

# Proposition of a new cabin optics increasing the field of view of the Pico Veleta 30m telescope

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This document is the definitive proposition for the new optical system of the 30m, increasing the field of view both for bolometers and heterodynes. It is based on an improved version of the preferred configuration presented in a previous document [leclercq], itself based on previous background works ([Navarro], [Greve], [Peñalver], [Zylka], [Thum], [Carter], [Gélin], [Lelercq]). The complete project is covered: specifications, description of the proposed design, discussion, and provisional time and costs table.

## Specifications.

List of the constraints that led to the design of the proposed optics:

- 1)  $FOV \geq 10$  arcmin for bolometers and  $FOV \geq 7$  arcmin for heterodynes.
- 2) Pixel size  $\approx \lambda + 5\%$ . Smaller would create additional diffraction from the pixel itself, bigger is less favorable for microfabrication (less pixels per wafer). This constraint imposes that a maximum of 11.4 arcmin can fit on an 8 inches wafer.
- 3) The optical elements must neither cut the beam nor touch the walls, roof and ground of the cabin.
- 4) The mirrors must measure less than 1.6 m in their largest dimension, roughly the maximum acceptable to polish a mirror surface at  $15\text{ }\mu\text{m}$  rms accuracy using affordable machining (guesstimate from J-L Pollet).
- 5) The system must count a minimum number of optical elements, and use mirrors instead of lenses when possible. Currently 7 mirrors (M1 to M7) and a thick lens are used for MAMBO II.
- 6) Enough room must be available for operators and cryogen bottles between the elevation cabin and M3.
- 7) Enough room must be available for a cylindrical instrument of diameter  $D = 0.5$  m and height  $h = 1$  m.
- 8) The entrance window of the instrument's cryostat must be as small as possible. Less than 20 cm is desirable, 25 cm is the upper limit of acceptance (*discussion with cryogenic labs needed for a better confidence number*).
- 9) The rotating system for the mirror M3 must be efficient and simple.
- 10) It is desirable that both horizontal and vertical orientations are available for future instruments, with a minimum number of optical elements changes.
- 11) It is desirable that several imaging options are available, with a minimum number of optical elements changes. Two particular but non-compatible options are a compact system or a telecentric<sup>1</sup> system.
- 12) The alignment and focus of the system must be easy and convenient.
- 13) The system must fulfill all specifications with margins at a minimum cost.

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<sup>1</sup> In a telecentric system the chief rays are parallel at zero angle of incidence. For the new optics design an image plane telecentric system, where the exit pupil is at infinity, may be desirable since it minimizes any angle-of-incidence dependence of the detectors, allows an uniform plane illumination without vignetting, and allow to adjust focus without changing the image size.

## Description of the new optical system.

The proposed design fulfilling all the specifications was achieved thanks to Zemax simulations and Excel sheets for the calculations of tilts, shifts and curvatures used for Zemax coordinate breaks and mirrors parameters. The optimal positions are presented Table 2, and the curvature parameters Table 4. In addition to a new heterodyne M4 mirror, 3 typical optical options for bolometers have been investigated: a telecentric mirror M5, a small cryostat window with a telecentric cold lens L6, and with a small L6. These 3 solutions have been simulated for a horizontal and a vertical cryostat, leading to 7 different optical options (1 heterodyne and 6 bolometers). For a given set of mirrors positions and cryostat orientation it is not necessary to simulate more options to embrace all the optical choices possible because on one hand for a system using no lens, non-telecentric images can be obtained with a smaller M5 whereas bigger M5 are useless, and on the other hand all interesting cold lens options are hybrids between the small diameter and the telecentric options. The characteristics of the different options are summarized in the following tables, with a comparison to the current configuration. The Zemax 2D drawing of mirrors, beams and cabins benchmarks are presented in the following pages.

Table 1. Maximum field of view reachable for current and new configurations, and size of the corresponding vertex window (polystyrene window at the entrance of the elevation cabin).

Configuration	Current	New heterodynes	New bolometers
Field Of View [arcminutes]	4.6	7.4	11.5
Vertex window diameter [mm]	1000	1400	

Table 2. Positions [mm, mm, mm] of mirrors vertex and distances [mm] between each element. The center of M3 is the reference center, and the axes x, y, z are respectively along the receivers cabin width (elevation axis), height (azimuth axis), and length. In the distances column the optical elements are identified with their number, and "I" is the image plan.

Elements	M4	M5	L6	Distances
Current configuration	700, 0, 0	n/a		d34 + d4I = 700 + 2480
New heterodynes	860, 0, 0	n/a		d34 + d4I = 860 + 2320
New bolometers, no L6	1000, 480, 980	-900, -1200, 1000	n/a	d34 + d45 + d5I = 1480 + 2536 + 608
New bolometers, small L6, cryostat vertical			-950, -310, 1000	d34 + d45 + d56 + d6I = 1480 + 2536 + 810 + 370
New bolometers, small L6, cryostat horizontal			-10, -1200, 1000	
New bolometers, L6 telecentric, cryostat vertical			-950, 10, 1000	d34 + d45 + d56 + d6I = 1480 + 2536 + 1210 + 370
New bolometers, L6 telecentric, cryostat horizontal			310, -1200, 1000	

The margins for the positions of the mirrors are very small for the 11.5 arcminutes FOV and all optical options (less than 2 cm for each mirror). They increase for smaller FOV and when the options are taken individually (more room available in different directions depending on the option).

Table 3. Optical elements elliptical contour given as  $2a[\text{mm}] \times 2b[\text{mm}]$  ( $a$  = semi-major-axis,  $b$  = semi-minor-axis). Even though the beam and mirrors fit in the allocated room with the elliptic contours, most of the mirrors could be grinded on some parts to let more space and margins (see drawings). Dimensions are given for the off-axis quadric surfaces (ellipsoids and hyperboloids), but optimization of aspheric corrections will permit to reduce sizes for all options of M5 and L6. As an indicator of the theoretical optimal sizes, the minimum diameter obtained from the paraxial ray tracing with on-axis equivalent lenses is given between parentheses. The cryostat window stands 450 mm before M5 for the M5 telecentric options, whereas it stands 840 mm after M5 in the cold lenses cases.

Elements	M3	M4	M5	Cryostat window	L6
Current configuration	1040×740	920×650	n/a		
New heterodynes	1440×1260	1170×810	n/a		
New bolometers, cold M5 telecentric, cryostat vertical		1190×1080 (1155)	540×470 (507)	450×400 (214)	n/a
New bolometers, cold M5 telecentric, cryostat horizontal			500×430 (507)		
New bolometers, cold L6 telecentric, cryostat vertical			870×820 (644)	420×370 (180)	390×380 (390)
New bolometers, cold L6 telecentric, cryostat horizontal				370×360 (180)	360×360 (390)
New bolometers, small cold L6, cryostat vertical				420×370 (180)	390×360 (208)
New bolometers, small cold L6, cryostat horizontal				370×360 (180)	350×340 (208)

The telescope (M1 and M2) equivalent focal length is  $F = 292$  m, so the image plane of a 11.5 field of view is a disc of diameter  $F \cdot FOV = 977$  mm. To get this image on a 8 inches (203 mm) instrument, at least one quadric optical surface (mirror or lens) must be used as a re-imaging system. But the limited room in the cabin and the necessity to correct the aberrations impose to use at least two quadric surfaces with aspheric corrections. Table 4 gives the quadric parameters of the mirrors M4 and M5, and lens L6 proposed for the different options of the bolometers new optics. M4 and M5 are off-axis mirrors, re-imaging rays concentrated at one of their focal point to the other, as shown in Figure 1.

