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TRSS : A Three Reflection Sky Survey at Dome-C with an Active Optics Modified-Rumsey Telescope

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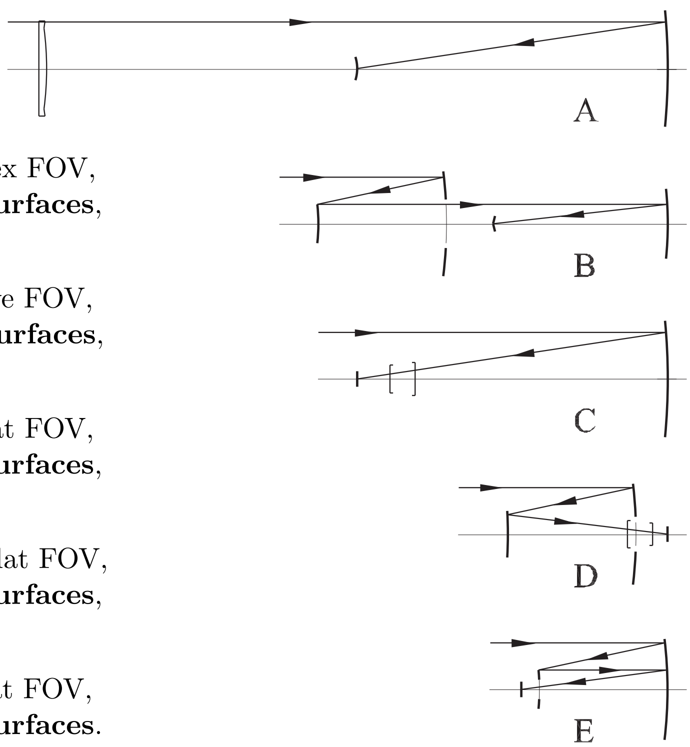
ABSTRACT : The Rumsey form of three mirror telescopes is an optimized design to achieve a flat field anastigmat with the minimal number of optical surfaces. This provides the capability of a wide field of view for astronomical imaging surveys. Compared to four other classic telescope designs, the Rumsey is the most compact, i.e. four times shorter than a Schmidt. In a *modified-Rumsey* form, such as presently proposed, active optics methods allow aspherizing the primary and tertiary mirrors by simultaneous spherical polishing of the two surfaces.

The presented diffraction limited quality obtained by a 44 cm aperture prototype – MINITRUST – demonstrates that a scaling up of the design with the largest monolithic Zerodur blanks of 8 m aperture by Schott should be feasible with the present state of the art. A 3-4 m aperture class *modified-Rumsey* telescope is proposed for a wide field survey imaging with a CCD detector array.

1 Comparison of Wide Field Telescopes for Astronomical Surveys

Five wide field designs are compared in Fig. 1. With a Rumsey-Lemaitre telescope, where actives optics methods allow the simultaneous aspherization of the primary and tertiary mirrors, the number of optical surfaces to polish is reduced to the minimum : only two surfaces are polished (cf. Fig. 1 - **E**).



(**A**) Schmidt with refractive corrector - convex FOV,
1 aspheric, length $\simeq 2F$, **3 polished surfaces**,

(**B**) Mersenne-Schmidt by Willstrop - concave FOV,
2 aspherics, length $\simeq F$, **3 polished surfaces**,

(**C**) Paraboloid and triplet-lens corrector - flat FOV,
1 aspheric, length $= F$, **7 polished surfaces**,

(**D**) Ritchey-Chrétien + doublet corrector - flat FOV,
2 aspherics, length $\simeq F/2$, **6 polished surfaces**,

(**E**) Modified-Rumsey continuous M1-M3 - flat FOV,
3 aspherics, length $\simeq F/2$, **2 polished surfaces**.

Fig. 1 - Telescopes with identical input beam aperture, focal length and field of view.

Among the existing imaging survey telescopes using large CCD arrays, the most remarquable of them are the following :

- Sloan Digital Sky Survey - SDSS : Design (**D**), $d_1 = 2.5$ m, f/5, FOV 2.0×1.5°,
- CFHT with Megacam : Design (**C**), $d_1 = 3.6$ m, f/4, FOV 1.0×1.0°,
- Converted-MMT with Megacam : Design (**D'**), $d_1 = 6.5$ m, f/5, FOV 0.5×0.5°.

