Design of systems involving easily measurable aspheres

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ABSTRACT

Aspheric surfaces provide significant benefits to an optical design. Unfortunately, aspheres are usually more difficult to fabricate than spherical surfaces, making the choice of whether and when to use aspheres in a design less obvious. Much of the difficulty comes from obtaining aspheric measurements with comparable quality and simplicity to spherical measurements. Subaperture stitching can provide a flexible and effective test for many aspheric shapes, enabling more cost-effective manufacture of high-precision aspheres. To take full advantage of this flexible testing capability, however, the designer must know what the limitations of the measurement are, so that the asphere designs can be optimized for both performance and manufacturability. In practice, this can be quite difficult, as instrument capabilities are difficult to quantify absolutely, and standard asphere polynomial coefficients are difficult to interpret.

The slope-orthogonal "Q" polynomial representation for an aspheric surface is ideal for constraining the slope departure of aspheres. We present a method of estimating whether an asphere described by Q polynomials is measurable by QED Technologies' SSI-A system. This estimation function quickly computes the testability from the asphere's prescription (Q polynomial coefficients, radius of curvature, and aperture size), and is thus suitable for employing in lens design merit functions. We compare the estimates against actual SSI-A lattices. Finally, we explore the speed and utility of the method in a lens design study.

Keywords: Design for manufacturing, Optical design, Asphere, Subaperture stitching interferometry, SSI-A, Orthogonal polynomials

1. INTRODUCTION

Aspheric optical surfaces can deliver significant performance benefits in a variety of applications. Improved image quality, compactness, and reduced weight are all possible by including aspheric surfaces into a system. But aspheres are more complicated than spheres, and thus those benefits do not come without cost. Some aspheres can be relatively easy to manufacture and test, while others are orders of magnitude more difficult. So while a design including aspheres may look very good "on paper", it may not be cost-effective to manufacture to the required specifications.

Typically, an optical designer will rely on their experience to guide whether aspheres should be added to the system. Assessing the manufacturability, realizable tolerances, and relative cost of any aspheric surfaces in the design is also largely left to the designer's experience[1]. It may involve sending preliminary design prints to component fabricators to obtain cost estimates. If the preliminary designs turn out to be cost-prohibitive, however, this iteration cycle can be quite long indeed. And even if the cost is "reasonable", how does one know if performance is optimal? There may have been an even more cost-effective design that was missed in the optimization process, since the optimization did not explicitly optimize over manufacturability. Clearly it is desirable to include the relative difficulty of fabricating and testing an asphere when optimizing an optical system's performance. This is a daunting task indeed, given the variety of fabrication and testing technologies available, as well as the need to map each technology to the entire space of designable aspheres! In this paper, we focus our attention on whether a particular asphere can be readily measured with the Subaperture Stitching Interferometer (SSI®)[2].

Aspheres are often tested interferometrically with dedicated nulls, either refractive designs or computer-generated holograms (CGH). These test setups are usually specific to a particular aspheric prescription, and furthermore it generally takes weeks to design and manufacture the null optics. The cost and lead time associated with such dedicated nulls have driven the desire for other, more flexible solutions, especially for prototyping and small production batches. Profilometry is an extremely versatile solution, especially for infrared optics. The accuracy of profilometry systems, however, is sometimes insufficient for visible light and short wavelength applications. The scanning pattern generally cannot deliver the same level of lateral resolution as an interferometer over the whole area of the surface, which renders

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the systems less capable of resolving the grinding and polishing artifacts common to aspheric fabrication processes (e.g. diamond turning grooves). The SSI is not quite as flexible as a profilometer, but it can interferometrically measure a variety of aspheres *without* the use of dedicated nulls. But how do we know whether a given asphere can be easily measured with an SSI?

2. PREVIOUS SSI TESTABILITY WORK

The SSI general product specifications on asphere capability are necessarily concise, and as a result not complete. For example, the QED website states[3]:

- Capable of measuring high-NA components with numerical apertures up to 1 (full hemispheres!),
- Plano, convex, or concave surfaces up to 200 mm diameter, and
- Aspheric optics up to 200 waves of departure from best fit sphere.

These capability "rules" are convenient and easy to understand, and excellent for general discussions of capability and determining whether a product demonstration makes sense for a particular customer. Testability specifics, however, are more complicated. For example, there are aspheres larger 200 mm in diameter that can be tested, while there are others that have less than 200 waves of departure that cannot be tested. Thus the aforementioned rules are really guidelines; they are not precise enough to adequately determine testability.