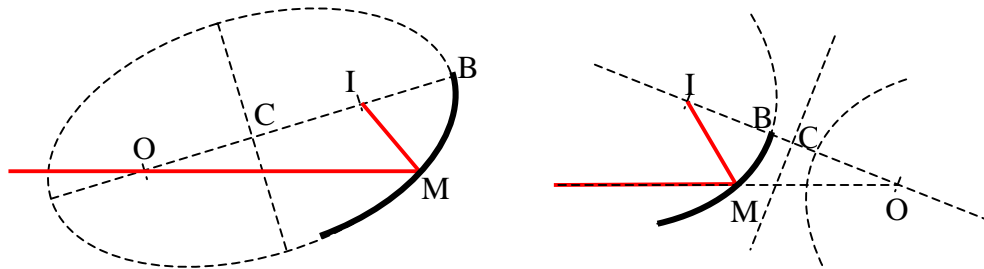


Figure 1. Illustration off-axis mirrors with quadric surfaces. An ellipsoid surface is presented on the left and a hyperboloid on the right. The placements parameters in Table 4 are the angle MOB, and the distance MB projected along the line OM and a line perpendicular to OM.

The placement of a mirror is characterized by (1) the angle between the optical axis (OM) and the line defined by the two foci of the quadric (OI), and (2) the position of the quadric semi-major-axis border (B) from the mirror vertex (M). For L6 there is no offset, but 2 surfaces, so 2 radiuses of curvature and 2 conical constants in Table 4.

Table 4. Curvature and placement parameters of the quadric surfaces used for the bolometers new optics (M4, M5 and L6). The curvature parameters are given in terms of **radius of curvature** [mm] ( $R=b^2/a$ , where  $b$  and  $a$  are the quadric semi-major and semi-minor axes) and **conical constant** [dimensionless] ( $k = -e^2 = -(c/a)^2$ , where  $e$  is the quadric eccentricity;  $k < -1$  for hyperboloids,  $k = -1$  for paraboloids,  $-1 < k < 0$  for ellipsoids,  $k = 0$  for spheres) ; in the current status of the study, there is no aspherical corrections yet, so only images on the optical axis are perfect. For identical optical solution (same distances between object focal point O, mirror vertex M, and image focal point I) but different cryostat orientations, the parameters are different (same  $a$ , but different  $c$ ) due to different angles of reflection.

Elements	M4	M5	L6
New bolometers, cold M5 telecentric, cryostat vertical	3598, -10.4 (15.4; 148, 431)	731, -0.34 (20.9; 30, 612)	n/a
New bolometers, cold M5 telecentric, cryostat horizontal		769, -0.30 (19.5, 13, 568)	
New bolometers, cold L6 telecentric, cryostat vertical	8407, -39.0 (18.7; 191, 513)	2187, -1.13 (47.0; 546, 776)	400, -2 350, -2
New bolometers, cold L6 telecentric, cryostat horizontal		2301, -1.13 (40.1; 417, 719)	
New bolometers, small cold L6, cryostat vertical		2187, -1.13 (47.0; 546, 776)	300, -6 500, -3
New bolometers, small cold L6, cryostat horizontal		2301, -1.13 (40.1; 417, 719)	

With all the new elements in the receiver cabin and the mirror M3 at the center of the beam, the proposed design offers the advantages of simplicity and low cost. It differs from the favorite proposition of my previous document on several points:

- Only 2 mirrors are used instead of 3; this limits the FOV to 11.5 arc minutes against 12 to 14 previously.
- M3 moves along 2 axis of rotation against 3 previously; allowing a simpler and cheaper motorization of the system, but implying a slightly bigger M3 for a given FOV and a more complex set of coordinate breaks in Zemax (5 breaks depend on elevation instead of 2).
- Several optical options with off-axis optics are proposed against only a telecentric M6 with vertical cryostat in the former proposition.

The two axis of rotation for M3 are along the azimuth axis and a perpendicular axis parallel to the cabin floor plan (this 2<sup>nd</sup> axis is not the telescope elevation axis, except for the heterodyne configuration). The movements of M3 are symbolized on Figure 2. For a given elevation  $t$ , the rotation angles  $h$  and  $g$  of M3 depend on the position  $x, y, z$  of the M4 vertex (values in Table 2 taken in the reference frame  $[X0, Y0, Z0]$  of Figure 2) and the distance  $d$  between M3 and M4 centers:

$$\tan(h) = \frac{-x}{z + d \cdot \cos(t)}$$

$$\tan(g) = \frac{y + d \cdot \sin(t)}{(z + d \cdot \cos(t)) \cdot \cos(h) - x \cdot \sin(h)}$$

In the focal plane of the telescope the FWHM size of a diffraction blob at the shortest wavelength is  $FWHM = (1.03 \cdot \lambda / D) \cdot F = (1.03 \cdot 0.8\text{mm} / 30\text{m}) \cdot 292\text{m} = 8 \text{ mm}$ . The distance between M3 and the telescope focal plane is  $d3F = 3.2 \text{ m}$ . Asking for a 20<sup>th</sup> of FWHM precision, the tolerance on each rotation motors of M3 is:

$$\Delta h = \Delta g = \frac{FWHM}{20 \cdot d3F \cdot \sqrt{2}} = 18 \text{ arcseconds}$$

