ALMA Memo No. 324
Proposal for ALMA Front End Optics

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1.0 Introduction

This memo presents a preliminary conceptual design of the optics for the ALMA front end. Previous work toward conceptual optical designs has been reported by Lugten and Welch [11], Belitsky [12], and Carter [1].

The main theme of the present approach is simplicity. A detailed list of the goals and constraints used is given in section 2.0, and the design is presented in the following two sections. Quantitative information and the results of performance calculations are presented in the spreadsheets listed in Appendices A and B.

It is important to stress that the design is preliminary. Many details required for implementation are not covered here.

2.0 Design Goals and Constraints

- Off-axis illumination of the subreflector is allowed, with band selection by re-pointing of the primary
- No moving parts
- Minimum number of optical elements for minimum loss and ease of alignment
- Cooled optics wherever possible for low noise temperature (not possible for Bands 1 and 2; see section 3.0)
- Frequency-independent coupling to feed horns for low spillover loss and maximum aperture efficiency over full ALMA band
- Off-axis aberration loss less than 1% for all bands
- Lowest possible polarization beam squint for Band 7
- Cartridge sizes and dewar layout same as RAL design [4] where possible
- Compatible with antenna interfaces
- Cartridge optical apertures (typically horns) assumed centered in each cartridge (easily changed for most bands if required)
- All apertures in secondary focal plane contained within 375 mm radius of primary optical axis, so as to clear hole in primary

3.0 Optics Design of Bands 1-2

For these bands, the beam waist at the secondary focus is very large, so that a window into the cryogenic subsystem would allow excessive infrared radiation to be absorbed (see Appendix A). To avoid this, two options were considered:

1. Use a warm horn and waveguide transition. The transition would include a thermal break to minimize the conduction load, and the radiation load would be negligible (being determined by the waveguide cross-sectional area only).

2. Use warm refocusing optics and a smaller window. The optics could consist of two mirrors, one ellipsoidal and one flat; or a single dielectric lens.

The selected design uses a warm dielectric lens. The warm horn and waveguide transition were rejected because (a) the estimated horn loss is 2%, and it was considered worthwhile to have this kept cold; and (b) even with a thermal break, the conduction load due to supports is significant; and (c) the mechanical design is difficult (but not impossible), since it must allow for blind disassembly and reassembly at a waveguide joint. The use of reflecting optics was also rejected because the mirrors would have to be very large, severely constraining the use of space in the focal plane for the other bands or requiring that they be movable.

The design of the lens-horn combination is copied from the Band 1 design for the Evaluation Receiver by Lamb [2], and scaled for Band 2. This design started from the earlier work of Ulich [3], and was then modified to fit the ALMA focal ratio of 8.0 and refined via computer modeling to achieve an efficient beam pattern that is nearly frequency-independent over the band.

The horn is placed as close as practical to the window so as to minimize the window area. The distance is taken as 40 mm, so as to allow room for IR filters. The arrangement is sketched in Figures 1 and 2.

This in-line optical arrangement requires that the window be located directly over the corresponding cartridge (assuming that the horn is part of the cartridge assembly). In the RAL dewar design [4], the cartridge centers are on circles at radii 150 mm, 295 mm, and 345 mm. These bands cannot be on the outermost circle because the beams would hit the edge of the main reflector aperture, radius 375 mm; and the aberration loss (astigmatism) would be marginally excessive. The second circle is also too large for Band 1, although it might work for Band 2. The innermost circle cannot be used because the lenses would block too much of the inner part of the focal plane, and this space is needed for the high frequency bands in order to keep aberrations sufficiently small. In view of these constraints, we arrived at the following solution: assume that the Band 1 and Band 2 cartridges are 120 mm in diameter (unlike the others on circles 1 and 2, which are 170 mm diameter); place them on a new circle at radius 270mm, replacing two of the four positions on the 295mm circle.

This still allows freedom in the azimuthal positions of the Band 1 and Band 2 cartridges. These are selected in connection with choosing the positions of the cartridges, windows, and mirrors for

Bands 3-10, as described in the next section.

4.0 Optics Design of Bands 3-10

4.1 General Description

Bands 3-10 are very similar in design, and will be discussed at the same time. The optics consists of a pair of mirrors, a tertiary ellipsoid located a fixed distance below the dewar window, and a quaternary plane mirror placed on the feed axis above the cartridge. Both mirrors are cooled to ~70K to reduce ohmic losses. The antenna beam waist is placed at the focal length of the tertiary mirror, forming a ‘Gaussian beam telescope’ with the subreflector. This effectively makes the output waist radius and distance invariant with frequency, permitting a very broadband match at the feed aperture. Another consequence of this arrangement is that the input and output waist distances from the tertiary are always equal. The antenna beam waist is positioned close to the dewar window; this minimizes the required window diameter. Calculated mirror and window sizes, focal lengths, and positions are given in the spreadsheet in Appendix B (parts 2-5). Each mirror and window is taken to have a diameter $5w$, where w is the beam radius at the mirror or window center.

4.2 Dewar Layout

The cartridge layout is close to that proposed by Harman [4], but with a few modifications. In [4], the Band 7-10 cartridges are on the 150mm radius circle and Bands 3-6 are on the 295mm radius one. We chose to re-locate Band 3 and Band 4 to the outermost (345mm radius) ring so as to make room for Bands 1 and 2, as explained in the previous section. These lowest-possible-frequency bands were chosen so as to minimize the off-axis abberations. The cartridges for Bands 3 and 4 must now be smaller (120mm vs 170mm diameter) in order to fit. This is probably acceptable, since there will likely be no quasi-optical components in these bands, and the remaining electronics will be quite compact. The windows and mirrors of the optical assemblies for these bands are arranged to avoid blockage by the quaternary mirrors of Bands 9 and 10. The final result is shown in Figures 3-5.

For ease of layout and construction, the top of the dewar is taken to be flat rather than the “tori-spheroid” shown in [4]. This is one of the implementation details that can be modified at the next stage of design, if necessary.