So what sort of computation *would* be adequate for determining testability? Since we want to use the computation to assess asphere testability at design time, and ideally as part of an optimization process, there are several features we'd like the testability function to have. These include accuracy, continuity, speed, and ease of setup. By accuracy, we mean the testability predictions should correspond reasonably to the actual difficulty of testing the asphere. Continuity means we want the function to not jump – e.g. we don't want "testable" and "not testable" to be the outputs, but rather a continuous function where an asphere that is harder to test returns a larger penalty value to an optimizing merit function. Speed means that the computation time is measured in milliseconds rather than seconds, as it could occur many times as part of an optimization loop. Finally, ease of setup means that the designer does not need to manage a large number of potentially proprietary system parameters, such as an entire SSI configuration file and library of transmission spheres. Ideally, it should be something simple, like a drop-down product list (e.g. SSI platform, ASI platform, Zygo® Verifire interferometer mainframe, QIS™ interferometer mainframe).

Now that we have established some desirable characteristics of the testability computation, let's look at what methods have been used in the past and how they measure up.

2.1 SSI lattice design software

The software that ships with SSI machines is the ultimate arbiter of whether a part can be tested on the SSI or not. For many years, attempting to design a subaperture lattice for the test asphere was the only way of assessing SSI testability with a significant degree of certainty. The user enters the part prescription into the software, which already knows about the machine characteristics and available transmission spheres. The user can then design lattices for each transmission sphere in turn. If a successful design is returned, then the part can be tested, at least in theory. But just because the lattice is designed does not necessarily mean the ensuing measurement will be a good one. After a lattice is designed, it is prudent to examine both the number of subapertures and the fringe density within them to assess whether the part is testable practically. The number of subapertures is a rough gauge of test difficulty, but there are other factors that have to be evaluated ad hoc. The speed (seconds or perhaps tens of seconds per TS evaluated) also renders lattice design impractical for any asphere optical design work other than a final check of a completed design.

In 2012, the SSI measurement design process was significantly enhanced with so-called "rating" step. This occurs after the aspheric surface is entered and the measurement goals chosen, but before any lattices are designed. Its principal purpose is to identify the transmission sphere most likely to achieve the best lattice design. Many factors (including constraints) are accounted for in the rating. These factors include: transmission element collision, interferometer focusability, machine axis limits, high slopes in the subapertures, and extension factor (number of subapertures needed to cross the part). The rating algorithm outputs a numerical estimate of accuracy and measurement speed for each transmission sphere, after culling out any transmission elements that do not result in a viable test. The entire rating process takes only a few seconds, which could be reduced by making some simplifying assumptions and optimizing the code. Currently, it requires quite a bit of system information; though this too could be improved with some simplifying assumptions.

Lattice design is the final arbiter of testability, but lacks many characteristics needed for effective use in lens design optimization. The SSI rating would be more effective in this application, but still is a bit slow, needs a lot of information to set up, and would require a significant software "port" to be usable by commercial lens design software.

2.2 Orthogonal polynomials

An alternate approach to assessing asphere testability relies on the surface representation itself. The "conventional" monomial-based asphere coefficients have basically no meaning individually (not even for sag), due to the cancellation between terms and the lack of normalization. Thus assessing aspheric departure, slopes, curvatures, or any other more testability-related metric of interest requires a bit of computation. Shifting to the Qbfs slope-orthogonal basis for the aspheric coefficients can provide significant gains in such calculations. For example, the full aperture non-null testability of an asphere can be evaluated simply by summing the squares of the Qbfs coefficients[4].

Stephenson used these polynomials coupled with some additional calculations to incorporate asphere testability in a lens design optimization[5]. He developed a custom set of parameters based on the aspheric shape to penalize aspheres that are difficult to test with an SSI or Zygo's Verifire Asphere (VFA™). He was able to apply this penalty function to drive design solutions toward testable aspheres, without significant performance loss. His method focused on minimizing the differences between the local principal curvatures to avoid designing aspheres with inflection points and gull wings. But it did not incorporate more specific SSI capabilities (and limitations) than this, and also did not have a means to avoid so-called "pancake" and "bathtub" aspheres (where the local radius in the center of the part is much longer than that toward the edge of the part's clear aperture).

Forbes developed an efficient computation for stitched testability of aspheres represented with Qbfs[6]. The basic idea is to solve for a transmission sphere numerical aperture (NA) that will make the majority of the asphere slopes resolvable by the interferometer detector. After this "optimal" NA is obtained, an extension factor (XF) is computed (approximately the ratio between the part NA and transmission sphere NA; or the ratio between the sizes of the full aperture and subaperture). Higher extension factors correspond to more subapertures and a more difficult stitching test – and thus XF is suitable for use in constructing a design merit function. While the calculation is a bit more involved, it is computationally efficient. And once coded, the calculation complexity is invisible to a user. He then demonstrated the utility of the computation by calculating the expected testability limits for aspheres with just 2 Qbfs coefficients. While this technique is very promising for use in aspheric lens design optimization, it is lacking in a few areas. Firstly, it does not account for other system constraints, in particular optical cavity limits and range of focusability. For example, it does no good if the stitch test has acceptable extension factor but cannot fit in the interferometer test cavity. Secondly, its output is not as simple as the full aperture testability metric. The full aperture testability has a very simple interpretation: if the subaperture slopes exceed some fraction of the detector limit, then the asphere cannot be tested full aperture. This can easily be converted to a penalty function, where say the penalty function = asphere slope / maximum acceptable asphere slope (thus having a value less than 1 for testable aspheres). This stitch calculation, however, has a TS speed and stitch extension factor to consider in setting the merit function, as well as possibly other considerations. It is not difficult to imagine a merit function based on these things, but that must be done before the calculation will be suitable for lens design optimization. Then of course it would need to be coded in a way that lens design and optimization software can easily and efficiently employ it.

