MILLIMETER ARRAY
MEMO NO. 102

A Possible Receiver Optics Layout for the mmA

James W Lamb
NRAO, Tucson
22 September 1993

1 Introduction

An extensive list of desirable features for the mmA receivers has been proposed, including: circular polarization, dual-polarization, simultaneous multifrequency observing, image rejection or separation, and very low system temperatures. It may not, however, be feasible to incorporate all these features without some significant compromises in overall performance. To start evaluating some possibilities and drawbacks, a possible receiver layout is proposed. This "strawman" design will certainly not be implemented, but it illustrates some possibilities and problems and provides a starting point for further development.

2 Specifications

The following specifications are met by the design using current technology:

- Frequency coverage: 65-118 GHz, 130-170 GHz, 200-300 GHz, 330-370 GHz
- Dual-polarization
- Diplex any two frequency bands in each polarization
- Image rejection
- Circular polarization at one frequency

3 Implementation

A block diagram of the receiver is shown in Figure 1.

3.1 *Circular Polarizer*

The first component of the receiver that the signal from the telescope passes through is the circular polarizer. A reflective waveplate (RWP), consisting of a wire grid in front of a plane mirror, is used. The grid reflects one linear component of the incoming circularly polarized field and the other is transmitted and then reflected by the plane mirror. A $\lambda/4$ path difference between the two components produces a linearly polarized signal. The oppositely-handed circular signals produce orthogonal linear outputs.

This device may be tuned to any frequency (by adjusting the grid to mirror spacing), has low-loss, and is relatively compact. In principle, it may be tuned to produce circular polarization at two frequencies simultaneously with the same restrictions as discussed by Kerr [1]. However, multifrequency operation requires a much larger range of adjustment: for a single frequency the range is about 300 times the resolution, but dual-frequencies would require a range of several thousand. Furthermore, at the larger separations the beam reflected form the grid is laterally displaced from the beam reflected by the plane mirror resulting in a walk-off loss. A Martin-Puplett interferometer avoids the walk-off loss but has a large internal pathlength.

If circular polarization at a single frequency is acceptable then the RWP with a small separation is a reasonable low-loss, compact simple circular polarizer.

3.2 Linear Polarizer

From the RWP, the signal enters a crossed-grid that separates the two linear polarizations. This device is symmetrical for the two polarizations, apart from the direction of polarization. It includes a termination for the cross-polarization. From this point on, the two polarizations are treated identically, though they may be tuned independently.

3.3 Frequency Diplexer

A Martin-Puplett interferometer (MPI) is used to diplex the signal into two frequency bands. This device is low-loss, has a wide tuning bandwidth, is well matched, and relatively insensitive to misalignments, but has a large internal path length. Kerr [1] has detailed the restrictions on frequencies that may be observed simultaneously, and found that only a few frequency combinations cannot be obtained with the required bandwidth.

3.4 Band Selection Mirrors

At the output of the diplexer the two signals are split into two orthogonal polarizations by a grid. Figures 2-4 shows how the two signals are transmitted to two frequency bands in the receiver. Because of the orientation of the mirrors, the signals which are orthogonally polarized at the grid arrive at the receiver feeds with the same polarization. This means that any two bands may be diplexed by moving the mirrors to the appropriate positions.

3.5 Image Rejection

The primary reason for including image rejection within the receiver is to minimize the system noise temperature by rejecting sky noise in the image band. Rejection of unwanted astronomical signals in the unwanted sideband is more effectively accomplished by phase-switching the LO's of the different antennas. Because the noise rejection is the primary concern, a very low image termination temperature is necessary. By locating the diplexer in the dewar the image does not need to exit and reenter the dewar through vacuum windows, major sources of additional noise. Also, since the diplexer is close to the feed where the beam is relatively small, its size may be kept to a minimum.

Again, an MPI is an ideal device for this function. At frequencies below about 130 GHz the size of the device is prohibitively large—the thickness required of the vacuum windows would make them too lossy and void the expected improvement from rejecting the image. However, in the low frequency band (65-118 GHz) the atmospheric transparency is generally lower than at the higher frequencies so that the added noise is less. Also, the SIS mixers in this band could be replaced by HFET amplifiers which have no image response. The feed shown in the Figures could be replaced by two or three feeds, one of which is selected by a small mirror.

