

# Wide Angle Cross-Folded Telescope for Multiple Feeder Links

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**Abstract**— An optical design for a reflective wide angle afocal telescope is presented. The telescope is a transmit antenna for optical downlinks from GEO. The Antenna features three separate input ports for three different feeders and images them to three different foot prints on ground. These foot prints spawn over the western Mediterranean Sea from Portugal to Greece. Thus three actually different channels are served by a single optical telescope. In order to reach the desired extend of the field of view, the ocular mirrors were split into three individual mirrors, while the front mirrors of the objective serve all three channels. The telescope is folded twice: in y-direction to obtain an off-axis configuration and in x-direction to accommodate the three channels.

**Keywords:** *Wide-Angle Field of View Optical Communication Telescope, Point-to-Multi-Point Laser Communication*

## I. INTRODUCTION

In 2009-2011, RUAG Space contributed to the ESA sponsored Study “Optical Reliable Feeder Links (ORELIA)”. The study was led by the German Aerospace Center DLR. The study considered optical links from geostationary orbit to ground stations. An essential goal consisted in achieving simultaneous site diversity, i.e. the ability of the optical payload to link with different ground stations simultaneously. This simultaneous site diversity is of great advantage for maintaining the link availability and link capacity in the presence of clouds. When a particular optical ground station is expected to become covered with clouds, the links would seamlessly be transferred to other stations with better visibility. These ground stations would be distributed preferably over territories with anti-correlated weather. Such anti-correlated weather conditions exist for instance between the Western and Eastern Mediterranean Sea, but also to some extent between the North/South and the West/East sides of the Alps. A sample distribution of the ground stations is drawn in Figure 1. The footprint corresponds to a radial field of view of  $\pm 2.1$  degrees from the optical axis. The main driver was the West-East spread. In the North-South-Direction, the field of view could be reduced to  $\pm 1.6$  degrees.

Modern payloads for optical communication as described in [1] have a rather small field of view. It is sized just enough to perform the acquisition of a counter terminal whose position is known with sufficient accuracy. Their large pointing range is achieved by means of a Coarse Pointing device which typically covers the half hemisphere, i.e. much larger than needed here.



**Figure 1: Proposed Footprint Envelope**

The use of a Coarse Pointing device would also not be appropriate for the defined purpose as it would provide sequential point-to-point links rather than simultaneous links.

Our task consisted in achieving a ground coverage equivalent to  $\sim 2$  degrees off-axis pointing from GEO (Figure 1) with a single telescope and to omit the coarse pointing device. For a paired uplink/downlink of 50Gbps/20Gbps, the telescope needs to have an aperture of at least 200 mm and would be preferable a reflective configuration at least for the larger parts.

## II. FIRST ORDER PROPERTIES

The First Order Properties of Optical System and other basic requirements result from the intended use of the telescope (TABLE I.).

TABLE I. BASIC REQUIREMENTS ON THE OPTICAL SYSTEM

Requirement	Value	Justification
Field of View	$\theta = \pm 2.1^\circ$ WE $\theta = \pm 1.6^\circ$ NS	scope
Entrance Pupil E	EPD = $\varnothing$ 200 mm	from Link Budget
Exit Num. Aperture	NA' = 0.1 – 0.13	Monomode Fibre Matching
F-Number	F# = 3.8 – 5	from NA'
Effect. Focal Length	EFL = 0.76 – 1 m	from F# and EPD
Image Height	$y' = 28 - 36$ mm	from EFL and $\theta$
Obscuration Ratio for centered systems	$\Omega = 0.28 - 0.36$	$y'/(EPD/2)$
System Transmission	$\tau > 96\%$	results to -1 dB Tx loss
Wave Front Error	WFE $< 0.14 \lambda$	

The above mentioned primary requirements are obvious except one, i.e. the central obscuration for centered systems. This central obscuration is not only driven by the Secondary Mirror, but also by the image size. If the image is behind the Primary Mirror, then the Primary Mirror will need a hole inside. If the image is in front of the Primary Mirror, there will be installations to accommodate the Focal Plane Assemblies. In both cases this generates a central obscuration, which has to be considered as a minimum. It is useful to size a central Secondary Mirror such that it generates not much more obscuration than already determined by the image size.