4.3 Off-Axis Aberrations

Because this is an off-axis design, much effort was given to placing the windows as close to the telescope optical axis as possible, to minimize coma and astigmatism. These were calculated using the expressions in Lamb [5] for all 10 bands, and are shown in the spreadsheet in Appendix B. All are well under the 1% gain loss deemed an acceptable limit by Lugten and Welch [6].

4.4 Polarization Distortion

Any off-axis conic reflector will introduce polarization distortion, in the form of cross polarization for linearly polarized radiation, or beam squint for circular polarization. For the subreflector this effect is quite small, given the relatively small offset from the telescope optical axis and the high f/D ratio of the subreflector. However, there is a significant contribution from the tertiary mirror, and this can be expressed as [7]:

$$\text{Beam Squint (beamwidths)} \sim 0.7 \tan(a/2)\, w/f$$

where a is the angle between the incident and reflected beams (the bend angle), w is the beam waist radius at the mirror, and f the focal length of the mirror. Appendix B (part 4) shows the calculated beam squint for Bands 3-10. To reduce distortion on Band 7, the tertiary mirror was raised and quaternary mirror lowered, to decrease the bend angle and allow a slightly longer focal length to be used. This markedly improved polarization performance, at a modest increase in the size of the tertiary mirror. Given the larger beam size for the lower-frequency bands, it would be more difficult to get a similar improvement without a change in the cartridge layout, dewar height, or window diameter.

4.5 Ohmic Loss in Mirrors

The ohmic loss (per mirror) at 80K, calculated at the highest frequency in each band, is given in Appendix B. Figures for gold and aluminum coatings are shown, based on estimates of DC electrical conductivity at 80K. The loss is then increased by an empirical factor of 2, to better estimate actual loss at millimeter and sub-millimeter wavelengths [8].

4.6 Comments about Feeds

Design of the feeds has not yet been completed; however, several comments can be made at this point. The invariance in the output beam waist (and hence feed aperture size) with frequency for fixed tertiary focal length f implies that for an equivalent phase error across the feed aperture a progressively longer feed would be required at higher frequencies. It is possible that the feed lengths for the highest bands would exceed the available space in the present dewar, or that the loss would be excessive. There are several possible remedies to this. One is to add a phase-matching lens to the feed, allowing a much shorter feed to be used. However, this may add significantly to the loss, especially at high frequencies. Another option is to progressively reduce the focal length of the tertiary mirror for the higher bands. This would reduce the required feed length, but as it also reduces the spacing between the input and output beam waists, which may create further problems with the mechanical layout of the optics and with window sizes. It also worsens the polarization distortion, but this could be offset by adjusting the mirror positions to reduce the bend angle. Optimization of feed lengths, focal lengths, window offsets and mirror placements is necessary to ensure that everything fits in the allotted space without sacrificing receiver performance.

5.0 Infrared Filtering and Estimated Thermal Loads

In spite of efforts to minimize the IR absorption, the total window area required by this design is fairly large and a substantial amount of radiation is admitted into the dewar. To avoid the need for an extremely large cryocooler, it is necessary to provide filters that will prevent most of this radiation from being absorbed onto the coldest components (this is also true for all other optics designs that have been considered). We assume that each band will have, inside the window, a three-layer filter consisting of two layers of expanded PTFE, each thermally floating, and one layer of solid PTFE connected to the 80K cryocooling stage. Preliminary tests [9] indicate that this arrangement can re-radiate 45% of the incoming IR flux outward and absorb 50% onto the 80K stage, allowing a residual 5% to pass to colder stages. Caution is required because the loss of such a filter at sub-millimeter wavelengths is not accurately known, and even the IR properties have not been thoroughly investigated. On the other hand, even more effective filtering may be possible with further development.

Assuming that the IR filter effectiveness given above is achieved for all bands, the total loading due to the windows alone is estimated as 4.1 W at 80K, 0.20 W at 20K, and 0.21 W at 4K (this assumes that the Band 3 receiver is at 4K; if it uses HFETs and is at 15-20K, 95 mW of load is moved from 4K to 20K). Details are given in Appendix A, which also shows the estimated thermal load due to windows for several other optical designs. For this design, the estimates use the window sizes in part 3 of Appendix A. For bands 1 and 2, the geometry of Fig. 1 and 2, respectively, is used. For bands 3 to10, the diameters are based on the secondary Airy disk, assuming that the focus is at the window; actually, the focus is slightly above the window (Appendix B, part 3, “Waist Pos.”), so the diameters should be slightly larger, but the effect on the total load is negligible.

This estimate assumes that the residual IR (5% of the flux transmitted by the window) is absorbed in each receiver, via its horn. For receivers with cold mirrors, this may be pessimistic. Those mirrors may scatter most of the IR, allowing it to be absorbed on shields at 70K or higher, rather than by the colder horn.

6.0 Water Vapor Radiometer

We have yet not given careful consideration to accommodating the required water vapor radiometer, except for including it in the estimated thermal loading due to windows on the assumption that it would be cooled to 15K (Appendix A). In a recent report [12], Hills *et al.* propose that a pair of room-temperature mirrors be used to place the instrument (also at room temperature) off to the side while keeping its secondary aperture near the axis. It can be seen from Figure 3 that considerable unoccupied space is available in the focal plane for the necessary pick-off mirror, which would have to be about 50 mm in diameter. For example, placing the WVR tertiary mirror between the Band 5 and Band 6 windows would put it within 130 mm of the apertures of Bands 5, 6, 7, 9, and 10, satisfying the desired beam separation (<5 arcmin, corresponding to about 140 mm separation) for those bands. However, under the constraint that we have adopted, we are so far unable to find a way to achieve this separation for all bands. (In the example just given, the largest separation occurs for Bands 1 and 2, where it is about 11 arcmin.)

7.0 Alternatives and Options

Another type of IR filter, integrated with the mirror optics, has been proposed by James Lamb of OVRO, and was analyzed further in [10]. The idea is to use a etch a blazed grating profile onto one or both mirrors. A blaze angle could be chosen to diffract most of the incoming IR back out the window (rather than absorbing it). At the desired RF wavelengths, the grating would function like a smooth mirror. By putting a grating on both mirrors, a very high amount of IR rejection may be possible. A test of the concept has not yet been done, and methods for fabricating coolable gratings in quantity and at reasonable cost still needs much research.