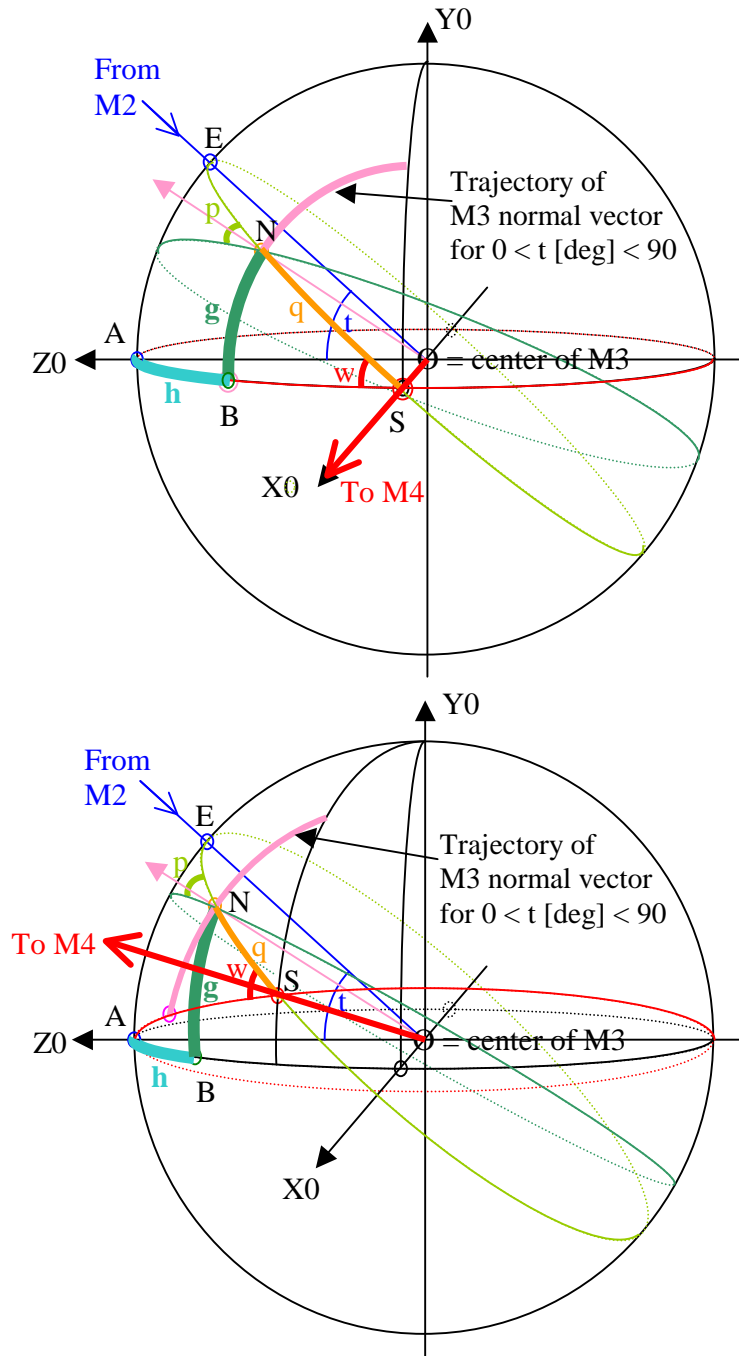
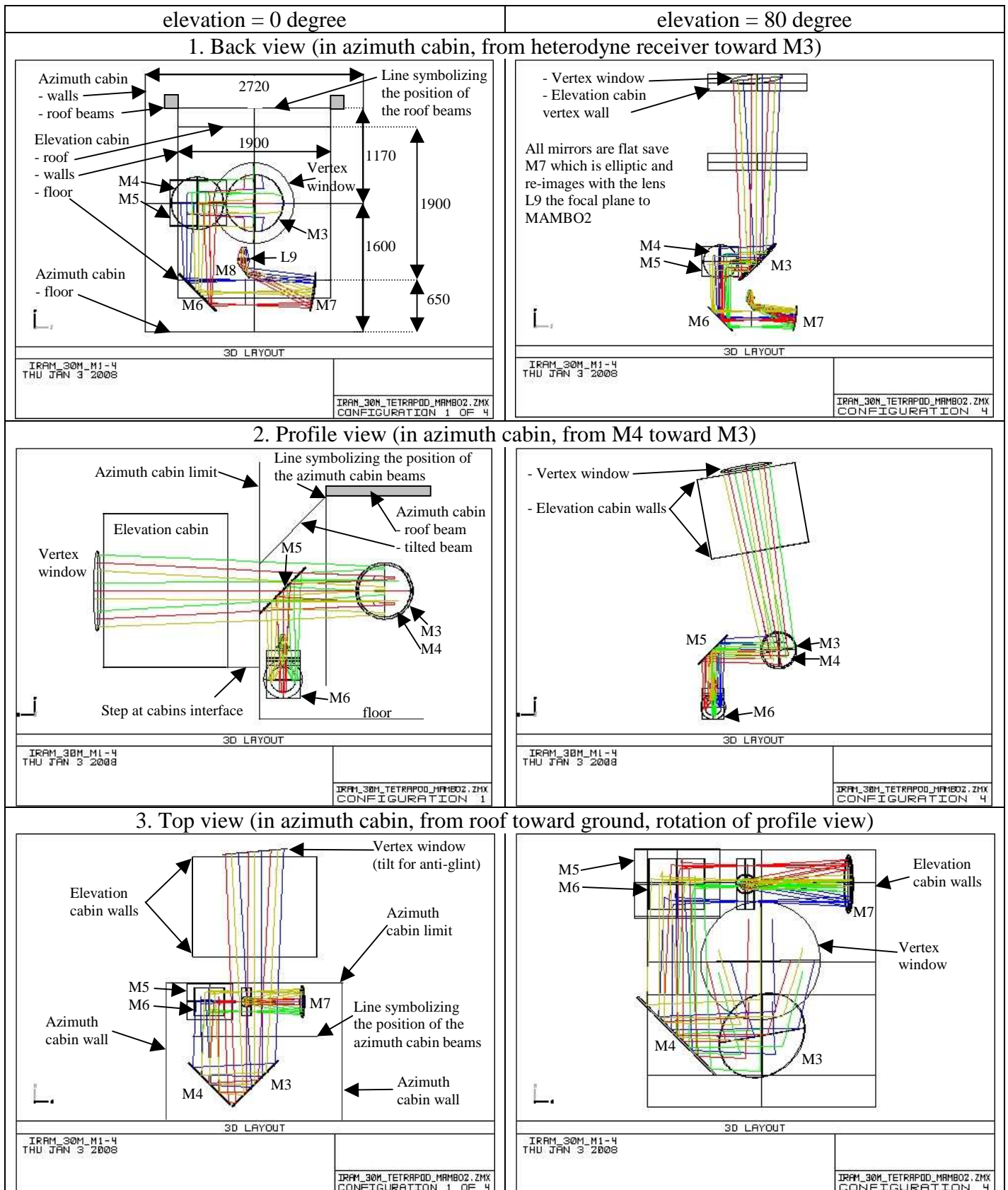


Figure 2. Symbolic 3D representation of the movement of M3 and coordinate breaks used in Zemax to follow the reflection on M3 of the optical axis incident ray (blue line) to the optical axis reflected ray (red line). The up drawing is for the heterodyne new optical system and the down drawing is for the bolometers new optical system. The coordinate system  $[X0, Y0, Z0]$  refers to the receiver cabin, where  $X0$  is the elevation axis and  $Y0$  the azimuth axis. E, N and S are at the intersections with the sphere centered on M3 of respectively the incident optical axis ray, M3 normal vector, and the reflected optical axis ray. A and B are the intersection with the sphere equator (plan  $[X0, Z0]$ ) of the meridians passing by  $Y0$  and respectively E and N. The 4 colored circles (plain line for the foreground and dotted line for the background) and the 6 angles  $t, h, g, p, q$  and  $w$  illustrate the coordinate breaks used in Zemax. The angles  $t, h, g$  are respectively the elevation, and the 2 rotations of M3 allowing to redirect images at various elevation to a fixed M4. For the heterodyne case  $h = 45$  degrees for all elevations as in the current configuration.