If very high image rejection is needed, a grid should be placed between the feed and the MPI, otherwise the cross-polar response of the feed will receive astronomical signals in the image band. However, the aim is to minimize noise and the additional noise from the cross-polarization of ≤ 1 K (for typically -18 to -25 dB cross-polar), is negligible if the grid and termination are omitted. Another reason for including the grid would be to separate the image into a second mixer, but this complication seems unwarranted at this stage.

3.6 LO Injection

No allowance has been made for injecting the LO optically as this increases the complexity of the optics considerably, as well as reducing the bandwidth and increasing the loss. Waveguide injection is assumed, but the feasibility of using a broadband coupler with a coupling of 16-20 dB needs to be assessed.

3.7 Beam Sizes

The simplest way to analyze the beam coming through the optics is to use a Gaussian beam description, but this is easily extended to non-Gaussian fields [2]. For this design it is assumed that a clearance of at least five times the beam radius of the nominal Gaussian beam is allowed at all points in the beam. It can be argued that more or less clearance is necessary at different planes, but a detailed study should come later. Offset reflectors are treated as simple lenses in their effect (apart from the change in beam direction), and lenses are assumed to affect the phase of the beam but not the amplitude.

The starting point is a beam-waist of 40 mm radius at a fixed position (which can be obtained in the antenna beam waveguide optics). For each band there is an offset mirror that focuses the beam into the dewar. It is assumed that the offset angle between the input and output beams is 45° so that beam distortion and cross-polarization are not too large. There is also a lens within the dewar that focuses the beam into a corrugated horn. Cooling the lens to 4 K minimizes its contribution to the receiver noise temperature.

With two focusing elements it is possible to transform the beam from the 40 mm waist radius so that it has a fixed beam radius, w_h, and radius of curvature of the wavefront at the horn aperture, R_h (see Appendix). The aperture of the horn should be 2-3 λ at the lowest frequency, and the distance from the throat to the aperture should be the same as the field wavefront curvature. Under these conditions, the field at the horn aperture is imaged at the secondary mirror with the correct size and curvature, independent of frequency. Finite apertures and the non-ideal behavior of the lenses will reduce the efficiency.

In the arrangement shown the distances of the different mixers from the starting beam-waist are different but the focal lengths and positions of the reflectors and lenses are chosen to assure that they are all in focus simultaneously, a requirement if frequency diplexing is implemented. In choosing the parameters the size of the lenses, vacuum windows, and mirrors need to be kept as small as practically possible. After some iterations the set of parameters given in Table I was arrived at. 3D views of the optics are shown in Figures 2-4.

	65-118 GHz	130-170 GHz	200-300 GHz	330-370 GHz
f_1	450.0	550.0	600.0	500.0
l_1	680.0	680.0	300.0	200.0
f_2	100.0	80.0	60.0	35.0
l_2	700.0	650.0	700.0	550.0
l_3	86.31	77.2	62.9	36.4
w_h	10.71	5.87	3.87	2.75
R_h	80.36	322.77	87.10	80.22

Table I Parameters used in the optics design. All dimensions are in mm.

4 Bandwidth

Kerr [1] has noted some bandwidth restrictions that are inherent in some of the optical components. These typically arise because of the sinusoidal passband of the interferometers used to perform the various required functions. The period of the sinusoid depends on the frequencies involved. In the case of image rejection and LO injection it depends on the intermediate frequency (IF). For frequency diplexing, the period depends on the relationship between the two frequencies. Devices used for circular polarization depend typically have large bandwidths, unless they are required to work at more than one frequency, when the pathlengths become much greater. Cascading several devices could place significant limitations on the bandwidth.