The beam squint due to the tertiary optics can be eliminated for one or two high-frequency bands by replacing the mirror pair by a cold lens, at the expense of slightly more loss. This would require that the windows for those bands be above their cartridges; this is possible in some cases, including Band 7, without any other re-arrangement.

References

[1] M. Carter, “ALMA Receiver Optics.” IRAM, report to ALMA JRDG, 2000-Jul-20.

[2] J. Lamb, “ALMA Evaluation Receiver Optics Design.” OVRO report dated 2000-Apr-24.

[3] B. Ulich, “Optimized cassegrain feed system.” NRAO Tucson Internal Report No. 6, 1980-Mar.

[4] M. Harman, “ALMA Prototype Cryostat Assembly.” RAL drawing number 1-KE0146-001-A, two sheets, dated 15Mar00 and 26May00.

[5] J. W. Lamb, “Optimized Optical Layout for MMA 12-m Antennas.” MMA Memo 246, January 1999.

[6] J. Lugten and J. Welch, “A Suggested Receiver Layout for the MMA Antenna.” MMA Memo 183, September 1997.

[7] Peter Napier, private communication, 2000-Aug.

[8] P. F. Goldsmith, *Quasioptical Systems*. IEEE Press, New York, 1998.

[9] J. Clarke and L. D'Addario, "Tests of Materials for Use in Multi-Layer Infrared Filters in Cryogenic Applications." ALMA Memo 269, 1999-Jul.

[10] W. Grammer, “Analysis of Reflective Gratings as Infrared Filters.” ALMA Memo 275, 1999-Sep.

[11] J. Lugten and J. Welch, “A suggested Receiver Layout for the MMA Antenna.” MMA Memo 183, 1997-Sep-15.

[12] V. Belitsky, “Suggestion on LSA/MMA Front-end Optical Layout.” MMA Memo 242, 1998-Dec.

[13] R. Hills, J. Richer, H. Smith, V. Belitsky, R. Booth, D. Urbain, “Developement of 183 Ghz Water Vapour Radiomenters for ALMA.” Preliminary report (undated, received 2000-Aug-30).

Appendix A: Printout from: http://www.tuc.nrao.edu/~ldaddari/AlmaOpticsWindows.wb3
Appendix B: Printout from: http://www.tuc.nrao.edu/~ldaddari/almaOptics.xls

Appendix A: Thermal Loading Due to Windows

Calculated IR loading for several designs, assuming 2-layer floating expanded PTFE filter, followed by solid PTFE filter sinked to 80K stage. 80K load is 50% of incoming flux, and 20K or 4K load is 5% of incoming flux.

Band	**Low freq** GHz	**High freq** GHz	**Basis** m	**Diameter** m	**Area** m^2	**IR flux** W	**80K load** W	**20K load** W	**4K load** W

1: Beam waist; no warm optics.

1	31.4	45	0.057	0.286	0.06417	29.47	14.74	1.474	
2	67	90	0.027	0.134	0.01409	6.47	3.24	0.324	
3	89	116	0.020	0.101	0.00799	3.67	1.83		0.183
4	125	163	0.014	0.072	0.00405	1.86	0.93		0.093
5	163	211	0.011	0.055	0.00238	1.09	0.55		0.055
6	211	275	0.009	0.043	0.00142	0.65	0.33		0.033
7	275	370	0.007	0.033	0.00084	0.38	0.19		0.019
8	385	500	0.005	0.023	0.00043	0.20	0.10		0.010
9	602	720	0.003	0.015	0.00017	0.08	0.04		0.004
10	787	950	0.002	0.011	0.00010	0.05	0.02		0.002
WVR	180	194	0.010	0.050	0.00195	0.90	0.45	0.045	
				Totals...	0.09760	44.82	22.41	1.842	0.399

Gaussian beam waist radius at low freq end, for f/D=8.0 and -12dB at subreflector edge.

Window in focal plane, requires cold refocusing.

Diameter for 99.8% power transmission (5.0w).

2: 1st Null; no warm optics.

1	31.4	45	0.093	0.205	0.03314	15.22	7.61	0.761	
2	67	90	0.044	0.096	0.00728	3.34	1.67	0.167	
3	89	116	0.033	0.072	0.00412	1.89	0.95		0.095
4	125	163	0.023	0.052	0.00209	0.96	0.48		0.048
5	163	211	0.018	0.040	0.00123	0.56	0.28		0.028
6	211	275	0.014	0.031	0.00073	0.34	0.17		0.017
7	275	370	0.011	0.023	0.00043	0.20	0.10		0.010
8	385	500	0.008	0.017	0.00022	0.10	0.05		0.005
9	602	720	0.005	0.011	0.00009	0.04	0.02		0.002
10	787	950	0.004	0.008	0.00005	0.02	0.01		0.001
WVR	180	194	0.016	0.036	0.00101	0.46	0.23	0.023	
				Totals...	0.05040	23.15	11.57	0.951	0.206

Airy disk radius at low freq end, at first null.

Window in focal plane, requires cold refocusing.

Diameter at first null plus 1 wavelength each side.

3: Lamb feed; using warm lens.

1	31.4	45	0.030	0.081	0.00520	2.39	1.19	0.119	
2	67	90	0.015	0.056	0.00248	1.14	0.57	0.057	
				Totals...	0.00768	3.53	4.06	0.200	0.206

Diameter of horn designed by J. Lamb for Eval Rcvrs, for use with warm lens.

Band 2 scaled from band 1 by 0.500.

Cold horn 40mm below window.

Diameter clears ray to edge of lens plus 1 wavelength each side.

80K and 4K loads include bands 3..WVR
using design #2 above.

Ref: J. Lamb, "ALMA Evaluation Receiver Optics Design." OVRO report dated 2000-Apr-24.

4: No windows; using warm horn and waveguide gap transition.

