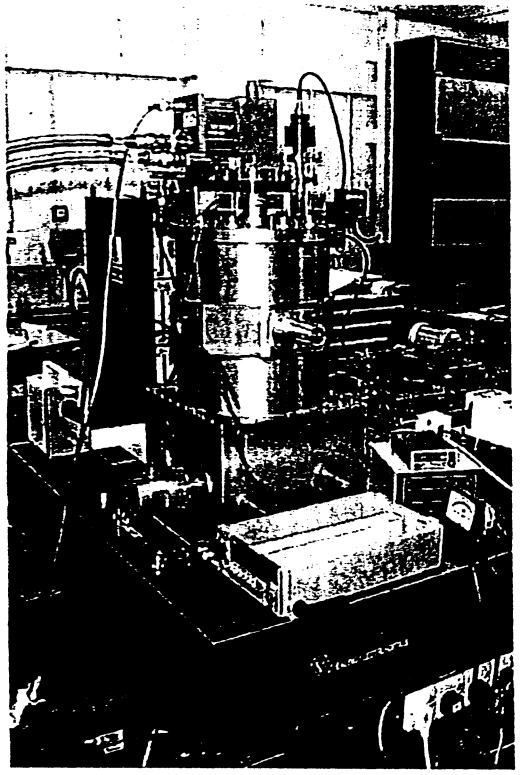


183 GHz water vapour monitor front-end unit

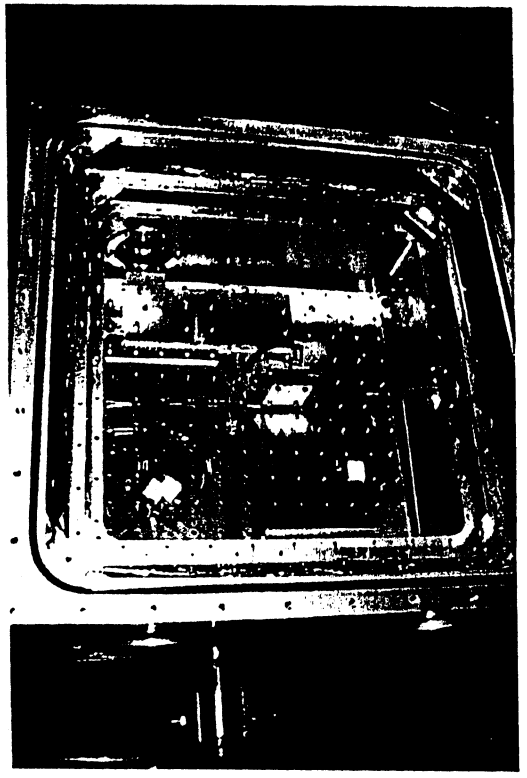


330 GHz atmospheric monitor front-end

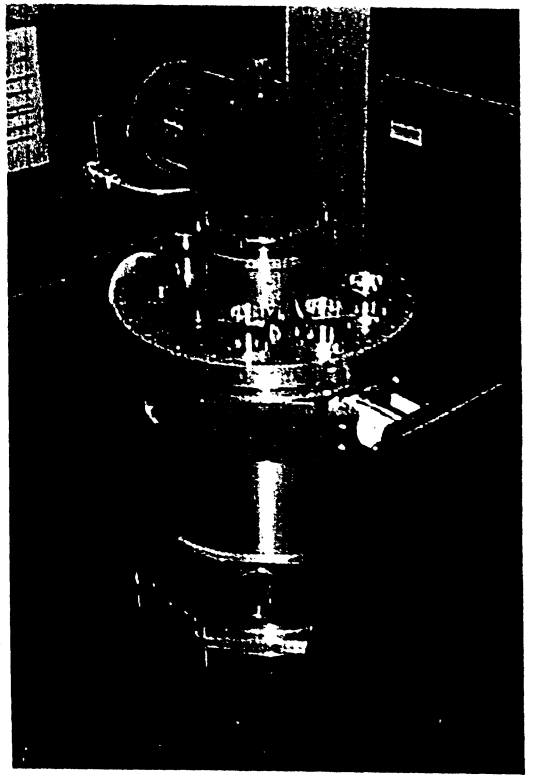
RAL Hybrid LHe Cryogenic Systems



EMCOR cryostat under test

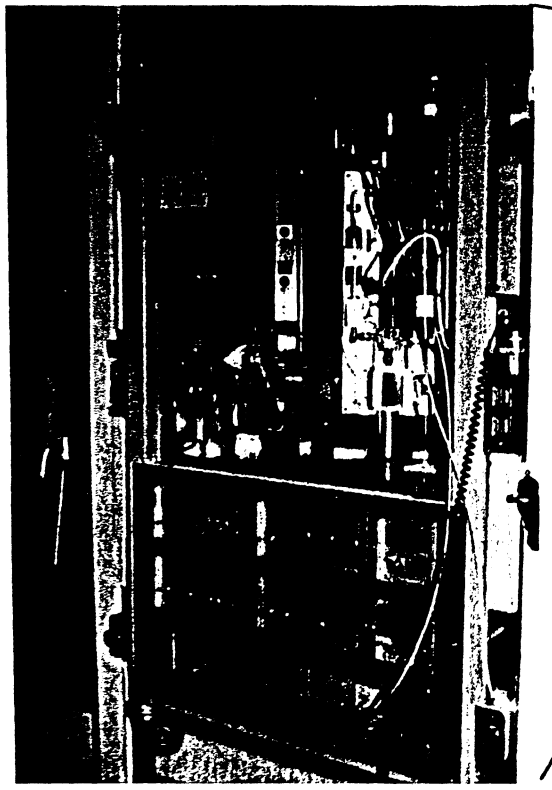


Internal view of EMCOR cryostat



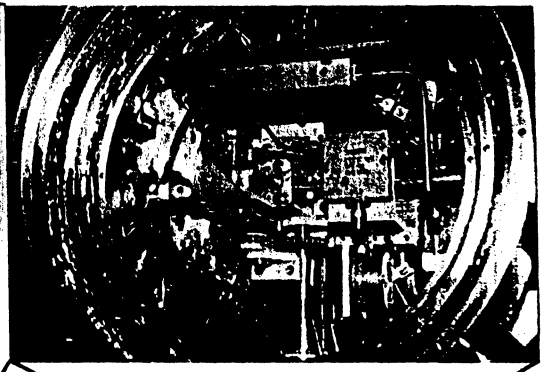
TIGRO 850 GHz cryostat

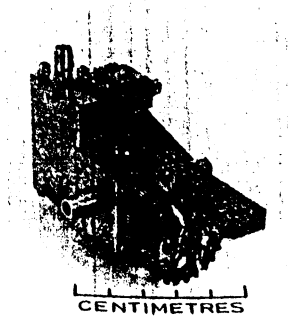
RAL Ground Based SIS Receivers



JCMT 500 GHz SIS receiver C2

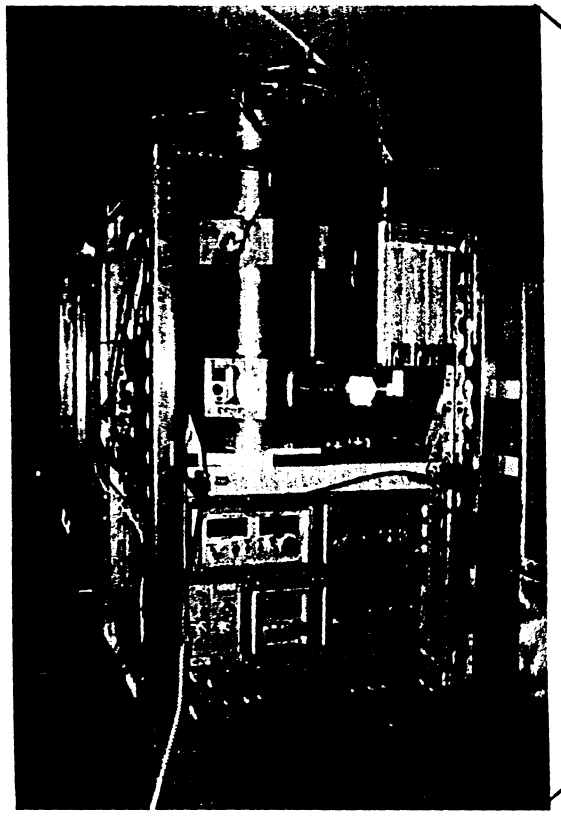
Internal view of receiver cryostat



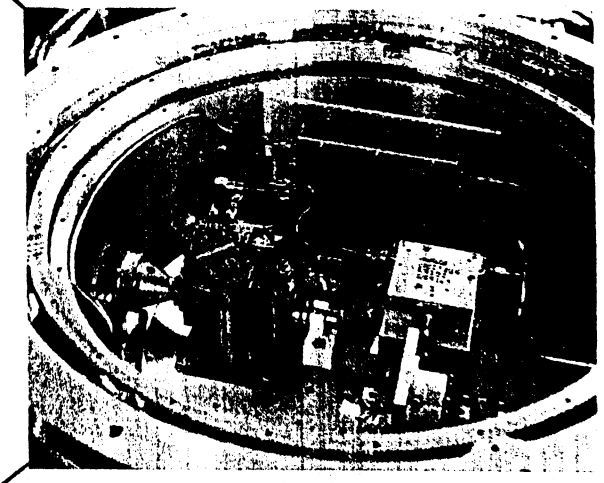


500 GHz SIS waveguide mixer block

RAL Airborne SIS Receivers

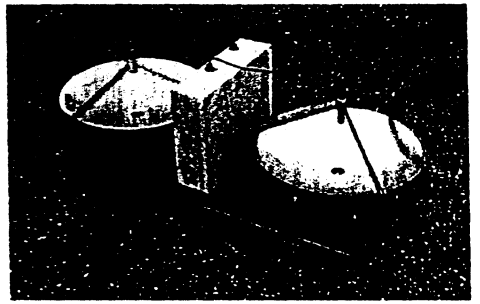


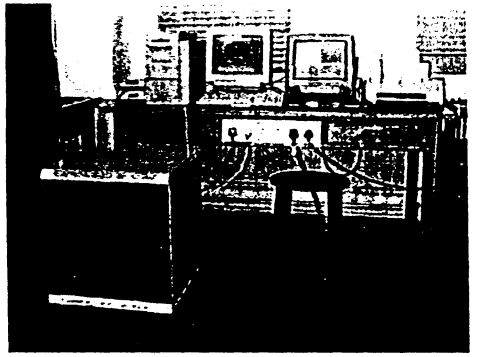
500 GHz airborne SIS receiver



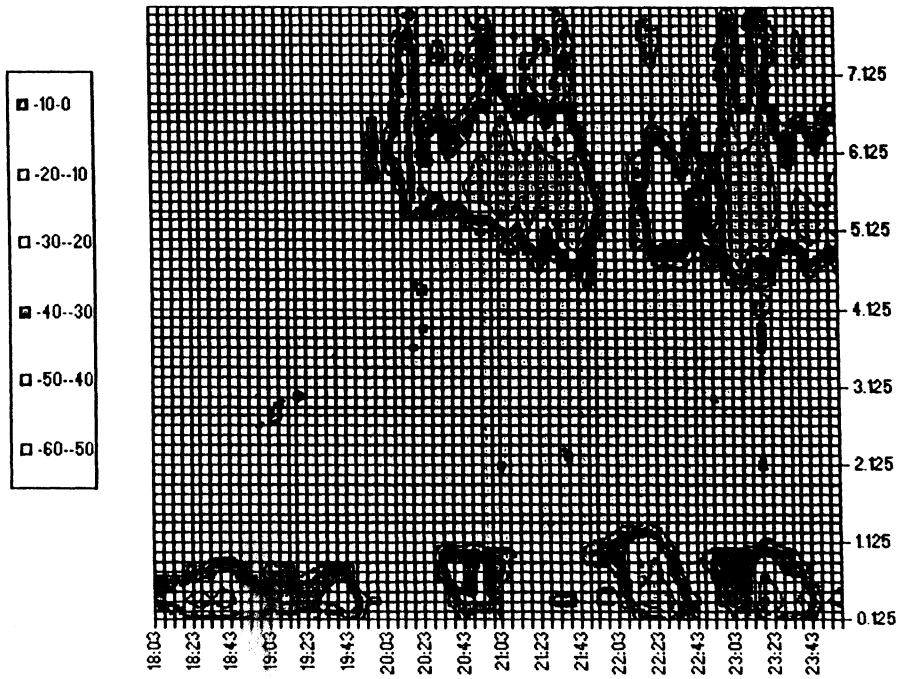
Internal view of receiver cryostat

RAL Cloud Radar System





78 GHz Prototype Cloud Radar



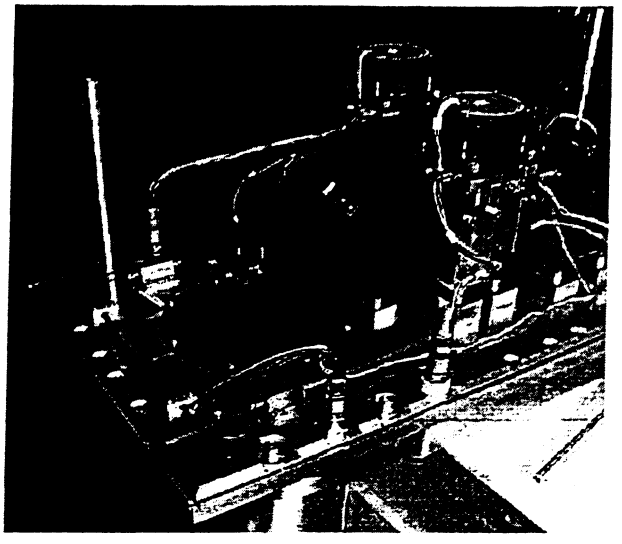
Typical cloud image (zenith sounding)

UKIRT Fast-Track Imager

0.8-2.5 μm

1998

ROE and University of Oxford



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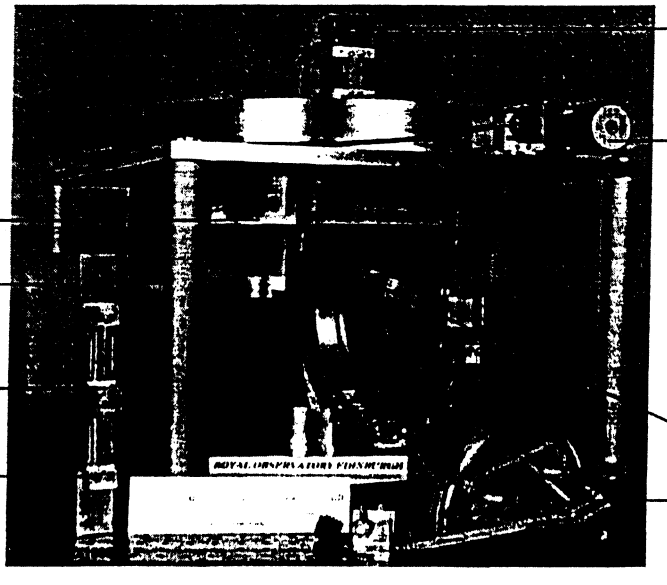
UK Astronomy Technology Centre

Michelle grating carousel

5 gratings

25K



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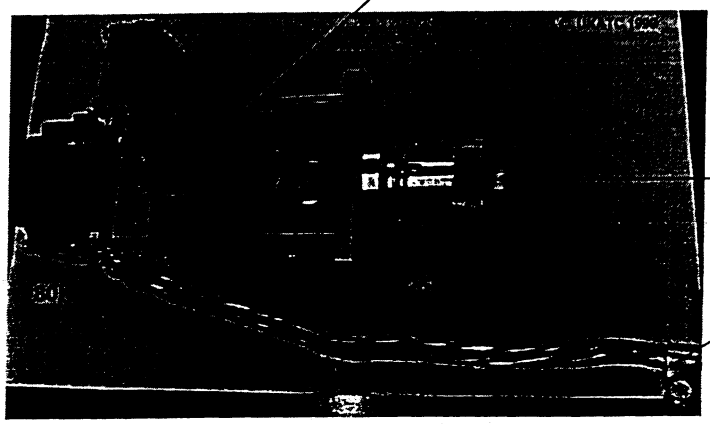
UK Astronomy Technology Centre

