Characterization of the AWARE 40 wide-field-of-view visible imager: supplementary material

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This document provides supplementary information to “Characterization of the AWARE 40 wide-field-of-view visible imager,” <http://dx.doi.org/10.1364/optica.2.001086>. Here we detail the manufacturing processes and design methodology employed in constructing the AWARE 40 Gigapixel visible Imager. © 2015 Optical Society of America

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S1. INTRODUCTION

The AWARE 40 visible imager is a parallel imaging system developed as part of the Advanced Wide-field-of-view Architecture for image Reconstruction and Exploitation (AWARE) program. Here we detail the design methodology and technical details associated with constructing a 2-40 Gigapixel camera system as a supplement to the article “Characterization of the AWARE 40 wide-field-of-view visible imager”. This supplementary document is organized as follows: Section 2 covers the mechanical design methodology of the full camera assemblies, section 3 details the software and electrical considerations we employed while developing the camera, Section 4 covers relevant details about camera assembly, and Section 5 concluded this supplementary technical document.

S2. OPTICAL DESIGN

For previous multiscale designs [1, 2], a monocentric objective was used because the aberrations of the objective are independent of field angle. Therefore only field angle independent aberrations, such as spherical aberration, axial chromatic aberration, and the combination of these, need to be corrected. To increase the focal length of the multiscale camera to resolve smaller objects, the focal length of the monocentric objective must be increased. To do this, the elements of the monocentric lens must be likewise scaled. Once the focal length of the objective lens scales beyond 150 mm, there are few available glass blanks large enough to be ground and polished into the elements of a monocentric objective. While large blanks of certain standard glasses such as BK7 or F2 may be obtained, a custom melt may be required which is extremely expensive. Therefore an

alternative objective design that has approximately field-angle independent aberrations, with individual elements that may be fabricated from standard glass blank sizes, is desirable.

The focal length of a monocentric lens is determined by the center element that contains the center of curvature which provides positive power, and the other surrounding meniscus elements which add negative power. To increase the focal length of a monocentric lens, either the refractive index of the center element must be decreased, the meniscus elements index must be increased, or both. As optical glasses vary in refractive index approximately between 1.43 and 2, this puts a limit on the degree to which refractive index may be manipulated to increase focal length. In addition, the center and surrounding elements must be selected to minimize spherical or chromatic aberration, and also be thermally compatible if cemented together. If a material with a very low refractive index and dispersion was available to use as the center element, this would likewise reduce the need for the surrounding meniscus elements to correct aberrations and increase the focal length. However, the lowest refractive index and dispersion glasses generally available are fluorite-based glasses, which are expensive, fragile, and difficult to work with.

To increase the focal length of the lens, an air gap may be inserted between the two halves of the central sphere of a monocentric lens. The medium at the center of the lens is then a combination of air and glass, thus lowering the effective refractive index. As the lens is no longer monocentric, field-dependent aberrations have been introduced. However, if the formerly monocentric lens is reflection symmetric over the stop and used at 1:1 conjugates, all odd-order aberrations are cancelled, including lateral chromatic aberration, coma, and distortion. As the lens is actually to be used with an infinite object distance, the

lens must be designed to accommodate this. Nevertheless, a nearly symmetric design reduces the lateral chromatic aberration, which in practice is the aberration that limits the image quality. Furthermore, the elements must be flattened so that these may be ground and polished from available blank sizes.

Fig. S1. AWARE 40 optical schematic. The objective lens is shown with 9 microcameras spanning a 36° field of view. The system nominally works at $F/3.05$.

Like the monocentric objective, the non-monocentric objective images onto a curved surface, and the microcameras are arranged to relay the image on that surface (Fig. S1). While astigmatism must be corrected, field curvature may be tolerated. However, unlike the case of the monocentric objective where the image surface is concentric with the objective center, the non-monocentric image surface is not concentric with any particular surface. Therefore the microcameras must be arranged with their optical axes intersecting the center of curvature of the image surface.