1	31.4	45		0.008	0.00005	0.02	0.00	0.123	
2	67	90		0.004	0.00001	0.01	0.00	0.106	
				Totals...	0.00006	0.03	2.29	0.229	0.206

Circular waveguide, no IR filtering.

Load at 20K includes 0.1W estimated conduction across gap support.

80K and 4K loads include bands 3..WVR using design #2 above.

5: Carter optics design

1	31.4	45		0.095	0.00709	3.26	1.63	0.163	
2	67	90		0.060	0.00283	1.30	0.65	0.065	
3	89	116		0.040	0.00126	0.58	0.29		0.029
4	125	163		0.036	0.00102	0.47	0.23		0.023
5	163	211		0.032	0.00080	0.37	0.18		0.018
6	211	275		0.030	0.00071	0.32	0.16		0.016
7	275	370		0.030	0.00071	0.32	0.16		0.016
8	385	500		0.028	0.00062	0.28	0.14		0.014
9	602	720		0.026	0.00053	0.24	0.12		0.012
10	787	950		0.024	0.00045	0.21	0.10		0.010
WVR	180	194		0.050	0.00196	0.90	0.45	0.045	
				Totals...	0.01797	8.25	4.13	0.273	0.140

Window diameters taken from draft report, except for WVR where design #1 is used.

Ref: M. Carter, "ALMA Receiver Optics." Report to JRDG dated 2000-07-25. (Window sizes from earlier version of this report, confirmed by recent private communication.)

Appendix B: ALMA Receiver Optics Spreadsheet

Revised: 9/19/00 W. Grammer

Ellipsoid+Plane Mirror Optics, Frequency-Independent Case (din=dout=f)

Note: Free parameters that can be adjusted are outlined in black; those in color are calculated values.

1) Main Antenna Parameters:

Primary Dia. (mm) =	**12000**	f/D =	**8.0**
Secondary Dia. (mm) =	**750**	Sec. Illum. Ang. (deg) =	**7.16**
Primary Focal Len. (mm) =	**4800**	Edge Taper (dB) =	**12**
Magnification =	**20.0**	Foci Spacing (mm) =	**6177**

2) Feed, Mirror and Lens Positions:

Band	Mirror1 (mm)	Mirror1 Offs. (mm)	Mirror1 Tilt (deg)	Mirror2 (mm)	Mirror2 Tilt (deg)	Bend Ang. (deg)	Mirror Sep. (deg)	Mirror Sep. (mm)	Feed Offs. (mm)	Feed Pos. (mm)	Feed->Mirr. (mm)
1	**-150.0**	**270.00**	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	**270.0**	N.A.	N.A.
2	**-75.0**	**270.00**	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	**270.0**	N.A.	N.A.
3	**175.0**	**233.95**	41.09	**168.0**	42.14	86.4	**17.5**	141.43	**345.0**	**251.57**	**48.32**
4	**175.0**	**233.95**	41.09	**168.0**	42.14	86.4	**17.5**	141.43	**345.0**	**251.57**	**50.82**
5	**175.0**	**154.25**	42.19	**168.0**	42.88	87.2	**0.0**	141.14	**295.0**	**251.86**	**52.36**
6	**175.0**	**154.25**	42.19	**168.0**	42.88	87.2	**0.0**	141.14	**295.0**	**251.86**	**52.86**
7	**175.0**	**51.42**	32.27	**130.0**	32.50	65.5	**0.0**	108.77	**150.0**	**246.23**	**85.23**
8	**150.0**	**51.21**	43.09	**145.0**	43.32	87.1	**0.0**	98.96	**150.0**	**246.04**	**73.79**
9	**150.0**	**51.21**	43.09	**145.0**	43.32	87.1	**0.0**	98.96	**150.0**	**246.04**	**74.29**
10	**150.0**	**51.21**	43.09	**145.0**	43.32	87.1	**0.0**	98.96	**150.0**	**246.04**	**74.29**

Notes: 1) 'Mirror1' is distance between dewar window and tertiary mirror or lens (neg. if outside dewar).
2) 'Mirror2' is approx. spacing between quaternary mirror and dewar top (neg. if outside dewar)
3) Mirror Sep. (mm) is distance (on beam axis) between tertiary and quaternary mirrors.
4) Mirror Sep (deg) is angular separation of mirrors, viewed from top and ref'd to dewar center.
5) Feed Pos. is approx. spacing between feedhorn aperature and dewar top (neg. if outside dewar)
6) Feed->Mirr. is approx. spacing between feedhorn aperature and bottom edge of Mirror2.

3) Antenna Gaussian Beam Properties (at lower band edge):

Band	Min. Freq. (GHz)	Max. Freq. (GHz)	Waist rad. (mm)	Conf. Dist. (mm)	Waist Pos. (mm)	Beam Rad. (mm)	Rad. of Curv. (mm)	Window Dia. (mm)	Window Offs. (mm)	Beam Ang. (deg)
1	31.3	45	**57.334**	1078.189	**529.0**	63.86	2726.53	**81.0**	**270.0**	N.A
2	67	90	**26.784**	503.691	**244.5**	29.77	1282.15	**56.0**	**270.0**	N.A
3	89	116	**20.163**	379.183	**50.0**	20.34	2925.60	**101.5**	**227.5**	2.11
4	125	163	**14.356**	269.979	**50.0**	14.60	1507.77	**73.0**	**227.5**	2.11
5	163	211	**11.009**	207.039	**50.0**	11.33	907.30	**56.5**	**150.0**	1.39
6	211	275	**8.505**	159.940	**50.0**	8.91	561.62	**44.5**	**150.0**	1.39
7	275	370	**6.526**	122.718	**50.0**	7.05	351.19	**35.0**	**50.0**	0.46
8	385	500	**4.661**	87.655	**50.0**	5.37	203.67	**27.0**	**50.0**	0.46
9	602	720	**2.981**	56.059	**50.0**	3.99	112.85	**20.0**	**50.0**	0.46
10	787	950	**2.280**	42.881	**50.0**	3.50	86.78	**17.5**	**50.0**	0.46

Note: Waist Pos. is distance from antenna beam waist to dewar window (neg. if inside dewar)