3. NEW SSI TESTABILITY MODEL

We have implemented an improved testability model based upon Forbes 2011 work[7], but incorporating some important constraints developed as part of the SSI rating software. We outline here the calculation itself, a sample of how it compares to an actual SSI rating and measurement design, and some practical software implementation details necessary for use in lens design optimization.

3.1 Testability calculation

Our new SSI testability calculation has a few basic steps:

1. calculation of optimal numerical aperture (NA) and resulting stitch extension factor (XF),
2. evaluation of constraints,
3. calculate refined NA and XF that respect constraints, and
4. compute the penalty function for lens design optimization.

We first employ the stitchability matrices described in the Forbes 2011 reference[8]. This requires some relatively simple system information (wavelength, effective detector elements, and fraction of Nyquist usable) in order to derive the interferometer's slope limit. We want to keep the peak slopes under the interferometer limit, or nearly so, to keep data dropout to a minimum. Since the matrix computation uses an rms slope, we set an approximate peak to rms ratio to convert between the desired constraint (peak) and the matrix computation (rms). Since the slope function is very low order, we employ a default value of 2.5 (or 0.4 of Nyquist) for the PV/rms ratio (a larger value would be used for a high order or noisy function). We then multiply by the interferometer's practical fraction of Nyquist (typically between 0.7 and 0.9). This information, plus the Qbfs coefficients and radius of the asphere serve as input to the function. The output is an optimal transmission sphere NA (optimal in the sense it is as large as possible while respecting the slope limit of the interferometer), and predicted stitch extension factor.

We next evaluate whether this NA is practically achievable. We estimate the radius and focal length of the transmission sphere with the given NA and interferometer aperture (typically 6" on SSI systems). The cavity and focusability can then easily be computed from the radius of the part (using either the best-fit radius for simplicity, or evaluating the local radii at multiple points across the aperture). Negative cavities correspond to a collision, and constrain us to employ a slower transmission sphere than the optimal one. Cavities that approach 1 meter or more are too long to fit in the machine working envelope, forcing the use of a faster transmission sphere (or perhaps a custom designed smaller transmission sphere to reduce the working distance). Finally, parts of relatively short radius (compared to the transmission sphere focal length) can be outside the range of the interferometer's focus staging. While a certain amount of defocus can be tolerated, this range is not unlimited and it therefore must be constrained. In such cases, a faster TS (with shorter focal length) must be employed.

If any of the constraints have been violated, we compute an NA that respects that constraint (a smaller NA to avoid a TS collision, or a larger NA to reduce the cavity or improve focusability). This new NA will no longer match the desired slope constraint. In the case of a slower TS (to avoid collision), the slopes get smaller and the main effect is the XF will go up. For faster TSs, however, the analysis is more complicated. No longer are subapertures expected to be fully filled with data – the high slopes will exceed the interferometer limit and cause data dropout. The effect on the XF and number of subapertures is not immediately clear (the subapertures with lower slopes will get larger but the high slope subapertures get smaller). So first we compute the new (non-optimal) slope factor, which is just the ratio between the constrained NA and the optimal NA, squared. From this, we can estimate the worst-case data dropout and estimate a new XF that better accounts for the variable-sized subapertures. The dominant slopes are assumed to be driven by astigmatism, which has a wavefront proportional to lateral coordinate squared. The wavefront slope is thus simply linearly proportional to the lateral coordinate. Therefore the reduced subaperture size (worst case) is just the inverse of the slope factor. To estimate the subaperture sizes for other than the worst case, we have to make some simplifying assumptions to keep the algorithm fast. We simply assume that the slope grows quadratically from the center to the edge of the part, and that the worst case is at the edge. *This assumption is only used to estimate a correction factor for the new XF* (accounting for data dropout). So even if the assumption is invalid, it does not grossly bias the resulting estimate.