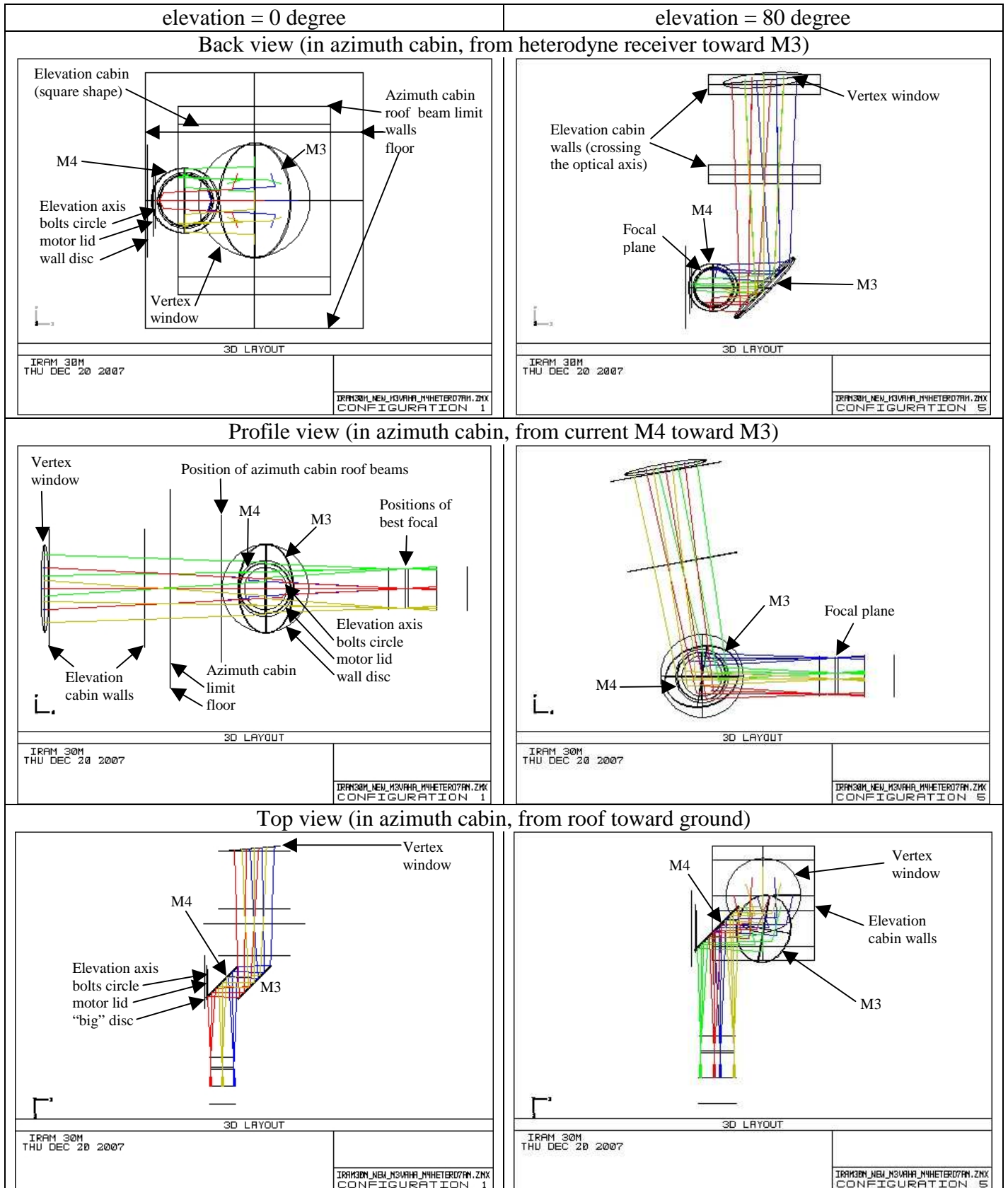
## 2D projections from Zemax for the current and proposed optics.

The dimensions in the drawings are in mm.