4) Tertiary Ellipsoidal Mirror, Beam Properties (at lower band edge):

			Input Beam				Output Beam		
Band	*f* (mm)	*M* (wo/wi)	Input Dist. (mm)	Beam Rad. (mm)	Beam Size (% of waist)	Tertiary Dia. (mm)	Output Dist. (mm)	Waist rad. (mm)	B.S. (beamwid.)
1	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
3	**225.0**	0.593	**225.0**	23.446	116.28	**117.0**	225.00	11.965	**0.068**
4	**225.0**	0.833	**225.0**	18.688	130.18	**93.5**	225.00	11.965	**0.055**
5	**225.0**	1.087	**225.0**	16.259	147.68	**81.5**	225.00	11.965	**0.048**
6	**225.0**	1.407	**225.0**	14.679	172.60	**73.5**	225.00	11.965	**0.043**
7	**225.0**	1.833	**225.0**	13.628	208.85	**68.0**	225.00	11.965	**0.027**
8	**200.0**	2.282	**200.0**	11.612	249.12	**58.0**	200.00	10.635	**0.039**
9	**200.0**	3.568	**200.0**	11.045	370.52	**55.0**	200.00	10.635	**0.037**
10	**200.0**	4.664	**200.0**	10.877	477.01	**54.5**	200.00	10.635	**0.036**

Notes: 1) Input Dist. is distance from antenna beam waist to tertiary (neg. if behind mirror)
2) Beam Rad. is antenna beam radius at the tertiary ellipsoid.
3) Output Dist. is distance from tertiary to output beam waist (at feed)
4) 'd' is the waist spacing.
5) 'M' is the magnification

5) Quaternary Plane Mirror, Beam Properties (at lower band edge):

Band	Input2 Dist. (mm)	Beam Rad. (mm)	Mirror2 Dia. (mm)
1	N.A.	N.A.	N.A.
2	N.A.	N.A.	N.A.
3	83.57	14.12	**70.5**
4	83.57	13.10	**65.5**
5	83.86	12.65	**63.0**
6	83.86	12.38	**62.0**
7	116.23	12.43	**62.0**
8	101.04	10.89	**54.5**
9	101.04	10.74	**53.5**
10	101.04	10.70	**53.5**

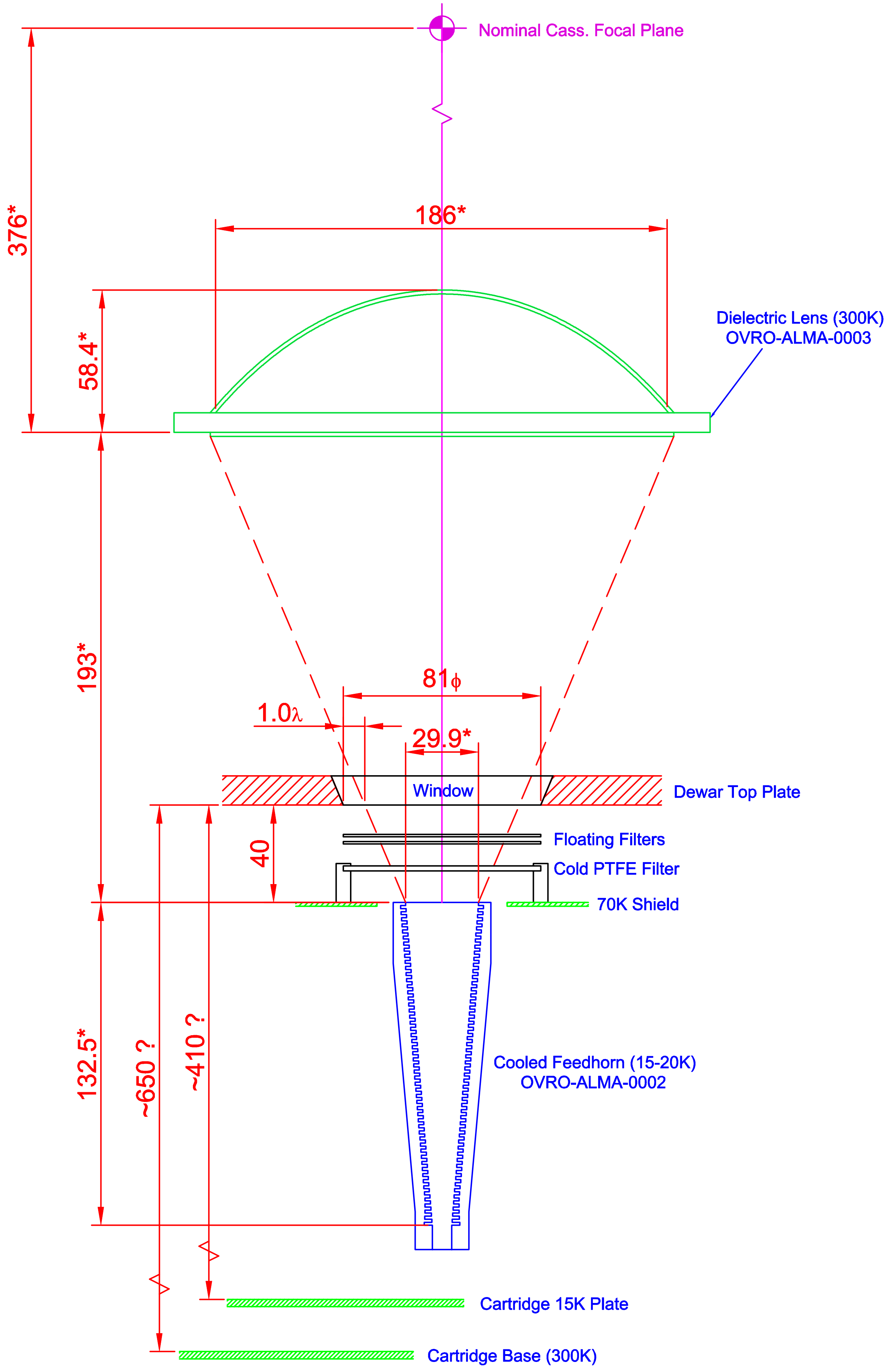
6) Off-Axis Aberrations (worst-case):

Band	Axial Offs. (mm)	Coma (max)	Astigmat. (max)
1	**270.0**	3.36E-06	3.13E-05
2	**270.0**	1.34E-05	1.25E-04
3	**227.5**	1.58E-05	1.05E-04
4	**227.5**	3.13E-05	2.07E-04
5	**150.0**	2.28E-05	6.56E-05
6	**150.0**	3.87E-05	1.11E-04
7	**50.0**	7.78E-06	2.49E-06
8	**50.0**	1.42E-05	4.55E-06
9	**50.0**	2.95E-05	9.43E-06
10	**50.0**	5.13E-05	1.64E-05

Notes: 1) Input2 Dist. is approx. spacing between output beam waist and quaternary mirror.
2) Beam Rad. is output beam radius at quaternary mirror.