2 Optical Design of a modified-Rumsey : MiniTrust-1 and -2

In order to built a large three reflection survey telescope, we have developed the active optics method and evaluated the performance by constructing two identical 44-cm aperture telescopes, "MiniTrust-1 and -2", following design **E** (Fig. 2). The optical parameters (Table 1) have been optimized for obtaining – by elastic continuity – the primary and tertiary mirrors, M_1, M_3, in a single substrate, a spherical polishing at the same curvature and same in-situ loading (cf. Sections 3 and 4).

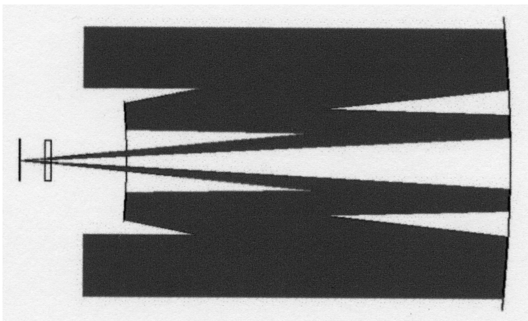


Fig. 2 - MINITRUST optical scheme with on-axis beams.

Norman Rumsey discovered the basic design of a three mirror flat field anastigmat in 1968 ([1]). He advocated the advantage of using a same blank for the primary and tertiary, thus avoiding the off-centering problem of these mirrors. In addition, we modify his design in order to obtain the hyperbolizations by active optics ([2,3]).

Considering the third-order theory of aberrations, 8 free parameters are availables : 3 mirror curvatures, 3 mirror conic constants and 2 axial separations of the mirrors. We use all of them for satisfying the 4 conditions $Sphe\,3 = Coma\,3 = Astm\,3 = Petz3 = 0$, for setting the back focal distance and for the 2 continuity conditions on sags and slopes of M_1 and M_3.

Table 1 - MODIFIED-RUMSEY design of MINITRUST – f/4.9 – 2° FOV – $\lambda\lambda$ [380 - 900 nm]

Slope and sag continuities of M_1-M_3 at $r = 90$ mm. $d_{1\,\max} = 440$ mm. Dimensions: [mm]

i	Surface	R_i	z_{Si}	D_i	E_i	Clear Aperture	(κ_i (⋆))
1	Primary	-2208.0	-630.000	$6.3905\,10^{-12}$	$3.1327\,10^{-19}$	440	(-1.5503)
2	Secondary	-1096.0	630.005	$2.7995\,10^{-10}$	$-2.4184\,10^{-16}$	Stop 200	(-3.9485)
3	Tertiary	-2197.2	-763.403	$7.5810\,10^{-11}$	$-6.9152\,10^{-17}$	180	(-7.4332)
4	Fused	∞	-10.000			59×59	
5	silica	∞	-25.000			58×58	
6	Focus	∞				56×56	

Equation of mirrors : $z_i = (1/2R_i)\,r^2 + D_i\,r^4 + E_i\,r^6$. Axial separations : z_{Si} .

(⋆) Equivalent 3$^{\rm rd}$-order Conic constant: $\kappa_i = 8R_i^3 D_i - 1$ ($\kappa = -1$ for a paraboloid).

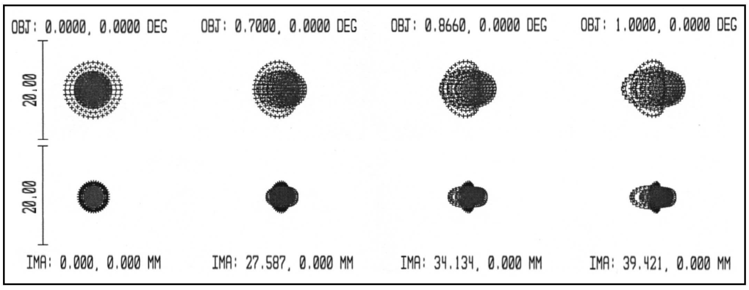


Fig. 3 - Residual blur images from Table 1 parameters. 2° FOV, $\lambda\lambda$ [380-900 nm]. (*Up*) 10 mm-thick plate (filter and cryostat window (*Down*) 5 mm-thick plate. Bars = 20μm. The chromatic variation of spherical aberration due to the filter and window plates is dominating.

3 Active Optics Methods

Several important advantages of actives optics methods can be stated as the following:

→ Generation of *smooth* and *accurate* optical surfaces, since using full size figuring tools. Therefore, no slope discontinuities appears. The high spacial frequency errors does not exist which classically are inherent to local polishing tools.