### III. BASIC DESIGN PRINCIPLES OF REFLECTIVE WIDE ANGLE TELESCOPES

A paper from 1980 [2] lists four basic principles, based on symmetry considerations, to design wide angle reflective telescopes with corrections up to the 5th order:

- (1) Aperture Stop and correction device in the center of curvature of a spherical mirror (Schmidt-, Bouwers- and Maksutov- Telescopes) (Figure 2)
- (2) Confocality of two parabolic mirrors working at infinite conjugates (Mersenne Afocal Telescope)
- (3) Concentric Mirrors (Figure 3)
- (4) Polar Strip Field coverage between a  $\theta_{min}$  and a  $\theta_{max}$ , being not applicable for our purpose

A fifth principle (5) would be the Schwarzschild-1 configuration with identical curvatures for Primary and Secondary Mirror and reciprocal conical constants (Figure 4). The principles can be used on their own or be combined, for instance a combination of (2) with mirrors M-1 and M-2 and (1) with M-3 (Baker Telescope).

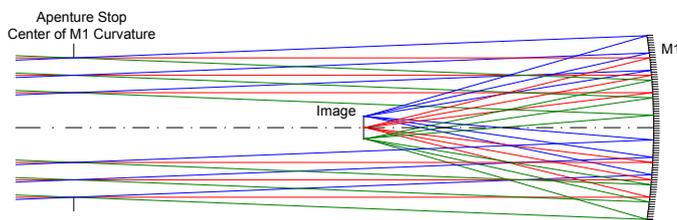


Figure 2: Aperture Stop at the centre of curvature of M1

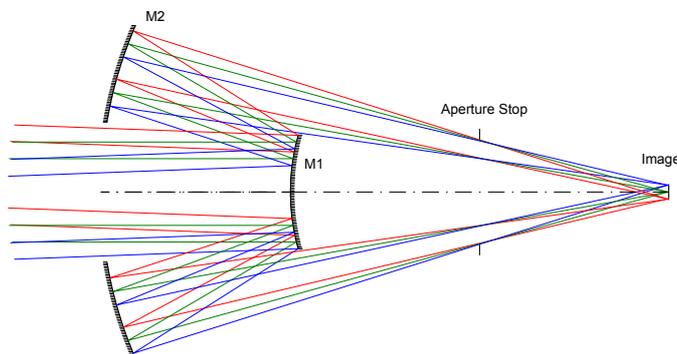


Figure 3: Telescope with concentric mirrors

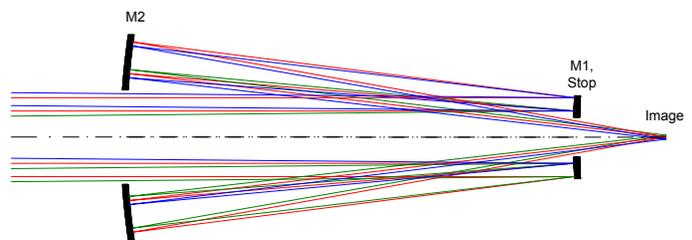


Figure 4: Schwarzschild-1 Telescope

The (3) and (5) are characterized by a Primary Mirror with negative power and consequently a Secondary Mirror which is larger than the Primary. Having in mind the required Entrance Pupil Diameter of 200 mm, the options (3) to (5) are quickly ruled out as Fore Optics and only (1) and (2) remain in the solution pool and are followed up in the next sections.

### IV. DESIGN ATTEMPT WITH A SCHMIDT-LIKE SYSTEM

Bernhard Schmidt discovered in 1929 the simple principle how to make the aberrations invariant to the field angle. If the Entrance Pupil is placed into the centre of curvature of a spherical mirror, nothing would happen if the beam rotates around this Pupil. The remaining need for correction concerns spherical aberrations. Schmidt solved this by inserting a free-form glass plate (“Schmidt-Plate”) at the Entrance Pupil. Bouwers (1941) showed that there is a simpler solution, i.e. a meniscus lens with surfaces concentric around this centre of curvature. A Maksutov telescope is a modification of the Bouwers such that the meniscus has aspheric surfaces. Our own design achieved a WFE of 22 nm in the center and 93 nm at 2.1° FoV (Figure 5).