5 Optics Losses

The large number of optical elements leads inevitably to a degradation of the system sensitivity. These losses include dissipative, diffractive, and cross-polar components. It is difficult to estimate the total loss in the optics described here, but some indication may be obtained from the receivers used on the 12-m at Kitt Peak. At 115 GHz the loss is about 0.13 dB in a system with a plane mirror, an offset paraboloid, and a crossed-grid. At 230 GHz the loss is also 0.13 dB, this time with an MPI for image dumping (two reflections from the rooftop, two grid transmissions and one grid reflection), and a crossed-grid. Some of these losses are increased as more elements are cascaded (such as ohmic loss), but others are not (the cross-polar is eliminated in one component). Judging the optics for this receiver to be two or three times more complex we estimate that the degradation could be of order 0.2 - 0.5 dB, adding 13 - 33 K to the receiver noise. In some instances this could amount to doubling the receiver noise temperature. Some more detailed measurements are clearly warranted.

Another way in which the efficiency is reduced is the overlap loss from the diplexers. This arises because the beams in the two paths of the diplexer are combined with a path difference so that their radii of curvature at the secondary are different [3], [4]. It depends on the pathlength in the diplexers and the number of diplexers used.

6 Discussion and Conclusions

A receiver design has been presented which fulfills some of the major requirements of the mmA. The complexity and size suggest that some simplifications be made to make the receivers more practicable. It should be carefully considered whether dual-frequency operation is needed, or whether consecutive observations can be made. If the correlation of quickly time-varying signals is required in some small number of instances (such as for solar observing) then the two polarizations may be tuned independently without restriction. Alternatively, if the polarization information is required, half the antennas could be used at one frequency and half at another.

It would be desirable in many ways to incorporate all the receiver channels in a single dewar. The present size of the optics (~1 m) makes this impractical, but further optimization could reduce it closer to the 0.6 m diameter used in the Kitt Peak 12-m receivers. A minimum number of frequency bands has been chosen to reduce the complexity, but it is probable that a larger number would be used to allow the maximum sensitivity at all frequencies. This makes the optics more complicated again.

The most important requirements need to be determined and another model of the receiver constructed. Some of the optics should be fabricated to determine the performance more precisely and uncover unforseen problems. In general, the receiver should be kept as simple as possible so that sensitivity is not compromised. This needs to be evaluated in terms of the increase in system temperature *vs.* the benefits of the increased complexity. For example, frequency diplexing could be justified if a lower frequency could be used to calibrate the phase for a higher frequency, giving better quality images despite an increase in system noise temperature.

A minimum receiver should probably include circular polarization at one (tuneable) frequency and dual polarization but not image termination or frequency diplexing. Optical injection of the LO should be used only where it can be shown that waveguide coupling is impractical.

7 Appendix: Frequency Independent Beam System

The system considered may be represented by the schematic in Figure 5. The reflector is represented by a thin lens, L1, and the cooled lens by L2. The beam size is fixed at the first beam waist, where the beam-waist radius is

$$w_{01} = 40.0mm \tag{1}$$

L1 focuses the beam down to a waist at a distance d_2 from the lens. This distance, and the waist radius, w_{02}, are both functions of frequency. The second lens, L2, refocuses the beam to another waist, w_{03}, at a distance d_4 past the lens. This waist is also frequency-dependent, but there is a plane to the right of the lens at a distance

$$l_3 = f_2 \frac{l_1 f_1 + l_2 f_1 - l_1 l_2}{l_1 f_1 + l_2 f_1 + f_2 l_1 - f_1 f_2 - l_1 l_2} \tag{2}$$

where the radius of the beam is constant and given by

$$w_k = \frac{f_1 f_2}{l_1 l_2 - l_1 f_1 - l_2 f_1 - f_2 l_1 + f_1 f_2} w_{01} \tag{3}$$

The radius of curvature of the wavefront is also fixed:

$$R_k = \frac{(f_1 f_2)^2}{(-l_2 + f_1 + f_2)(l_1 l_2 - l_1 f_1 - l_2 f_1 - f_2 l_1 + f_1 f_2)} \tag{4}$$

A corrugated horn with an aperture diameter of [5]

$$a = \frac{w_k}{0.6435} \tag{5}$$

and a flare angle of

$$\theta = atan\left(\frac{a}{R_k}\right) \tag{6}$$

will be an optimum match to the beam.

8 References

[1] A. R. Kerr: "Circular polarization and multi-band operation: implications for mmA receiver design", *mmA Memo No. 72*, January 1992.