Michelle grating carousel grating selection drive slipping clutch



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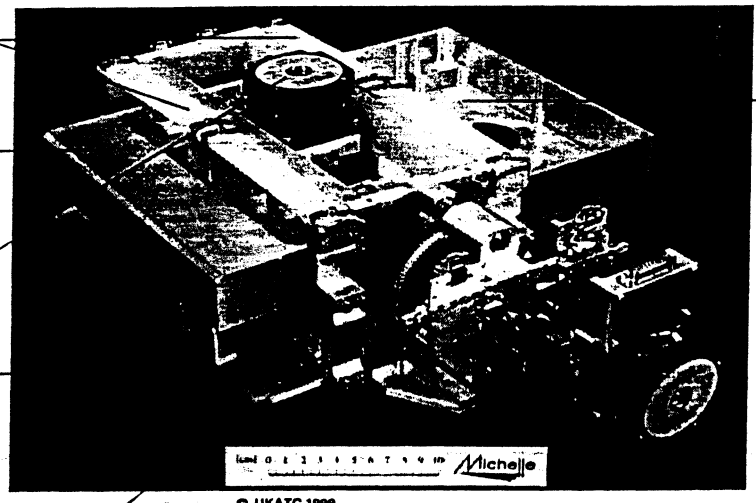
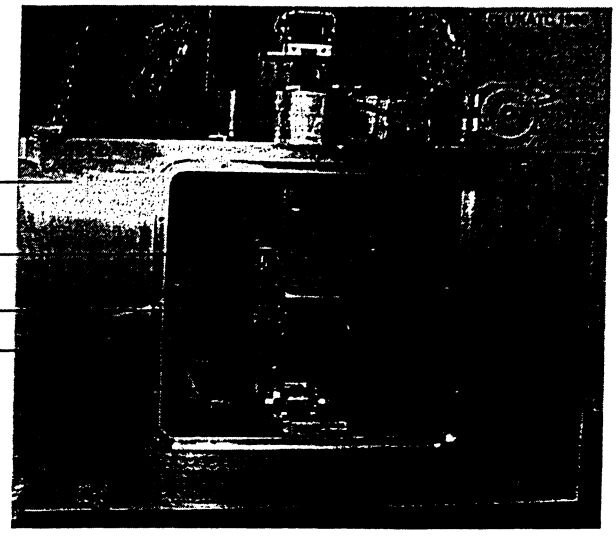


Michelle focus and translation unit

Rutherford Appleton Laboratory

UK Astronomy Technology Centre

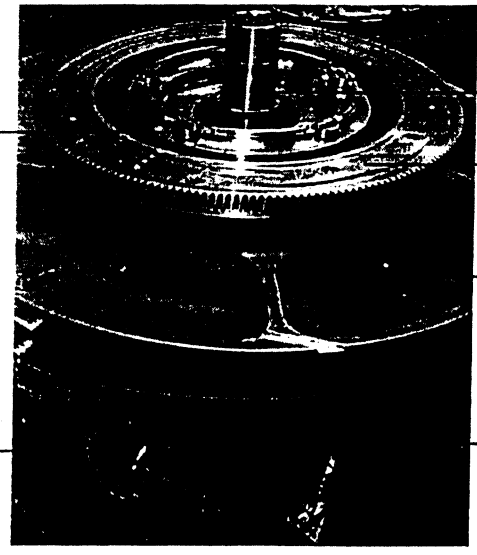
Michelle grating carousel



Rutherford Appleton Laboratory

UK Astronomy Technology Centre

Michelle grating carousel



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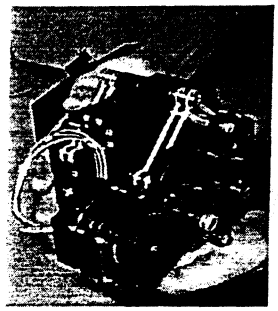
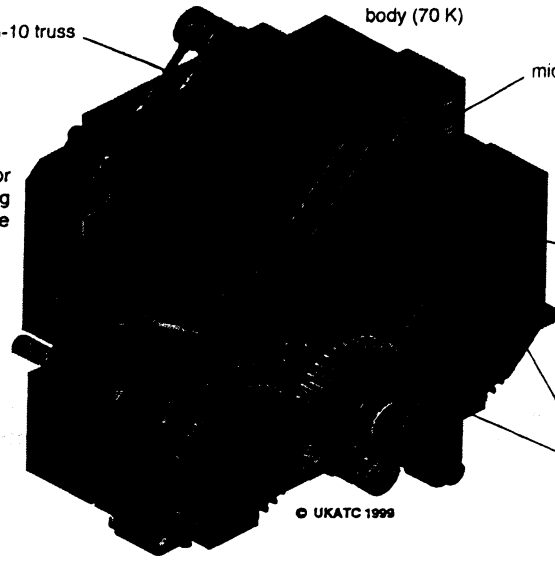
UIST
focus
mechanism
4/98





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Main Design Drivers

1	Known Technology	We are baselining what is available now. Have to build 70.
2	Modularity	To enable manufacture of the instruments at different sites.
3	Water Vapour monitor	This takes the central position in the dewar
4	Servicibility	The dewar components need to be demountable and easily changed.
5	3 Arc minute specification	Constraint on the use of 3arc min (85mm radius) for optics from the water vapour monitor.
6	Availability of window materials of the right bandwidth	This determines the number of windows in the dewar.
7	Temperature	Mounting face 4K stability 10mK 4.5K before changeout.
8	Single dewar for all the main bands	The 35Ghz channel 1 will be serviced by an external flip mirror.
9	Cycle time - pump and cool - down < 5 days	Stainless steel clean design & possible LN2 loop for quick cooldown.
10	Size, Mass	Minimum (Maximum ?) cabin door size is 1 m wide by 1.6 m in height. Max mass 550kg.
11	Manufacturability	Design needs to be compliant with large scale manufacture.
12	Channels	9 observing channels considered plus water vapour monitor.

Rutherford Appleton Laboratory

UK Astronomy Technology Centre

- Prototype and production receivers must be developed on a time scale consistent with deployment of the production antennas.
- Receiver system design should give consideration to issues associated with construction, operation, reliability and maintenance.
- Cryogenic system should be able to accommodate alternative receiver RF designs.
- Baseline system should ideally accommodate science goals. However, this may need re-evaluation as both instrument development and time scales evolve. It may also require the imposition of some technical constraints. For example:

  ⇒ Where possible, use should be made of existing technology with demonstrated heritage.

  ⇒ Reliance on the development of 'new' technology for the early receivers (RF, cryogenics etc.) should be treated with great caution and preferably avoided. This is crucial in relation to 'critical path' components.

  ⇒ **However**, allowance should be made in overall system design for future component upgrade.

Beam Waist and Window Aperture Sizes for Pre-ALMA Channels

Cryostat window apertures corresponding to pre-ALMA channels

Channel	Low Freq (GHz)	Centre Freq (GHz)	High Freq (GHz)	Beam Waist Rad. at Low Freq. (mm)	Window Dia. at –35 dB (mm)
1	30	35	40	63.4	253.7
2	67	79	90	28.4	113.6
3	89	103	116	21.4	85.5
4	125	144	163	15.2	60.8
5	163	187	211	11.7	46.7
6	211	243	275	9.0	36.0
7	275	323	370	6.9	27.7
8	385	442	500	4.9	19.8
9	602	660	720	3.2	12.6
10	787	869	950	2.4	9.7

- Beam waist radius calculated at focus of Cassegrain antenna with F ratio of 8, and edge illumination of –13dB.
- Suggest a maximum window diameter of ~ 45mm is used and re-image channel 2 to 5.

roposed ystem pproach

- Single vacuum vessel containing RF observation channels 2 to 10 and 183 GHz WVM - Channel 1 located in separate cryostat.
- Total of 6 separate RF vacuum windows accommodate Channels 2 to 10 and WVM.
- Total of 5 beams are incident on the sky simultaneously and clustered around 6th and central WVM beam. [Note: Channel 1 is accessed via a flip mirror.]
- Four main beams on the sky accommodate a pair of frequency channels. For example, 3 & 5 and 4 & 6 etc. are coincident on the sky.
- Martin-Puplett polarising interferometers (MPI's) are used to provide simultaneous polarisation and frequency discrimination and IR filtering.
- MPI's mounted within cryostat at 77K on a rigid optical reference plate.
- Wide IF band, single ended SIS mixers proposed for Channels 3 to 10.
- SIS mixers and LNA's (at 4K) and LO's (at 77K) are located on removable cartridges in polarisation and frequency pairs.
- Autonomous system operation e.g., bias, housekeeping etc. under local μP control.

Proposed System Advantages - 1

- Beam locations on sky are within 3 arc min of WVM (Channel 1 excluded).
- Close proximity of beams on sky and channel frequency pairing provides high speed frequency switching.
- SSB and DSB operation accommodated.
- Potential for future dual frequency operation with paired channels.
- Frequency extension provides redundancy at core line frequencies, e.g. 230 GHz.
- Use of individual LO's (one/mixer) provides additional channel redundancy.
- WVM channel accommodated on central axis and in separate removable cartridge.
- Number of RF windows reduced from 10 to 5 (excluding cooled WVM).

Proposed System Advantages - 2

- Window apertures reduced to ~ 45mm in order to minimise thermal load on cryogenic system and enhance vacuum integrity.
- Channel 1 placed in separate cryostat - access to telescope focal plane achieved via a flip mirror. {Note: Channel 1 and WVM can be used simultaneously.}
- Cryogenic system is versatile and, we believe, can accommodate other system designs.
- Cartridge design allows relatively easy maintenance of critical system components.
- IR blocking filters not required.
- Receiver calibration system included.
- Proposed receiver does not require development of critical technologies.

Proposed System Disadvantages

- Use of flip mirror for Channel 1 excludes simultaneous use of Channel 2.
- Two room temperature mirrors required per channel pair.
- Use of MPI's limits SSB IF instantaneous bandwidth to ~4 GHz for ~ 4% band edge loss for IF centred at 8GHz. {Note: that system can be set to DSB mode to achieve 8GHz bandwidth requirement).
- Use of MPI's increases optical complexity.
- Four cryogenic motors and positioning systems required. {Note: Ganging MPI moveable mirrors together reduces total number of motors and sensors required to 4.}
- LO injection scheme via dielectric membrane is inefficient (~2% LO used). [Note: This is also true for waveguide couplers.]
- Calibration system requires use of 4 external (room temp.) motors. Potential truncation of cold load beam will raise effective cold load to a level above 77K.

183 GHz Water Vapour Meter Channel

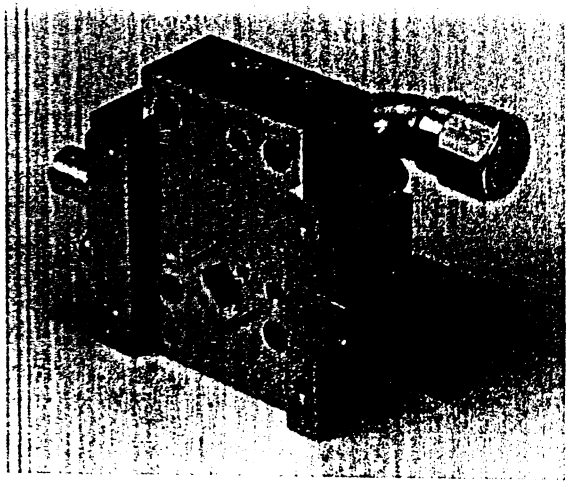
If sensitivity permits, recommend the use of Schottky diode sub-harmonic mixer technology.

Advantages:

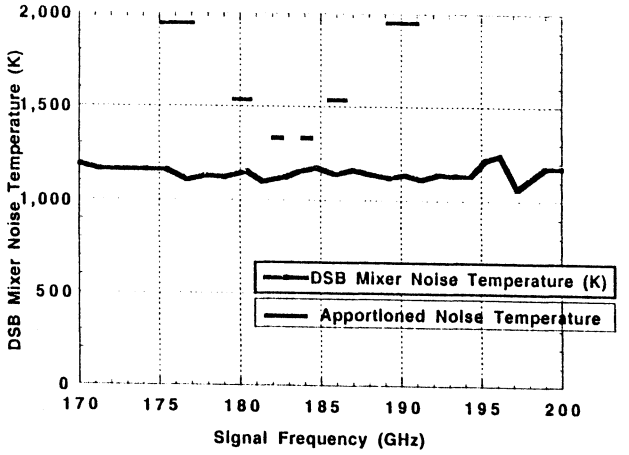
- Proven technology - devices have been used extensively room temp. and cryogenic applications.
- Highly reliable - devices have been space qualified [e.g. vibration, thermal cycling etc..]
- Compact and simple - fixed tuned, wideband operation with waveguide LO input and integrated LNA if required.
- If necessary, dual polarisation operation can be accommodated via two systems separated by a wire grid.

Due to their past heritage and proven reliability we do not consider integration of a Schottky based WVM within the main receiver cryostat to present a reliability issue.

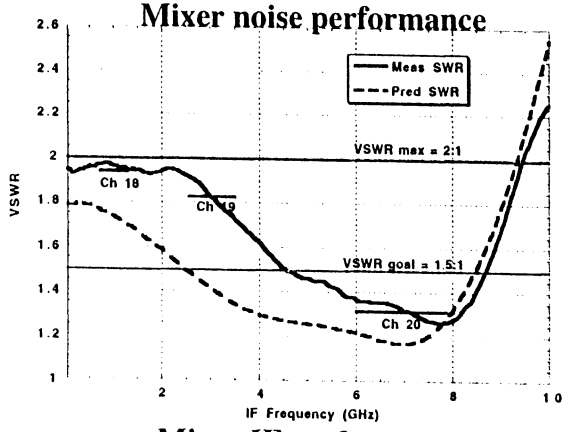
However, if integration is perceived to be undesirable our design also allows for room temperature or separate cryostat operation.