### 1. Current disposition of mirrors M3 and M4, and Mambo 2 optics.

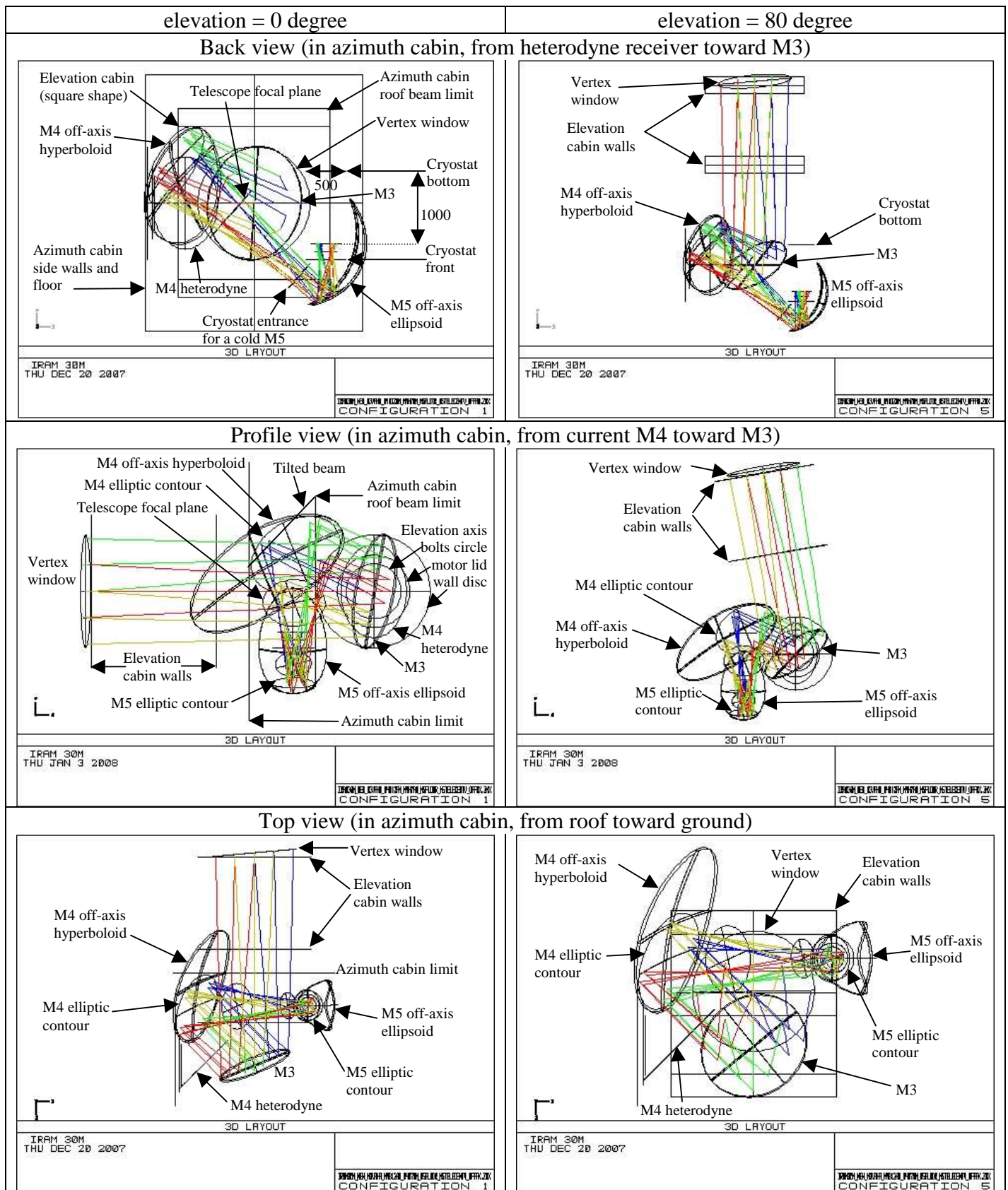


## 2. New optics for heterodynes (7.4 arc minutes).



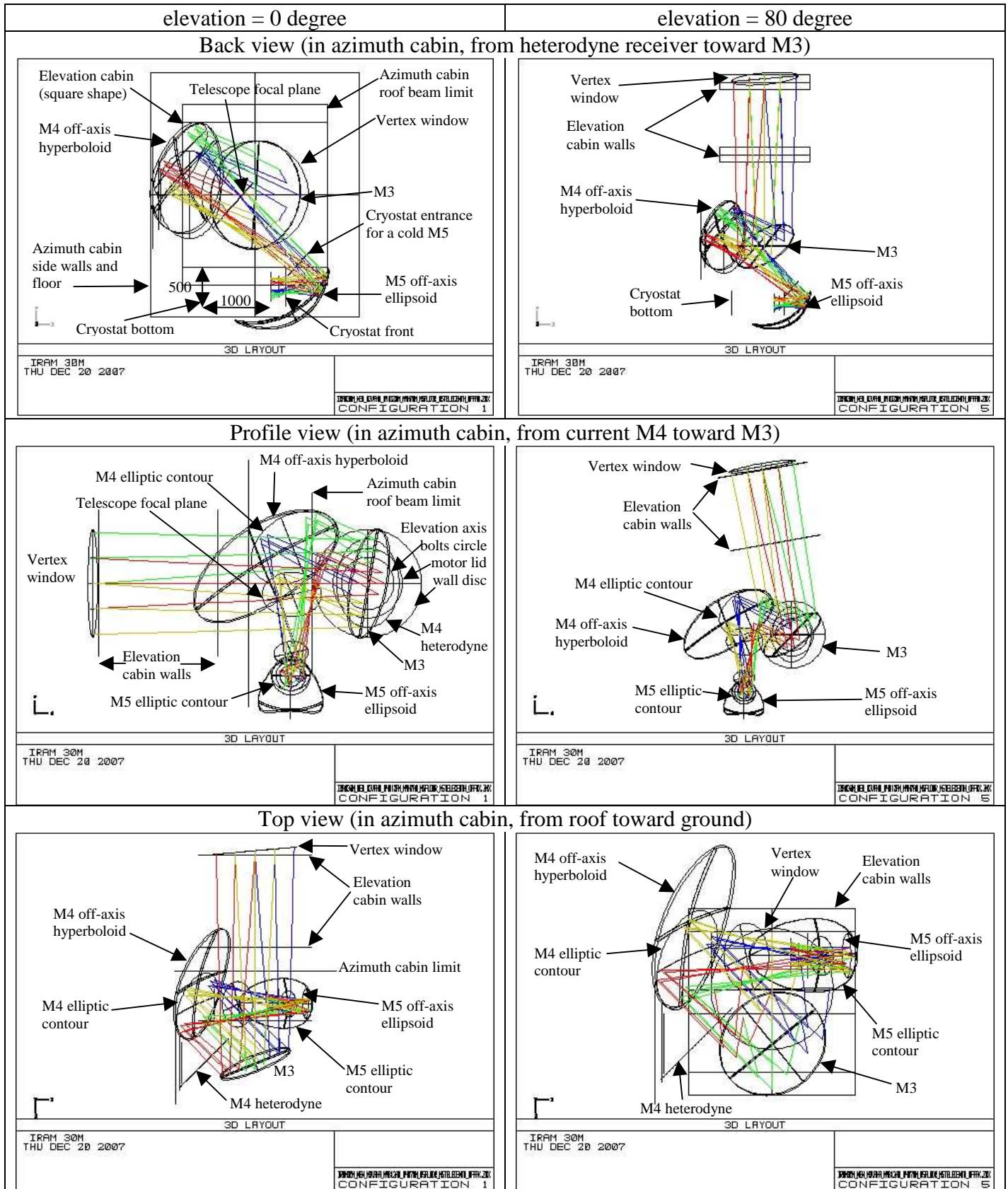