→ Capability of generating *non-axisymmetrical* and *variable-surface* optics by using vase form, meniscus form, tulip form, cycloid-like form, etc ([2–4]).

The present field developments of Active Optics methods are, for instance:

1 - Large amplitude asphERIZATION of optics by *stress polishing* and/or by *in situ stressing*,[2–12]

2 - *In situ compensation* of large telescope mirrors due to their deflection in the field gravity,[12–14]

3 - Availability of a *variable asphericity* for telescopes with multi focii selected by mirror interchanging,[6,7]

4 - Field compensation and cophasing of optical telescope arrays by *variable curvature mirrors*,[4,15]

5 - Segments and diffraction gratings aspherized by *replication techniques* from *active submasters*,[6]

6 - Mirror *concept* with superposition mode capability useful for *adaptive optics systems*.[15–17]

4 Elasticity Design of M_1-M_3 Substrate by In-Situ Stressing

The analysis of the deformation to achieve is carried out with the Reissner Theory of Shell by using variable thickness distributions of the mirror substrates M_1, M_2 and M_3, and a uniform loading. For M_1 and M_3 mirrors, the elasticity parameters are derived from basic *vase form* configurations (Fig. 4) where one searches for the thicknesses of the adja

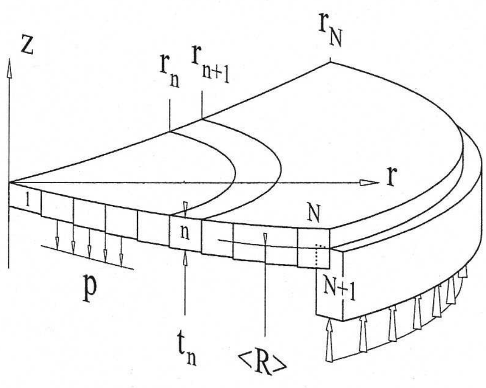


Fig. 4 - THEORY OF SHELLS: Geometrical parameters of an element ring.

The elasticity design of M_1-M_3 has been considered with these mirrors on a common substrate in vitroceram Zerodur which is polished spherical with a full aperture tool. This led to develop a particular substrate geometry called a *double vase form* ([3]).

The M_1-M_3 substrate is surfaced and polished spherical when not is applied on it. The hyperbolizations are achieved by *in situ stressing* i.e. at the telescope. The loads generated by air de-pressures are the same for the two mirrors and denoted p. An appropriate intermediate ring provides the link between the mirrors which takes into account the reduced rigidity of the tertiary, thus ensuring a polynomial form deformation of the primary. The Young's modulus and Poisson ratio arfe denoted E and ν. The result of iterations with a dedicated code allows defining the substrate geometry, that is, axial thickness t_{z13} vs radius r (Table 2).

In the converging process, the sum of the spherical figure with the flexure, which gives the optical shape, was carried out in a repe

Table 2 - Elasticity design of M_1-M_3 global substrate – DOUBLE VASE FORM.
Zerodur : $\nu = 0.240$, $E = 920\,10^3\,\mathrm{kgf/cm^2}$. Load $p = -0.8\,\mathrm{kgf/cm^2}$. Dimensions [mm]

r	0	18	36	45	54	63	72	81	90^-	
t_{z13}	12.042	12.044	12.053	12.061	12.070	12.082	12.096	12.112	12.130	
r	90	110	110^+	132	154	176	198	220^-	220	240
t_{z13}	30.190	30.183	20.317	20.402	20.502	20.617	20.741	20.868	68	68

Two alternative designs of the M_1-M_3 substrate are displayed by Fig. 5. These designs use both the above thickness distribution and their outer ring have an equivalent rigidity with respect the outer boundaries reacting at the primary outer edge.

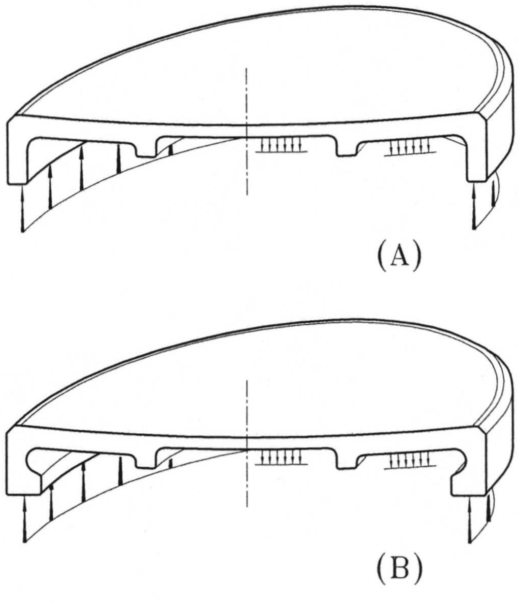


Fig. 5 - Two alternative geometries of double vase form for M_1 - M_3 substrate.
Design A : with cylindric outer ring. *Design* B : with folded L-shaped outer ring.