183 GHz Sub-harmonic mixer

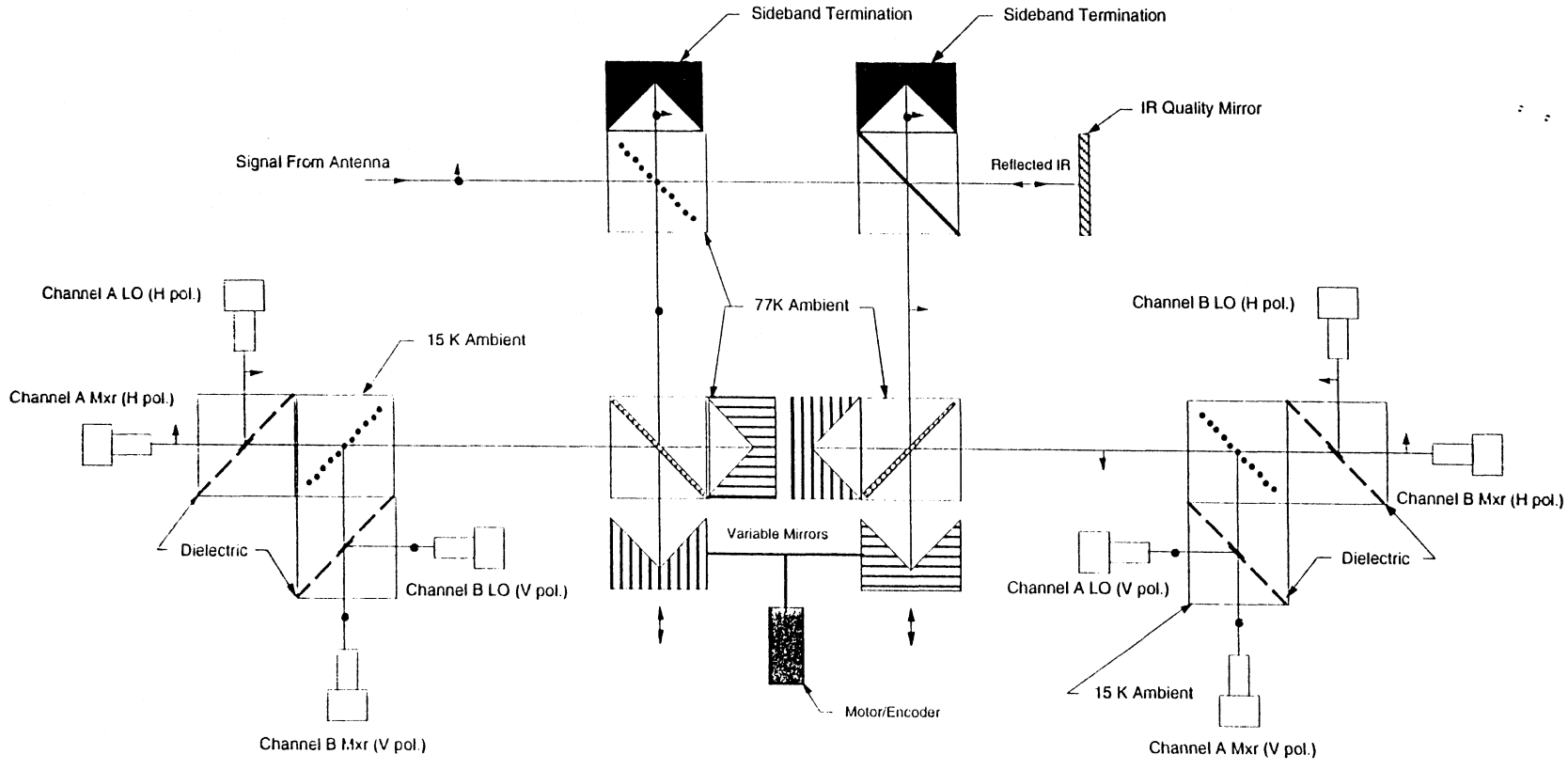


Mixer noise performance



Mixer IF performance

RF System Schematic



Approximate schematic. Not all optical components shown

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Proposed Readjusted ALMA Channels

Readjusted ALMA Frequency Channels

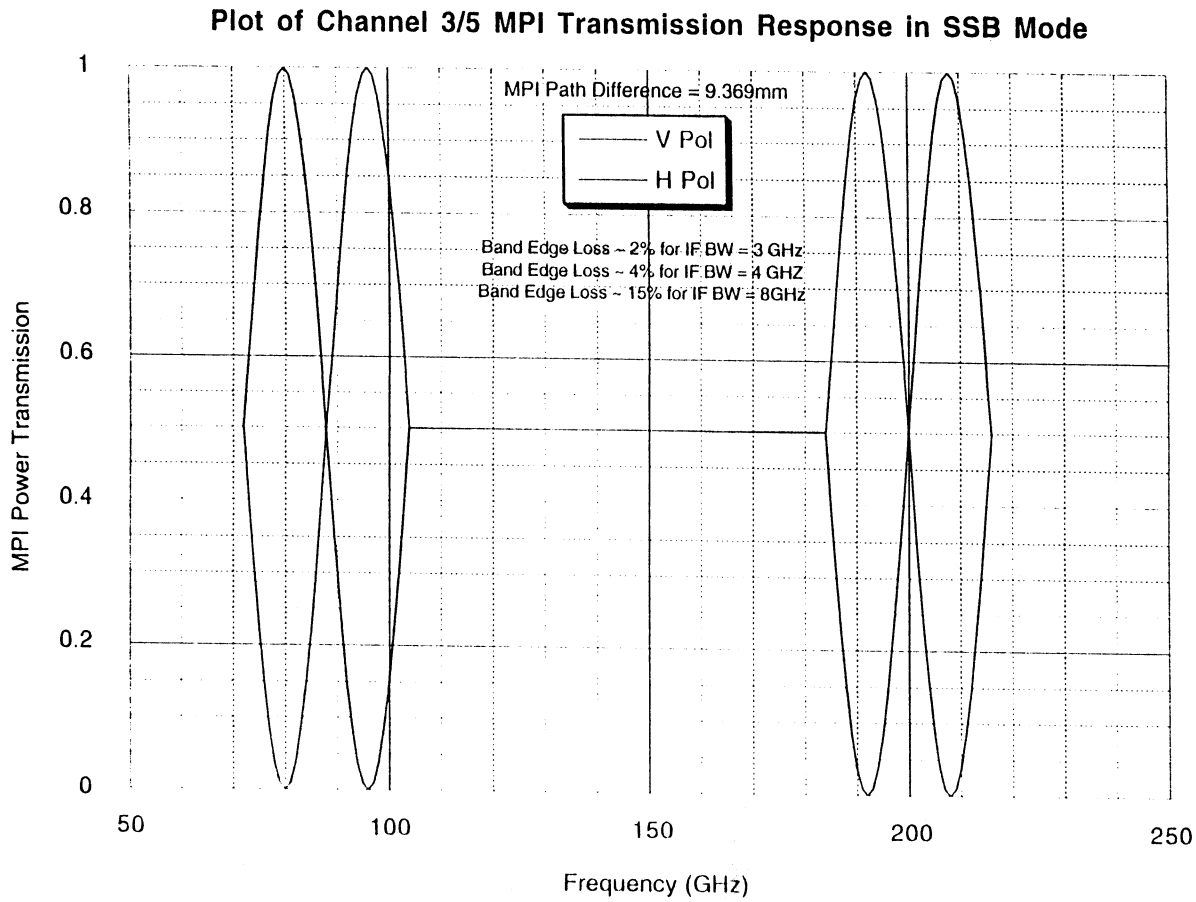
Channel	Low Freq (GHz)	Centre Freq (GHz)	High Freq (GHz)	Beam Waist Rad. at Low Freq. (mm)	Window Dia. at –35 dB (mm)
1	30	35	40	63.4	253.7
2	64	80	96	29.7	118.9
3	76	96	116	25.0	100
4	115	140	165	16.5	66.1
5	152	192	232	12.5	50.0
6	215	280	345	8.9	35.4
7	275	325	375	6.9	27.7
8	380	435	510	5.0	20.0
9	580	650	720	3.3	13.1
10	785	870	955	2.4	9.7

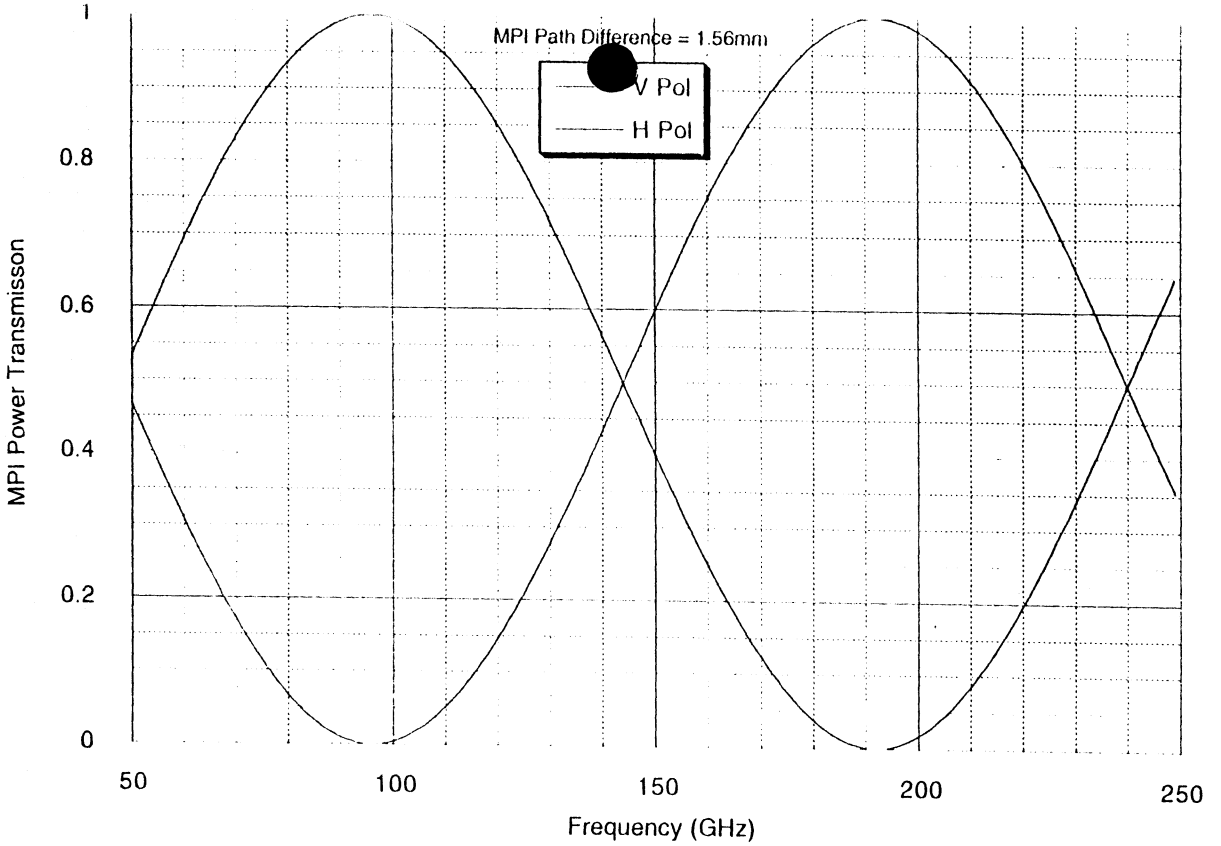
Suggested Channel Window Configuration

Channel and Cryostat Window Configuration

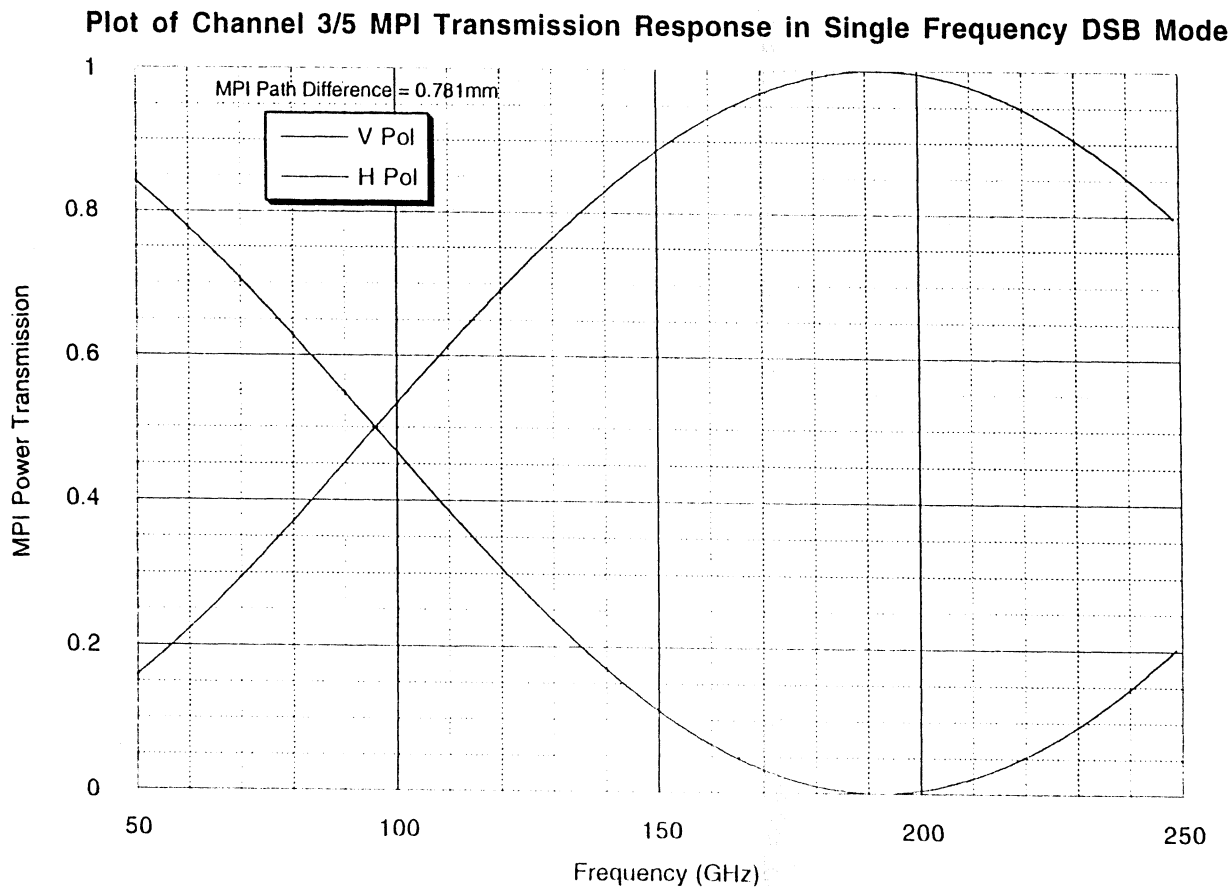
Channel	Low Freq (GHz)	Centre Freq (GHz)	High Freq (GHz)	Window Dia. (mm)
WVM	173	183	183	45
2	64	79	90	45
3	76	96	116	45
5	152	192	232	
4	115	140	165	45
6	215	280	345	
7	275	325	375	40
9	580	650	720	
8	380	435	510	30
10	785	870	955	