### 3.1.1. New optics for bolometers (11.5 arc minutes), M5 telecentric, cryostat vertical.

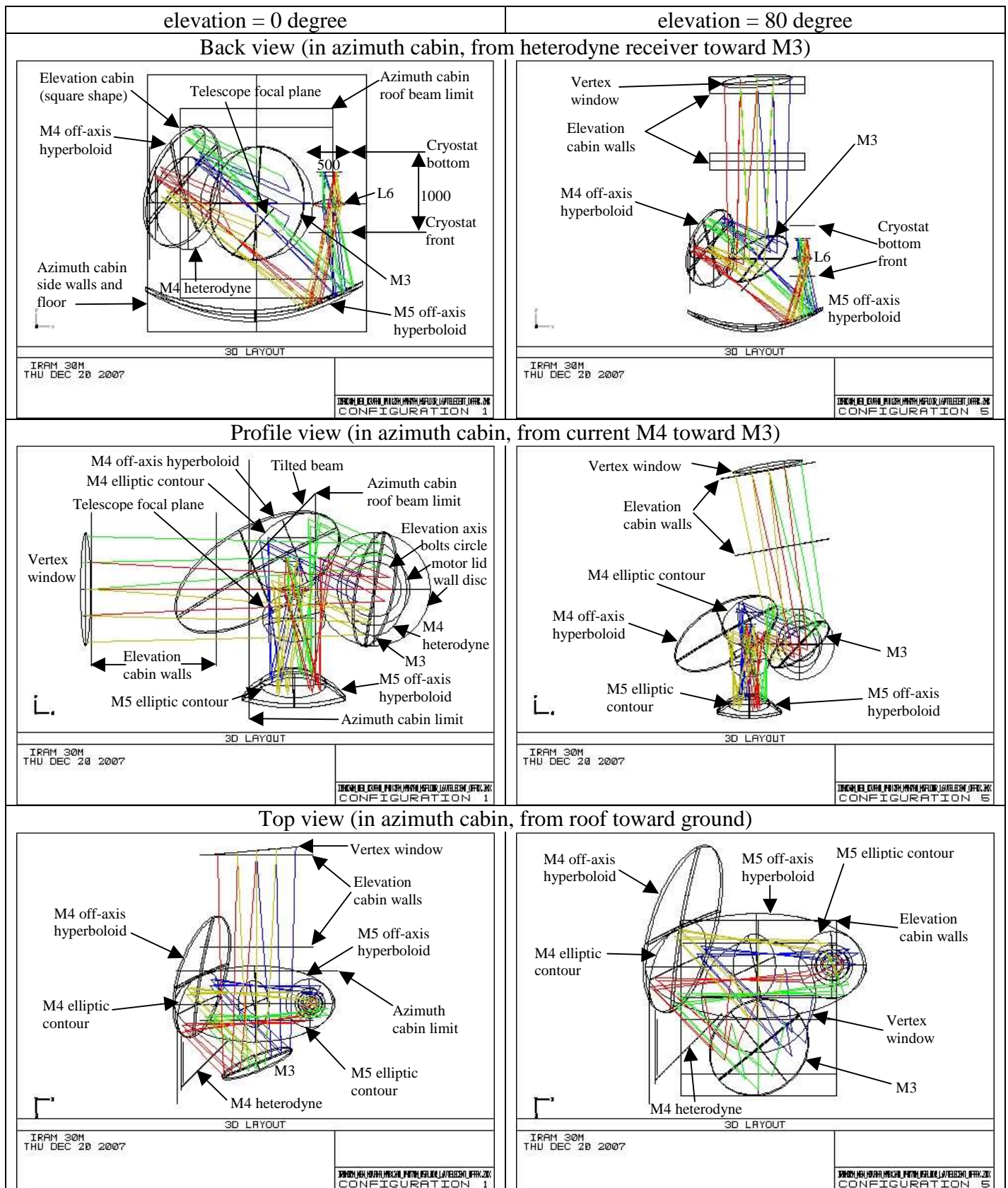




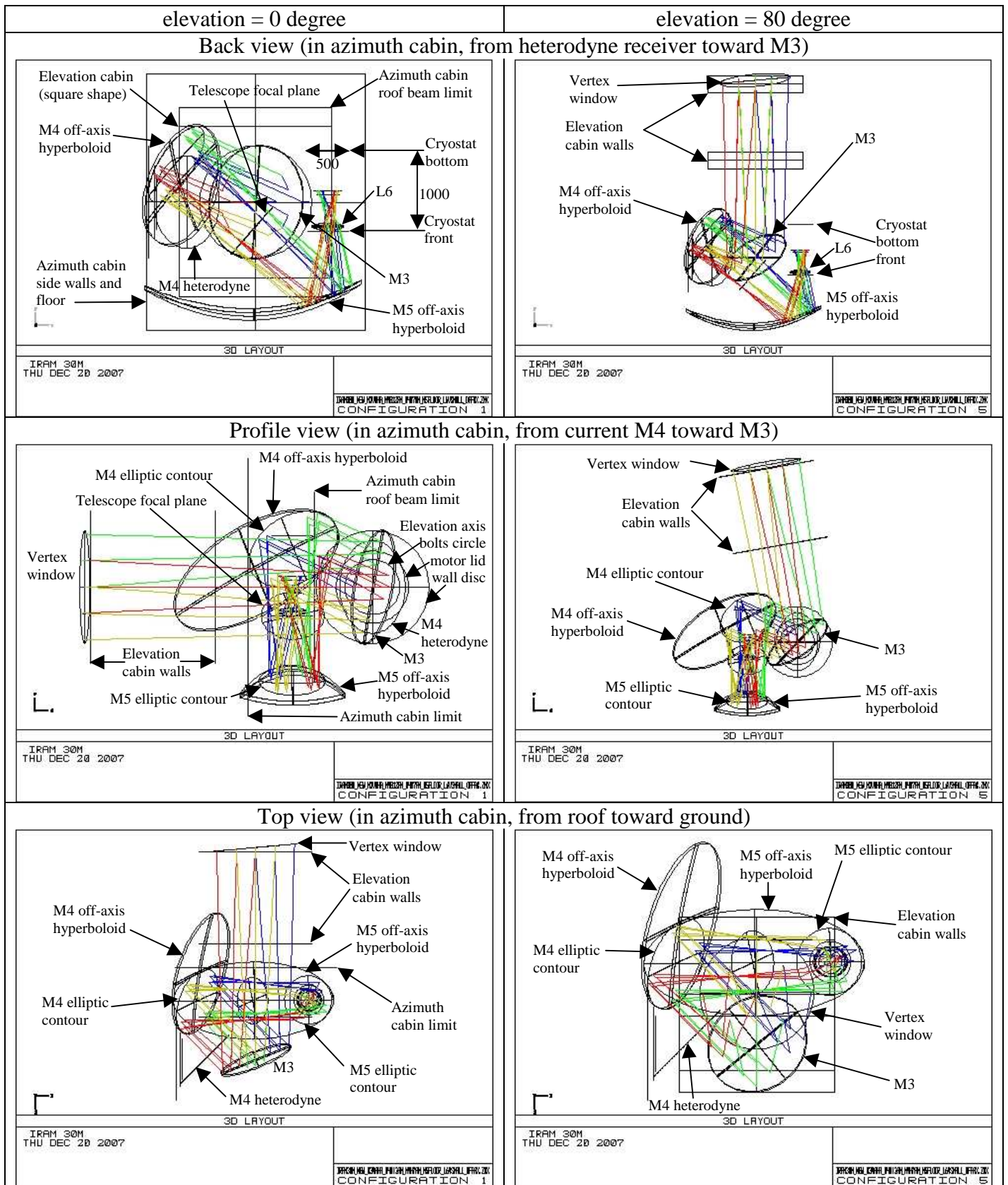
### 3.1.2. New optics for bolometers (11.5 arc minutes), M5 telecentric, cryostat horizontal.