[2] J. W. Lamb: "Beam-mode expansion applied to focal region fields", *IEE Proc.-H*, Vol. 139, No. 6, pp 513-520, December 1992.

[3] P. F. Goldsmith.: "Quasioptical techniques at millimeter and submillimeter wavelengths", Infrared and Millimeter Waves, 6, K. Button (*ed.*) (Academic, 1982), pp. 277-246.

[4] J. W. Lamb.: "Quasioptical coupling of Gaussian beam systems to large Cassegrain antennas", ***Int. J. Infrared and Millimeter Waves***, 1986, Vol. 7, pp1511-1536

[5] R. J. Wylde: "Millimetre wave Gaussian beam-mode optics and corrugated feed horns", ***Proc. IEE, Pt H***, 1984, Vol. 13, pp. 258-262

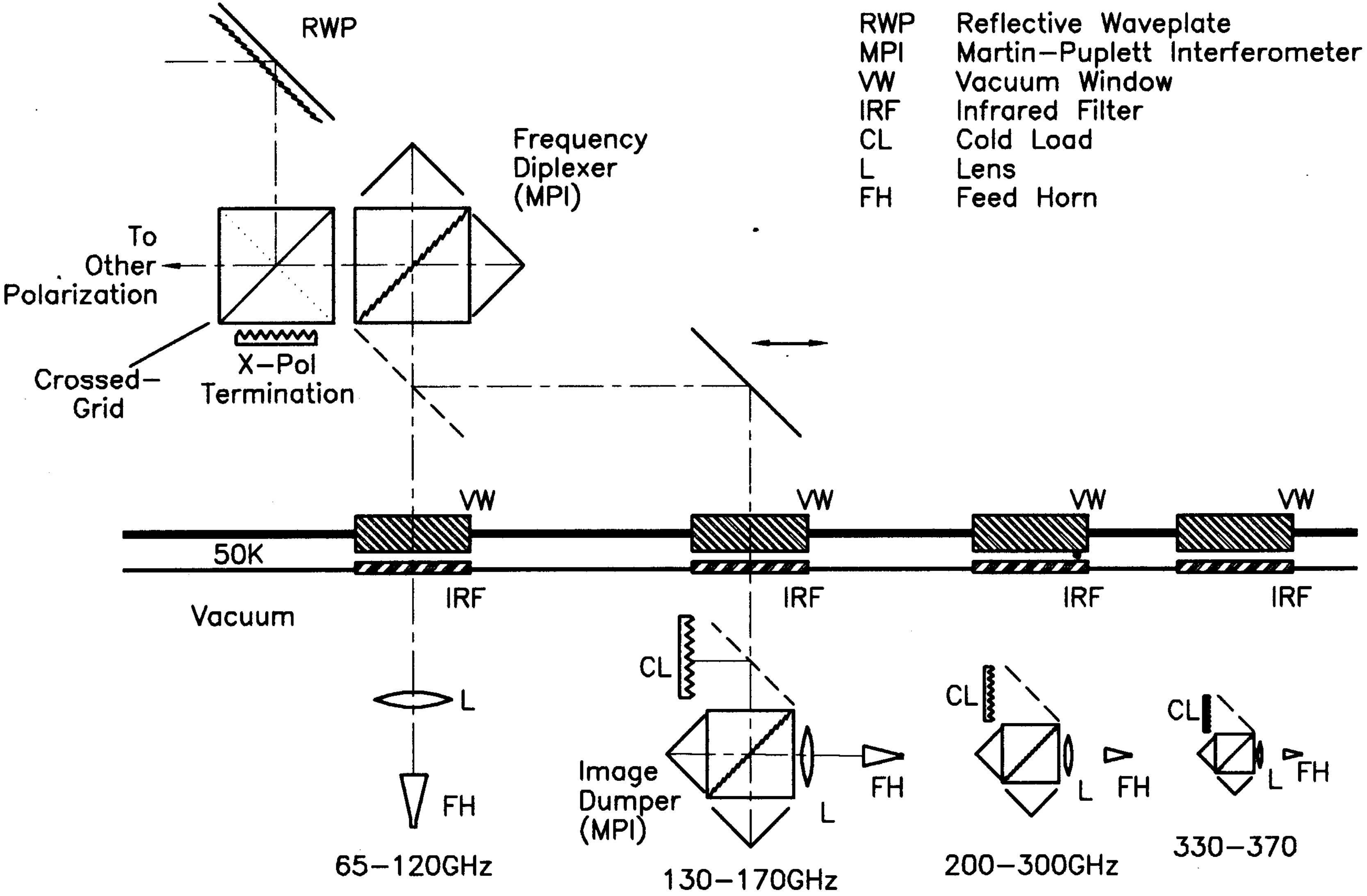

Figure 1. Schematic diagram of the proposed receiver. For simplicity, some of the mirrors are omitted. Only one polarization is shown.