7) Mirror ohmic loss (per mirror), 80K:

Band	Loss (Al)	Loss (Au)
1	N.A.	N.A.
2	N.A.	N.A.
3	**0.0023**	**0.0022**
4	**0.0028**	**0.0027**
5	**0.0031**	**0.003**
6	**0.0036**	**0.0035**
7	**0.0042**	**0.0042**
8	**0.0048**	**0.0047**
9	**0.0058**	**0.0056**
10	**0.0067**	**0.0065**



*These dimensions from Lamb report, 2000-04-24

Figure 1: ALMA Band 1 Receiver Optics

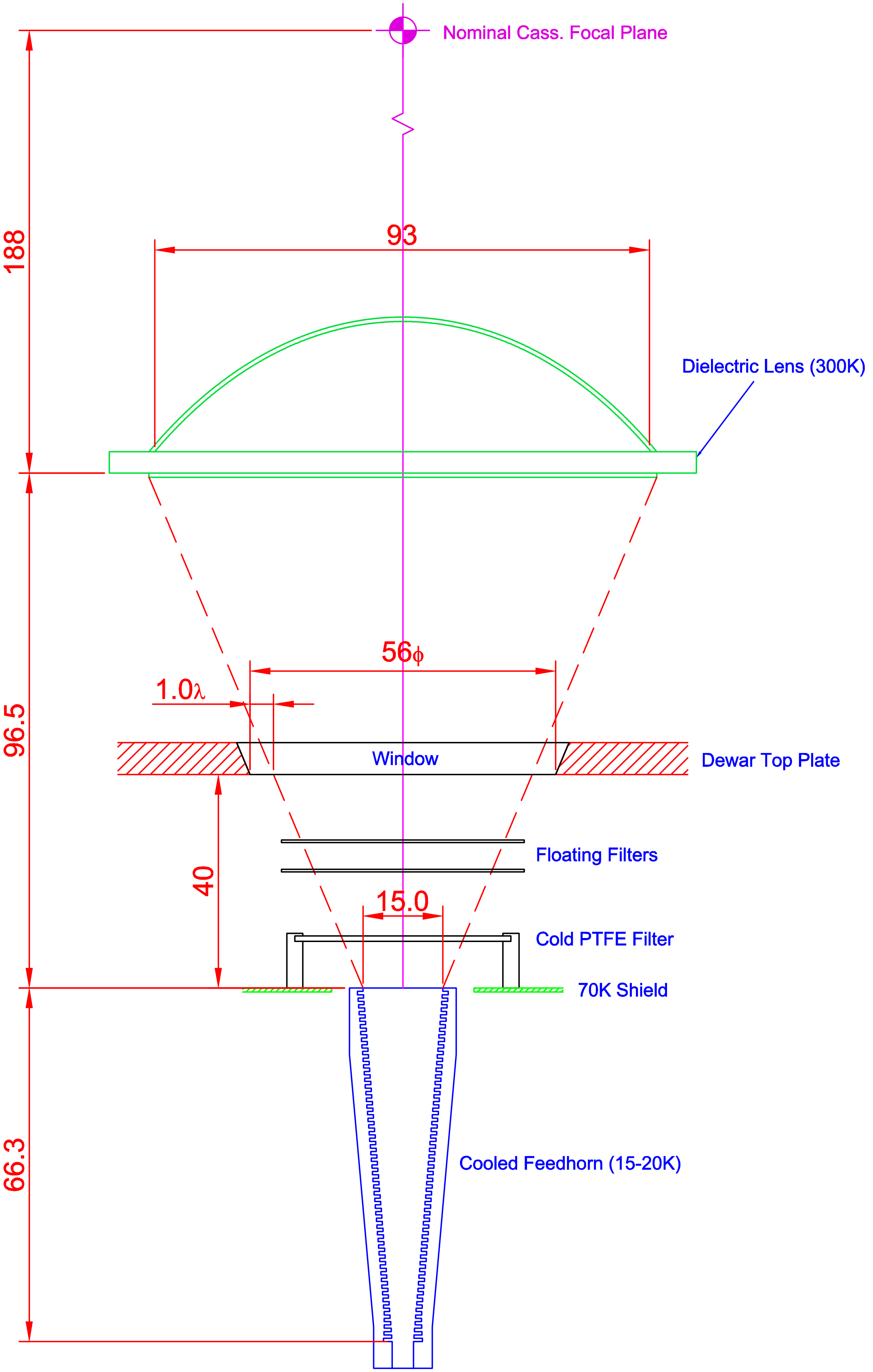
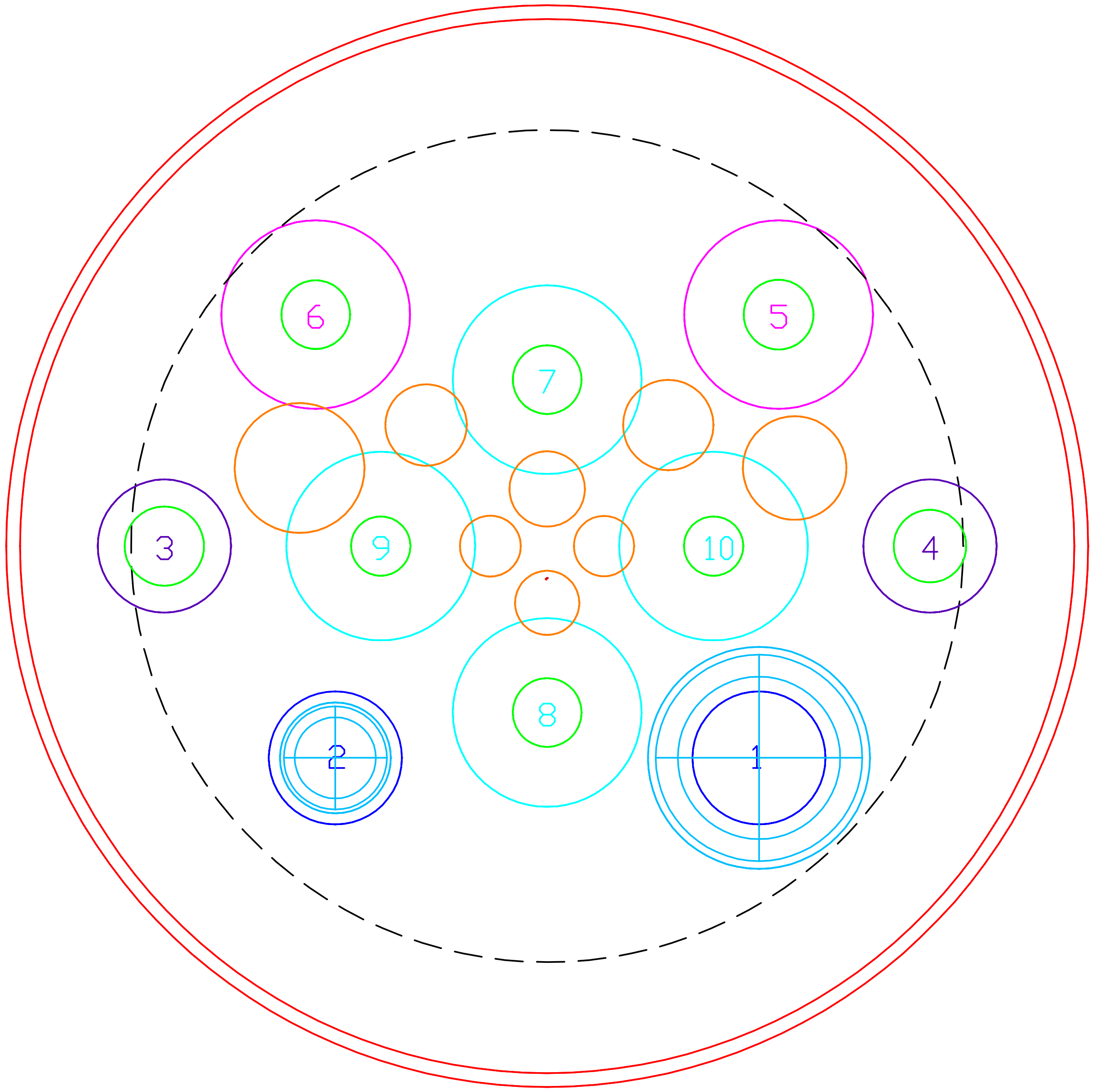