We selected realizing the design B which required a thinner blank. The M_1 - M_3 blank was shaped to the double vase form by diamond tooling with a numerical control machine by Cibernetix Corp. (Fig. 6). The substrate design is light weight but remains conveniently rigid, the outer ring preventing from astigmatism. The triangle or other angular deformation modes caused by the gravity effect are cancelled with a six-point rear support using three pivots couples. The enclosure ensuring the loading was realized by a metal disk optically ground for accuracy at the edge contact of the substrate and sealed with a removable rubber tape.

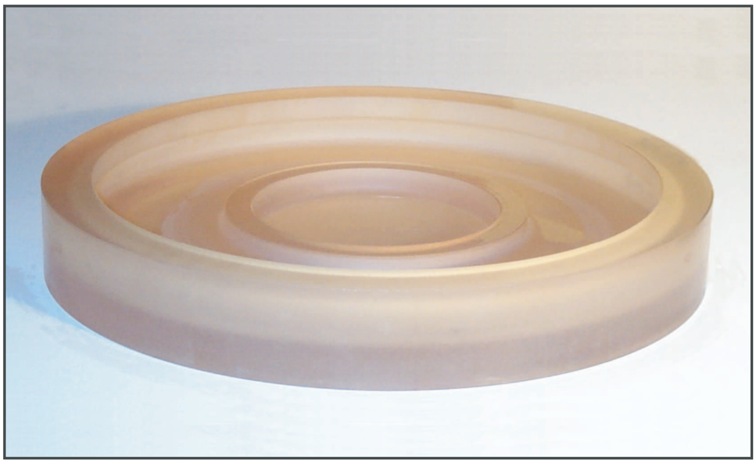


Fig. 6 - Rear view of double vase mirrors M_1-M_3 after diamond turning.

Fig. 7 - In-Situ Stressing - He-Ne Fizeau interferograms of M_1 and M_3.

Autocollimations achieved at $\sqrt{3}/2$ of clear aperture radius r_{max} with respect to a sphere. Aperture radii : $r_{1max} = 220$ and $r_{3max} = 90$ mm. From M_1 interferogram, the source is moved of 13.32 mm towards the substrate to get M_3 interferogram.

5 Elasticity Design of M_2 Substrate by Stress Polishing

Due to the central hole of MiniTrust secondary and in order to avoid adding central obstruction to the incident beams at primary mirror, it has been found interesting to develop an elasticity design based on a thickness distribution of the *tulip form* ([2,6]).

This form belongs to the class of variable thickness distributions (VTD) resulting from a force applied at the center for non-holed substrate. With this class we obtain a theoretical axial thickness $t_z(0) \rightarrow \infty$ which can be limited to a finite value in accordance to a small flexure residual within the Rayleigh criterion. Considering MiniTrust secondary, this form leads to a substrate starting with a rigid ring around the central aperture, continuing with a decreasing thickness for the clear aperture area, and ending with a null thickness. With this *free edge* solution, the outer diameter of the tertiary can be just little larger the tertiary clear aperture which is also the telescope pupil (cf. Table 1). A uniform load p is applied to all the rear area of the substrate while the reacting ring force is located at the rear side edge of the central rigid ring. For this, a central meniscus in Zerodur is mounted simply supported at is edge in order to close the rigid ring hole at optical side, thus also providing a better surface continuity of the polishing. An outside metal cylinder reaching the level of M_2 edge provides the enclosure for partial vacuum by using a waterproof paste.

Assuming that the middle surface of the substrate clear aperture will appear relatively flat, the theory of thin plates applies to the determination of the M_2 VTD. The boundaries are defined from 1) a bounded central meniscus of radius r_{int} closing the central hole for the polishing and also to improve the built-in condition, 2) a constant thickness rigid ring from r_{int} to r_{min}, 3) a VTD to be determined which is built-in at the ring outer radius corresponding to the M_2 inner clear aperture radius r_{min} and expanding up to the free edge of radius r_{ext} little larger than the outer clear aperture radius r_{max}. The resulting VTD for a uniform load $p = -0.80\,\mathrm{kgf/cm^2}$ is displayed by Table 3 and Fig. 8. The result of optical tests are in Fig. 10.