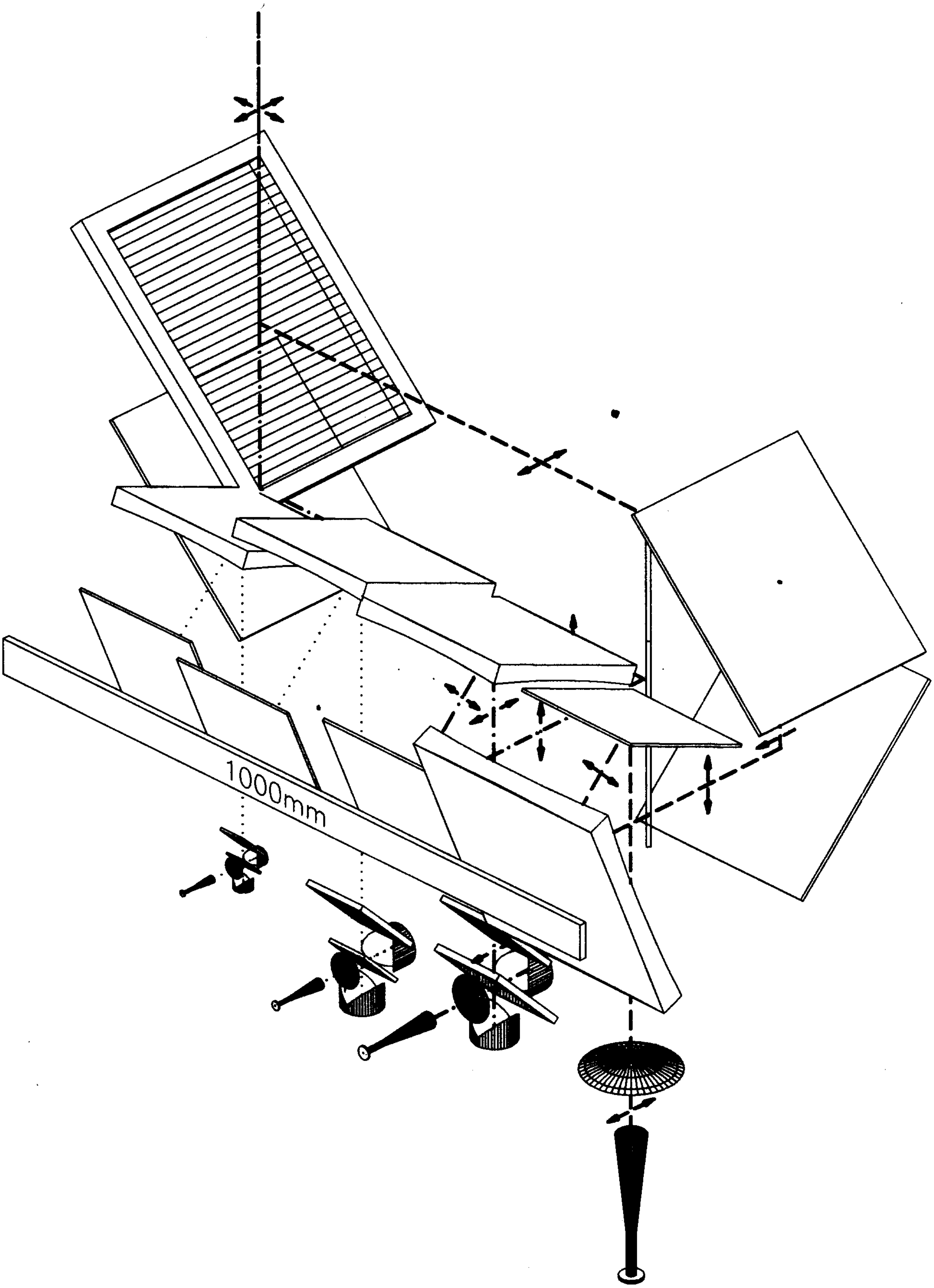

Figure 2. Isometric view of the optics. Only the lower grid of MPI frequency diplexer is shown. The crossed-grid is also omitted for clarity.