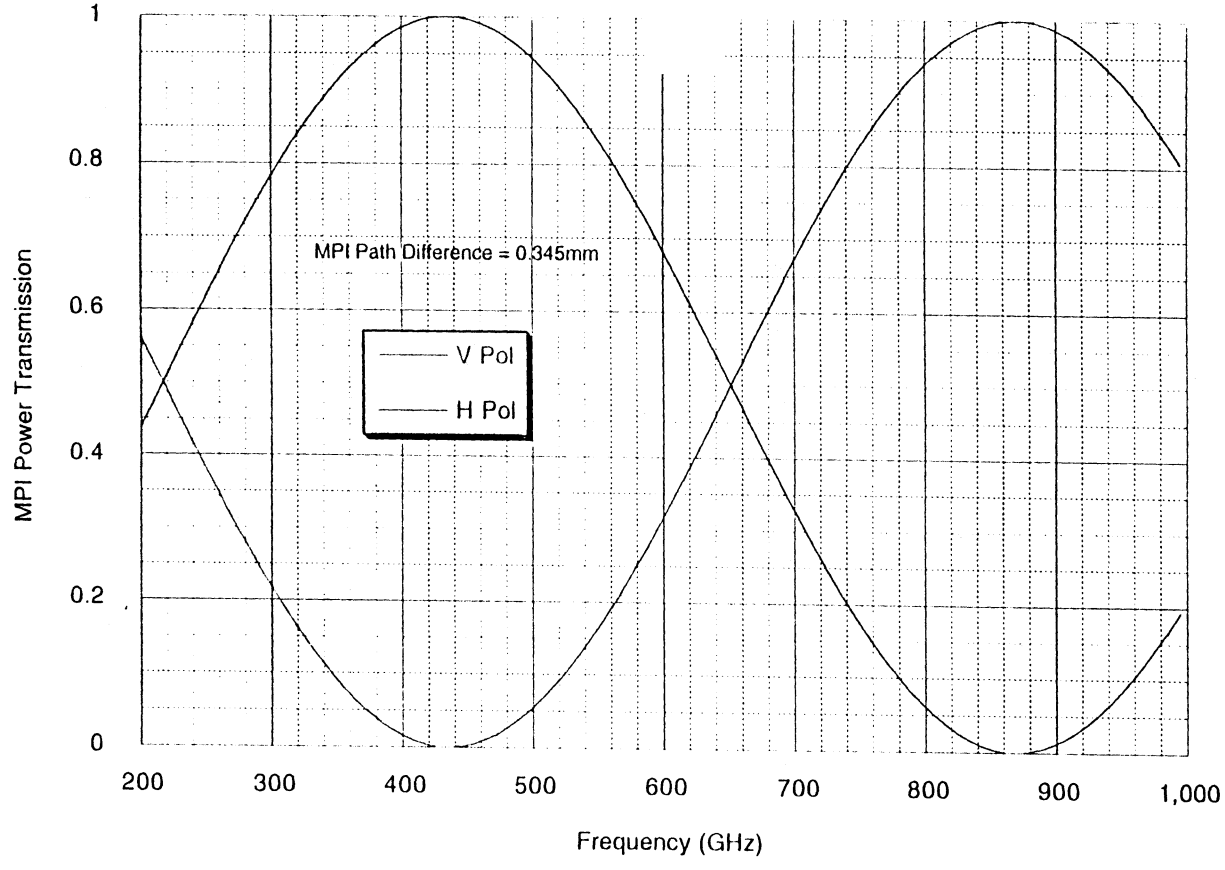
Channel 3/5 MPI Response in SSB Mode




MPI Path Difference = 1.56mm
V Pol
H Pol
MPI Power Transmisson
1
0.8
0.6
0.4
0.2
0
50
100
150
200
250
Frequency (GHz)

Channel 3/5 MPI Response in DSB Single Freq. Mode




MPI Power Transmission
1
0.8
0.6
0.4
0.2
0
200
300
400
500
600
700
800
900
1,000
Frequency (GHz)
MPI Path Difference = 0.345mm
V Pol
H Pol

12 - 2 -99/B

Possible LO Configuration

LO Multiplier Configuration

Channel	Low Freq (GHz)	Centre Freq (GHz)	High Freq (GHz)	Multipication order
1	30	35	40	Direct (2nd LO)
2	64	80	96	Direct (2nd LO)
3	76	96	116	Direct (1st LO)
4	115	140	165	Direct or x2*
5	152	192	232	x2
6	215	280	345	x3
7	275	325	375	x3
8	380	435	510	x5
9	580	650	720	x2x3
10	785	870	955	x3x3

Nominal fundamental tuning range = 74.3 to 122 GHz (8 GHz IF band centre)

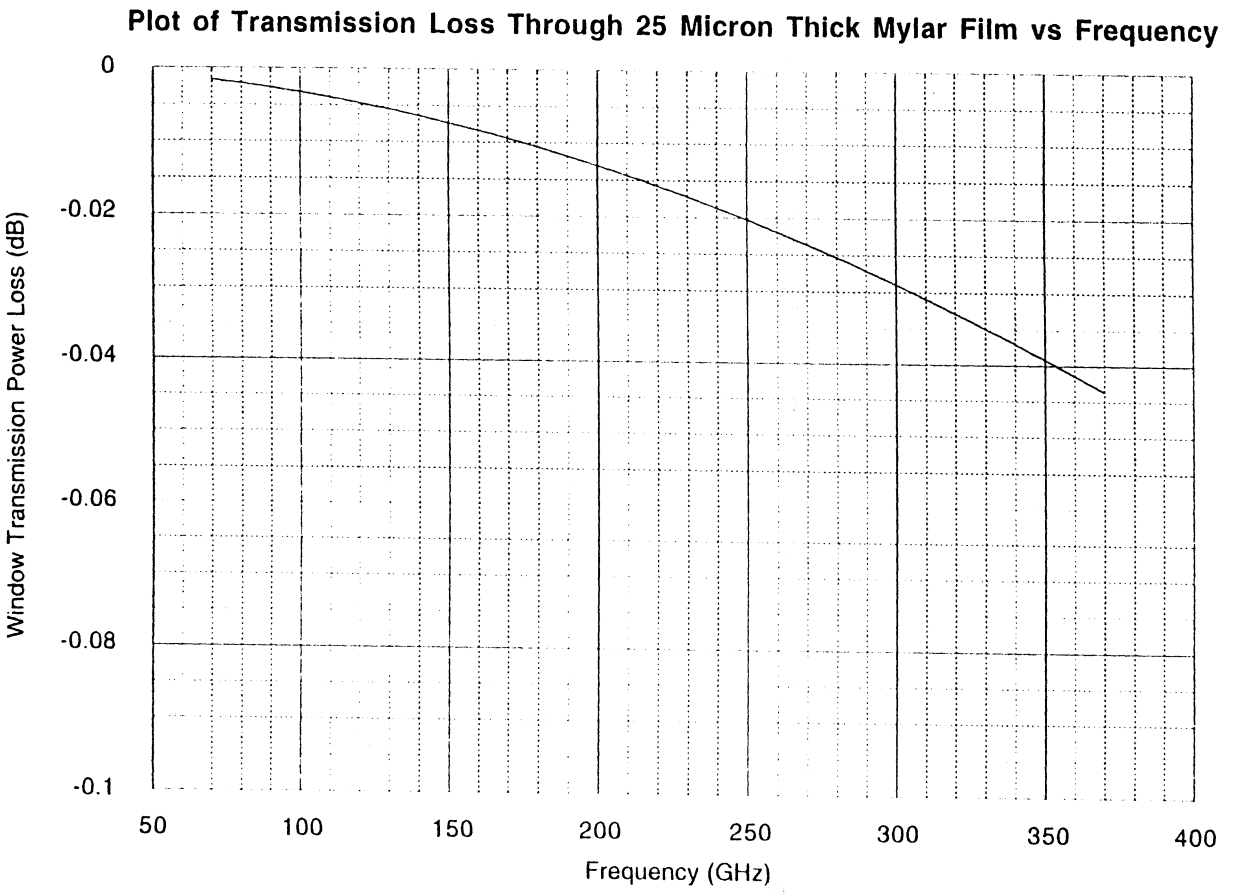
* x2 fundamental range = 61.5 to 78.5 GHz (8 GHz IF band centre)

Cryostat RF Vacuum Window Materials

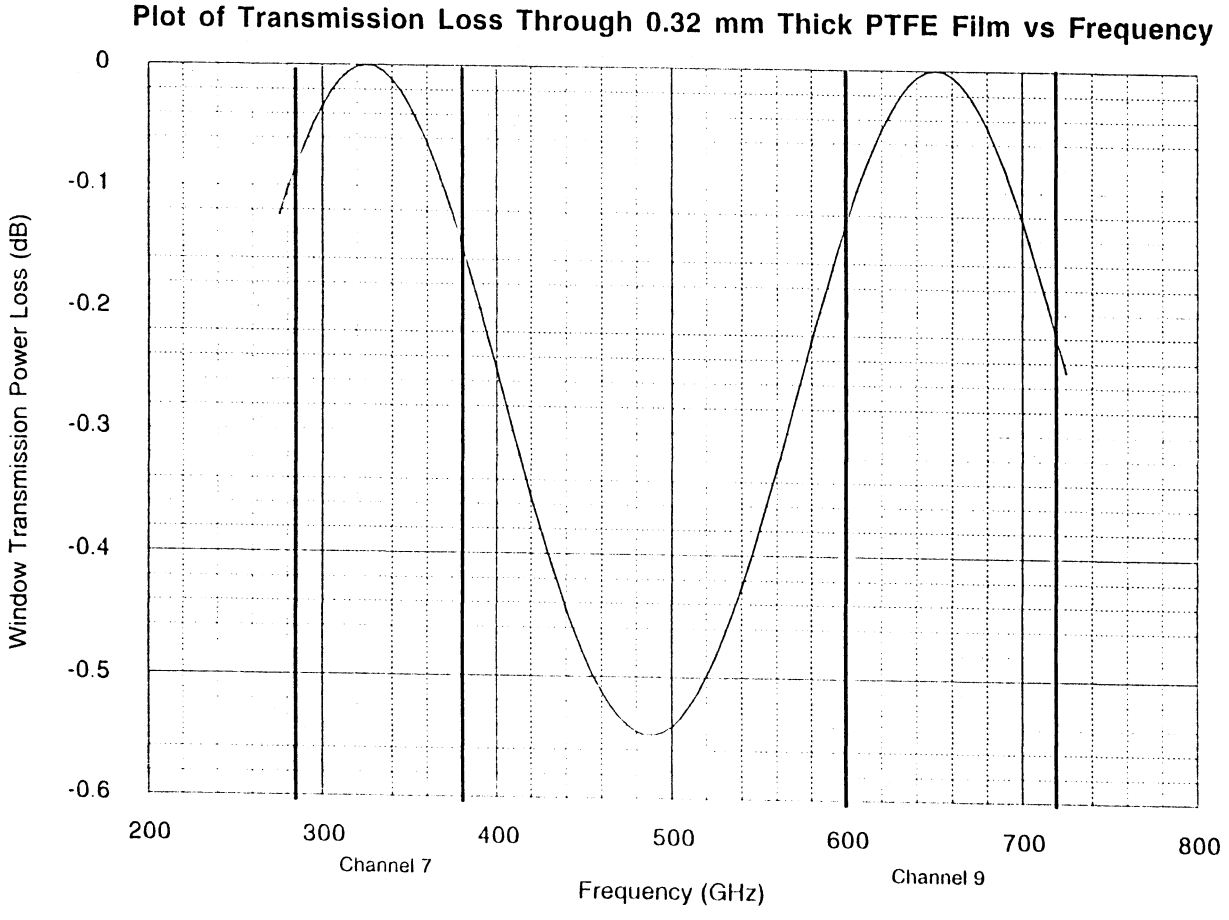
Possible window materials and properties

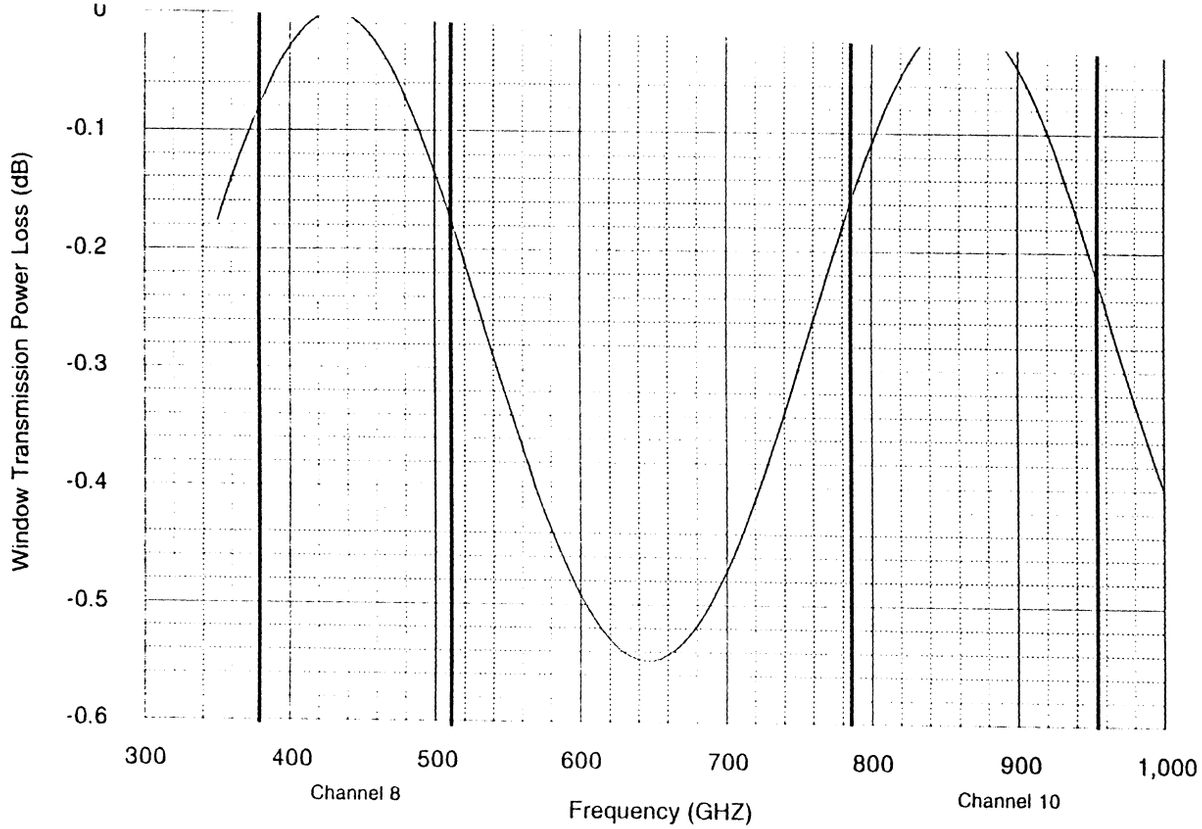
Channel	Centre Freq (GHz)	Window Material	Window Thickness mm	Ref. Loss at Band Edge dB	Abs. Loss dB
WVM	183	PTFE/TPX	0.57	~0.1@163	~-0.02
2	80	PTFE	1.33	-0.10	<-0.02
3	96	Mylar	0.025	-0.01	<-0.01
5	192			-0.07	<-0.01
4	140	Mylar	0.025	-0.015	<-0.01
6	280			-0.14	<-0.01
7	325	PTFE/TPX	0.322	-0.15	-0.01
9	650			-0.20	-0.03
8	435	PTFE/TPX	0.244	<-0.20	-0.02
10	870			-0.20	-0.04

WVM window could be made thicker and blazed


Plot of Transmission Loss Through 25 Micron Thick Mylar Film vs Frequency
Window Transmission Power Loss (dB)
0
-0.02
-0.04
-0.06
-0.08
-0.1
50
100
150
200
250
300
350
400
Frequency (GHz)

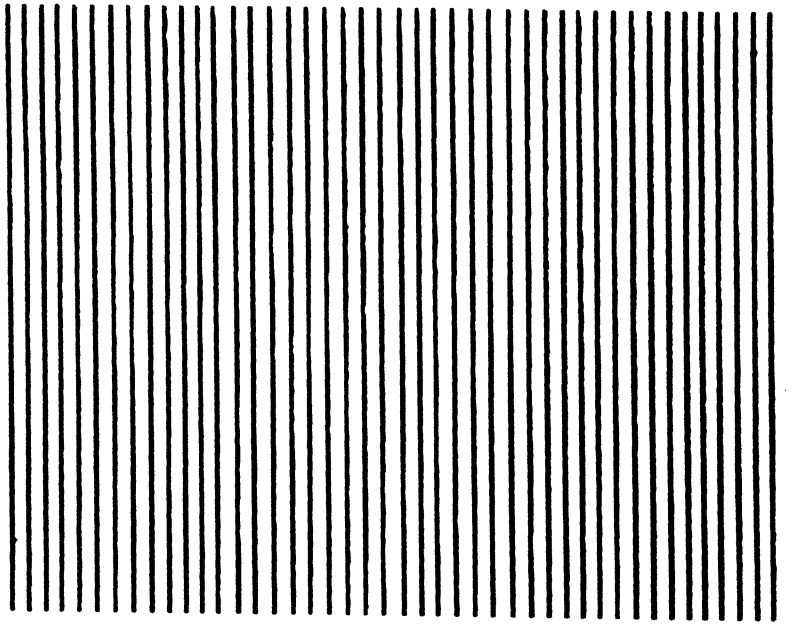
PTFE RF Window Transmission Loss
Channel 7/9