### 3.2.1.1. New optics for bolometers (11.5 arc minutes), L6 telecentric, cryostat vertical.

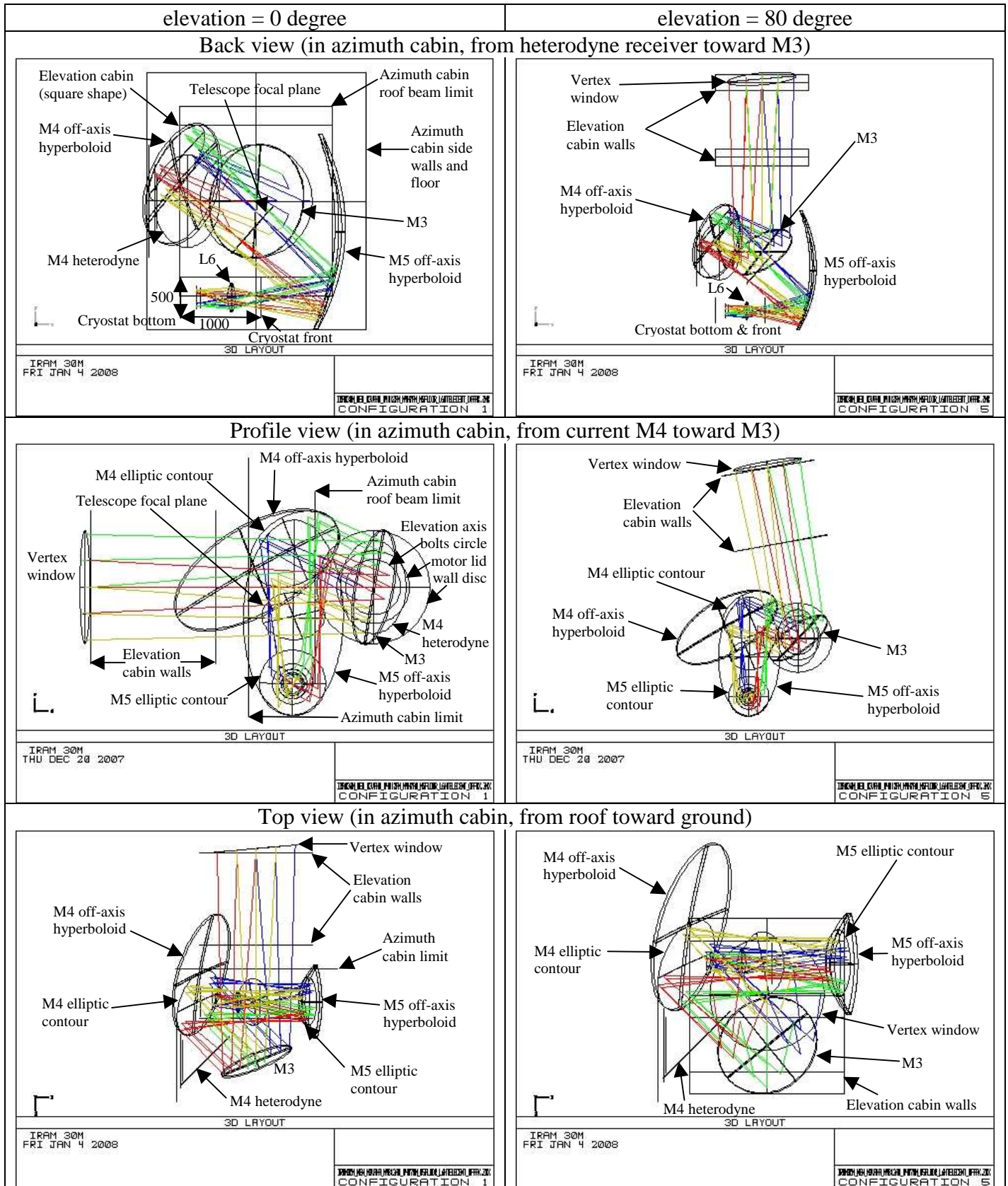


### 3.2.1.2. New optics for bolometers (11.5 arc minutes), L6 small, cryostat vertical.

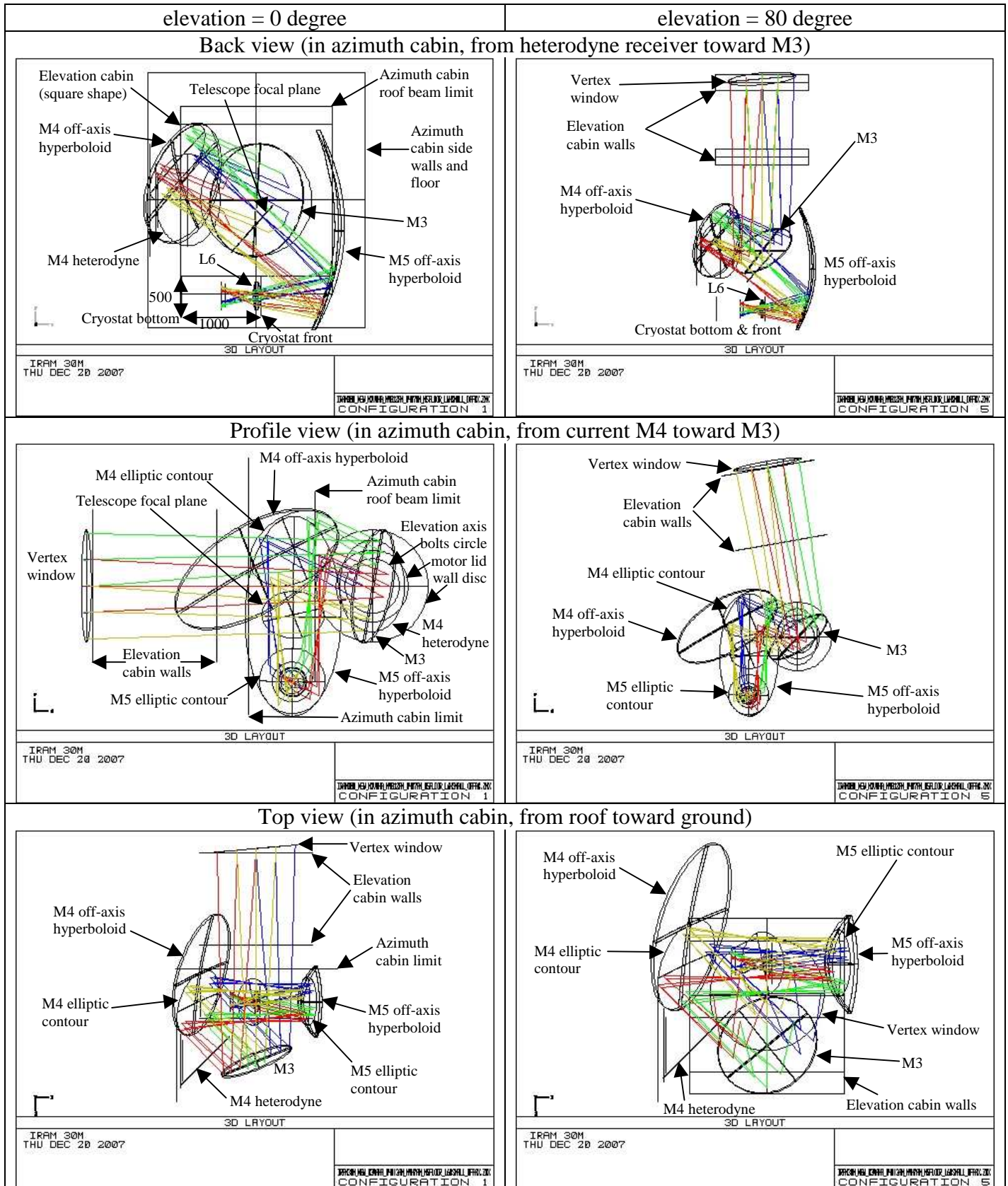




### 3.2.2.1. New optics for bolometers (11.5 arc minutes), L6 telecentric, cryostat horizontal.



### 3.2.2.2. New optics for bolometers (11.5 arc minutes), L6 small, cryostat horizontal.



## **Planning of tasks and costs for the proposed new cabin optics of the 30m telescope.**

The tasks needed to accomplish the realization of the new optics are listed in the Table 5 with their estimated cost and date of realization. This table benefits from J.L. Pollet's remarks on a draft version written in November 2007 for on-axis spherical mirrors.

Few noticeable points do not appear clearly in the previous pages but worth to be stressed before listing tasks and costs:

- The design is presented for the biggest field of views possible (heterodynes and bolometers), therefore the margins available for the positions of the mirrors are so small that some mirrors need to be grinded on small parts of their thickness to fit perfectly at the allocated positions. The illumination of the mirrors is not perfectly elliptic, so more sophisticated cut of the mirrors contour would allow more margins. Of course smaller fields of view increase also the margins.
- The support structures of the mirrors have not been studied yet, and some mirrors (like both M4) are very close to the walls and cabin roof and tilted beams. Though the design has been thought with this constraint in mind and enough room for the supports is already available.
- The cohabitation of M4 heterodyne (M4h) and M4 bolometers (M4b) is possible at the condition that M4h is mounted on vertical rail allowing to lower the mirror close to the ground during bolometer observations and to put it back in place for heterodyne observations. If the support structure of M4h is well designed, there is no need to move M4b for heterodyne observations.
- The chopper currently in place in the cabin is too small for the new heterodyne field of view, and its support structure is in the way of M4b. Thus for the new optics it will be necessary to dismount the chopper and change it or at least change its support structure. Since some decision must to be taken to include or not the chopper in the new optics works, nothing concerning the chopper is listed in the following table.
- The aspheric corrections for the minimization of aberrations of the new bolometer optics are not defined yet, but their optimization should reduce the size of the beam on some portions, giving more margins for the placements.
- 3 different designs with 2 cryostat positions each are proposed for the bolometers optics. It is probable that only one of these options is enough to covers all the needs of a future instrument. It is surely desirable to discuss the matter with the candidate teams for the realization of the instrument. As a start point, I make the hypothesis that the cold lens option is chosen; it is maybe not the optimal solution, but it is the most common and uses the biggest M5, therefore the most expansive, which give the upper cost estimation. In the budget I suppose IRAM will built the mirrors M3, M4h, M4b and 2 M5 (one per cryostat orientation) and the candidate teams will built the optional cold L6 (though IRAM has the savoir faire for the fabrications of such lenses).