Table 3 - Thickness distribution of M_2 substrate – Tulip Form.
Zerodur vitro-ceram : $\nu = 0.240$, $E = 920\,10^3\,\mathrm{kgf/cm^2}$. Load $p = -0.8\,\mathrm{kgf/cm^2}$. Dimensions [mm]
Clear aperture radii $r_{min} = 50$ and $r_{max} = 100$. Outer edge $r_{\mathrm{ext}} = 103$. Stress $\sigma_{max} = 64\,\mathrm{kgf/cm^2}$.

r	30	50	50^+	60	70	80	85	90	95	100	103
t_{z2}	32.000	31.273	14.343	9.997	7.108	4.896	3.926	2.999	2.069	1.042	0.308 (°)
$z_{\mathrm{B}}(\star)$			9.318	5.471	3.173	1.641	1.044	0.512	0.200	0.000	0.000

(°) The thickness $t_{z2}(r_{\mathrm{ext}})$ is derived from the tangent at $t_{z2}(r_{max})$.
($\star$) z_{B} represents the shape of rear surface when not stressed which ends flat at edge.

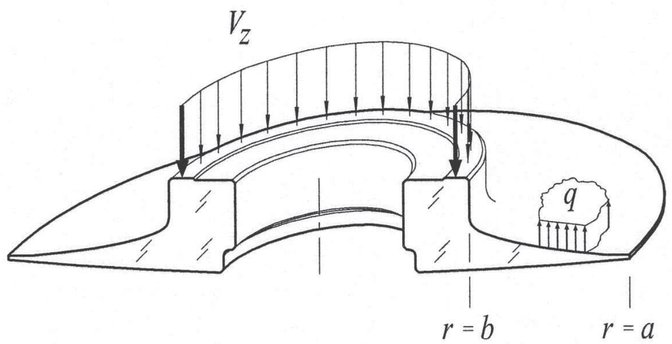


Fig. 8 - Tulip Form elasticity design of M_2 mirror – Pupil mirror.

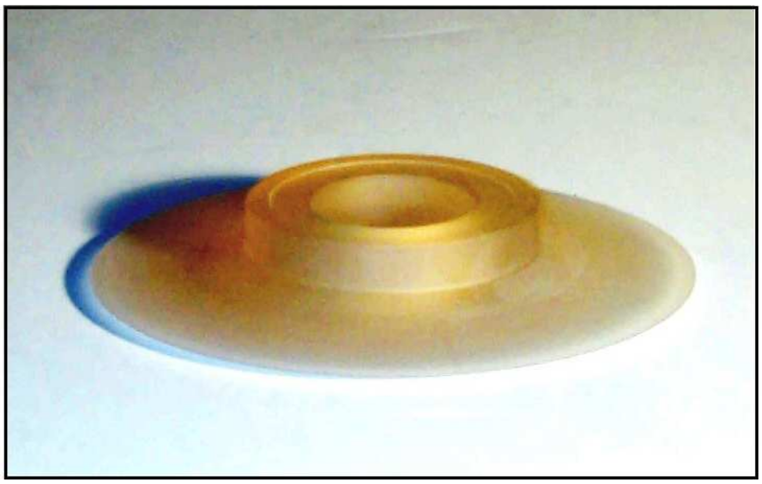


Fig. 9 - Rear view of M_2 Mirror – Diamond tooling.