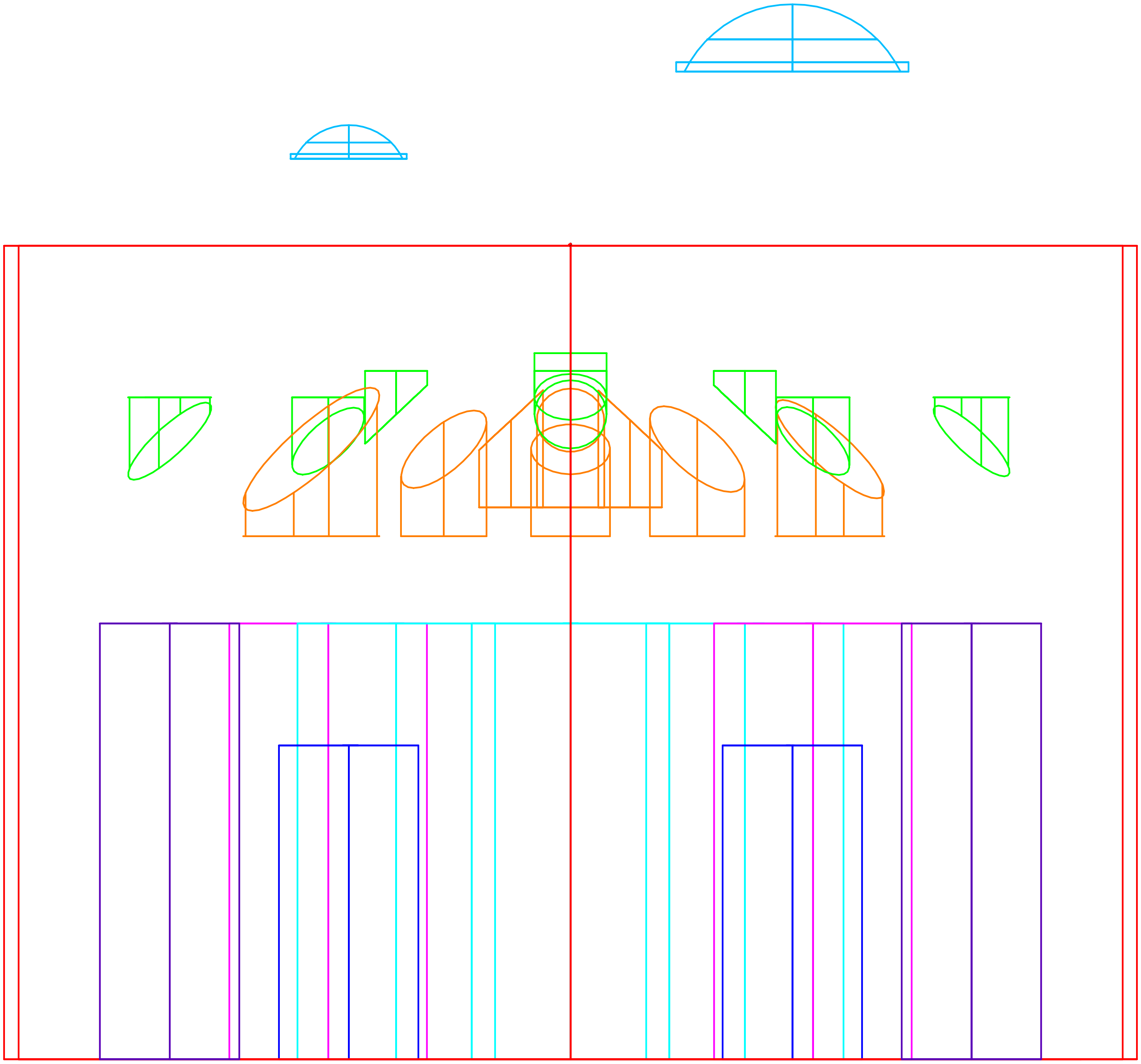
Figure 2: ALMA Band 2 Receiver Optics

FIGURE 3: Top View of Dewar



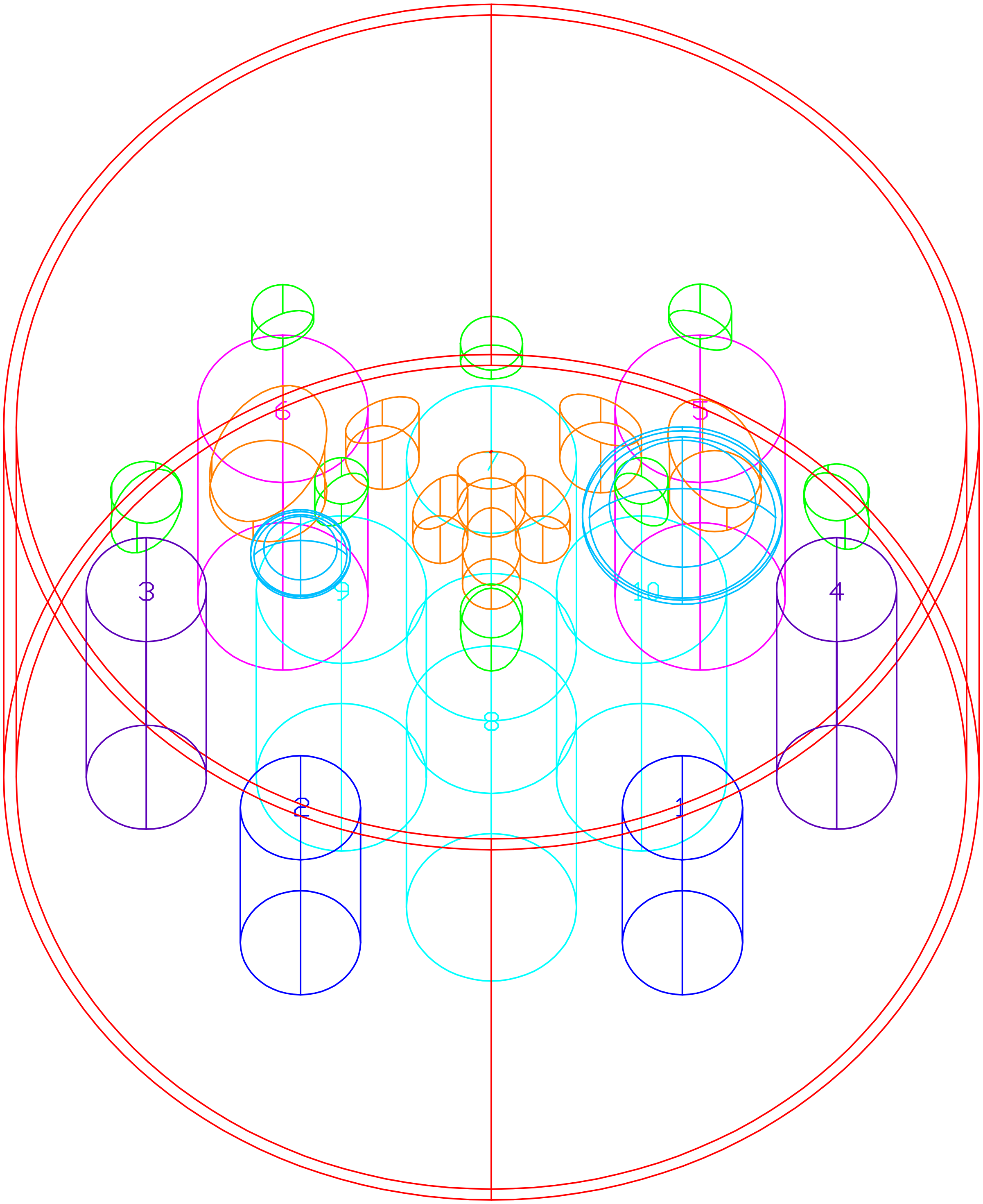
BLACK - Dewar Windows
ORANGE - Tertiary Mirrors
GREEN - Quaternary Mirrors
LT. BLUE - Lenses
BLUE - Bands 1-2 Cartridges
VIOLET - Bands 3-4 Cartridges
PINK - Bands 5-6 Cartridges
CYAN - Bands 7-10 Cartridges
RED - Dewar Cylinder

FIGURE 4: Side View of Dewar



ORANGE - Tertiary Mirrors
GREEN - Quaternary Mirrors
LT. BLUE - Lenses
BLUE - Bands 1-2 Cartridges
VIOLET - Bands 3-4 Cartridges
PINK - Bands 5-6 Cartridges
CYAN - Bands 7-10 Cartridges
RED - Dewar Cylinder

FIGURE 5: Isometric View of Dewar



ORANGE - Tertiary Mirrors
GREEN - Quaternary Mirrors
LT. BLUE - Lenses
BLUE - Bands 1-2 Cartridges
VIOLET - Bands 3-4 Cartridges
PINK - Bands 5-6 Cartridges
CYAN - Bands 7-10 Cartridges
RED - Dewar Cylinder