0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
Window Transmission Power Loss (dB)
300
400
500
600
700
800
900
1,000
Channel 8
Frequency (GHZ)
Channel 10

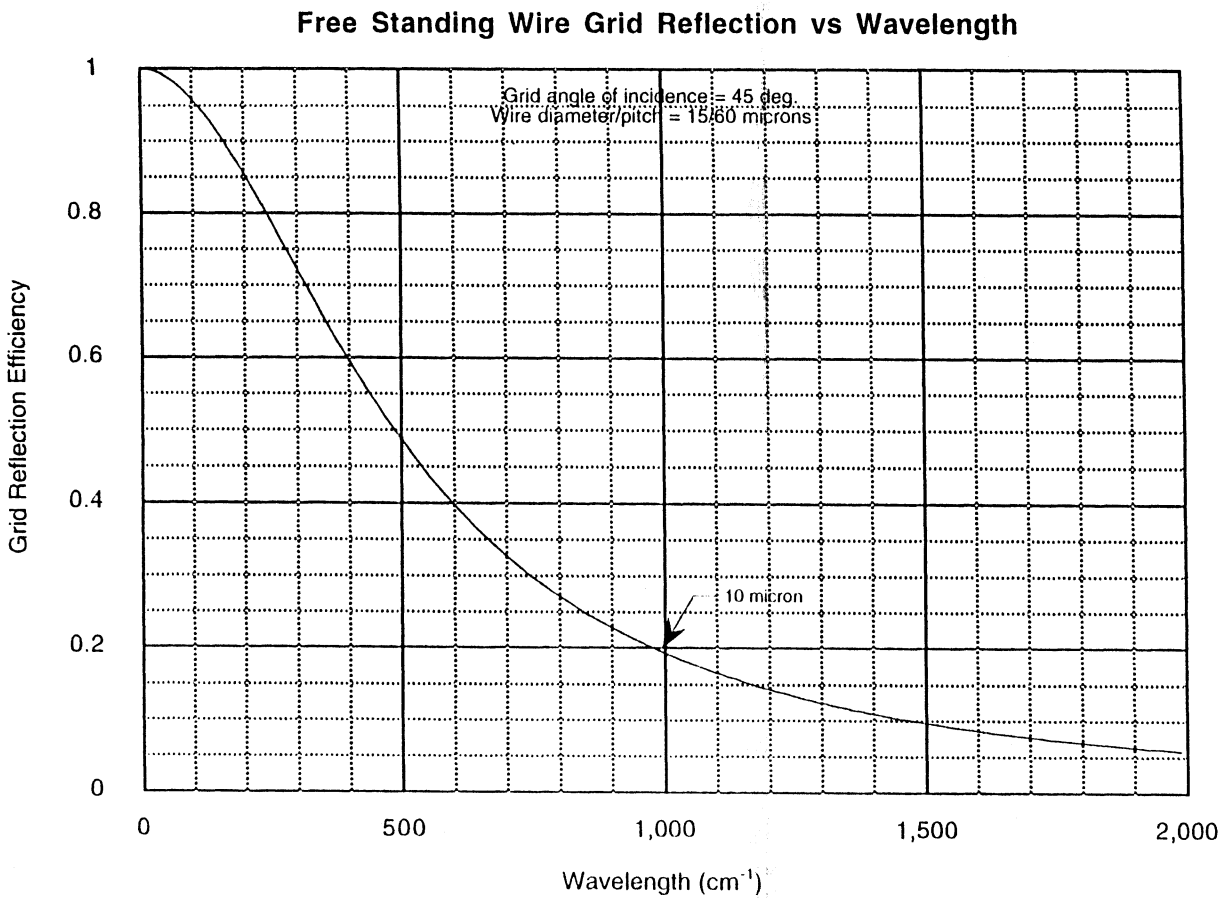
Free Standing W Grid Example

RAL wire grid example.



Grid produced using high resolution computer controlled positioning system
Wire type: Gold plated Tungsten. Wire diameter = 15μm. Wire Pitch = 50 μm.

Free Standing Wire Grid IR Reflection Estimate



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Mirror Losses - Aluminium Alloy

Single reflection mirror absorption loss at ALMA band centre frequencies – Al 6061

Channel	Centre Freq (GHz)	Mirror (300K) Al(6061) (dB)	Mirror (77K) Al(6061) (dB)	Mirror (20K) Al(6061) (dB)
1	35	-0.007	-0.004	-0.004
2	80	-0.010	-0.007	-0.006
3	96	-0.011	-0.007	-0.007
4	140	-0.014	-0.009	-0.008
5	192	-0.016	-0.010	-0.010
6	280	-0.019	-0.012	-0.011
7	325	-0.021	-0.013	-0.012
8	435	-0.024	-0.016	-0.014
9	650	-0.029	-0.019	-0.017
10	870	-0.034	-0.022	-0.020

- RMS surface finish assumed < $\lambda/50$ (6 μm at 1THz). Obtained by conventional machining. Higher quality surface achieved via diamond machining.
- Bulk dc conductivity values reduced by factor of 2.

Mirror Losses - Pure Gold

Single reflection mirror absorption loss at ALMA band centre frequencies – Au

Channel	Centre Freq (GHz)	Mirror (300K) Au (dB)	Mirror (77K) Au (dB)	Mirror (20K) Au (dB)
1	35	-0.005	-0.002	-0.0006
2	80	-0.008	-0.004	-0.0010
3	96	-0.009	-0.004	-0.0010
4	140	-0.010	-0.005	-0.0013
5	192	-0.012	-0.006	-0.0015
6	280	-0.015	-0.007	-0.0018
7	325	-0.016	-0.007	-0.0020
8	435	-0.018	-0.008	-0.0023
9	650	-0.022	-0.010	-0.0028
10	870	-0.026	-0.012	-0.0032

- RMS surface finish assumed < $\lambda/50$ (6 μm at 1THz). Obtained by conventional machining. Higher quality surface achieved via diamond machining.
- Bulk dc conductivity values reduced by factor of 2.

Mirror Losses - OFHC Copper

Single reflection mirror absorption loss at ALMA band centre frequencies – OFHC

Channel	Centre Freq (GHz)	Mirror (300K) Cu (dB)	Mirror (77K) Cu (dB)	Mirror (20K) Cu (dB)
1	35	-0.005	-0.002	-0.0005
2	80	-0.007	-0.002	-0.0007
3	96	-0.008	-0.003	-0.0007
4	140	-0.009	-0.003	-0.0009
5	192	-0.011	-0.004	-0.0010
6	280	-0.013	-0.005	-0.0013
7	325	-0.014	-0.005	-0.0014
8	435	-0.016	-0.006	-0.0016
9	650	-0.019	-0.007	-0.0019
10	870	-0.022	-0.008	-0.0022

- RMS surface finish assumed < $\lambda/50$ (6 μm at 1THz). Obtained by conventional machining. Higher quality surface achieved via diamond machining.
- Bulk dc conductivity values reduced by factor of 2.

Wire Grid Reflection and Absorption Loss

Single grid reflection & absorption loss at ALMA channel centre frequencies

Channel	Centre Freq (GHz)	Reflection Loss (dB)	Grid (300K) (dB)	Grid (77K) (dB)	Grid (20K) (dB)
1	35	-	-	-	-
2	80	-	-	-	-
3	96	0.004	0.017	0.008	0.002
4	140	0.004	0.020	0.010	0.003
5	192	0.004	0.024	0.011	0.003
6	280	0.009	0.029	0.013	0.004
7	325	0.004	0.031	0.014	0.004
8	435	0.004	0.036	0.017	0.005
9	650	0.020	0.044	0.021	0.006
10	870	0.030	0.051	0.024	0.007

Gold plated tungsten wires used. Bands 3/5 and 4/6 use 25μm dia. wire on 100μm pitch. Bands 7/9 and 8/10 use 15μm dia. wire on 60μm pitch. Calculated values are for normal incidence.

Accumulated Optics Reflection and Absorption Loss

	Accumulated Channel Loss (dB) - All apertures truncated to –35dB level (max).									
Component	1	2	3	4	5	6	7	8	9	10
Al Mirror 300K (x2)	0.014	0.02	0.022	0.028	0.032	0.038	0.042	0.048	0.058	0.068
RF Window	~0.1	0.12	0.020	0.025	0.080	0.024	0.16	0.22	0.23	0.24
Grid 77K Abs. (x2)	-	-	0.016	0.020	0.022	0.026	0.028	0.034	0.042	0.048
Grid 77K Ref. (x2)	-	-	0.008	0.008	0.008	0.018	0.008	0.008	0.040	0.060
Au Mirror 77K (x2)	-	-	0.008	0.010	0.012	0.014	0.014	0.016	0.020	0.024
MPI Coupling Loss†	-	-	0.004	0.002	0.001	Neg.	Neg.	Neg.	Neg.	Neg.
Au Mirror 20K (x1)	-	-	0.001	0.001	0.002	0.002	0.002	0.002	0.003	0.003
Grid 20K Abs. (x1)	-	-	0.002	0.003	0.003	0.004	0.004	0.005	0.006	0.007
Grid 20K Ref. (x1)	-	-	0.004	0.004	0.004	0.009	0.004	0.004	0.020	0.030
Sub Total	0.11	0.14	0.09	0.10	0.16	0.14	0.26	0.34	0.42	0.48
LO Beamsplitter 20K	-	-	0.10	0.10	0.10	0.10	0.10	0.13	0.13	0.22
MPI Band Edge Loss*	-	-	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Total Loss	0.11	0.14	0.29	0.30	0.36	0.34	0.46	0.57	0.65	0.80

* Combined reflection and absorption loss extending to band edge.

† Diplexer coupler loss evaluated for mirror at SSB position, 8GHz IF centre frequency ωo = 12.5mm.

* Assumes SSB 3.0 GHz ΔIF centred at 8 GHz. Bandwidth can be increased to 8GHz with typical loss of 0.01dB when in DSB mode and MPI set to short path difference.

Accumulated Optics Noise Contribution

	Accumulated Channel Noise (K) - All apertures truncated to –35dB level (max).									
Component	1	2	3	4	5	6	7	8	9	10
Al Mirror 300K (x2)	1.0	1.4	1.5	1.9	2.2	2.6	2.9	3.3	4.0	4.7
RF Window	3.0?	3.1	0.9	1.0	1.9	3.1	3.3	4.8	5.5	6.2
Grid 77K (x2)	-	-	0.28	0.35	0.39	0.46	0.50	0.60	0.74	0.85
Au Mirror 77K (x2)	-	-	0.14	0.18	0.21	0.25	0.25	0.28	0.35	0.42
Au Mirror 20K (x1)	-	-	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Grid 20K (x1)	-	-	0.02	0.02	0.02	0.04	0.02	0.02	0.09	0.14
Sub Total	4.0	4.5	2.85	3.46	4.73	6.46	6.98	9.01	10.69	12.32
LO Beamsplitter 20K	-	-	1.8	1.8	1.8	1.8	1.8	2.3	2.3	3.8
MPI Band Edge Loss*	-	-	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Total Noise	4.0	4.5	6.4	7.0	8.3	10.0	10.5	13.1	14.7	17.9

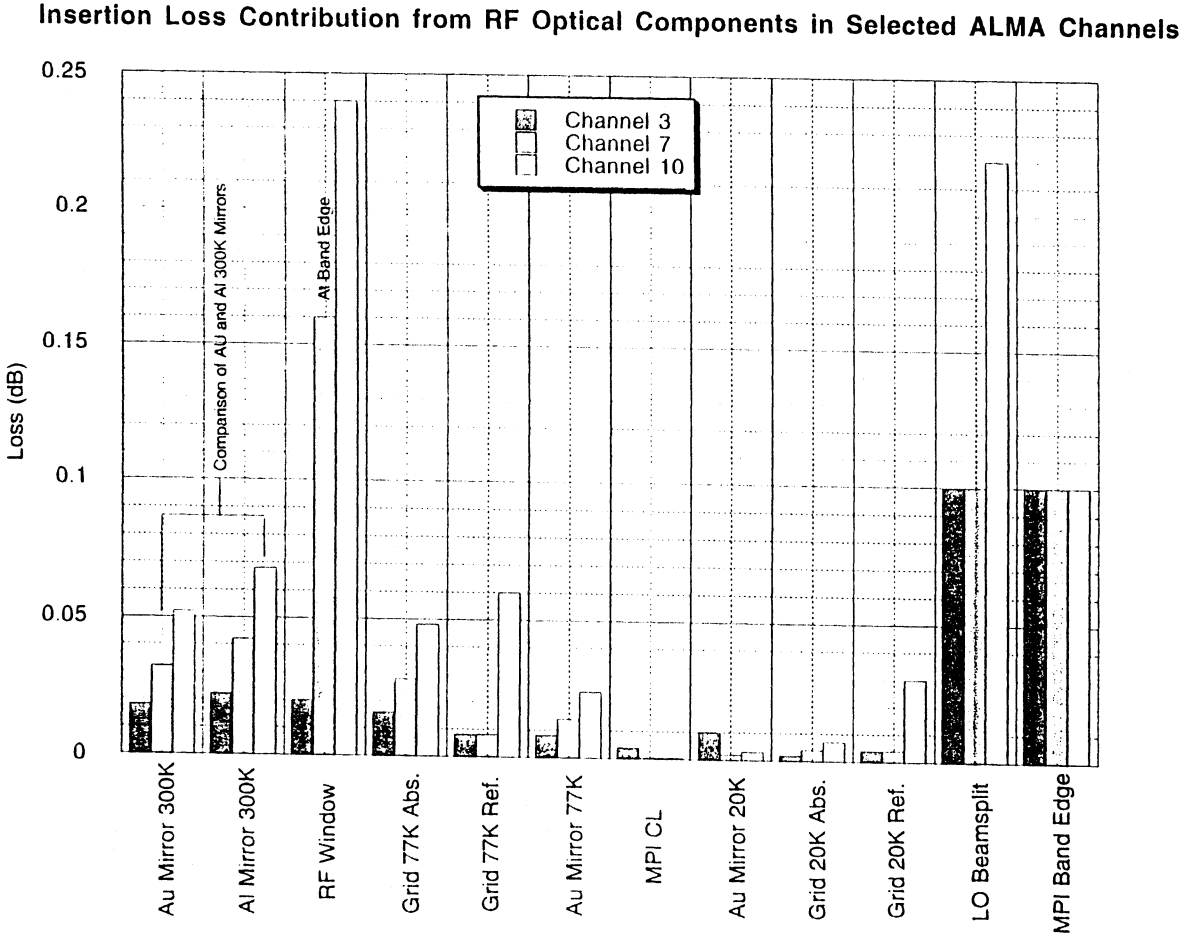
Grid and mirror noise contribution derived using lossy attenuator model.