Finally, we compute a quality factor for the test, suitable for use in a penalty function for a lens design optimization. The empirical "rules of thumb" we usually go by is XFs < 3 are ideal, XF < 6 is acceptable, and XFs between say 6 and 10 are possible – but likely to have relatively a large low-order uncertainty. High fringe densities also play a role in the quality of the test; these are prevalent in constrained cases where a larger NA TS had to be used. Our "rules of thumb" for high slopes (low fill) are that no dropout is ideal (slope factor of 1 or less), half-sized subapertures are acceptable (slope factor of say 3 or less), and tenth-size is the absolute limit (slope factor of 10). For lens design optimization purposes, it is convenient to have a penalty function rather than a merit function. Furthermore, we want some physical meaning to our penalty function, specifically taking a value:

- of 1 or higher if the surface is effectively untestable by SSI,
- between 0.5 and 1 if the surface is difficult to test with the SSI, or
- between 0 and 0.5 if the surface is a good match to the SSI capability.

So we devised two simple linear penalty functions, and just add them together for the "net" penalty. The XF penalty function starts at 0 for an XF of 1, and grows to a penalty of 1 when the XF is 10. Similarly, for the simplest slope penalty function we just multiply the slope scale factor by 0.1 (which takes a value of 1 when the slope factor is 10, corresponding to 10% fill).

Finally note that we presume a "standard" suite of TSs are available (e.g. 6" f/2.2, 3.5, 5.3, 7.2) to the user of the SSI. The algorithm may predict a particular asphere is testable by the SSI, but a user may not be able to test it if they lack a suitable TS.

3.2 Implementation for lens design software

In order to control the testability of aspheric surfaces during the optical design process, we have implemented the penalty function as a user-defined optimization constraint in the CODE V® optical design software[9]. It is important that the penalty function's execution be rapid since the constraint may be evaluated frequently during optimization. For this reason, we have implemented the computationally intensive part of the testability assessment as a user-defined subroutine (USR) in a compiled dynamic-link library (DLL).

To constrain the testability of a surface during optimization, the designer defines a constraint macro in CODE V specifying the surface number, the zoom position, and the assessed aperture semi-diameter (the default is the radius of the smallest circle containing the surface's aperture). During each optimization cycle, the macro calls the USR in the DLL, passing it the surface parameters (curvature, asphere coefficients, aperture size, etc.). The first time it is called, the USR reads a configuration text file containing SSI system parameters (camera resolution, axis travel limits, focusability parameters, etc.) as well as assessment parameters (preferred and maximum slope scales, etc.). The USR assesses the surface's testability according to the steps below.

1. The surface to be assessed, which may be of Qbfs, Qcon, or standard asphere (conic plus even order polynomial) form, is (re)fit to Qbfs form, with the normalization radius set equal to the assessed semi-diameter, using the fast technique described by Forbes[10].
    a. Note that the fitting is performed internally in the USR; the CODE V lens database is not altered.
    b. Also note that it is not necessary to perform this fit if the surface is already in Qbfs form with a normalization radius equal to the assessed semi-diameter.
2. The optimal extension factor (XF) and transmission sphere NA are computed as discussed in Section 3.1.
    a. The XF and NA are first computed without regard to constraints.
    b. The focusability is assessed; if it is inadequate, a new NA is computed to satisfy the focusability constraints (typically reducing the cavity length).
    c. The physical interference constraints are checked; if a collision of the surface under test and the transmission sphere is predicted, a new NA is computed in order to increase the cavity length.
    d. The cavity length is computed, and the vertical (Z) machine axis position is estimated. This position is compared to the axis travel limit from the configuration file; if the travel limit is violated, a new NA is computed in order to reduce the cavity length.
    e. Using the unconstrained XF and NA and the constrained NA, a slope scale factor is computed, which provides a measure of worst-case subaperture fill. From the slope scale factor, the unconstrained XF and NA, and the constrained NA, a new XF is computed.
3. The XF and slope scale factor are used to compute the optimization penalty function, as described in Section 3.1.

An editable configuration file allows the assessment to be tailored to the available interferometer system. Currently, configuration parameter sets for QIS (six-inch aperture) and Zygo Verifire (six- and four-inch apertures) interferometers are provided; other interferometers can be accommodated in the future by adding the appropriate parameters.

4. APPLYING THE TESTABILITY CALCULATION TO A REAL LENS DESIGN

Finally we demonstrate the module in actual designs and evaluating the actual designs in SSI-A software. For this example, we optimize a 0.5 NA microscope objective design that includes a single bi-aspheric element. Figure 1 shows the cross section of the nominal design. Surfaces 13 and 14 are the aspherics; 13 is easily testable with the SSI-A, but 14 is not. We re-optimize applying the SSI-A testability penalty function to drive surface 14 to an aspheric prescription that will be easier to test (and thus manufacture at lower cost). We show the prescriptions and SSI-A penalty functions of the aspheres before and after re-optimization in Table 1.

