Apache Point Observatory 3.5-m Telescope
Optical Camera Upgrade White Paper

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I. Introduction

Several hardware improvement projects on the 3.5-m telescope at Apache Point Observatory (APO) are currently nearing completion. As facility resources and capital improvement funds are freed up, the Astrophysical Research Consortium (ARC) is now considering options for upgrading the instrumental suite on the telescope. ARC has identified the need to upgrade the visible light imaging capabilities of the facility as one of the key areas to study. In this white paper, we present several options for improving the imaging capabilities of the ARC 3.5-m telescope at visible wavelengths. In Section II, we summarize the current imaging instruments on the telescope, while in Section III, we discuss feedback from the user community concerning their use of the current instruments and what performance specifications they would desire in an upgraded system. In Section IV, we present several options for new instruments. Three options, a general-purpose optical camera, a simultaneous multicolor camera, and the modification of the NOAO QUOTA prototype camera for use at APO are discussed in detail, including the development of preliminary optical designs for the general purpose camera and initial estimates of cost and build schedule for all three options. Finally, in Section V, we present conclusions and suggestions for future work.

II. Current Imaging Capabilities

For scientific applications at visible wavelengths (leaving aside guide cameras), the 3.5-m telescope currently has an imaging camera, SPIcam, and a high-speed photometer, AGILE. Outside of the visible waveband, there is also a near-infrared camera, NIC-FPS.

SPIcam is a general-purpose optical CCD camera, covering 3200 – 10000 Å, mounted on the Nasmyth 2 (NA2) port on the telescope. Its field of view (FOV) is 4.8 arcmin square diameter with a sampling of 0.14 arcsec/pixel. Given the typical seeing conditions at APO (median seeing 0.9 arcsec), SPIcam images are usually binned at 2x2, to 0.28 arcsec/pixel sampling. SPIcam contains no internal reimaging optics, so the plate scale is set by the telescope optical prescription. SPIcam contains a six-position filter wheel, with a wide variety of broadband and narrowband filters available, including MSSSO UBVRI and SDSS ugriz broadband filter sets, narrowband Hα, and an assortment of narrowband emission line filters available upon request. The CCD operates with a gain of 3.36 e^- and a readnoise of 5.7 e^-/pixel. Quoted sensitivities on the SPIcam web page at APO (http://www.apo.nmsu.edu/arc35m/Instruments/SPICAM/) give instrument zero points (target magnitudes that generate 1 DN/sec at low airmass) of roughly m = 22 – 25 from U to I bands.

AGILE is high-speed photometer operating at visible wavelengths (3200 – 7500 Å). The CCD has been backside-illuminated, thinned, and coated to optimize its blue wavelength response. It is mounted on the TR2 port of the telescope. Using internal focal reducing optics, AGILE obtains a FOV of 2.5 arcmin square diameter and a plate scale of 0.15 arcsec/pixel. AGILE uses a frame transfer CCD to read out an exposure while the subsequent exposure is taking place. For various combinations of pixel binning and readout rate, AGILE can obtain exposures as short as 0.3 – 1.1 sec with no deadtime between images. AGILE can use the same filters available to SPIcam, although only one filter can be loaded at one time.

III. Community Response

In an effort to determine how an upgraded optical camera could best serve the scientific needs of the 3.5-m telescope user community, we carried out several discussions with ARC members, including the director of the APO 3.5-m telescope (Suzanne Hawley), the telescope Instrument Scientist (Jon Holtzmann), and members of the observing community who have used SPIcam in recent years.

First, there has been a desire, as expressed by the ARC Futures Committee, for a general-purpose upgrade to SPIcam. SPIcam's relatively small FOV and aging components are believed to increasingly place the 3.5-m telescope at a competitive disadvantage in the area of visible light imaging. Indeed, the use of SPIcam has declined by 50% in the past 3-4 years. Within the envelope of a "general-purpose" upgrade, there are a number of possible areas of improvement and design and cost trades to be made between them. Accordingly, we asked the observing community to consider which upgrades would most benefit their science goals in the future. We received responses from several observers and we summarize their comments below.

The Johns Hopkins University group has been using SPIcam to observe reflected light from the nuclei of comets. They have been happy with SPIcam's performance for this work. They expressed a desire to shorten readout times on the CCD from the current 45 sec to improve observing efficiency. They also stated that a larger FOV is desirable: a FOV of around 10 arcmin, for example, would allow them to search for comets with uncertain ephemerides. While they were generally interested in improvements to spatial resolution and sensitivity, they would not like these to come at the expense of observing efficiency. (Image sizes of 0.5 arcsec or below would be useful for observations of faint comet nuclei, V=24, however.)