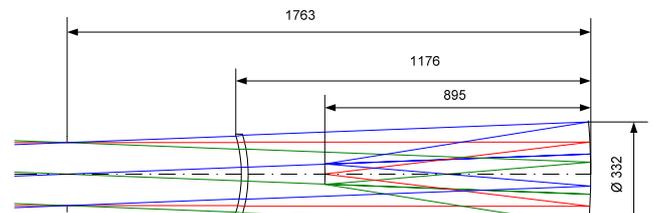
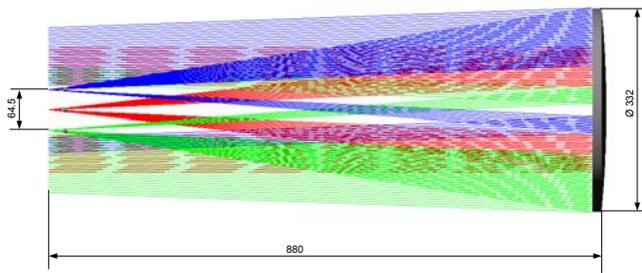


Figure 5: Design of a Maksutov Telescope with  $\pm 2.1^\circ$  FoV.

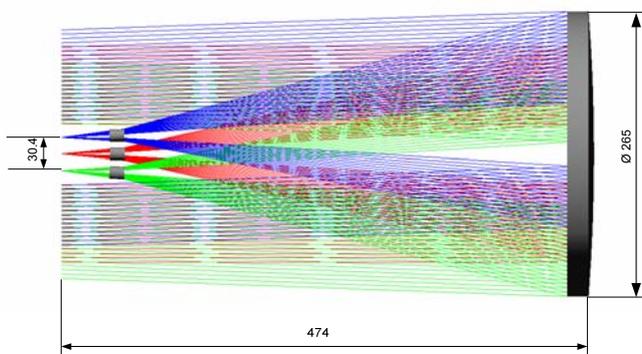
The Maksutov telescope achieves good imaging quality over the whole field of view. There are yet two objections against the use of such configuration: its considerable length and the presence of a big refractive component.

At this point, we introduce a constraint into the requirements of Table I: We assume no longer a continuous focal plane assembly, which uses a continuous field of view. Instead, we would have a set of optical feeders (Monomode Fibers) which would use a limited FoV for themselves, but maintain the overall FoV envelope for the whole set of feeders. The correction of the spherical aberrations would be transferred from the big meniscus lens in front to small aspheric lenses which are installed in front of the fibers (Figure 6). The big meniscus is eliminated by that way. The physical stop is also transferred to the feeder assemblies (fiber + lens). The directions of the chief rays, materialized by the alignment of the feeders, remain such that they intersect at the centre of curvature of the mirror, as if the Entrance Pupil would be there.



**Figure 6: Modified Schmidt with correction lenses in front of the feeders.**

The shown configuration of Figure 6 saved half of the length of the Maksutov (Figure 5). A further reduction of length is achieved if the lenses are not only used for the purpose of correction, but also introduce some power. In order to maintain the exit numerical aperture (fiber matching), the lenses are designed as focal reducers. The WFE results to 3 nm for all channels (Figure 7)



**Figure 7: Modified Schmidt with lenses for correction and focal reduction**

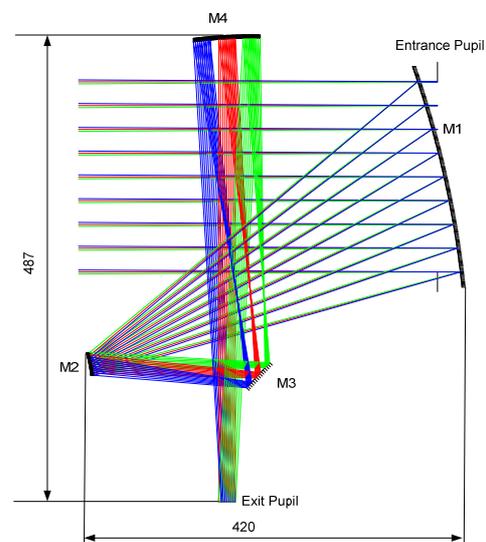
The focal reduction was a factor of two. We obtained a reduction in the overall length and of the size of the Mirror. At the same time, the focal length of the Primary Mirror has shortened by a factor of two. Consequently, the size of the image through the mirror becomes smaller by a factor of two. We have now less clearance between the feeder assemblies and consequently less feeder assemblies can be installed. The overall length trades against the space for feeders. The more feeders of the same type shall be installed, the longer the system becomes and the larger the mirror becomes.