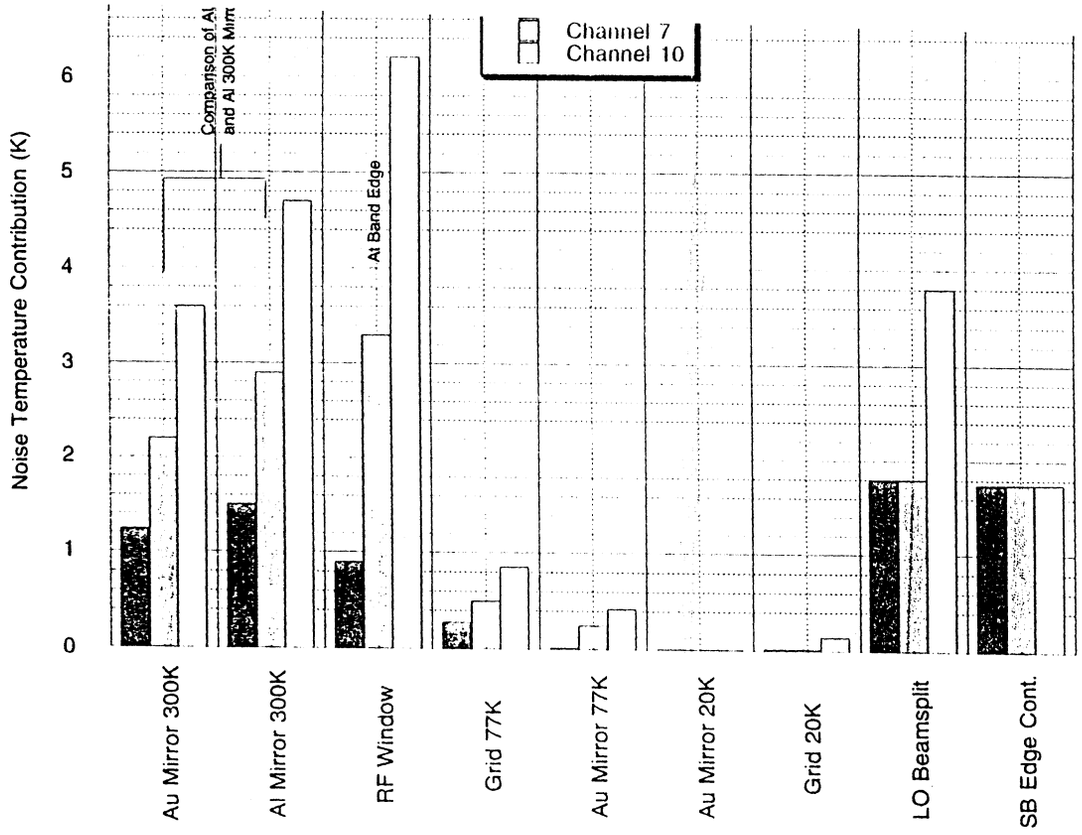
* Combined reflection and absorption loss extending to band edge. Absorption loss assumed to radiate 300 K. Reflection loss assumed to reflect ~ 77 K.

** LO port assumed to be a 77K black body.

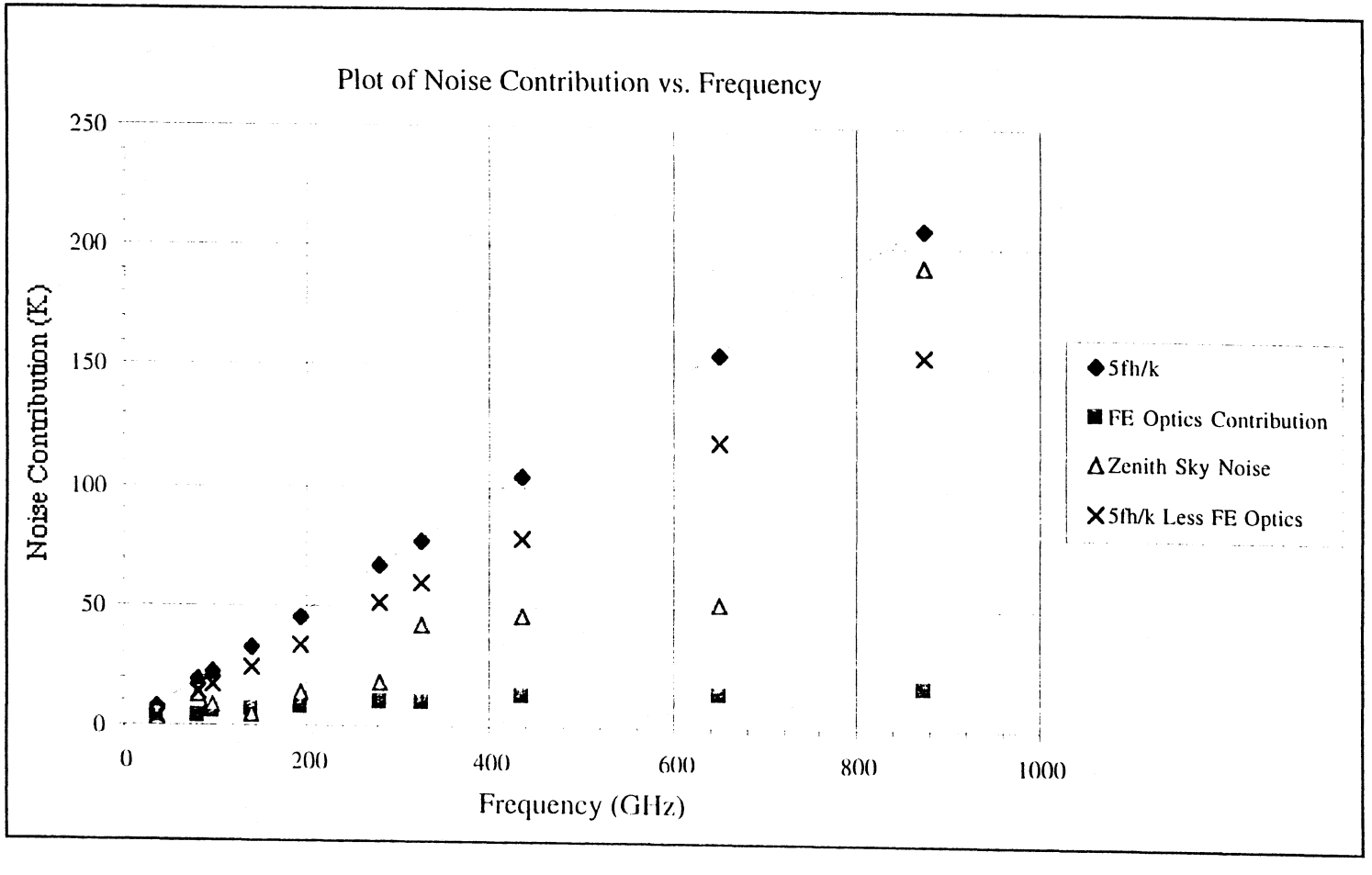
† Unused sideband terminated in 77K load. Contribution stated for 2% MPI band edge. Reduce by cooling load to 20K

Front-End Optics Insertion Loss Contribution

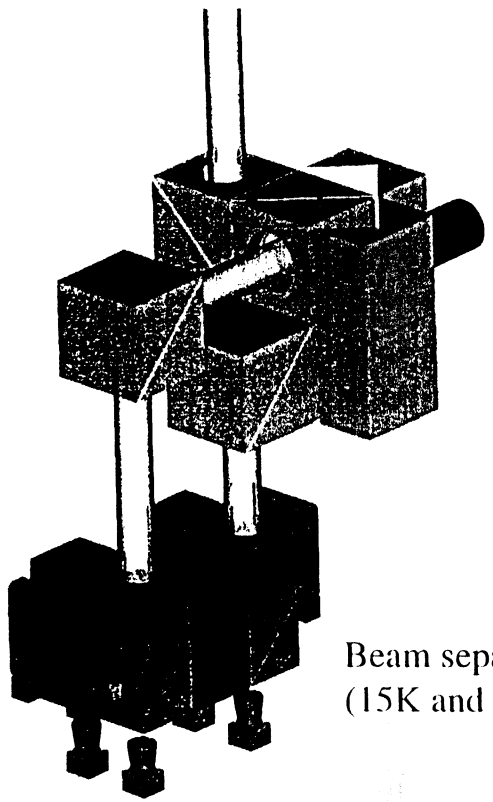



Channel 7
Channel 10
Noise Temperature Contribution (K)
0
1
2
3
4
5
6
Comparison of Al and Al 300K Mirr
At Band Edge
Au Mirror 300K
Al Mirror 300K
RF Window
Grid 77K
Au Mirror 77K
Au Mirror 20K
Grid 20K
LO Beamsplit
SB Edge Cont.

System Noise Contribution



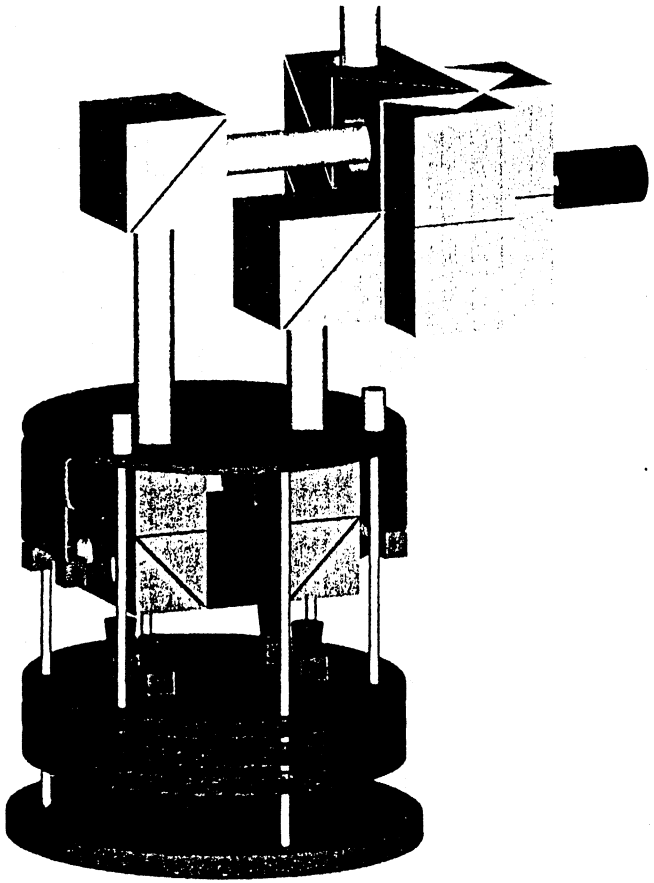
Visualisation of System Layout - 1



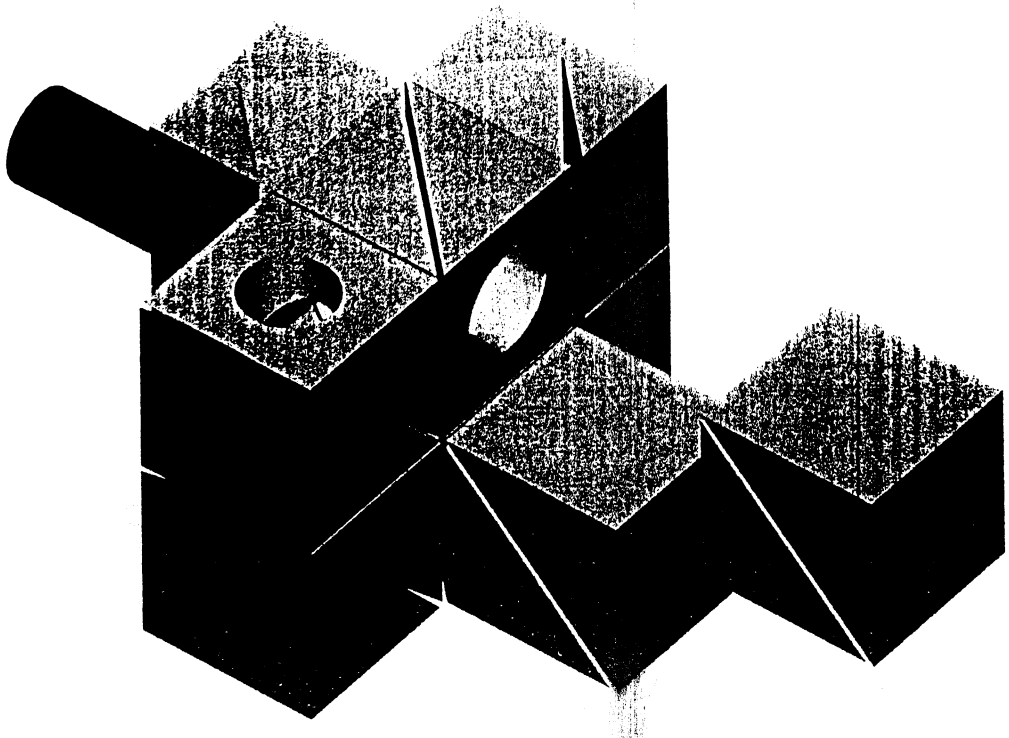
MPI's at 77K

Beam separation and LO injection
(15K and 77K respectively)

Visualisation of System Layout - 2



MPI's at 77K



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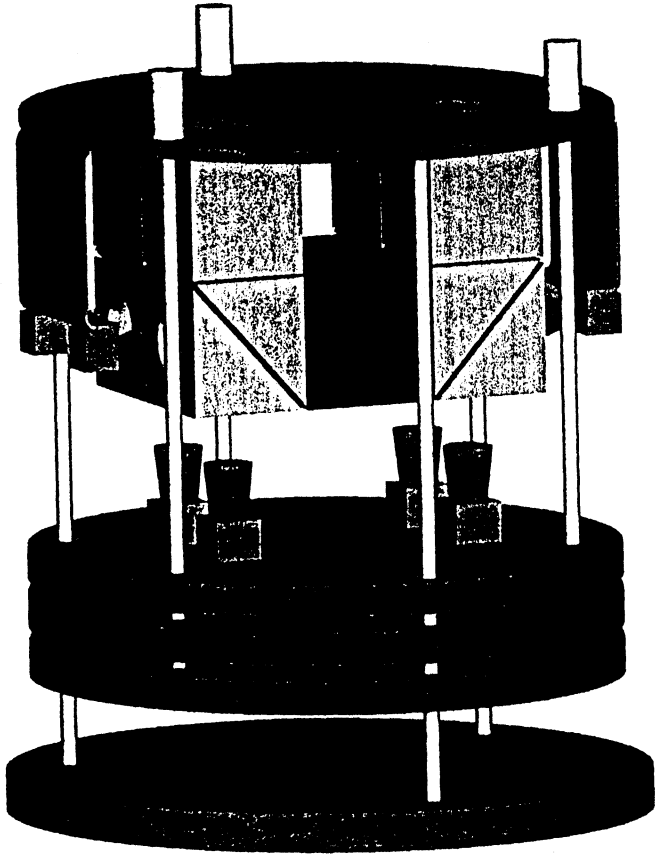
Channel 3 -10 Mixer and LO Cartridge System



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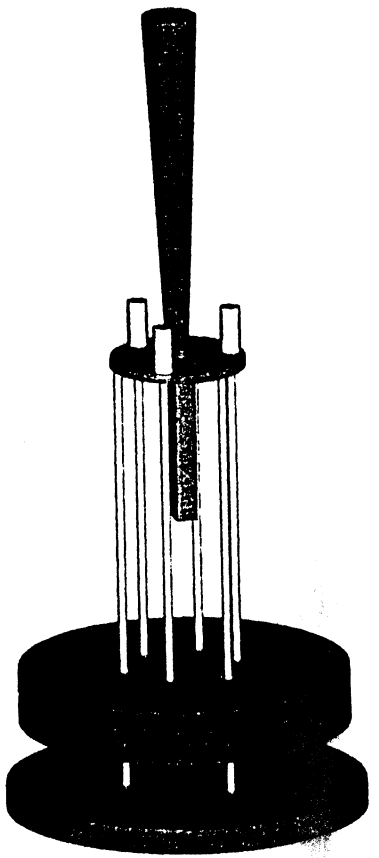
Channel 2 LNA Cartridge System



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SIS Mixers

SIS mixers have following key features:

- Use single tunnel junctions mounted in waveguide embedding structure.
- Corrugated feedhorn used to couple mixer waveguide to free-space.
- Fixed tuned backshort.
- Separate LNA is attached directly to mixer block,but not integrated inside mixer. Allows LNA to be easily separated from mixer for either mixer or LNA replacement/repair.
- Instantaneous IF bandwidth is 8GHz centred at 8 GHz.
- Internal protection bias resistors,
- Internal IF matching circuit - if required.
- Magnetic field supplied by superconducting coil in close proximity to mixer.

