OWL OPTICAL DESIGN, ACTIVE OPTICS AND ERROR BUDGET

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Abstract

We explore solutions for the optical design of the OWL 100-m telescope, and discuss their properties, advantages and drawbacks in relation to top level requirements. Combining cost, design, fabrication and functionality issues, and taking into account the scale of the telescope, we conclude that the requirements are best met with a design based on spherical primary and secondary mirrors. The combined active and adaptive correction capability envisioned for the telescope allows substantial relaxation of otherwise critical subsystems specifications. We elaborate on the telescope correction capabilities, including alignment and focusing, and derive the structure of the optical error budget.

Keywords: OWL, extremely large telescope, optical design, active optics, error budget.

1. INTRODUCTION

The optical design of astronomical telescopes is, usually, a conceptually simple task; classical solutions involving a very limited number of surfaces are well known and the system and feasibility implications of each design parameter are generally evident. Feasibility of the primary mirror being frequently the main concern, it is also the first addressed and most discussions revolve around the blank technology, the mirror figuring and its focal ratio. The path followed in the conceptual design of the OWL 100-m optical telescope is, in this respect, rather conventional as early discussions focused on the mirror feasibility issue[1]. The exercise, however, is not to design a scaled-up version of an existing telescope concept, but to design a system that provides all functions necessary to realistically meet requirements. Once it appeared that the technological difficulty of the primary mirror fabrication had been largely overestimated[1,2,3], a broader assessment of the requirements, constraints and acceptable solutions underlying the optical design would inevitably follow. Of particular relevance is the fact that large telescopes are to be conceived as controlled opto-mechanical assemblies, whose optical design must be integrated into a global system approach.

This assessment supports early design considerations, which involve suitability of long-lead and high-cost subsystems for mass production, as well as built-in availability of critical functions such as active optics and field stabilization. The importance of field stabilization can hardly be overstated, for the sheer size of the telescope does not permit efficient shielding from wind buffeting. As will be shown later on, it also supports the idea that designs based on aspheric primary and secondary mirrors fail to provide substantial advantages over spherical primary mirror solutions.

The requirements applicable to the design and performance of the OWL concept are discussed elsewhere[4,5] and will only be briefly summarized (section 2). Concepts based on extremely large monolithic mirrors and very large adaptive components are excluded, in view of the unacceptable technology extrapolation and reliability issues such concepts imply. We also assume that adaptive correction of atmospheric turbulence is taken care of by dedicated subsystems and we require that the telescope concept minimizes constraints on the design and functional requirements of the adaptive systems. In brief, the telescope is required to deliver seeing-limited wavefront prior to adaptive correction.

Once the essential functions and characteristics of the design are identified, sensitivity analysis and error budgeting are used to consolidate the design. A first iteration has been completed, revealing no evident show-stoppers and allowing to derive a possible scheme for the telescope active optics. Further iterations are required to optimize the distribution of risks and constraints.

The current baseline design is a 6-mirror solution with spherical, segmented primary and flat, segmented secondary mirrors. A four-mirror corrector including three aspheric and a flat provides for the correction of spherical and field aberrations. The corrector incorporates active optics and field stabilization capabilities. Fabrication aspects are discussed elsewhere[4] and will not be detailed here. A thorough trade-off on the primary and secondary segments dimensions is still to be made. Under the assumption that those dimensions will have to be maximized -mainly for control and reliability reasons- within the limits permitted by cost-effective transport (standard container), we come to a tentative dimension of ~2.3-m, which translates into ~1,600 and ~210 segments for the primary and secondary mirrors, respectively.

2. OPTICAL DESIGN

The requirements applying to the optical design at technical focus i.e. prior to adaptive modules, are as follows:

- Diffraction-limited field of view larger than 30 arc seconds (goal: 60 arc seconds) at λ=0.5 μm, 2 arc minutes (goal: 3 arc minutes) at λ=2 μm.
- Unvignetted field of view 2 arc min, goal 3 arc minutes (derived from the maximum required science field in the infrared).
- Technical field of view larger than 10 arc minutes, goal ~20 arc minutes.
- Optical quality in the technical field of view ~0.20 arc second RMS or better (seeing-limited).