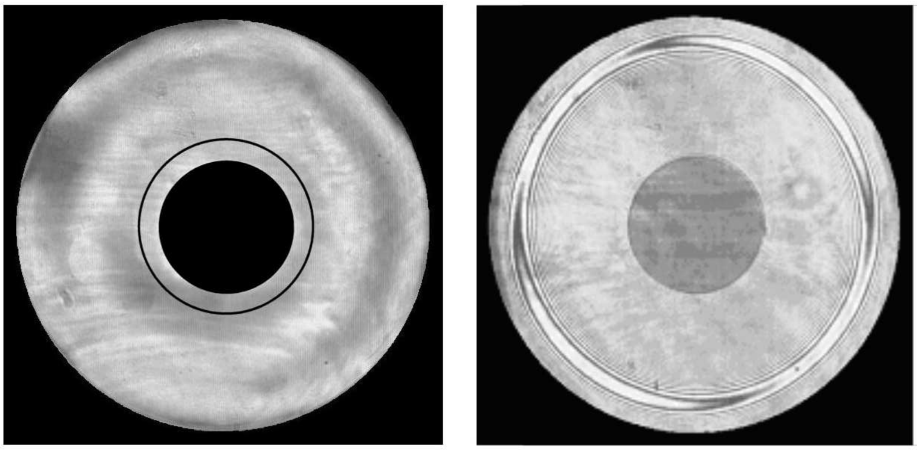


Fig. 10 - Hyperbolization by stress polishing – He-Ne Fizeau interferograms of M_2.
[*Left*] Mirror shape during stressing. [*Right*] Shape after elastic relaxation.

6 Integration and Interferometric Results with MiniTrust-1

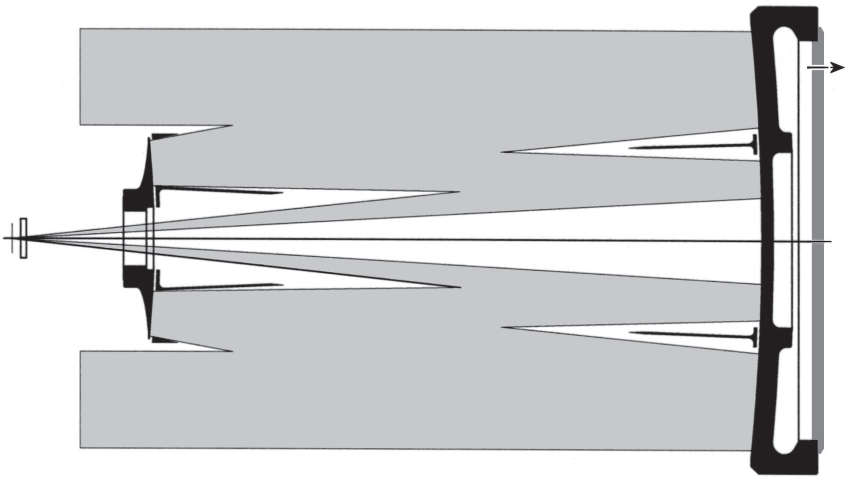


Fig. 11 - MiniTrust final design. Entrance pupil on M_2. Substrates. On-axis beam. Baffles.

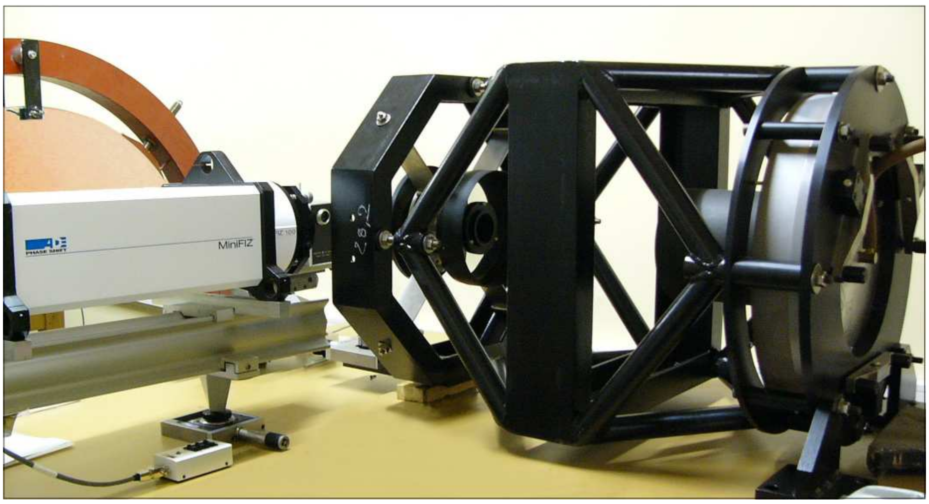


Fig. 12 - View of MiniTrust-1. Alignment and double-pass test by auto-collimation on a flat.

The final design of MiniTrust is displayed by Fig. 11. After integration of the optics in a Serrurier truss (Fig. 12), the first double-pass tests by autocollimation on a large flat showed on the axis a de-centering coma (Fig. 13-*Left*). After the optical set up of the spider supporting the secondary mirror, the double-pass wavefront showed a diffraction limited image (Fig. 13-*Right*).