The steps to the design of a non-monocentric objective are summarized briefly and shown in Fig. S2. A symmetric monocentric objective has a sphere of a particular glass containing the center of curvature. An air gap is inserted into the center so that the stop is halfway between the two halves of the sphere, which is the split monocentric lens in the figure. The system radii of curvature are optimized with the air gap inserted. Typically a third glass element is inserted between the stop and image to reduce the lateral chromatic aberration. The thickness of this element is comparable to the other elements already present. After insertion of a pair of elements around the aperture, the configuration is similar to a symmetric double Gauss lens as shown. Then the merit function is modified to penalize element thicknesses and diameters not available. The element and air spacings are allowed to vary to accommodate the element thickness requirements. In addition, air gaps may be closed if desired. Furthermore, glasses are exchanged to similar types on the Abbe diagram to reduce the lateral chromatic aberration. The result is the bottom objective in the Figure. An additional 4 mm of diameter and 2 mm of thickness were added to the required optical blank size to allow for material inhomogeneities that occur near the blank surface. In the case of the OHARA glasses used, blank thicknesses up to 160 mm diameter by 40 mm thick were available, however this is subject to change. The design of the objective is in Table S1 between surfaces #2 and #16.

To reduce the lateral chromatic aberration to minimum levels, a melt adjust was performed. Reports on the refractive indices and Abbe numbers were furnished for the particular optical blanks used. The actual refractive index data were inserted into the design software, and the radius of curvature of surface #10 was adjusted to optimize the imaging performance with the blanks to be used. The focal length was held constant during the adjustment of the curvature. In addition, an element (surfaces #2 and #3) was laterally adjusted during assembly and cemented

Fig. S2. Steps to design a non-monocentric lens from a monocentric lens.

into place to minimize axial coma due to misalignment of other elements with the optical axis.

Once an objective was designed, the microcamera optics are similar to that of previous designs such as the AWARE 10. As the chromatic aberration of the objective is already well corrected, the microcamera design needed to correct only residual geometric aberrations. One complication with the microcamera design is that the objective lens produces residual field-dependent aberrations. Therefore the microcamera must be optimized at many field positions relative to the objective lens, both at the center and periphery of the objective lens field to ensure that high quality imaging is achieved throughout and that the microcamera is not correcting the aberrations only at one particular field point. This leads to rather large, slow, and difficult-to-construct merit functions, as the optimization must occur over all field points in each microcamera and for the objective lens as well, and axial symmetry may not be assumed. Nevertheless, this step is necessary to ensure that the image quality can be simultaneously optimized for all of these field points.

S3. MECHANICAL DESIGN

The AWARE 40 dome was designed using a similar hole-packing algorithm to the previous generation AWARE 10 system [2]. This was a distorted hexagonal packing algorithm which preserved the overlap across the entire field of view. Microcameras were aligned by a machined aluminum dome with 262 identical, tightly-toleranced hole bores and mounting features evenly distributed across the imager's 36° field of view. The dome was mated to an intermediate plate which served as a single interface between the dome and the compound objective lens (Photon Gear, Inc.). This configuration seals the optical train from the rest of the camera, which prevents dust contamination and reduces alignment errors due to tolerance stacking compared to a more complicated mechanical configuration. The assembled objective, dome, and microcameras were mechanically isolated from the rest of the protective frame by the use of rubber vibration dampening mounts (McMaster-Carr). A durable aluminum frame was constructed around the optical train to protect the optical system from the external environment. The frame, dome, and objective mount were manufactured by Wagner Machine Company.