Although not strictly necessary, a linear field size on the order of ~2-m would provide convenient design space for sensors at the technical focus. In addition, the design should provide for conveniently located surfaces for active optics and field stabilization -*conveniently located* being essentially meant for intermediate pupil images.

Figures 1 to 4 show a few optical designs, all with primary-secondary mirror separation of 95-m. A Dall-Kirkham solution is not considered in view of its extremely small field of view.

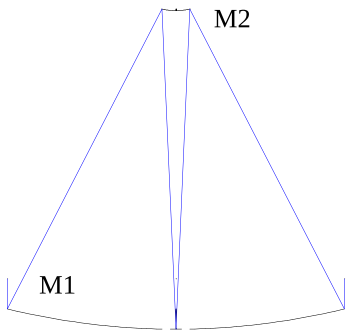

Figure 1. f/11.5 Ritchey-Chrétien

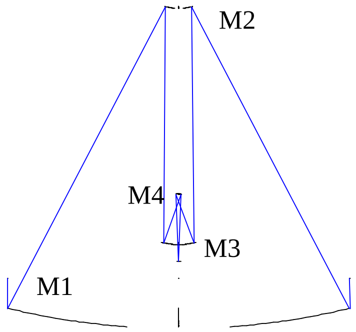

Figure 2. f/13 all-aspheric (field stabilization with M4)

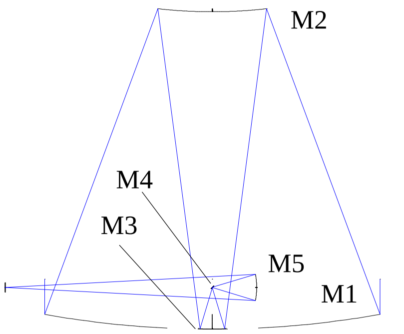

Figure 3. f/9.6; spherical primary and secondary mirrors.

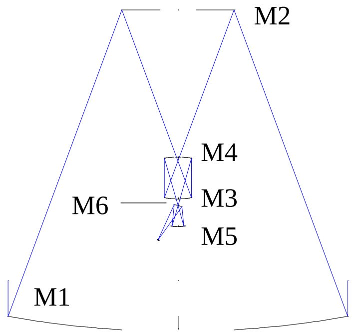

Figure 4. f/5.1; spherical primary and flat secondary mirrors

Figure 1 shows a Ritchey-Chrétien design, with f/1.04 primary mirror and 8.4-m, f/1.1 active secondary mirror. A Ritchey-Chrétien design is attractive in terms of the theoretically achievable optical quality with only two surfaces. There is, however, a serious cost issue as figuring of the primary mirror segments implies more complex processes than spherical surfaces. Assuming polishing on planetary machines of warped segments, combined with computer-generated hologram testing and ion-beam finishing, the minimum cost increase with respect to all-identical spherical segments is plausibly on the order of ~50% for figuring and ~30% for substrates, possibly more in view of the tight specifications on residual stresses. In this respect, it should also be pointed out that off-axis aspheric segments imply a higher schedule risk than spherical ones, because of the lower predictability of figuring warped mirrors.

Design and fabrication of the secondary mirror is an issue as well. A monolithic solution implies a diameter of ~8.4-m at most, which leads to

- a fast ~f/1 primary mirror, thereby exacerbating the difficulty to fabricate its off-axis segments;
- high sensitivity to decenters (~3 microns on-axis wavefront RMS, tilt not included, per millimeter of secondary mirror lateral decenter);
- a critical fabrication issue for the convex mirror, in particular with respect to testing (prohibitively high complexity, risk, and cost).

Last but not least, the design does not provide a realistic solution for field stabilization, unless the secondary mirror is made even smaller, at the cost of a higher sensitivity towards decenter and the added complexity of combining active optics and field stabilization functions in a single subsystem.