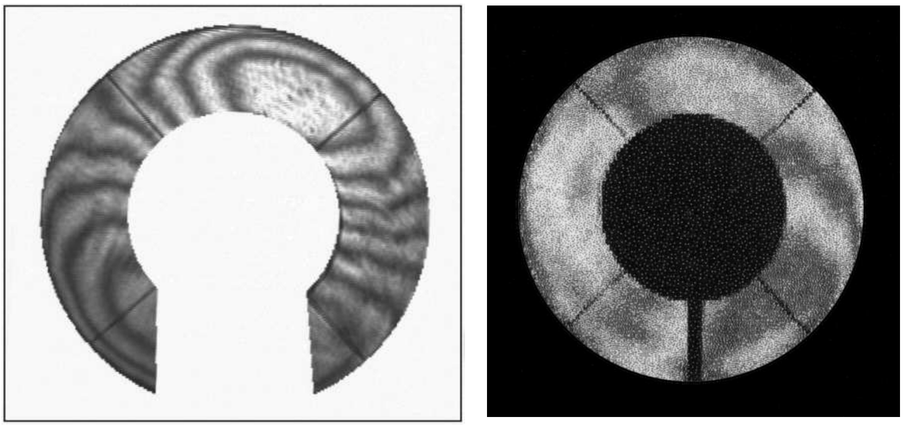


Fig. 13 - MiniTrust-1 optical tests: He-Ne wavefronts after double pass.
Left: Decentering coma before M_2 set up. *Right*: Wavefront after M_2 set up.

The final data reduction of He-Ne wavefronts, issued from double pass, analysed with a Phase-Shift interferometer gave the following PtV residuals

$$Sphe\,3 = 0.06\,\lambda, \quad Coma\,3 = 0.07\,\lambda, \quad Astm\,3 = 0.42\,\lambda,$$

where those quantities should be divided by two for a wavefront from a star: The sum including all the aberrations is

$$0.280\ \lambda\ \mathrm{PtV} \quad \Leftrightarrow \quad 0.048\ \lambda\ \mathrm{RMS}.$$

With this first telescope entirely built by active optics, the obtained optical quality demonstrates the great accuracy and potential use of these new methods for constructing larger telescopes.

7 TRSS Proposal: A Three Reflection Sky Survey at DOME C with an Active Optics Modified-Rumsey Telescope

The previous results encouraged us to investigate the development of a three reflection sky survey – called TRSS – based on the concept of an active optics modified-Rumsey telescope. For instance, considering a 3 m aperture design, a precalculation of the optical parameters (Table 4 and Fig. 14) shows a high performance imaging of 0.25 arsec blur images over a 2 degree field of view from ultraviolet to infrared (Fig. 15).

Table 4 - TRSS with a 3-meter aperture modified-Rumsey telescope.
f/5 – 2° FOV – $\lambda\lambda$ [300 - 1000 nm] – M_1-M_2 continuity of slopes and sags at $r = 560$ mm.

i	Surface	R_i	z_{Si}	D_i	E_i	Clear Aperture	(κ_i ($\star$))
1	Primary	-13298.8	-3936.356	$2.4238\,10^{-14}$	$5.674\,10^{-23}$	3000	(-1.452)
2	Secondary	-6577.6	3936.398	$1.4074\,10^{-12}$	$-3.208\,10^{-20}$	Stop 1140	(-4.204)
3	Tertiary	-13204.3	-4142.356	$4.5446\,10^{-13}$	$-5.116\,10^{-21}$	1100	(-9.370)
4	Fused	∞	-20.000			348×348	
5	silica	∞	-50.000			346×346	
6	Focus	∞				341×341	

Equation of mirrors: $z_i = (1/2R_i)\,r^2 + D_i\,r^4 + E_i\,r^6$. Axial separations: z_{Si}. Dimensions: [mm]