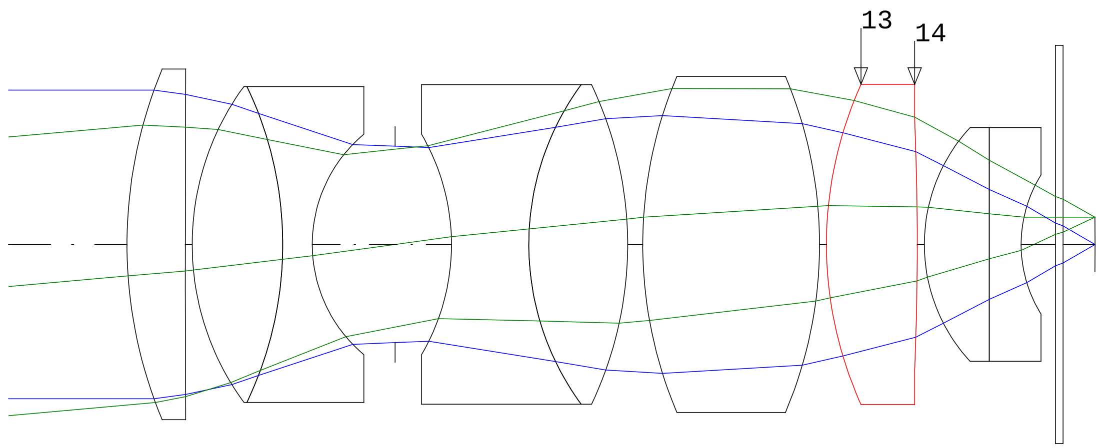

Figure 1: Cross section diagram of the nominal design of our microscope objective optimization example. The two aspheric surfaces are labeled 13 and 14.

Table 1: Aspheric Qbfs coefficients and SSI-A penalty functions for the optical design before and after reoptimization based on the SSI-A testability penalty function.

Asphere prescription	**S13**	**S14**	**S13 reoptimized**	**S14 reoptimized**
Rbfs (mm)	19.3264	151.48	20.3922	105.9630
Aperture (mm):	14.734 (14.44 CA)	13.037 (12.78 CA)	15.866 (14.38 CA)	13.702 (12.82 CA)
a[0] (mm):	0.0159384	0.0420783	0.0117255	0.0246469
a[1] (mm):	-0.0027330	-0.00195258	-0.0043510	-0.0001652
a[2] (mm):	-0.0003621	0.000890548	-0.0006945	0.0010352
Testability output				
f/#:	1.850 (optimal)	6.359 (constrained)	1.548	5.636 (constrained)
XF:	1.396	3.143	1.096	1.237
Penalty function	0.144 (good)	2.404 (untestable)	0.111 (good)	0.532 (fair)

Now let us look at some of the details of the aspheric surfaces. The initial prescription of surface 13 is easy to test with the SSI-A, as indicated by its penalty function (0.14 significantly less than 1 shown in Table 1), mild departure and local radius plots (Figure 2a), and easily designed lattice (Figure 2b). The initial prescription for surface 14, however, is problematic. Despite its relatively mild aspheric departure, the local radius plots indicate an inflection point (in plane radius changes sign) as shown in Figure 3a, and that no lattice could be designed over the clear aperture (Figure 3b). This is consistent with the high penalty function for this surface (2.4 > 1 as shown in Table 1).

(a) (b)