Observers at the University of Virginia use SPIcam to image brightest cluster galaxies (BCGs) in Hα as a tracer of recent star formation and cooling materials. These data are used to support X-ray studies. The availability of a narrowband Hα filter is useful for this work. While the current FOV is sufficient to support these observations, increased FOV and improved sensitivity (especially at blue wavelengths) is desirable. Improved spatial resolution would also be desirable.

An observer at the University of Colorado also expressed a desire for improved image quality, such as with the addition of a tip-tilt system. Another CU observer stated that the narrowband filter complement on SPIcam is quite useful. While a larger FOV (at least 10 arcmin) would be desirable, they have generally been happy using SPIcam to observe nearby, bright galaxies in Hα.

An observer at Princeton University has been using SPIcam to image faint, relatively nearby red galaxies. She reports that this effort has been hampered with SPIcam because of the inability to get scattered light correction to support detection of faint (R~26) diffuse sources. The observer notes that she has obtained better data in the southern hemisphere with a smaller telescope (2.5-m), so the issue appears to be scattered light on SPIcam. Even with the revised baffling system on the telescope, scattered light may still be the limiting factor for sensitivity of low surface brightness targets. The user also expressed a desire for increased FOV, as the low-redshift clusters cover a sizable fraction of a degree on the sky. A 15 arcmin field would be desirable. SPIcam has also been used to monitor AGN variability, for which the user has had no problems.

A group at the University of Washington is currently using AGILE to observe planet transits, which is working quite well (with the telescope defocused to smear the stellar image over multiple pixels). The group would be interested in a camera that takes advantage of the full FOV of the telescope to allow it to be used as a survey-type facility, including extended follow-up on interesting targets from larger surveys such as SLOAN and Kepler. A larger FOV would also allow for more reference stars to be observed in each pointing, improving the absolute photometry. A simultaneous multicolor camera would be another way to enable efficient follow-up of interesting targets from large survey projects. The use of an orthogonal transfer device to allow for on-chip guiding and improved spatial image quality would also be desirable.

To summarize, comments from the current SPIcam user community were variable, although a few recurring themes appeared. Most users expressed a desire for a larger FOV (10 – 15 arcmin generally being quoted). There was definite interest in improving sensitivity (particularly in the blue) and spatial image quality over current values as well as calls for better observing efficiency. One advantage of SPIcam that should be propagated into an upgraded instrument is the rich set of broadband and narrowband filters available at APO.

IV. Upgrade Options

As a result of the previous conversations, we decided to focus on three main instrument concepts for an upgrade to the visible light imaging capability on the 3.5-m telescope: a general-purpose optical camera; a camera that provides simultaneous multicolor imaging; and the deployment of QUOTA, a prototype camera that uses orthogonal transfer array CCDs to enable on-chip image correction, at APO. We discuss each option below.

A. New General-Purpose Camera

<u>f/2.07 Camera Design</u>

Since the goal of this white paper was to examine upgrade options rather than to propose specific designs, we chose here to study a mid-range camera design that probes some of the potential capabilities available and how those will have to be weighed against complexity, cost, and required facility modifications. Accordingly, we chose the following specifications: a FOV of 10 arcmin diameter, sampling at 0.35 arcsec/pixel, and a pixel pitch of 12 μm. The 10 arcmin FOV increases the area coverage over SPIcam by a factor of >4. The pixel scale allows for Nyquist sampling of a 0.7 arcsec seeing disk, which we chose as an example of a "good" seeing night on the 3.5-m telescope (given the 0.9 arcsec median seeing). The 12 μm pixels, coupled with the chosen spatial sampling, are not ideal for the 10 arcmin camera, as the resulting final f-number for the camera is f/2.04, which provides some challenging design constraints. However, relatively small pixels and a fast camera will be required if the community wishes to increase the FOV to >10 arcmin, so we matched the pixel size to typical values for off-the-shelf CCDs with $\geq 2048^2$ pixels. In the section below, "f/5.4 Camera Design," we examine a relaxed design that would be more suitable for a 10 arcmin or smaller FOV camera.

Figure 1 presents the optical design for a f/2.07 camera for the 3.5-m telescope at APO. Figure 2 shows the spot diagram for the 4000 – 5000 Å waveband. The camera design compromises included trading off between the number of surfaces and limiting the use of aspheric lenses. The final design contains 3 aspheres with cost and technical driver set by the 135 mm radius aspheric lens that reimages to the pupil, which has an aspheric conic constant <1 and will require special testing by the vendor. The design forms an exit pupil near the achromatic doublet where a stop can be inserted to limit scattered light. The camera was optimized in 1000 Å intervals between 4000 – 9000 Å with the filter as the only optical element that changes in each waveband. The filters are 11 cm across and include slight curvatures to compensate for wavelength-dependent field aberrations. As a result, special filters will have to be purchased for the camera; the existing APO filter set cannot be reused with this design.