Figure 2 shows an all-aspheric solution, with f/1.03 primary mirror, 8-m, f/0.99 secondary mirror, 10-m, f/1.2 tertiary mirror and 1.6-m, f/1.2 quaternary mirror. In this type of design, central obscuration is set by the hole of the tertiary mirror and is on the order of 30% for a field of view of ~10 arc minutes. Excellent optical quality can be attained over a substantial field of view -thanks to the four aspheric surfaces- but field curvature is very strong. Sensitivity to secondary mirror decenter is comparable to that of the Ritchey-Chrétien design; sensitivity to corrector decenter is on the order of 2.4 microns wavefront RMS, on-axis, tilt not included, per mm of lateral decenter. This design suffers from the same drawbacks as the Ritchey-Chrétien one, except for the availability of the small quaternary mirror for field stabilization. If monolithic, the tertiary mirror dimensions (~10-m) imply extrapolation from demonstrated mirror technology.

Figure 3 shows a spherical primary and secondary mirror design. It has been shown[6] that spherical primary mirror designs imply a fairly large, spherical secondary mirror; it is the case here, with a secondary mirror diameter on the order of 30-m. This figure could nevertheless be substantially reduced, at the cost, however, of a proportionally longer structure. Although this design meets the optical quality requirements, there is little margin left at the edge of the science field of view. The tertiary and fifth mirrors have a diameter of ~8-m and would be active. In its present state the design does not provide a surface suitable for field stabilization. Further evaluation is needed to assess whether the diameter of the fifth mirror, which is an intermediate pupil, could be reduced to a dimension allowing tip-tilt correction at the required frequency (~5-7 Hz). In spite of its drawbacks, this design is still being explored as it seems favorable to a further -and substantial- reduction of the structure height.

Figure 4 shows the design which has been provisionally selected as baseline. With a total of six surfaces, it is the least attractive in terms of throughput (number of surfaces) but it meets all requirements and, in particular, provides all required functions. It also has best characteristics with respect to decentering errors. The primary mirror is spherical (f/1.4) and the secondary flat. The option of a large flat secondary mirror is quite counter-intuitive. Secondary mirrors are normally associated with a major error source in classical telescope designs: depointing and decentering coma. Hence, every effort should be made to minimize this error, which translates in tight constraints on centering tolerances, *mass (dimensions)* and structural stiffness at a location where the latter is most difficult to achieve. The advantage of a flat secondary mirror is to eliminate the effect of lateral decenters. The influence of tilt is reduced as well, as a flat mirror does not yield angular magnification. Additionally, proper mechanical design allows to reduce the amplitude of mirror tilt under varying gravity load.

The corrector consists of three aspheric mirrors, two of which active with ~8-m diameter, and a 2.5-m flat ideally located for field stabilization and for switching to different instruments (by rotation about the telescope axis). Sensitivity to corrector decenters is about a factor 5-10 smaller than for aspheric primary mirror designs, and it should be noted that its location is favorable in terms of mechanical design and structural stiffness.

Decenters within the corrector itself are more critical but there should be no difficulty to design a fairly stiff structure. In this respect, it should be noted that the corrector itself is about the size of an 8-m class telescope and that there is ample design space for its structure.

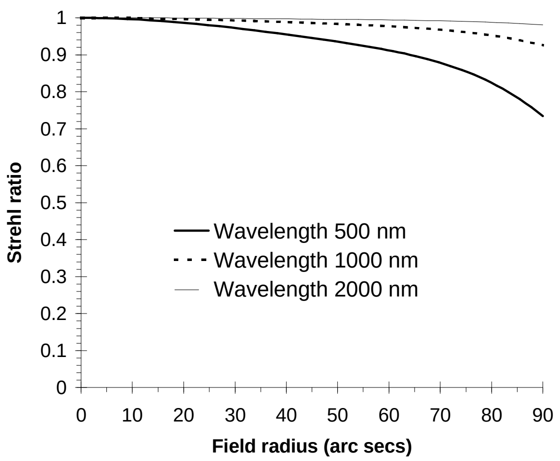

Figure 5. Strehl ratio, 6-mirror design (curved field)