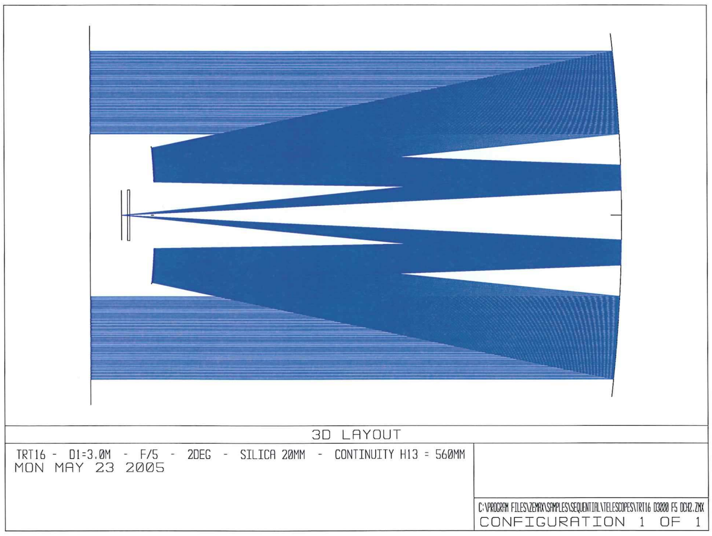


Fig. 14 - TRSS: d_1=3 m, f/5, FOV 1.5×1.5°, $\lambda\lambda$ [300 - 1000 nm].

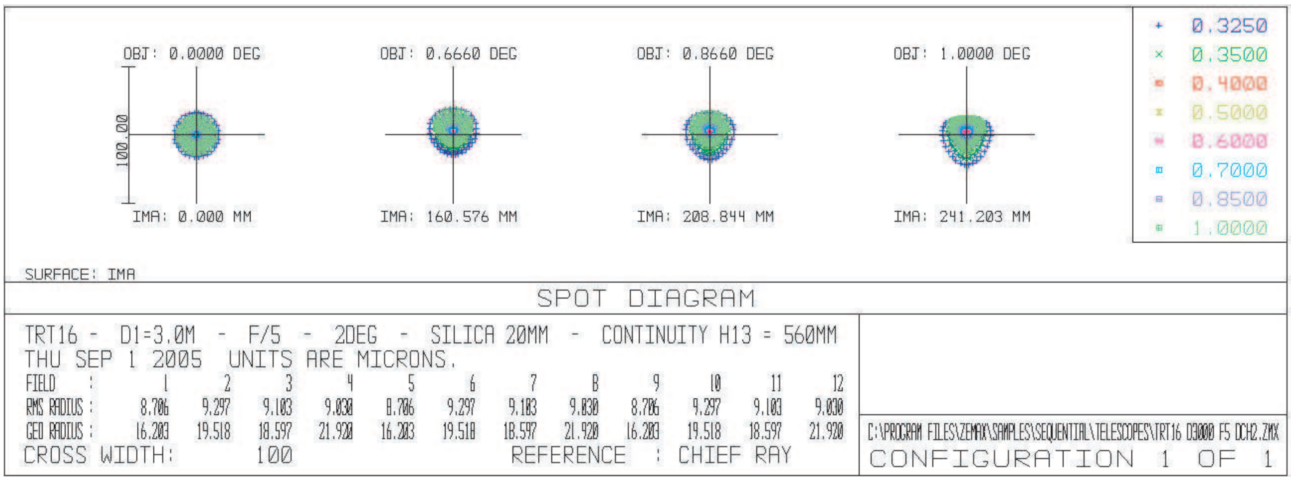


Fig. 15 - Ray tracing with TRSS. Diameter of image blur residuals: 18 μm RMS $\equiv$ 0.25 arcsec.

8 Conclusion

The project features lead to a compact telescope of high imaging quality which would benefit of a minimum number of optical surfaces to polish.

Active optics methods allow the simultaneous and spherical polishing of only one surface to hyperbolize both M_1 and M_3 mirrors; therefore all the telescope optics are achieved by the *polishing of two surfaces only*. The off-centering problem of M_3 with M_1 is canceled since those mirrors are in a same substrate. The supporting of M_1-M_3 mirrors against gravity deformations is considerably simplified by use of perimeter points at the mirror edge of M_3. A perfect asphericity is easily and accurately achieved by *in situ control* [10−14] of the intensity of a same uniform load applied over all the M_1-M_3 substrate. With only two spherical surfaces to polish and considering the performance obtained with MINITRUST, this compact design can provide a diffraction limited field imaging in any wavelength range.

Although large Zerodur blanks of 8-m aperture from the current technology by Schott are sufficiently homogeneous and would directly allow to actively built *Modified-Rumsey* telescopes in the 8-m class, we presently restrict to the proposal of such 3- or 4-meter aperture survey telescopes for observations from the ground (such at Antartica, Concordia station, Dome C [18−20]), where the seeing conditions in winter are presently under measurement but still remain to be confirmed as exceptional) and also from space.

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