The full FOV of the camera is actually 12 arcmin with 8% vignetting over the outer 2 arcmin. The 70% encircled energy radii are typically 10 – 12 μm or better over the full field and the rms wavefront error induced by the camera is <1 wave in each 1000 Å bandpass (compared to 10-20 waves of seeing-induced error). It was challenging to extend the full performance down to 3200 Å because of changes in glass properties <4000 Å. The camera can provide 3200 – 4000 Å imaging but it will require a U-band corrector or the acceptance of degraded imaging performance (non seeing-limited). The camera is laid out end-to-end, but the distance to the final focal plane is 3 meters, so a final design would require the use of one or more fold mirrors to reduce the physical dimensions of the instrument (which should extend <1.5 m from the telescope focal plane at NA2).

In the area of performance, this camera provides a considerable improvement in FOV and comparable to slightly better throughput performance compared to

SPIcam. The camera provides a factor of >4 increase in area (a factor of 6.25 if the full 12 arcmin FOV is considered). The throughput estimates depend on the relative performance of the CCDs and on the reflective losses due to the optical elements in each camera. A new CCD will have better quantum efficiency and lower noise than the SPIcam CCD. For example, standard E2V CCDs coated for broadband response have peak QEs around 85% and can exceed 90% for mid-band optimized coatings. The Scientific Imaging Technologies (SITe) CCD used in SPIcam has a quoted QE that is comparable to these values but the vendor measured the QE at room temperature and is not clear that the cold operate QE can match this level. (The Magellan IMACS camera team found that their QE increased by >50% when they replaced the SITe CCDs in their f/2 camera with E2V devices, for example.) A new CCD will also have better performance (15% – 25%, depending on choice of coat) at its blue (3000 -- 4000 Å) and red (8000 -- 9000 Å) extremes. In addition, the SPIcam CCD has 5.7 e^- readnoise, compared to ~3 e^- for newer CCDs, although in general the imaging S/N is not readnoise-dominated.

SPIcam is an extremely simple imager, with the CCD placed at the natural focus of the telescope and with no intervening optics except for the entrance window and the filters. The new camera design contains 16 surfaces, which will result in a throughput after reflective losses ~85% (not including fold mirrors which will be needed for packaging), compared to ~98% for SPIcam (assuming 1% reflective losses at each surface). If the newer CCDs can provide 50% greater QE over the SPIcam CCD, then the resulting throughput of the new camera would be ~30% better than SPIcam in its midband performance. The formation of a well-defined pupil and the use of a pupil stop to reduce scattered light will also improve the sensitivity, particularly to faint and/or diffuse targets.

This design was intended to show that a well-corrected, 12 arcmin FOV camera with good full-field broadband and narrowband performance from 4000 – 9000 Å can be designed for the 3.5-m telescope. It should not be taken as a final or recommended prescription for a camera for the 3.5-m telescope. The optical elements are complex and will likely be quite expensive. Much the complexity can be removed by a more judicious choice of design specifications. We did not attempt to optimize the design in this study because we found that in the absence of specific performance requirements derived from science drivers, we had to make choices that may or may not represent the best options for meeting the needs of the APO observing community. A complete design study that considers science use cases and subsequent flowdown to the technical requirements will be necessary to fully evaluate design and cost trades.

This design can be considered as an entry point for larger FOV cameras: the same final focal speed matched to a 4096^2 CCD with the same pixel pitch and spatial sampling would cover a 24 arcmin FOV, for example. The NA2 port has a full field (minus baffling) of 30 arcmin, although the guide camera begins to vignette the field on one side at 24 arcmin. However, the field correction becomes increasingly challenging as the FOV increases and may prohibit a significantly larger FOV at reasonable cost. The design constraints can be relaxed by finishing with a slower final camera. This could be matched to the detector by increasing the CCD pixel sizes, oversampling by more than two pixels, or by accepting a finer pixel spatial sampling. A 0.25 arcsec/pixel sampling matched to 12 μm pixels requires a less challenging f/3 camera, for example, and would give an 8.5 arcmin FOV for a 2048^2 CCD or a 17 arcmin FOV for a 4096^2 CCD.

Figure 1: The optical design for a 12 arcminute FOV camera for the NA2 port on the 3.5-m telescope at APO. Light enters from the telescope on the right.