The dimensions of the two last mirrors, 4.2-m and 2.5-m, respectively, are strongly dependent on the total field of view. A reduction to ~6 arc minutes (Laser Guide Star solution for adaptive optics) would allow to reduce these figures by about a factor 2. In case such option would become attractive, the two last mirrors could be exchanged for smaller ones without the need to replace the other mirrors of the corrector -an offset of the active quaternary mirror shape would suffice.

Field of view and obscuration are limited by the same geometrical constraints than the four all-aspheric mirrors design. The f/5.1 design shown in figure 4 provides a ~3 arc minutes diffraction-limited field of view in the visible, and a total field of 11.4 arc minutes with images better than 0.2 arc seconds RMS i.e. suitable for seeing-limited imaging and for accurate wavefront sensing. Figure 5 shows the Strehl ratio up to a field diameter of 3 arc minutes. It is planned to increase the focal ratio to ~f/6.5 at the next design iteration, in order to ease the design of the relay optics in the adaptive modules.

The major drawbacks of this design are the difficulty to fabricate the highly aspheric quaternary mirror, which has a deviation with respect to best fitting sphere of ~9.5 mm, and the limited design space available for the field stabilization mirror. A suitable fabrication test set-up for the quaternary mirror has been identified[6] and should permit computer-controlled figuring to acceptable quality. This mirror is located on an intermediate pupil image. The beam compression - from 100-m to 8.2-m- implies that any mirror slope error translates into a ~6 times lower slope error on the sky i.e. tolerances could be relaxed by a factor 6 compared to e.g. VLT primary mirrors for equal seeing-limited performance. In adaptive regime, further correction would become possible down to spatial periods of ~15 mm with an adaptive module tailored for correction down to r_0~200 mm. On such spatial scales, the VLT primary mirrors have surface misfigure lower than ~3 nm RMS.

3. ACTIVE OPTICS

In the following, discussions concentrate on the 6-mirror design presented in the previous section. A detailed active optics strategy, including correction of the effect of decenters, is still to be established. A sensitivity analysis already provides useful clues as to the possible schemes. Table 1 gives the effect of 1 mm axial and lateral decenter and 10 arc seconds tilt of each subsystem. Tilts are considered at vertex of each surface, and, for the corrector, at the vertex of its entrance diaphragm (vertex of the quaternary mirror). The third column gives the depointing on-axis, in arc seconds. The fourth and fifth columns give the 3rd and 5th order spherical Zernike coefficients; the 6th column gives the defocus Zernike coefficient at the edge of the field of view. With axial decenters, this coefficient corresponds to the axial translation of the telescope focus. With lateral decenters and tilt, it corresponds to the tilt of the image surface. The 7th to 10th columns give the off-axis coma and astigmatic Zernike coefficients. The 11th and 12th columns give the wavefront variation, in nm RMS and arc seconds RMS, at the edge of the field of view (wavefront tilt excluded). The last column gives the wavefront RMS variation at the edge of a 2 arc minutes science of view, *after removal of all field-independent terms*, which can be removed by active compensation of alignment errors and active deformation of the tertiary and quaternary mirrors. Assuming infinite accuracy of the active optics correction these are the maximal residual errors that would be seen by the infrared adaptive module. With a field of view 4 times smaller, visible adaptive modules would see wavefront errors ~4 times smaller as field-dependent terms are essentially linear with the field of view (tilt of image surface, linear astigmatism).