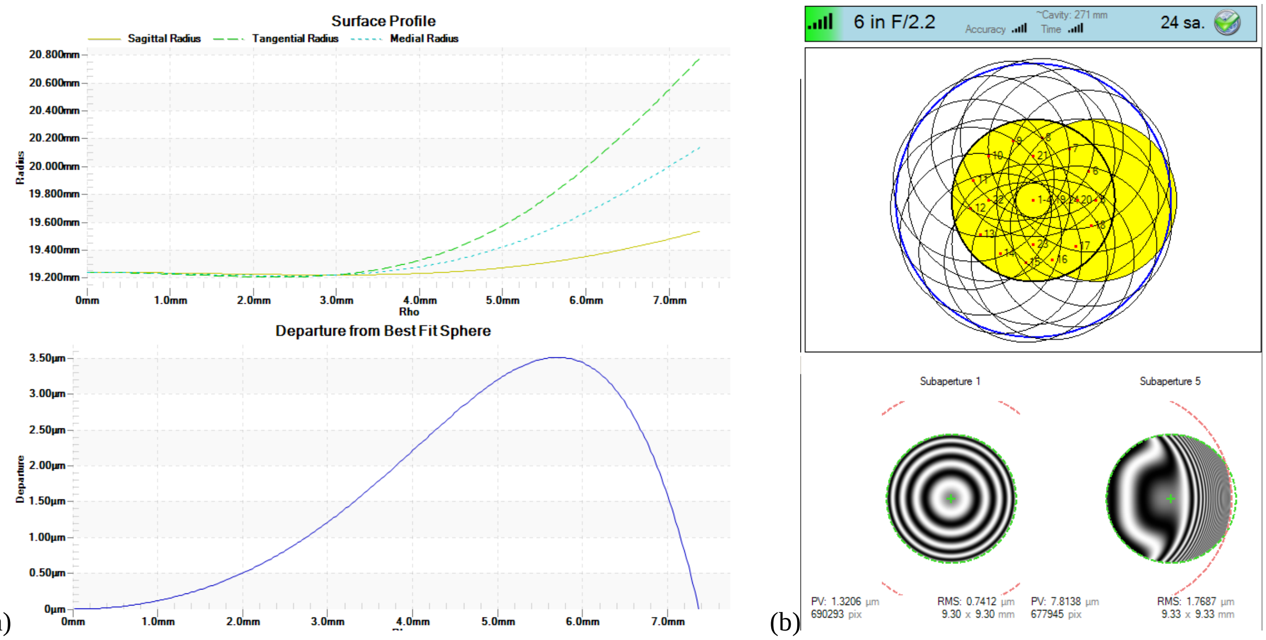

Figure 2: Characteristics of S13 prior to optimization (a) local radius of curvature and departure plots and (b) lattice design

(a) (b)

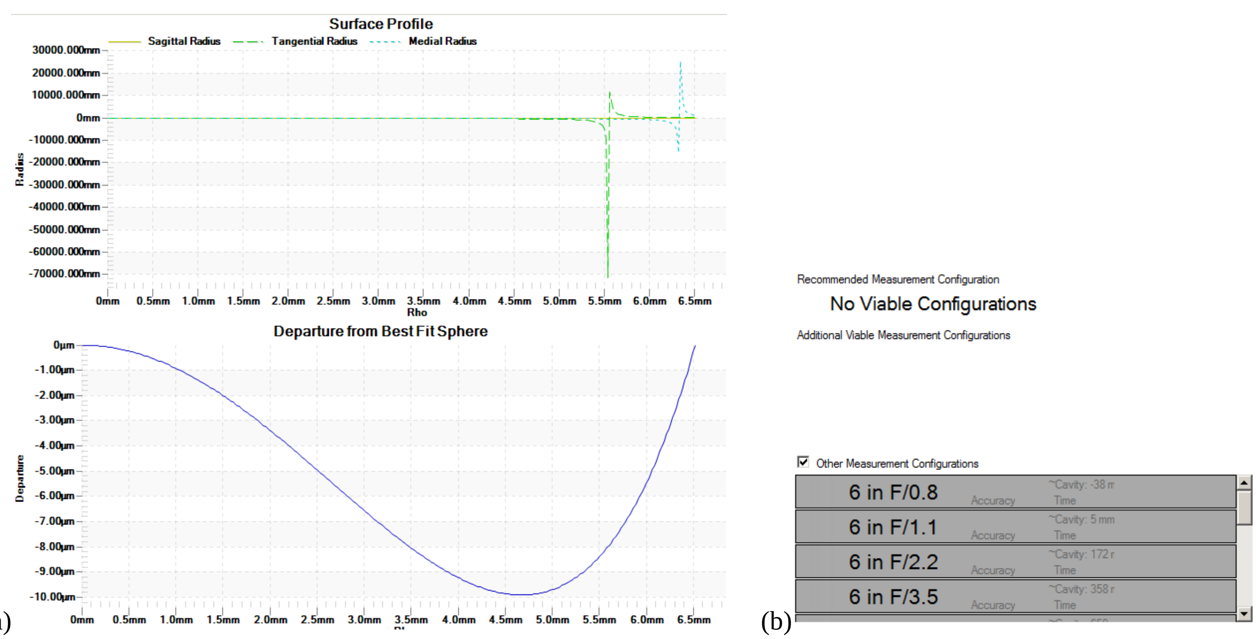

Figure 3: Characteristics of S14 prior to optimization (a) local radius of curvature and departure plots and (b) lattice design. No SSI lattice can be designed despite the relatively mild departure, due to the inflection point inside its clear aperture.

Why is S14 so difficult to test? At 10 micrometers of departure, it falls well within the stated nominal capabilities of the SSI-A. Furthermore, the testability plot in the Forbes 2011 reference also suggests this surface should be testable[11]. The issue is machine constraints: the optimal TS is f/26 (as a result of the part itself being very slow: R/12). An f/26 TS would require a cavity of over 2 meters for a 4" or 6" transmission sphere – an SSI has only ~1 meter. This cavity limit could be worked around by using a small custom transmission sphere, but it turns out that the interferometer cannot focus on the part either (S14 with an f/26 TS would require an order of magnitude more focus range than a typical interferometer has). Practical machine and interferometer considerations prevent the optimal test configuration for S14 from being used. The largest TS f/# that respects the machine constraints is a mere f/6, which simply does not provide enough magnification to reasonably resolve the aspheric slopes. Therefore, to be testable by a "real" SSI, the asphere must be made faster, or the Q coefficients reduced (or both).