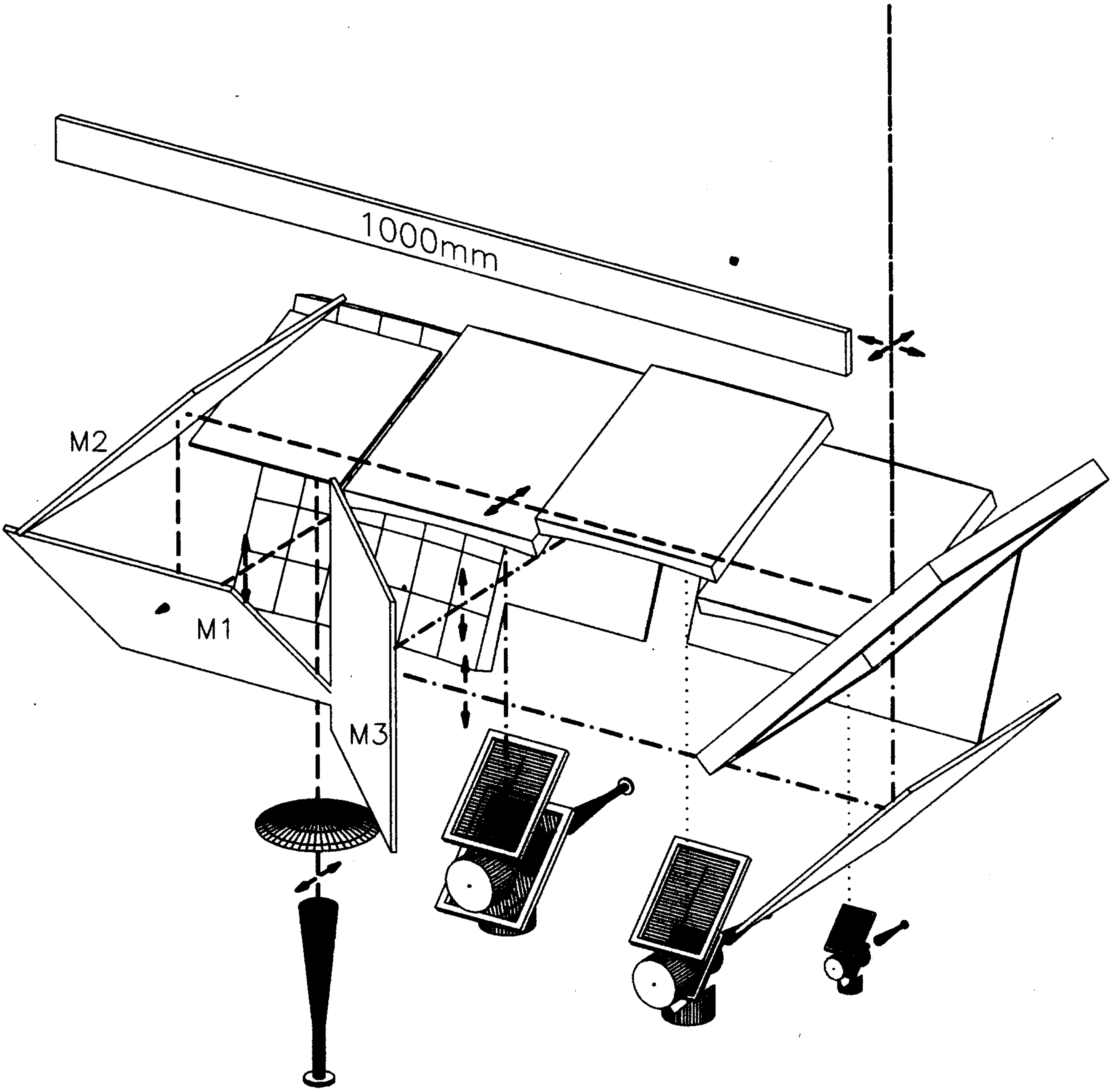

Figure 3. Isometric view of the optics. The 3-mm band and the 2-mm band are being diplexed. M1, M2, and M3 are moved to change bands.