			Depointing (arc secs)	Spherical (nm) 3rd ord.	Spherical (nm) 5th ord.	Focus (nm)	Coma (nm) 3rd ord.	Coma (nm) 5th ord.	Astigmatism (nm) 3rd ord.	Astigmatism (nm) 5th ord.	WFE RMS (nm) (1)	arc secs RMS (1)	WFE RMS (nm) (2)
M2	Lateral (mm)	1	0.000	0	0	0	0	0	0	0	0	0.000	**0**
	Axial (mm)	1	0.000	0	0	30999	1	0	0	0	15846	0.378	**0**
	Tilt (arc secs)	10	6.144	0	0	1216	33219	122	845	76	11943	0.320	**72**
Corr.	Lateral (mm)	1	1.426	0	0	264	1741	13	31	16	640	0.017	**4**
	Axial (mm)	1	0.000	0	0	30999	1	0	0	0	15846	0.378	**0**
	Tilt (arc secs)	10	0.064	0	0	50	12940	33	360	4	4645	0.124	**27**
M3	Lateral (mm)	1	1.453	0	0	673	23810	351	471	7	8564	0.232	**55**
	Axial (mm)	1	0.000	315	143	30857	515	18	10	1	15710	0.374	**37**
	Tilt (arc secs)	10	1.612	0	0	615	25900	201	400	45	9307	0.250	**46**
M4	Lateral (mm)	1	1.112	0	0	390	28416	327	938	17	10216	0.276	**74**
	Axial (mm)	1	0.000	595	148	19476	596	17	21	0	9842	0.232	**38**
	Tilt (arc secs)	10	1.594	0	0	554	3706	12	1096	50	1438	0.037	**90**
M5	Lateral (mm)	1	1.544	0	0	789	2862	39	452	6	1119	0.029	**62**
	Axial (mm)	1	0.000	279	5	22040	143	1	21	0	11219	0.266	**9**
	Tilt (arc secs)	10	0.701	0	0	1353	439	8	411	1	731	0.017	**114**
M6	Lateral (mm)	1	0.000	0	0	0	0	0	0	0	0	0.000	**0**
	Axial (mm)	1	0.000	4	0	4258	116	0	18	0	2178	0.052	**38**
	Tilt (arc secs)	10	0.462	0	0	200	0	0	0	0	115	0.002	**20**

(1) edge of technical field (dia. 11.4 arc min) and after tilt correction

(2) edge of science field (dia. 2 arc min) and after correction of field-independent terms

Table 1. Sensitivity to decenters, 6-mirror design.

It should be noted that the static axial decenter of the secondary mirror under gravity load could, in principle, easily be compensated by a suitable dimensioning of the interface between the corrector and the structure, allowing identical axial displacements under gravity load. Although the implementation would certainly be more complex, it could also be conceived that the corrector be mounted in a flexion system providing rigid body rotation around the center of rotation of the secondary mirror under gravity load, thereby eliminating the effect of gravity.

The results shown in table 1 indicate clearly that several options are possible as to active correction of decenters and that it would be possible to close the active correction loop within a single iteration if each surface could be maintained within ~1 mm and ~5-10 arc seconds from their nominal position, a task that could be achieved by internal metrology and relatively simple actuation mechanisms. Such internal metrology also allows to reduce the range of the necessary active corrections and limit deviations from the nominal telescope prescription. Table 1 also shows that the system is sufficiently well described by 3rd order terms.

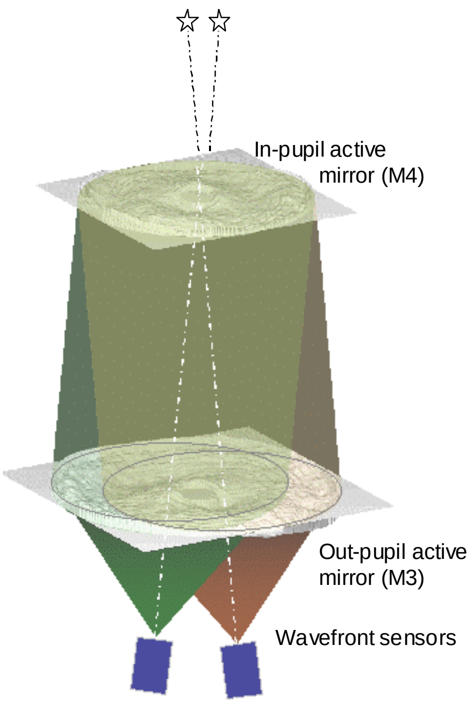

Figure 6. Schematic principle of bi-conjugate active optics.