We applied the SSI-A testability function to the lens design optimization, and the redesigned aspheres became much easier to test (see the "reoptimized" columns in Table 1). Asphere S13 now has some higher order polynomial terms, but it even easier to test than before (see Figure 4). Asphere S14 is now testable; although the test is not optimal (there is some data dropout and the penalty function is 0.53), it should be acceptable (see Figure 5).

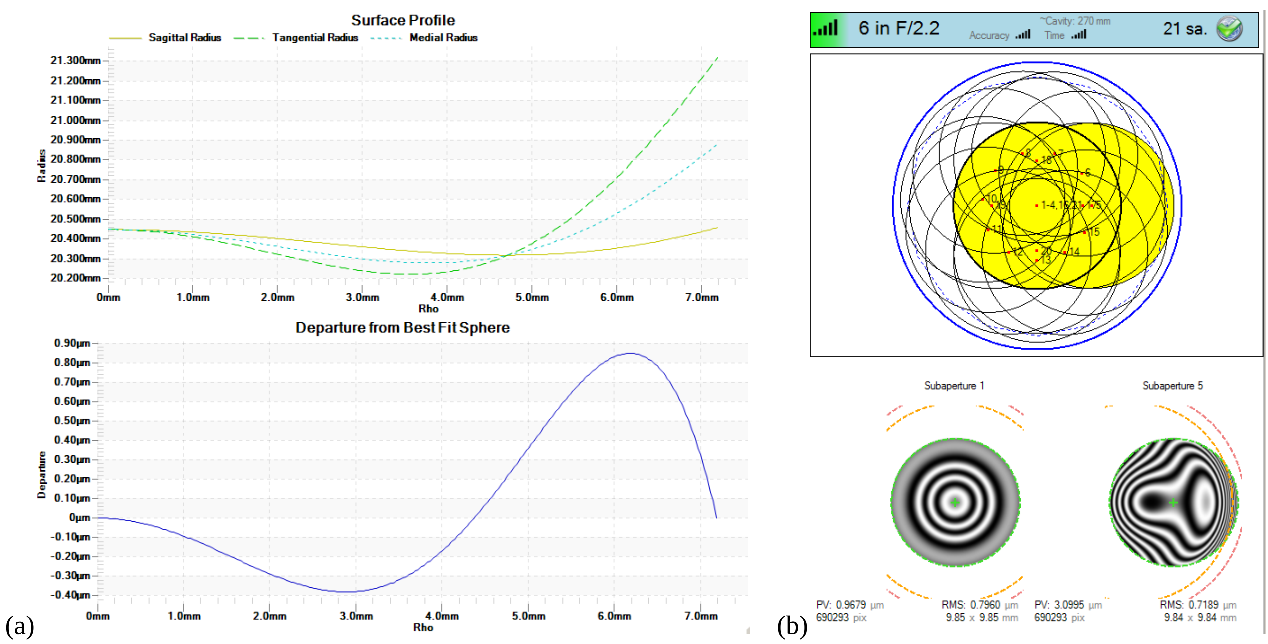

Figure 4: Characteristics of S13 after optimization (a) local radius of curvature and departure plots and (b) lattice design