No	Radius	Thick- ness	Glass	Nd	Vd	Semi- diameter	Comments
1	∞	∞					Object
2	146.818	20	S-BSM15*	1.623070	58.176511	130.578	Objective begin
3	249.004	12.435				120.93	Lateral adjustment
4	441.298	15.649	S-BSM15*	1.623070	58.176511	112.476	
5	76.41	0.015	NOA61	1.559021	66.343724	94.51	
6	76.41	24.094	S-FPL51*	1.497050	81.350194	94.502	
7	∞	5.045				88.95	
8	∞	21.848				85.49744	Image center of curvature
9	∞	46.114				59.23	
10	-1225.68	23.196	S-FPL51*	1.497050	81.350194	93.792	Nominally flat, surface curvature adjusted to melt data
11	-111.835	0.015	NOA61	1.559021	66.343724	99.91	
12	-111.835	16.612	S-LAM60*	1.743220	49.284905	99.918	
13	-268.857	0.015	NOA61	1.559021	66.343724	111.562	
14	-268.857	26.544	S-BSM15*	1.622950	58.165304	111.57	
15	-171.242	260.709				123.052	Objective end
16	-395	90				17.46207	Intermediate Image
17	88.3258	2.5	H-ZK14	1.603112	60.633158	12.564	Microcamera begin
18	-88.3258	13.205				12.564	
19	68.17506	4	H-F1	1.603423	38.009116	11.564	
20	-10.08557	3	H-LAK52	1.729164	54.669031	11.564	
21	∞	5.062168				10.51178	
22	∞	0.7				8.7	Stop
23	-105.3804	2	H-ZF52A	1.846670	23.791236	10.564	
24	19.92345	3	H-LAK52	1.729164	54.669031	10.564	
25	-19.92345	23.10346				10.564	
26	∞	3				9.939631	
27	63.26888	2.5	H-ZK14	1.603112	60.633158	10.35	
28	∞	2.7				9.674297	
29	13.46682	7	H-ZF52A	1.846670	23.791236	9.35	
30	8.153025	2.5				5.583375	Microcamera end
31	∞	0.4	S-BSL7	1.516330	64.142022	6.045391	
32	∞	0.125				6.00843	Sensor cover glass
33	∞					4.990826	Image Plane

Table S1. Prescription of objective and microcamera together. Glasses with an asterisk have their refractive indices measured from the specific melt the glass blank originated from. Surface #10 is nominally flat, but is adjusted to compensate for melt variations. Glasses beginning with "S-" are OHARA glasses, and glasses beginning with "H-" are CDGM glasses. NOA61 is an optical cement.

Fig. S3. Assembled microcameras installed into the dome, prior to full-system assembly.

S4. ELECTRICAL DESIGN AND DATA MANAGEMENT

At the heart of each of the 262 individual microcamera units is a sensor module developed specifically for the AWARE project, common to the AWARE 2, AWARE 10, and AWARE 40 imaging systems. Each of these sensor modules contain a 14 Megapixel sensor (Aptina, inc.), piezo focus actuator (NewScale, inc.), and electronic interface for communicating with upstream acquisition nodes (Distant Focus, Inc.). After mating to the optical components and installation into the dome, the sensor modules are connected to an array of Field Programmable Gate Arrays (Altera), each of which is responsible for the data management and control of 32 microcamera units. Each of these units routes its image data through 10-Gigabit fiber connection to a host PC through a commercial router.

Streaming data received by the host PC is managed by a low-level software library developed specifically for these camera systems. Image data from individual microcameras is then organized and displayed in an OpenGL-based viewing application which allowed the user to pan and zoom around the field of view. In order to preserve bandwidth, incoming data is down-sampled prior to transmission based on the viewpoint of the user - this approach allows the imaging system to achieve video-rate acquisition. In addition, a snapshot capability allows the user to acquire a full-resolution image from all microcameras using a global digital shutter and download the individual image buffers after acquisition. The fully assembled imaging system required approximately 450W of power during video-rate acquisition.

S5. ASSEMBLY

The AWARE 40 microcameras were installed prior to full system assembly for validation of optical performance. Microcamera optical assemblies were mated with sensor modules using a thermal epoxy to aid thermal conductivity from the sensor to the dome heatsink. Prior to assembly, the optical performance of assembled micro-cameras were tested using a slant-edge MTF test, similar to that employed in the primary manuscript but without the objective lens. The microcameras were checked against a specification of 220 cycles per mm at 20% contrast across the microcamera field of view. Microcameras were then inserted into the aluminum dome prior to full system assembly (Fig. S3).

Microcameras are retained using stainless-steel photo-etched wires (NewCut, Inc.), similar to previous AWARE imaging sys-

Fig. S4. CAD drawing of an AWARE 40 microcamera affixed to the dome.

tems [1, 2]. However, the intermediate plastic insert used as an intermediate between the harness and dome was removed in favor of a ring-shaped undercut retaining mechanism to increase the thermally conductive surface area between the microcamera barrel and the dome (Fig. S4). This new retaining wire geometry also improved the rotational constraint of the microcameras through torsional force, helping reduce microcamera clocking errors encountered in the previous systems.