Local Oscillator System

Local oscillator system has following key features:

- One LO system required per mixer - annoying!
- Fixed tuned frequency multiplier operation.
- Integrated with SIS mixer cartridge.
- HEB's or varactors (x2, x3, x5) cooled to 77 K.
- Mixer injection via dielectric beamsplitter mounted at 15K.
- Optical path length minimised to reduce baseline modulation when cryostat tipped.
- Fundamental pump frequency provided via waveguide to external source (Option II photonic solution). Standard waveguide vacuum seal used.
- Flexible system that can accommodate future upgrade to Option III - full photonic LO.

Receiver Cartridge Interface

Cartridge Interface for single mixer polarisation.

Interface	No. of Leads	Type	Heat Load	Comments
RF input to mixer	-	-	<7.5mW	Per pair of mixers.
LO Input to mixer	-	-	< 1mW	Radiative loading.
Mixer bias	4	0.125μm dia. BeCu	~0.01mW	15 to 4K only.
Magnet bias	2	0.125μm dia. Cu	~2mW	Assume max mag I ~ 100mA
LNA at 4K	7	0.125μm dia. BeCu	15mW/~10μW	On/Quiescent.
IF (4 – 15K, 15 – 77K, 77 – 300K)	1	SS-SS 0.141 Coax	~ 2mW	Requires Cu coax at some point for flexure.
Bias leads for x2 LO	2	0.125μm dia. BeCu	~ 3mW	300 to 77K.
Bias leads for x3 LO	2	0.125μm dia. BeCu	~ 3mW	Not required for HEB's
Waveguide input for multiplier	1	tbd	tbd	Also applicable for direct LO, e.g. channels 2 & 3.
Temp. sensor 4K	4	LakeShore Diode	~0.01mW	0.125μm dia. BeCu leads.
Temp. sensor 15K	4	LakeShore Diode	~ 1mW	0.125μm dia. BeCu leads.
Temp. sensor 77K	4	LakeShore Diode	~ 4mW	0.125μm dia. BeCu leads.
Stage heater (4K)	4 (paired)	0.125μm dia. BeCu	tbd/~10μW	On/Quiescent.

Multiply leads and heat loads (except RF window) by 4 for total cartridge (Channels 3 to 10).

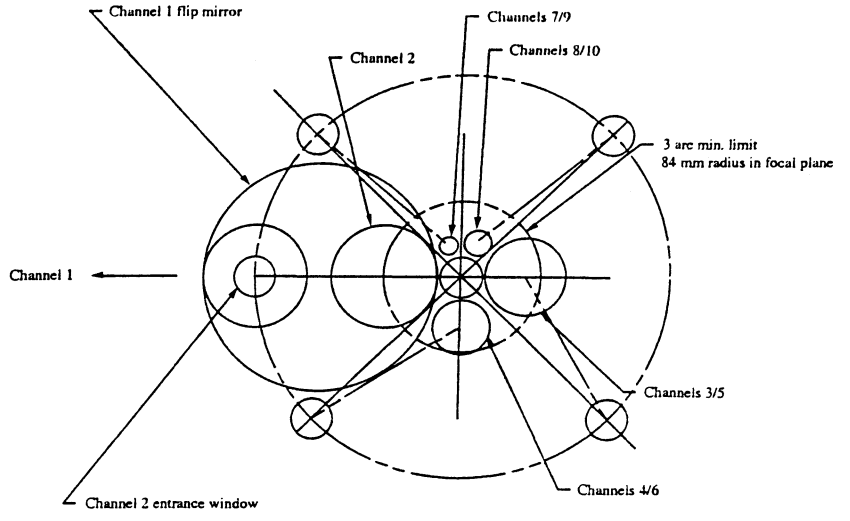
Receiver Cartridge Connector Interface

Cartridge Connector Interface Encompassing All Channels

Interface	Min. No of Pins	Connector Type
RF input to mixer	-	-
LO Input to mixer	-	-
Mixer bias	16	Amp/Bendix 26 Way
Magnet bias	8	Amp/Bendix 26 Way
LNA at 4K	28	Amp/Bendix 26 Way
IF (4 – 15K, 15 – 77K, 77 – 300K)	1	SMA Hermetic
Bias leads for LO	16	Amp/Bendix 26 Way
Waveguide input for multiplier	4	WR10 vacuum sealed waveguide flange.
Temp. sensor 4K	16	Amp/Bendix 32 Way
Temp. sensor 15K	4	
Temp. sensor 77K	4	
Stage heater (4K)	16 (paired)	Amp/Bendix 26 Way

All DC electrical leads should be filtered for EMI.

Plan view of light sample input into cryostat



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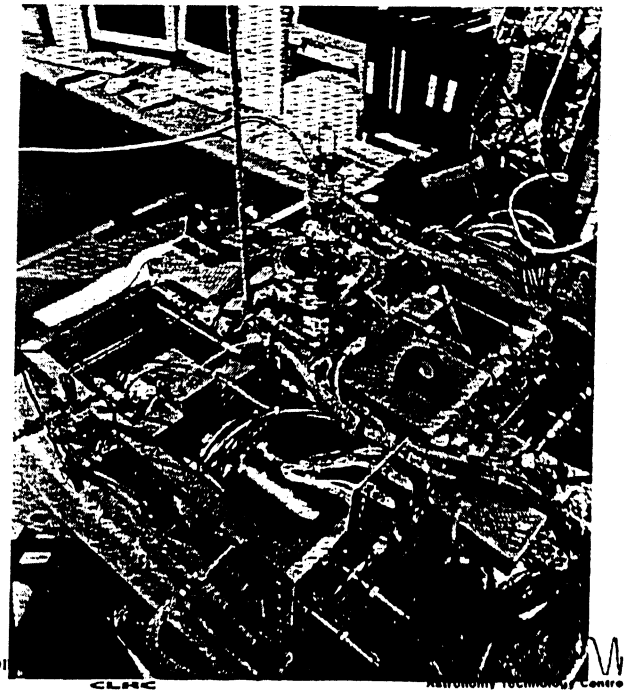
4K Demonstrator for Planck Explorer - An ESA mission to study the Cosmic Microwave background. Joint undertaking with UK, France, Italy, US, Sweden, Germany...



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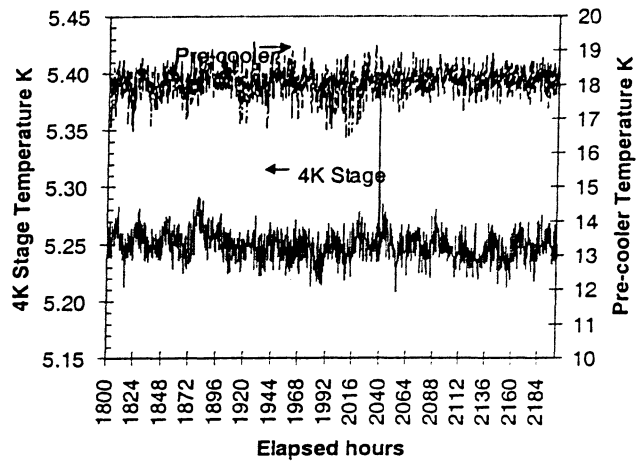
JT Lifetesting

Long term testing on JT system showed diurnal variation in temperature to be < 20mK. These test performed on a small system using diaphragm spring compressors during a 6 month lifetest. For Alma the use of a liquid reservoir could be considered. JT pre-cooled with a GM cooler with crude temperature control.



JT Lifetesting

Contamination issues

Life of a JT system is limited by contamination of the working gas. Water is the main enemy but many metals outgas hydrogen in a time independent manner.

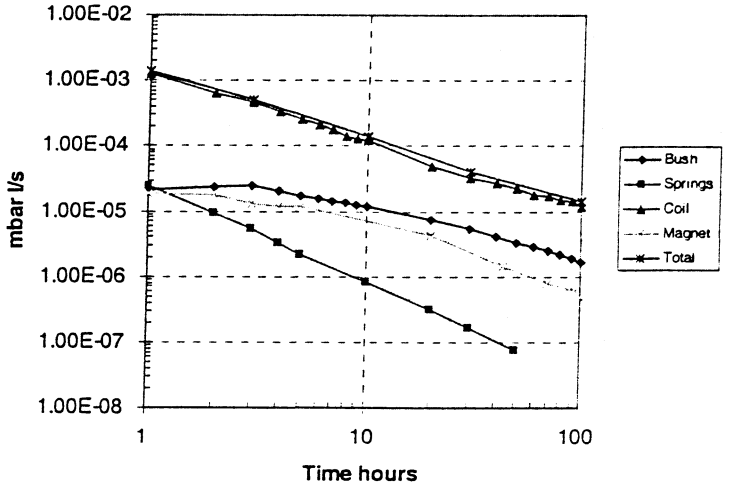
Approach on RAL JT systems:

- Hot reactive getter at Room Temperature.
- Micron filters for particulate contamination
- Cold filters on each of the stages
- Clean system to start with - fluxless vacuum brazing and good cleaning.

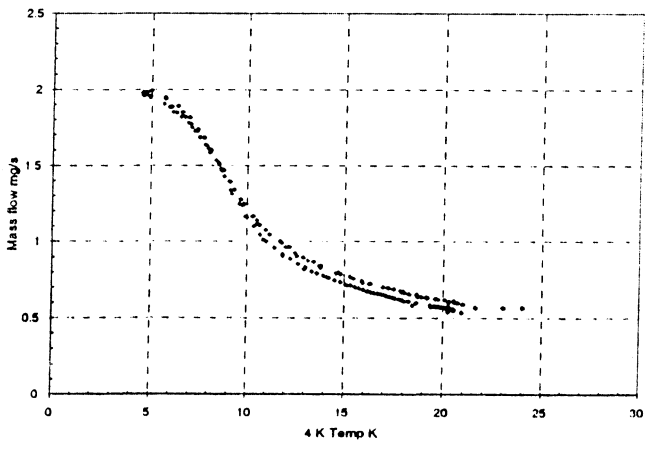
RAL Systems have a flow of around 3mg/s and a fixed orifice size of about 12microns.

JT Design Aspects

Outgassing tests on cooler components



JT Analysis



The flow through the orifice is a strong function of temperature so the cooling power available is non linear with temperature. Need to make sure we can achieve base temperature!!

Cryostat Design

Plug in Modules

- Modularity of components as far as is reasonably practicable

  Water Vapour monitor on 100mm unit in centre

  Channel 1 on 100mm unit

  Other channels on 240mm units (two on each module)

- Two channels on each 240mm module is an acceptable compromise; ten modules would be too complex, 5 is reasonable from the design and operational point of view.

Cryostat Design

Cryocooler & services - These will fit into the side ring of the cryostat with the cryocoolers at some angle to improve temperature stability of the units. Design will be "Cryocooler Neutral"

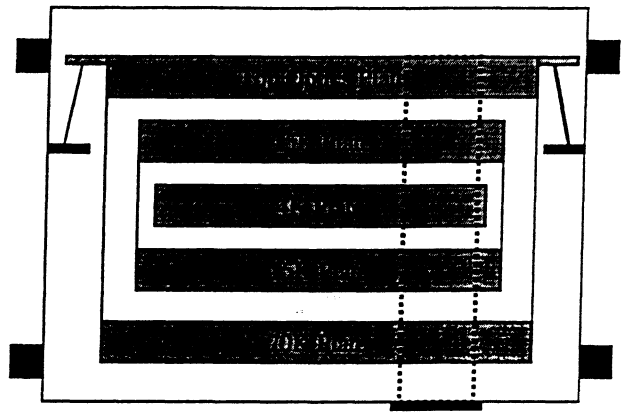
External Optics Plate - This will fit on to the top of the cryostat on a plenum structure to avoid distortions from the top plate of the cryostat bowing during pumpout.

Internal Optics Plate - This will be mounted at "70K" rigidly on the cryostat mid-section.

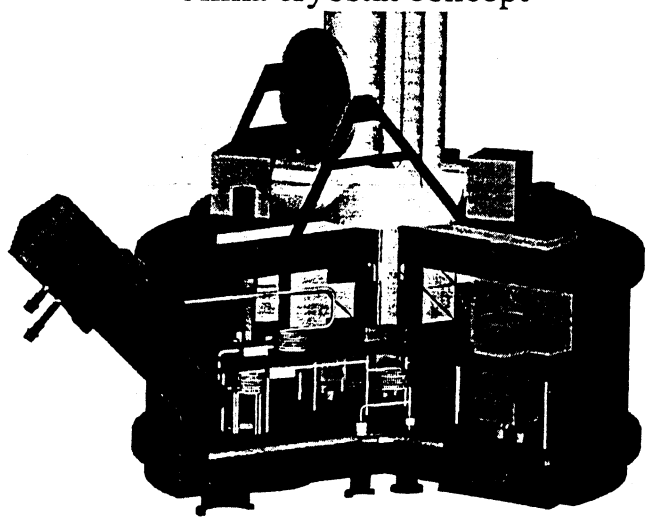
Thermal Model

Top optics plate rigidly attached to 300K cryostat centre section.

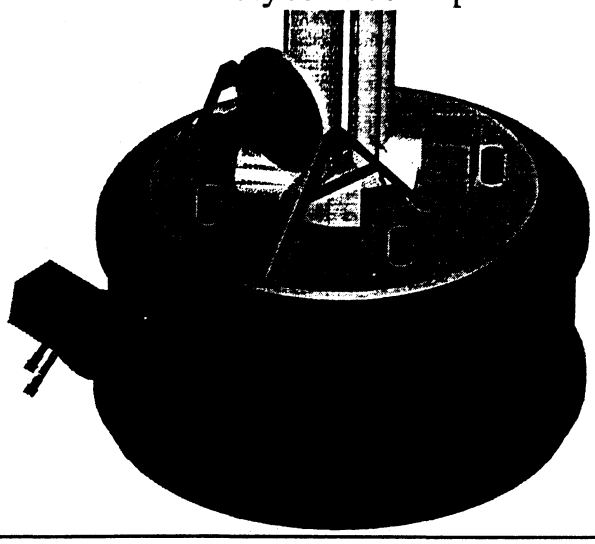
May be better plugging modules in from top - better alignment, fewer thermal interfaces - will there be space for wiring ?