## V. AFOCAL SYSTEM

The afocal system follows up option (2). The fundamental system was discovered by Marin Mersenne in 1636 and consists of two confocal parabolas. The intermediate image may be either real or virtual. The basic Mersenne-Telescope has two weak points: a considerable building length and an inconvenient position of the exit pupil. Access to the exit pupil is essential for the use of an afocal telescope.

More generally, an afocal telescope consists of two parts: an objective and an ocular. They are placed confocally, i.e. the

image position of the objective is identical to the object position of the ocular. For the purpose of Petzval correction, this intermediate image must be real. For a desired afocal magnification  $\Gamma$ , the focal length  $f_1$  of the objective is  $\Gamma$  times that of the ocular  $f_2$ . If the entrance pupil is placed on the Primary Mirror, the exit pupil distance  $t'$  results from  $t' = (f_1 + f_2)/\Gamma$ , thus  $t'$  is not much larger than  $f_2$  for magnifications of  $\sim 10$ . In order to obtain a comfortable exit pupil distance, one would design rather large  $f_1$  and  $f_2$ . Concerning the objective, this leads to considerable building lengths if the objective is made from a single mirror M1. The length can be mitigated by the introduction of a second objective mirror M2. The objective would become something like a Ritchey-Chretien-Telescope, which leverages the focal length against the building length. The system is made off-axis. An additional folding mirror M3 provides that the ocular mirror M4 can be put on the side and the beam is delivered to the exit pupil at the other side. The prototype of such configuration is shown in Figure 8 below. The field of view is yet small.



**Figure 8: Prototype of an afocal off-axis telescope**

Good correction can be achieved up to field angles of  $\pm 0.6^\circ$ . A larger field can be achieved by falling back on the approach used in section IV: We assume that particular feeders do not need to have access to the whole field and a continuous field of view is not needed. This enables to use a specific feature of the prototype shown in Figure 8: The beams for the three fields (red, blue, green) do not overlap on M3 and M4. The beam shifts over these mirrors along the field of view. Thus one could break these mirrors apart into 3 parts for instance. The three M4 could then have different aspheric designs and achieve better corrections for the larger field angles. Also, the tilt would be adjusted such that the three field segments are delivered to three different exit pupils [3]. By that means, we obtain three individual channels, which share only M1 and M2 as common components (Figure 9). The achieved FoV-envelope spawns  $\pm 0.62^\circ$  in North-South-Direction and  $\pm 2.12^\circ$  in West-East-Direction (Figure 10). The coverage spawns from Spain to the continental part of Greece (Figure 11). The Wave Front Error is between 20 and 65 nm.