Focusing is most conveniently achieved with the fifth mirror; an accuracy of ~0.1 mm would correspond to ~0.026 arc seconds RMS on the sky and is sufficient in seeing-limited mode. Better accuracy would be desirable but not strictly necessary to reduce the residual error (~1 micron RMS focus) which will have to be corrected by the adaptive modules in diffraction-limited mode. It is yet unclear whether wavefront sensing prior to adaptive correction could provide a commensurate accuracy i.e. ~0.005-0.010 arc seconds RMS. One should take note, however, that the information collected by the adaptive optics wavefront sensors on the low spatial frequency quasi-dc errors could be sent back to the active optics control loop.

A detailed analysis is still to be performed in order to identify which of the aspheric mirrors is best suited for the correction of coma (e.g. by rotation about center of curvature).

It should be noted that the presence of two active mirrors (tertiary and quaternary) provides an additional degree of freedom for active control of the telescope prescription. With a single active mirror (e.g. VLT), wavefront control is, in principle, achieved at a single field position only -in practice, that of the wavefront sensor. With two active mirrors and three wavefront sensors it becomes possible to differentiate the wavefront errors introduced by each mirror and, to some extent, to reconstruct the third order properties over the entire field of view. Availability of 3 suitable guide stars for active optics correction is not a concern; Shack-Hartmann sensors with 50x50 to 25x25 pupil sampling would correspond to subpupils of 2 and 4-m, respectively, i.e. 25 to 100 times larger in area than with the VLT.

Figure 6 illustrates schematically how the wavefront error of each mirror could be reconstructed; the differential measurement between two wavefront sensors provides the differential of the surface of the out-of-pupil mirror along the direction of the two guide stars. The actual beam excursion on the tertiary mirror is relatively small (maximum ~250 mm) in comparison to the spatial frequencies of the mirrors eigenmodes.

Cross-talk between segmented mirrors phasing errors and active optics control of continuous surfaces is an area of concern. While piston errors could, in principle, be brought to negligible values by means of position sensors and actuators -same approach as with the Keck-, segments tilt may be more difficult to differentiate. Further analysis are required to evaluate the problem, set tolerances and derive solutions. In the worst case figure, whereby it would turn out to be necessary to control segment tilt and active optics independently, wavefront sensing at the prime focus may provide a solution -albeit a complex one in view of the enormous spherical aberration at this focus.

4. ERROR BUDGET

The error budget is derived from the top level requirements, which include seeing-limited performance without adaptive correction (technical field of view) and diffraction-limited resolution after adaptive correction (science field of view). In adaptive mode, the Strehl Ratio requirement is minimum 20%, with a goal at 40% for $\lambda \geq 0.5$ µm.

It is assumed that wavefront control is achieved along the following scheme:

1. Telescope pre-setting. Each subsystem is brought in a location and state allowing the active optics loop to be subsequently closed.

Detailed analysis is still required to set the quantitative requirements on the telescope characteristics after pre-setting. We expect those requirements to eventually correspond to ~1 arc second RMS image quality and ~2 arc seconds RMS pointing error, the latter being probably the dimensioning requirement. Pre-setting would be achieved through the following functions:

- Centering of each subsystem according to internal metrology and calibration data, to an accuracy of ~0.5-1 mm for axial and lateral decenters and 5-10 arc seconds for tilts.
- Force actuation of flexible mirrors, according to force sensors reading and calibration data. In view of the beam compression on the flexible mirrors and the implied relaxation on surfaces slope accuracy, this step is probably trivial.
- Phasing of the segmented mirrors according to position-sensor data for piston and -if required- prime focus wavefront sensors or internal metrology for segments tilt.