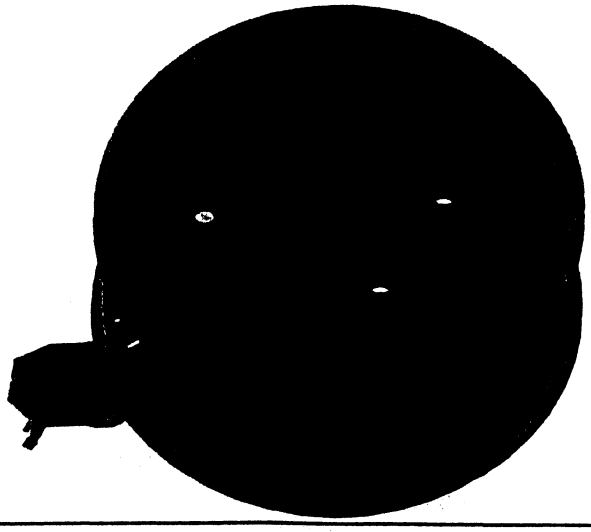
Alma cryostat concept



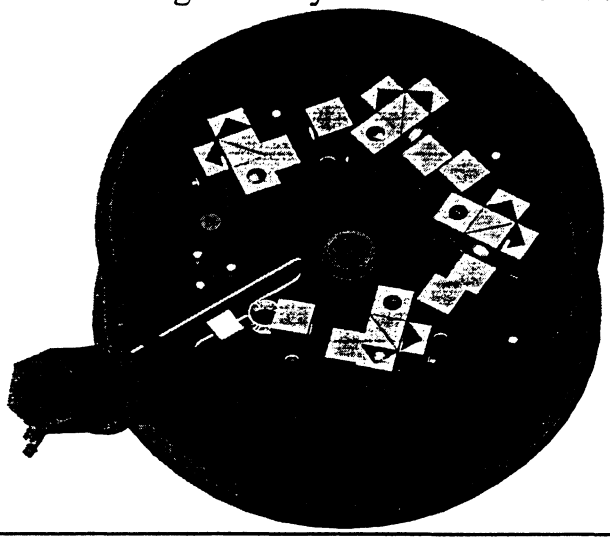
Alma cryostat concept



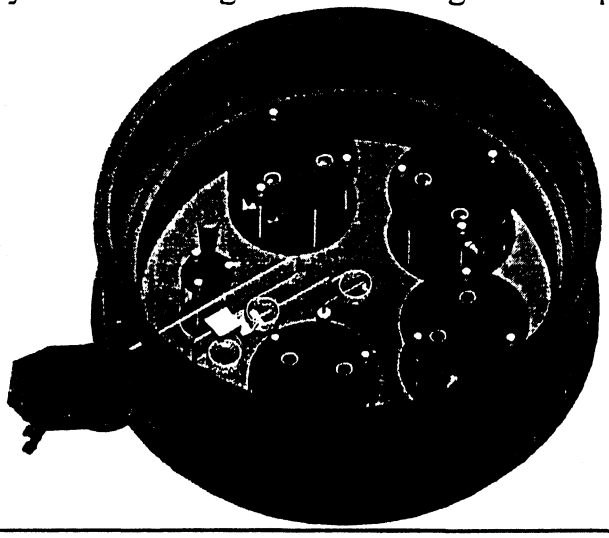
Cryostat excluding warm optics



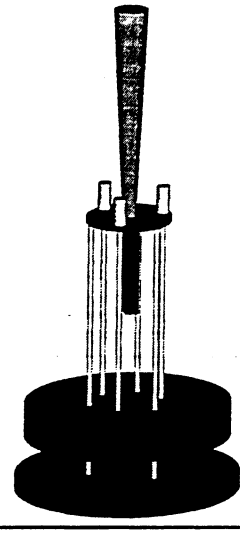
Cryostat showing MPI layout mounted on 77k plate



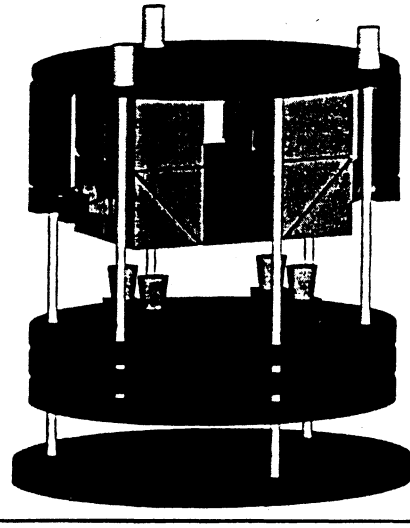
Cryostat showing mixer cartridges & 4k plate



Band 2 cartridge (ø100)

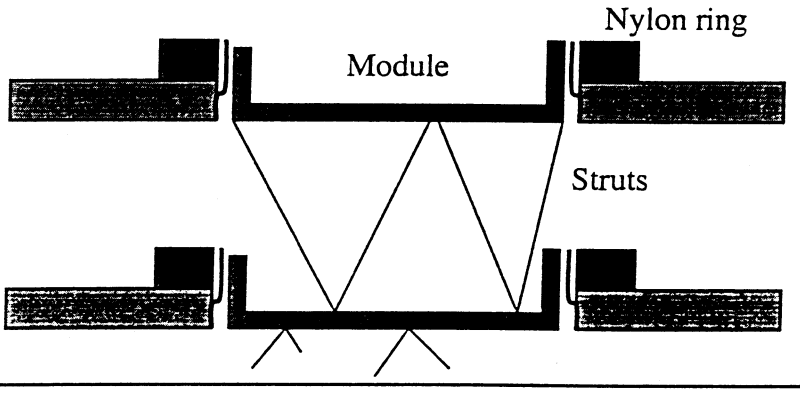


Band 3-10 Cartridge (ø240mm)



Cryostat Design

Module concept - the nylon ring contracts on to the Be-Cu fingers and makes good thermal contact with the plate. Used on dilution refrigerators at 100mK. Module can be withdrawn at room temperature for servicing/change without dismantling the cryostat.



JT Analysis

Heat exchanger effectiveness calculated on each stage from thermal resistances

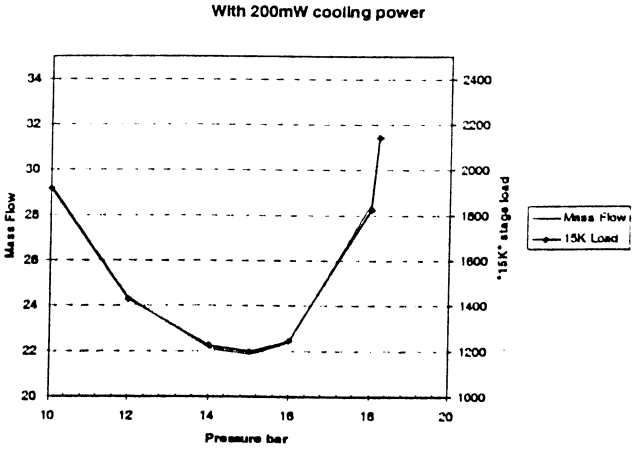
Temperature varying properties calculated

Model Validated with performance

Pressure drop on lowP side needs to be carefully controlled

Aim is to keep mass flow as low as possible commensurate with achieving cooling power

Margin taken on cooling power



Thermal Modelling

Very preliminary model yields the following heat loads:

Summary

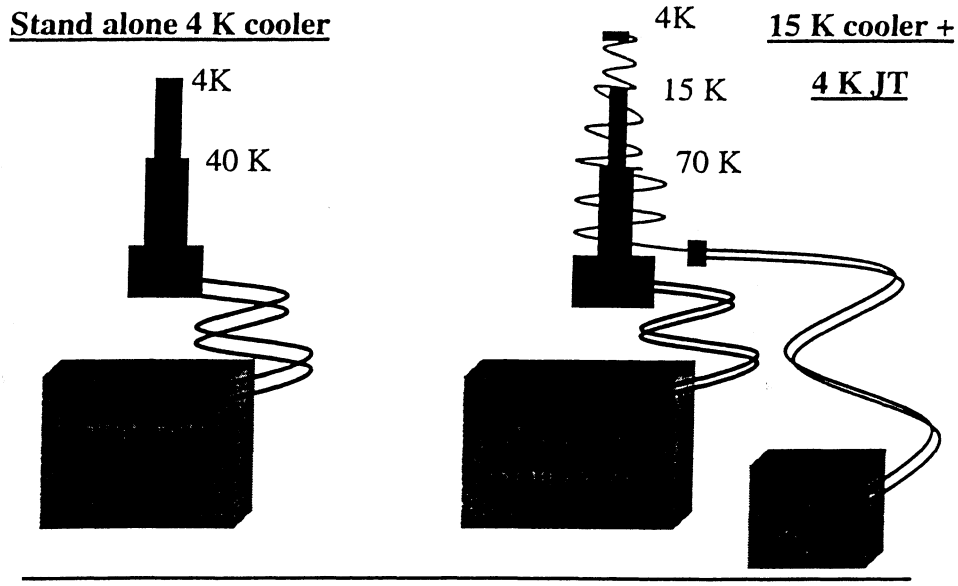
Item	Temp	Load
Top Optics plate	70	1.26 W
Top 15K plate	15	0.24
4K plate	4	0.098
Bottom 15K	15	1.35
Bottom 70K	70	2.30

Item	Cond + rad.	JT load	Total
"70K"	3.567	2.141	5.7 W
"15K"	1.593	1.200	2.8
"4K"	0.098		0.098

A detailed ESATAN analysis will be made by the Thermal Modelling group in Space Science Department (S Peskett et al.)

Cooler selection

Cycle Options	
Gifford-McMahon	Moving displacer Large compressors – water or air cooled, may be oil free Sensitive to orientation
Pulse Tube	No moving displacer Compressor similar to GM Sensitive to orientation
Stirling cycle	Moving displacer Valveless compressor May be oil free



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Cooler selection (2)

	Advantages	Disadvantages
Cool directly to 4K	Simple system One Compressor Commercially available	Vibration Single point cooling Limited cooled stages (40-50 K) 4K temperature very sensitive to cooler performance
Precool to 10-15 K, use JT to achieve 4 K	Distributed cooling at 4 K Some vibration isolation 4 K temperature less dependent on precooler performance Shield cooling at 80 K and 15 K Good temperature stability Precoolers commercially available	Second compressor required More complex plumbing Custom designed JT system required
Use 4 K cooler to reliquefy helium	Distributed cooling at 4 K Some vibration isolation Commercially available	More complex system Cooling loops required

Optimum system

15 K precooler with 4 K JT -

distributed cooling, vibration isolation, better temperature stability

Optimum cycle

Pulse tube -

No vibration, most reliable

Commercial availability

15 K GM machines available from several manufacturers

4 K pulse tubes available - 15 K simple development

Baseline cooler selection

Baseline known technology - GM+JT

Find manufacturer of 15 K pulse tube

Input Power

Commercial systems - GM - around 2-3 kW

+ around 400W for JT compressors

NB 0.5W @4 K pulse tube (Cryomech) 5kW

0.5 W @4K GM (Janis) 3kW

JT system

High pressure - 15 atm

Low pressure - 0.5 atm at compressors

allowing 0.2 atm pressure drop in heat exchangers

gives 0.7 atm at cold plate = 3.85K

Oil free compressor - reciprocating or scroll type

Reliability

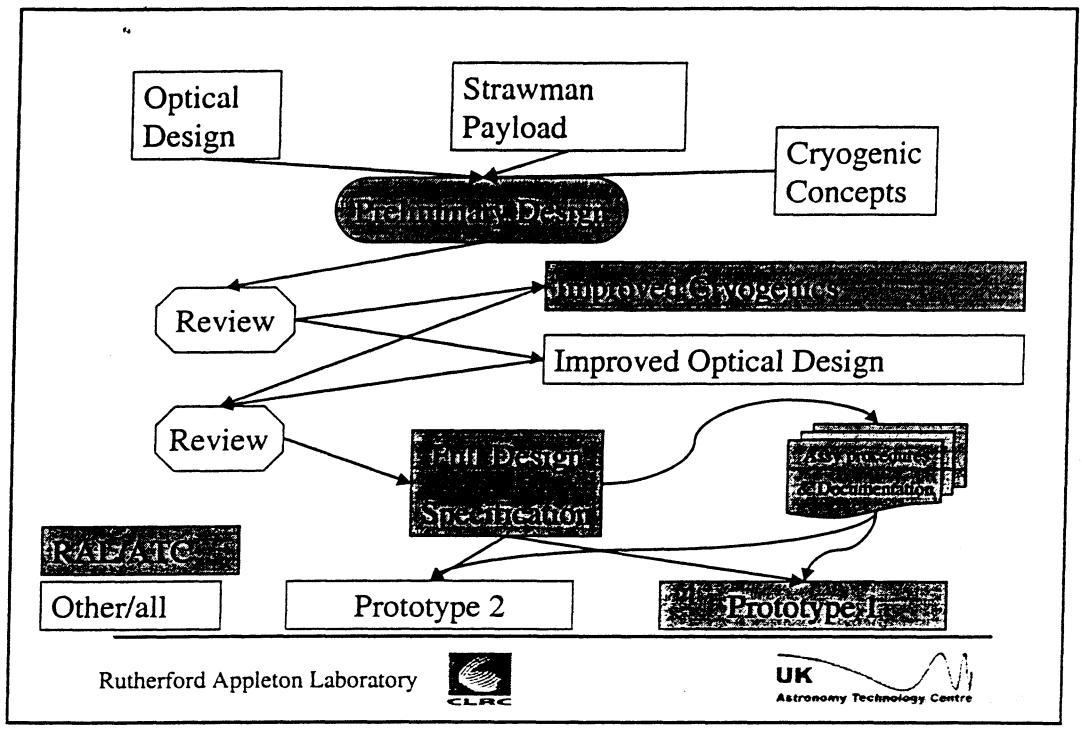
GM coolers have Mean Time between Maintenance (MTBM) of 10,000 hours

This is the interval at which the seals in the displacer require changing

Compressors require maintenance at 20,000 hours (2.3 years)

Pulse tube coolers have no seals in the cold head and should have MTBM of 20,000 hours - with no need to disturb the dewar

JT compressors should have MTBM of 20,000 - no need to disturb dewar


Optical Design
Strawman Payload
Cryogenic Concepts
Preliminary Design
Review
Improved Cryogenics
Improved Optical Design
Review
Full Design Specification
RAL/ATC
Other/all
Prototype 2
Prototype 1
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System Compliance Matrix - 1

Item	Requirement	Achieved	Compliant	Comments
Frequency coverage	30 to 1000GHz	30 to 1000GHz	✓	Could be provided be existing technology.
SSB operation	>10dB SB rejection	>15dB	✓	For 4 GHz IF.
Dual polarisation	>-25dB non-orthogonality	>-25dB DSB >--17dB SSB	✓	At band edges.
Circular pol.	tbd	Needs additional optics	X	May be possible.
Mixer noise	<10fh/k	tbd	tbd	
IF bandwidth	4GHz min. (Goal 8GHz)	4GHz SSB 8GHz DSB	✓	Only for band edge loss ~2%.
IF interface.	4 - 12GHz	4 -12GHz	✓	IF 4 – 12 GHz.
Beam separation on sky rel. to WVM	3 arc min.	3 arc min.	✓	Some channels well within requirement.
WVM operation	Simultaneous with channels	Simultaneous with channels	✓	Within same cryostat as RF channels.
Frequency change - slow	1.5sec.	~ 1 sec.	✓	MPI motort limited on dual freq. Channels.

System Compliance Matrix - 2

Item	Requirement	Achieved	Compliant	Comments
Frequency change -fast	10msec.	10msec.	✓	For no change in MPI mirror.
Cryogenic LO	77K	77K	✓	
Mixer ambient temp.	4.2K max. 4.0K typ.	4.0K	✓	
Additional cooling stage temperatures	15K and 77K	15K and 77K	✓	
Stage temp. stability	tbd	< 20mK	tbd	
Heat lift (4K)	750mW max.	> 750mW	✓	
Cryostat mass	550 kg	420 kg	✓	Includes 20% margin.
Cryostat size	1m dia. 1.6 ht max.	0.95m x 1.5m	✓	Will fit through door!
System pwr requirement	tbd	<4kW	tbd	
System cycle time	≤ 5 days	4	✓	
Component packaging	Removable assembly	Cartridge system	✓	2 pol's and 2 freqs/ cartridge for channels 3 – 10.
Solar observing	No comp. dmge	Window concern	X	Needs further thought.
Rx system stability	tbd	tdb	tbd	

Summary

We have proposed a receiver design for the ALMA project that fulfils a majority of the basic system requirements as outlined in the CODC guidelines.

The essential element of our design are:

- An alternative method of distributing the RF beams on the sky.
- Close co-alignment of channel beams with the 183 GHz WVM.
- Reduced number and size of vacuum windows.
- Versatile cryogenic system capable of accepting a variety of RF layouts.
- Ease of maintenance and construction.
- Use of existing technology for core components e.g., mixers and cooling mechanism.