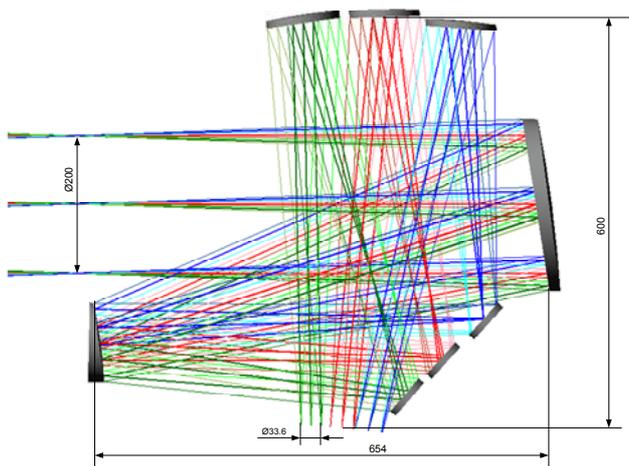


Figure 9: Afocal telescope with three individual channels

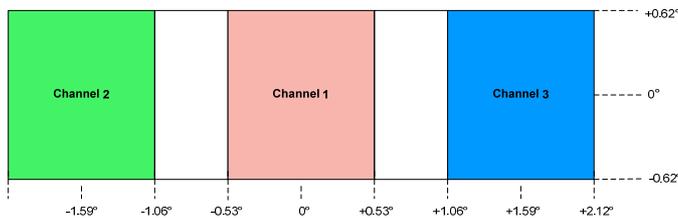


Figure 10: Field-of-View Plan



Figure 11: Resulting Foot Prints

During the design process, the challenge consisted in, apart from the efforts to obtain correction, to keep sufficient clearance of the components to the ray envelope. As can be seen in Figure 9, the space inside, in particular around the M3 and the exit pupils is really crowded. The potential of this design solution is exhausted for the given envelope.

There is yet potential to improve the situation. The system of Figure 9 has broken apart the components in the plane where the prototype was already folded. Thus the long field of view is also in this direction. A mitigation of the envelope constraint can be achieved by putting the long field of view into the across direction, i.e. perpendicular to the plane of folding. Such system is shown in Figure 12, together with three feeders represented by ideal lenses. The M3 are apart such that they could be made in the form of a single prism. The M4.2 (left channel 2) and M4.3 (right channel 3) are identical aspheres, making this a more economical solution.

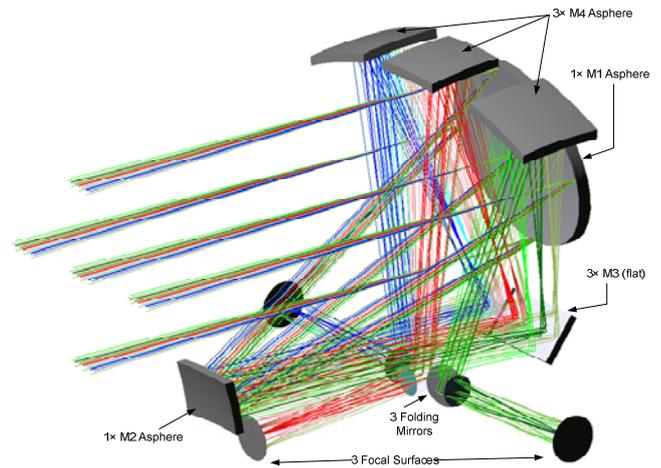


Figure 12: Cross-Folded Telescope

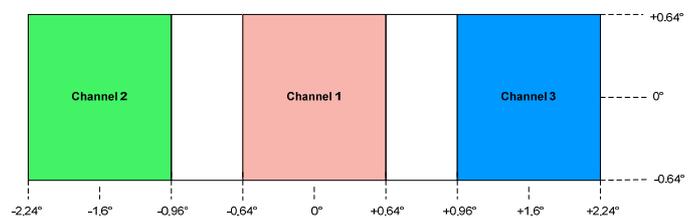


Figure 13: Field-of-View Plan of the Cross-Folded Telescope



Figure 14: Resulting Foot Prints

TABLE II. DESIGN ENVELOPE OF THE CROSS-FOLDED TELESCOPE

	Data
Magnification	8
Entrance Pupil	Ø 200 mm
Optical Envelope	401×301×258
Y-Field of View	±0.64°
X-Field of View	1: 0 ±0.64°
	2: -1.6° ±0.64°
	3: +1.6° ±0.64°
Wave Front Error	50 – 100 nm

The field of view of the segments (Figure 13, Figure 14) could be increased in the West-East-Direction and somewhat in NS-direction, while almost keeping their center directions. The separation between the three foot prints is less. But the main achievement was the comfortable clearance between the parts and the ray envelope. There is now sufficient space for three folding mirrors at the exit pupils. These folding mirrors could

be further designed as beam steering mirrors. By this way, each feeder connected to one particular channel could be steered over the whole foot print of that channel.

## VI. SUMMARY

We have identified two candidates for wide-angle telescopes which cover a major part of Europe from GEO and can provide simultaneous links to several ground stations. The first solution is a modified Schmidt-Telescope, where the Schmidt Plate is omitted and the correction takes place with lenses, which become part of the feeders. The second solution consists in a cross folded afocal telescope. The first folding makes the telescope off-axis, the second  $\times$ -folding breaks the ocular part of the telescope apart in three difference channels.

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