2. Active correction at ~0.03 Hz and field stabilization at ~5-7 Hz. Wavefront quality is brought to ~0.1 arc seconds RMS or better over the maximum science field, including tracking, without correction by the adaptive module(s). This figure is comparable to the VLT performance and corresponds to a Central Intensity Ratio of ~80% with a seeing of 0.40 arc seconds at λ=0.5μm. For low spatial frequency terms, the equivalent wavefront excursion is on the order of 3-4 μm RMS.

3. Adaptive correction. Wavefront quality is brought to Strehl Ratio ≥ 20% over the science field. This budget is split in two parts:

   - Strehl Ratio associated with all error sources except atmospheric turbulence ≥ 50% (goal ≥ 70%);
   - Strehl Ratio associated with the correction of atmospheric turbulence ≥ 40% (goal ≥ 60%).

   We tolerate that the adaptive module(s) be required to compensate telescope errors, however such residual errors must be small in comparison to atmospheric turbulence.

Table 2 shows the first level of the on-axis error budget in active and adaptive modes. The last column gives the RMS wavefront error equivalent to the Strehl requirement in adaptive mode and is provided for reference only. Wavefront RMS figures are assumed to combine quadratically, Strehl Ratios multiplicatively. The figures shown correspond to the initial top-down iteration and should be considered as extremely preliminary. The contingency is calculated against a maximum wavefront error of 3 μm RMS after active correction and a Strehl Ratio of 20% after adaptive correction.

ON-AXIS OPTICAL QUALITY BUDGET	Active WFE RMS (μm)	Vis. Adaptative Strehl at λ=0.5 μm	WFE RMS (nm)
TOTAL BUDGET (excl. contingency)	2.155	0.205	100
Optical design (telescope)	0.000	1.000	0
Surfaces	2.010	0.808	37
Phasing	0.035	0.827	35
Active optics & Guiding	0.592	1.000	0
Adaptive optics	n/a	0.400	76
Dispersion compensation	0.038	0.800	38
Local turbulence	0.500	0.960	16
CONTINGENCY	2.087	0.974	13

Table 2. Preliminary error budget.

It is assumed that the adaptive modules provide partial compensation of telescope errors, in particular:

- High spatial frequency surfaces misfigure, up to spatial periods of ~200 mm in the entrance pupil; it should be noted that this spatial period corresponds to ~100 active points for each primary mirror segment and ~900 active points for each secondary mirror segment i.e. some correction of the primary and secondary mirror segments misfigure should be possible. However, the budget shown in table 2 makes very limited use of this capability for fear that discontinuities between segments could yield undesirable residuals.
- Residual static and dynamic alignment errors;
- Residual tracking errors.

The accuracy within which this compensation is achieved is included in the adaptive optics allocation, which explains the zero allocation for active optics and guiding in adaptive mode.

A provision is made for the compensation of atmospheric dispersion. Suitable glasses have been found to compensate for the effect over large wave bands (>100 nm) in the blue and up to 60^{o} zenithal distances, within the budget specified in table 2, but no detailed design has been made so far. Taking into account the accuracy requirements in adaptive mode and the complete telescope spectral coverage, several Atmospheric Dispersion Compensators (ADC), operating in closed loop, are likely to be required. The chromatic variation of adaptive correction and the differential chromatic effects between conjugated layers and adaptive mirrors are still to be addressed.

5. CONCLUSIONS

The optical design of the OWL 100-m telescope is converging towards a consolidated baseline meeting specifications and providing all required functions. Alternatives have been reviewed, and a second design is still under evaluation. Aspheric primary mirror solutions have been rejected as they do not provide equivalent functionality -nor substantially higher throughput- at a competitive cost, and are inherently less suitable for mass-production.

Although conceptually more complex than with Ritchey-Chrétien designs, alignment control and active optics with two flexible mirrors is possible and provides for extended control of the telescope prescription. A detailed strategy and the implied tolerances will have to be assessed by modeling, but preliminary sensitivity analysis yield promising results.

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