Table 5. Provisional timetable for the new optics of the Pico Veleta 30m telescope. All costs given here include material only, not salary.

Task	Cost [k€]	Start time	Duration	Comments
Duration is in weeks from start time to end time, (not necessarily continuous work).				
<u>DONE:</u>				
Pre-study	0	12-sept-06	2	Bibliography => 3 solutions: all vertex / el axis to vertex / el axis to az cabin
1st definition of objectives and constraints	0	13-sept-06	1	FOV / Room / Mirror sizes / Rough cost
Study and choice optical design software	0	28-sept-06	16	Tests & 30m in Optalix and Zemax, biblio others => Optical_software_investigation
Buy Zemax EE	2,1	6-févr-07	1	Licence for new version including physical optics
Simulation Zemax various configurations	0	19-avr-07	9	All mirrors 30m telescope, with cabin benchmarks, 0-90 elevation, bolo & hetero
Study movements non-Nasmyth M3	0	15-mai-07	5	Excel: calcul_param_new_M3. A.Leandri : 30m in Solid Works, rapport de stage.
Send document different solutions	0	27-avr-07	8	New_cabin_mirrors_for_30m_telescope v1 -> v3 (best solution = hetero 7am, bolo 12am)
Improved study based on best solution	0	26-nov-07	4	Tougher constraints => new design, off-axis, different cryostat optics and orientations
<b>Total pre-study: 2,1</b>				
<u>TO DO:</u>				
Final decision on the optics design	0	janv-08	1	
Curved mirrors aspheric corrections	0	janv-08	4	Need to learn and use physical optics and optimization tool in Zemax
Study of motors for M3 and M4h	0?	janv-08	8	2 axis of rotation for M3, up-down translation for M4h
Study of mechanical support for new mirrors	0?	janv-08	8	Definition of all structures at IRAM, but technical drawings and prod to contractor ?
Study of an integrated laser for alignment	0?	févr-08	8	Laser on tripod with micrometric orientation ?
Study of new support for chopper	0?	févr-08	8	Current support blocks path for M4b
Check of complete optics project	0?	mai-08	4	Will the Zemax definition be enough, or do we need a check by external contractor ?
Study of electronics for mirrors control	0?	mai-08	10	Includes electrical parts, electronics cards, control software
<b>+25 k€ IF STUDY DONE OUTSIDE IRAM</b>				
Consultation for approbation of the project	0?	juil-08	8	
Approbation of the project	0?	sept-08	4	
Buy raw material for M3	6.3	mai-08	16	
Buy raw material for M4h	3.3	mai-08	16	Estimation of raw Al cost based on past commands by JLPollet:
Buy raw material for M4b	4.5	mai-08	16	rough cost = 10 €/kg ; ~ 15% Al remain after machining ; Al density = 2,6 kg/dm <sup>3</sup> ;
Buy raw material for M5 (option cold lens & cryostat vertical)	2.5	mai-08	16	the volume of each mirror is estimated on contour semi-axes and 2cm thickness: V[dm <sup>3</sup> ] =
Buy material for M5 lens (option cold lens & cryostat horizontal)	2.5	mai-08	16	2a*2b*0,2
Buy optical quality disks mirrors	0,1	mai-08	16	1 disk per mirror, D = 50 mm
Buy 2 motorized rotary tables for M3	10	mai-08	8	Each table: ~10 arcsec accuracy, support > 10 kg
Buy 1 motorized linear table for M4h	3	mai-08	8	Position accuracy < 1mm, support > 10 kg
Buy support bars for M3 to M5	2	mai-08	10	AL bars: 5*0,1*0,1 m <sup>3</sup> /mirror ; 10 €/kg
Buy small hardware for mounting	1	mai-08	10	Screws, bolts, washers, tools ...
Legs for M3 and M4h ?	2	mai-08	10	Cut and move current legs or buy new ones ?
Buy electric and electronics parts	3	juin-08	8	
Laser system for alignment	2	juin-08	8	Laser, support frame, and micrometric screws

Machining preparation for M3	3,2	juil-08	16	
Machining preparation for M4h	1.7	juil-08	16	
Machining preparation for M4b	2.3	juil-08	16	0,5 * raw material cost per mirror
Machining prep M5 vertical cryo	1.3	juil-08	16	Preparation includes final technical drawings and machines programing
Machining prep M5 horizontal cryo	1.3	juil-08	16	
Machining prep optical disks	0,1	juil-08	16	
Realization of electrics and electronics	0?	juil-08	8	
Programming of control software	0?	juil-08	8	
Cut & polish M3	25.2	sept-08	16	4 * raw material cost per mirror
Cut & polish M4h	13.2	sept-08	16	5 steps: (1) rough out 2 faces, (2) finishing back face, (3) stabilization (~ 1 month for natural
Cut & polish M4b	18	sept-08	16	stabilization of Al 5083), (4) finishing front face
Cut & polish M5 v	10	sept-08	16	quadric shape with aspheric corrections at 15 $\mu$ m
Cut & polish M5 h	10	sept-08	16	rms surface accuracy, (5) control.
Cut & polish optical disks	1	sept-08	16	10 * raw material cost to polish to optical quality
<b>Total final study and fabrication:</b>	<b>129</b>			
Assemble and adjustment	0?	janv-09	10	
Ship all new optics material to Pico Veleta	5	avr-09	2	
Install new optics in receiver cabin	0	mai-09	8	
Annex costs	2			

**Total new optics project: 136 09/2006 150 New optics ready for summer 2009**

#### Remarks:

- In the table it is considered that all the mirrors are fabricated with the same method. In practice, it is maybe better to buy directly the flat mirrors M3 and M4h (need to be discussed with S. Navarro).
- The biggest uncertainty in the cost table comes from the “Cut & polish” lines: I chose the factor 4 as an intermediate between 2 rough extreme estimations from J.L Pollet: on one hand machining ~ 2x raw material cost, on the other hand a D = 1.5 m subreflector at 15  $\mu$ m rms total cost is about 100 k€.

As a conclusion, the project presented in this document proposes a new optics with a motorized M3, 2 new M4 (one 7.4 arcmin for heterodynes, the other 11.5 arcmin for bolometers) and 2 M5 for bolometers. 3 mirrors only are used for the bolometers against 7 currently.

**One big question remains: which of the bolometer options do we choose (re-imaging M5 alone or M5 for cold L6) ?**

The cost table is a rough estimate and could change significantly after discussions; likewise the operational date which could slip few months around summer 2009.