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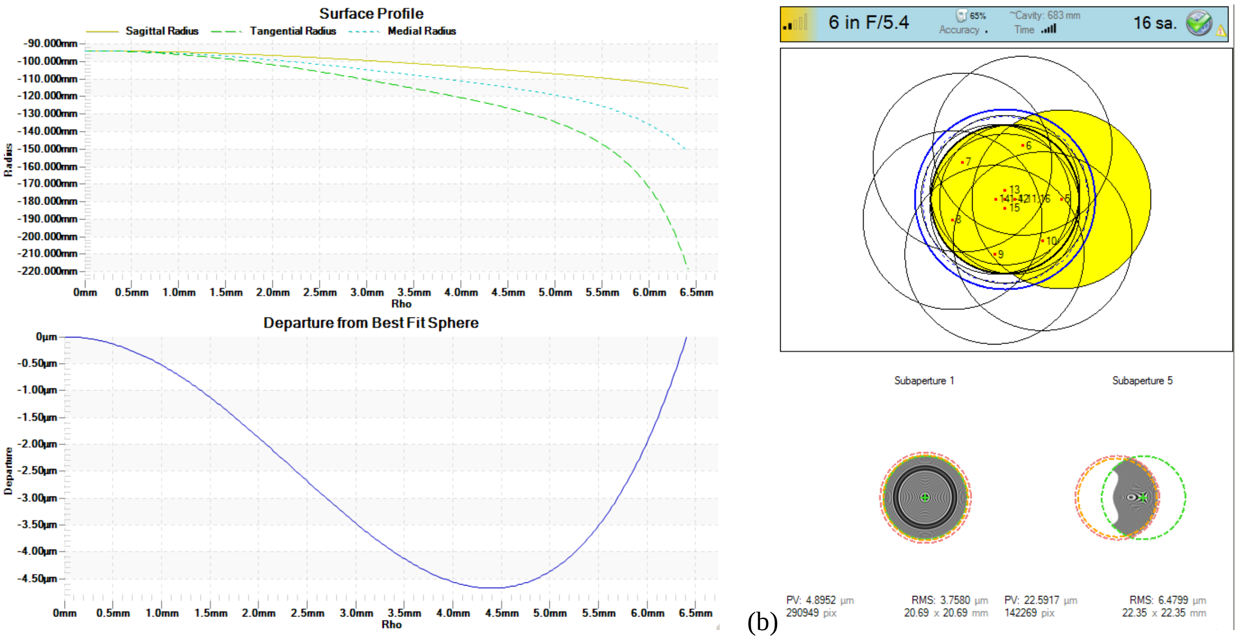
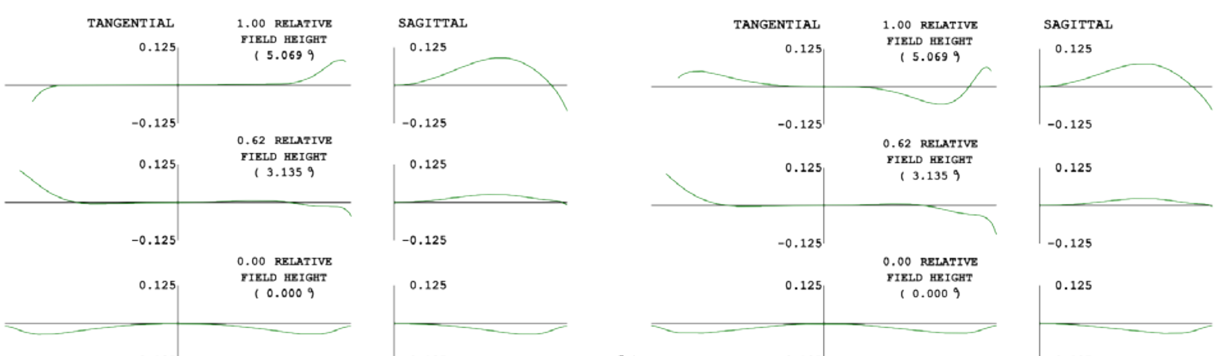


(a) (b)

Figure 5: Characteristics of S14 after optimization (a) local radius of curvature and departure plots and (b) lattice design

Both aspheres are easier to test with an SSI-A after reoptimization with the testability penalty function. But does the design achieve the same level of optical performance, or did we pay a price for the improved testability? Figure 6 shows the wavefront aberrations predicted for the 2 designs. Observe that the magnitudes of the aberrations are quite similar; the average rms wavefront over the field points was 0.0214 waves initially, and 0.0237 waves after the aspheres were reoptimized for testability. We paid a 2 milliwave rms performance price by imposing the SSI-A testability penalty – an inconsequential difference in this design. The optimizer found a comparable solution that uses more easily tested aspheres. This is common in lens design, as there are often many solutions that are nearly the same from a performance standpoint. If there are important side constraints, like being able to test the aspheres, you often just need to "ask". This new tool provides a means of "asking" for testable aspheres, by encouraging the design merit function to move towards such solutions.



(a) (b)

Figure 6: Wavefront plots (in waves 632.8 nm) for the system with 15.5 mm focal length, ±5° field of view, and 0.5 NA: (a) initial (b) after SSI-A penalty function reoptimization – the average rms over the field points changed from 0.0214 to 0.0237 waves (an insignificant amount for this design)

5. CONCLUSIONS

We have developed a tool to rapidly estimate the SSI-A testability of an aspheric surface. The tool accounts for important machine constraints such as available working envelope and interferometer focus stage range. We incorporated the testability calculation into lens design software, enabling penalization of aspheric surfaces that are more difficult to test with an SSI-A. We demonstrated application of the testability penalty function on a microscope objective design example. The lens design optimizer was able to find an equally good solution from a wavefront point of view, yet uses aspheres that are significantly easier to measure and thus make the system more manufacturable.

Numerous opportunities for exploring and enhancing the tool are available. The tool also supports standard and Qcon aspheres, but those cases were not evaluated as part of this optimization assessment. Other design forms could certainly be evaluated as well; only one example was considered here. And while the example here was performed in CODE V, the calculation could be applied to other lens design codes as well. In the longer term, the testability assessment could be extended to non-rotationally symmetric aspheres (freeforms); as both the Q polynomials and the SSI-A are in principle compatible with freeform. The testability calculation could also be extended to the Aspheric Stitching Interferometer (ASI®) when using the Variable Optical Null (VON™) – but this would require new, more complicated, testability calculations.

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