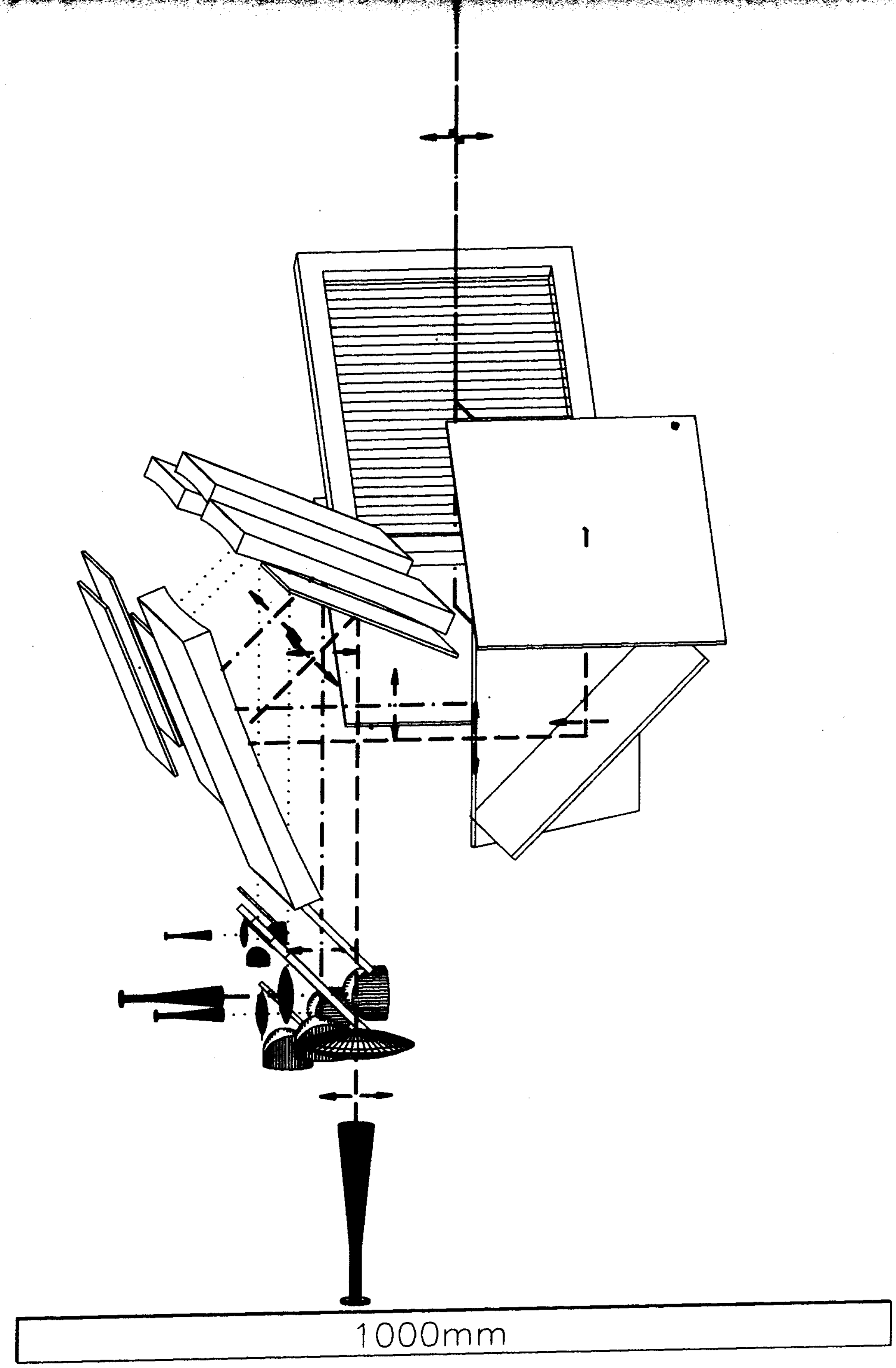

Figure 4. Isometric view of the optics.