S6. PERFORMANCE TESTING

Fig. S5. Low-resolution raw image of a SFR-plus target as captured by an AWARE 40 microcamera to evaluate the camera's performance. The full-sized image is 14 megapixels.

The primary manuscript focuses on the performance of the AWARE 40 as deployed in the field. Here, we show details of how we performed the assembled AWARE 40's resolution and longitudinal chromatic aberration tests. A downsampled version of an image captured by a single AWARE 40 microcamera

is shown in Fig. S5. The ImaTest Spatial Frequency Response (SFR)-plus target is placed 50m away to approximately fill a single microcamera's unvignetted FOV. For each microcamera, a single focus position is selected for the resolution and chromatic aberration analysis via a contrast-based algorithm implemented directly onto the FPGA hardware, but we choose the best image of a 5-image focal stack (captured with focal adjustment increments of $20\mu\text{m}$) focally centered about the achieved auto-focus point to ensure maximum on-axis MTF. Figs. 3-4 of the primary manuscript show MTF and lateral chromatic aberration results from the image within the stack that yielded the sharpest contrast in the center of the microcamera FOV. For a complete performance evaluation, we test squares near the center, 0.5 field, and 0.7 field of the microcamera; field angles greater than 0.7-field (i.e. $.875^\circ$) are overlapped by adjacent microcameras. The layout of the microcameras comprising the overall FOV is shown in Fig. 2 of the primary manuscript; the highlighted cameras represent those tested for resolution and lateral chromatic aberration.

Fig. S6. AWARE 40 camera in the field.

The use of slanted edge targets for MTF measurement has been recognized as standard for years [3]. Fortunately, the slant edge images also double as convenient targets for lateral chromatic aberration performance. Let ϵ_c denote the lateral displacement (in units of pixels) between the centroid of a slanted edge target as observed at the red and blue sensor pixels. Given a slanted edge that subtends a particular region of interest (ROI) of the image, Imatest provides the percentage of lateral chromatic aberration relative to the ROI's field angle. This value may be expressed as

$$\epsilon_{pct} = 100 \frac{\epsilon_c}{r}, \quad (\text{S1})$$

where r is the number of pixels between the image center and the center of the ROI. This metric is similar to the well-known percentage of distortion quoted for commercial-quality lenses. We solve Eq. (S1) for the true lateral chromatic aberration distances ϵ_c and scale these values from pixels to microns; the results are plotted in Fig. 4 of the primary manuscript.

S7. PANORAMA ACQUISITION

As mentioned in the primary manuscript, the upper two thirds of the AWARE 40 camera are used to capture the panorama due to an obscuration atop Duke University's Parking garage. Fig S6 shows the AWARE 40 camera mounted upon a gimbal next to its host PC. We rotated the gimbal approximately 15 degrees (6 full microcamera fields-of-view) between 5 consecutive shots

to collect images comprising the full panorama (Fig. S7). The microcamera images were subsequently stitched together with the AutoPano Giga software.

Fig. S7. Five consecutive shots taken to stitch the 2.4GPixel image shown in Fig. 5 of the primary manuscript. Each semicircle represents one of 5 camera shots. The solid black lines represent the workable rectangular panoramic region, and the dotted black line denotes the region we cropped due to lack of image detail above this line. The gray shaded area represents the field of view of the final panorama.

Once images from all 5 shots were acquired, we loaded the constituent microcamera data into AutoPano. The upper 3 rows of microcameras (cameras 1-24 according to Fig. 2 in the primary manuscript) were omitted from the final result due to lack of detail, reducing the microcamera count per shot to 156. Additionally, since the fields of view between the consecutive shots overlap significantly, the final 2.4-gigapixel panorama consists of far fewer pixels than the raw data. Some out-of-focus images had to be removed from the panorama since they provided poor control points for AutoPano Giga. These poor control points led to misregistration and unnatural warping of adjacent microcamera images. After stitching, Autopano performs a standard blending procedure to produce the final panoramas.

S8. CONCLUSION

Here we have presented relevant technical details about the AWARE 40 multi-scale system design, as a supplementary document to the article "Characterization of the AWARE 40 wide-field-of-view visible imager". The previous sections contain relevant information about the optical design, mechanical design, electrical design, microcamera and full system assembly, and deployment into the field.

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