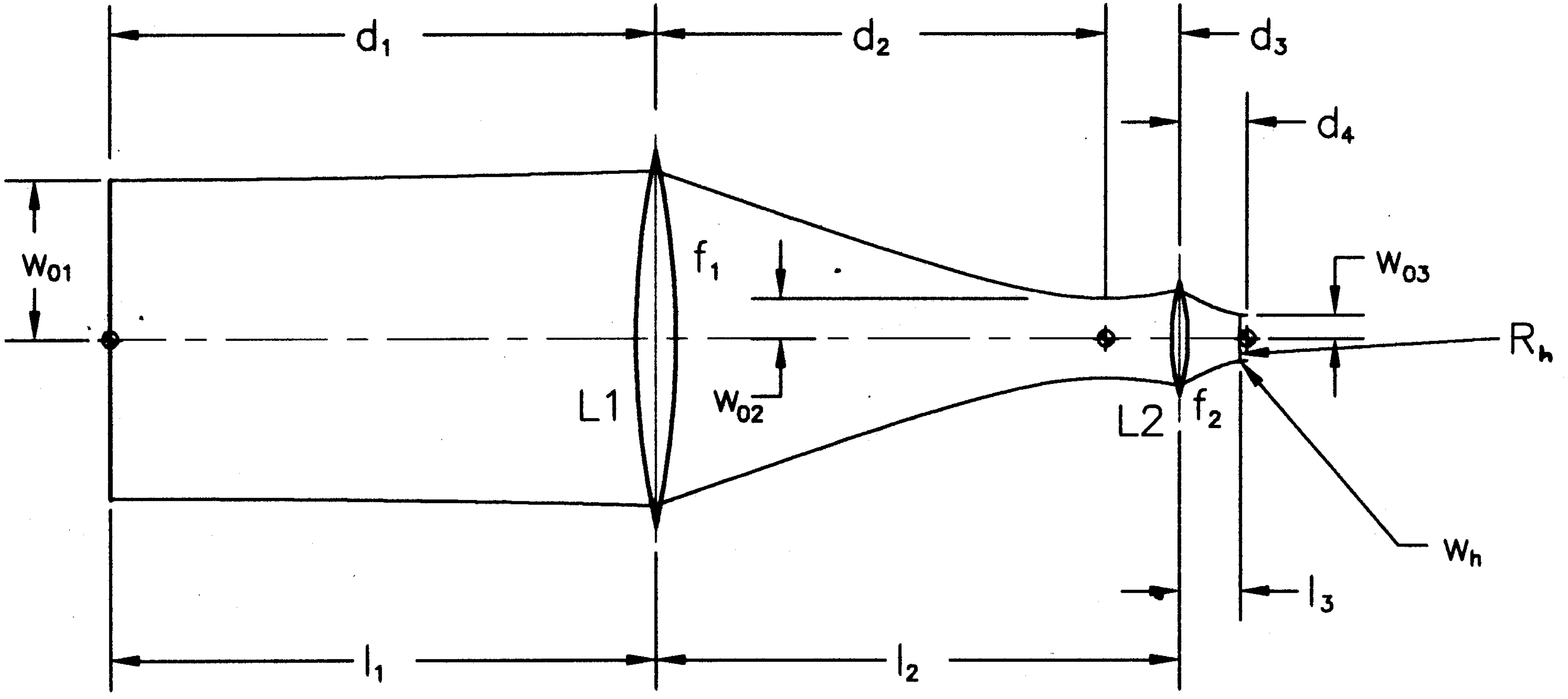

Figure 5. Frequency–independent beam path. L1 represents the offset mirror and L2 the cooled lens. The horn aperture is at a distance l_3 to the right of L2.