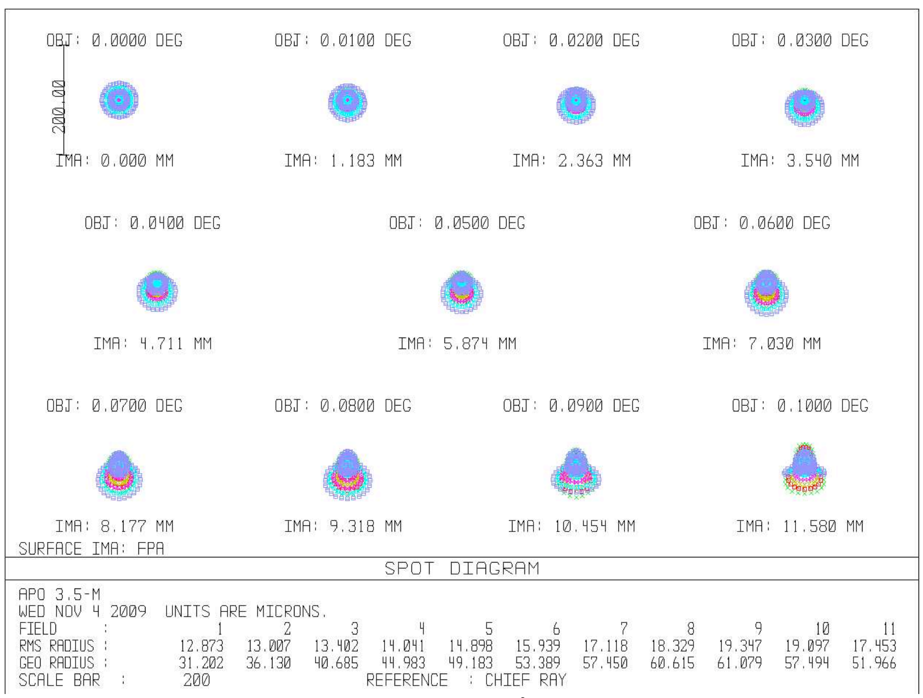

Figure 2: Spot diagram for the 5000 – 6000 Å waveband for the camera design shown in Figure 1. The pixel sampling is 0.35 arcsec/pixel matched to 12 μm pixels, so the 200 μm scale shown on the figure corresponds to 5.8 arcsec. The 70% encircled energy radii are typically 10 – 12 μm over the full FOV.

f/5.4 Optical Design

For a camera with a 10 arcmin or smaller FOV, a less challenging optical design with a slower camera can be matched to a detector with 24 μm pixels. This could be achieved by recycling the SPIcam CCD or by purchasing a new CCD with larger pixels (although most of the off-the-shelf ≥2048^2 CCDs have 12 – 15 μm pixels so a custom order might be necessary, which increases the cost). In Figure 3, we present an example of an optical design for a camera with a f/5.4 final beam speed. Matched to 24 μm pixels, the camera gives 0.27 arcsec/pixel sampling and a 9 arcmin FOV. This is an existing design taken from the imaging component of the Robert Stobie Spectrograph on the SALT telescope (formerly named PFIS; Burgh et al. 2003, Proc. SPIE, 4841, 1463). Figure 4 shows the spot diagram for the camera if used on the 3.5-m telescope at APO.

This design is not optimized for APO but it shows how a camera at ~f/5 could provide an improvement in FOV over SPIcam (~4 times the area) with optical elements that are smaller and less challenging to construct than for the f/2.07 camera. This camera provides excellent color correction over the full visible waveband, including down to the atmospheric limit in the blue. There is some lateral color shift in the design; though the effects are small over standard visible wavebands. The camera is more compact than the f/2.07 design above (2 meters vs. 3 meters) and the optical elements, though numerous, are smaller and easier to fabricate. As with the f/2.07 camera, the formation of a good pupil will allow internal baffling to reduce scattered light. The camera is probably over-designed for the needs of APO: the collimator, in particular, provides an extremely well-collimated beam that may not be necessary for APO, unless users wish to include dispersive elements (such as grisms) into the instrument design.

The design has a fairly large number of optical elements, resulting in 42 optical surfaces. Assuming ~1% reflective losses at each surface, the optical throughput will be about 0.65. If the current SPIcam CCD is used, that would result in a ~33% drop in the overall throughput compared to SPIcam (which has only one optical element, the filter, with two surfaces). A new CCD with 50% higher QE would offset the reflective losses, resulting in a camera with a throughput comparable to SPIcam. In either case, careful baffling at the pupil will likely improve the scattered light blocking and increase the sensitivity to faint, diffuse targets.

Most of the current APO filters could be used with this camera. SPIcam uses 3x3 in filters, including some broadband and narrowband interference filters. Based on information provided by one filter manufacturer (Custom Scientific), the current interference filters (matched to f/10) will experience central wavelength shifts of 3.0 – 4.7 Å from 4500 to 7500 Å when used in an f/5 beam. The FWHM will also broaden by 2.25 – 3.5 Å. For the broadband filters ($\Delta\lambda$ > 300 Å), this shift is acceptable. The narrowband filters ($\Delta\lambda$ < 100 Å) may be usable at f/5 (or faster) but they will need to be remeasured to verify that the emission is not shifted out of band. Alternately, the filters could be placed in the collimated beam.

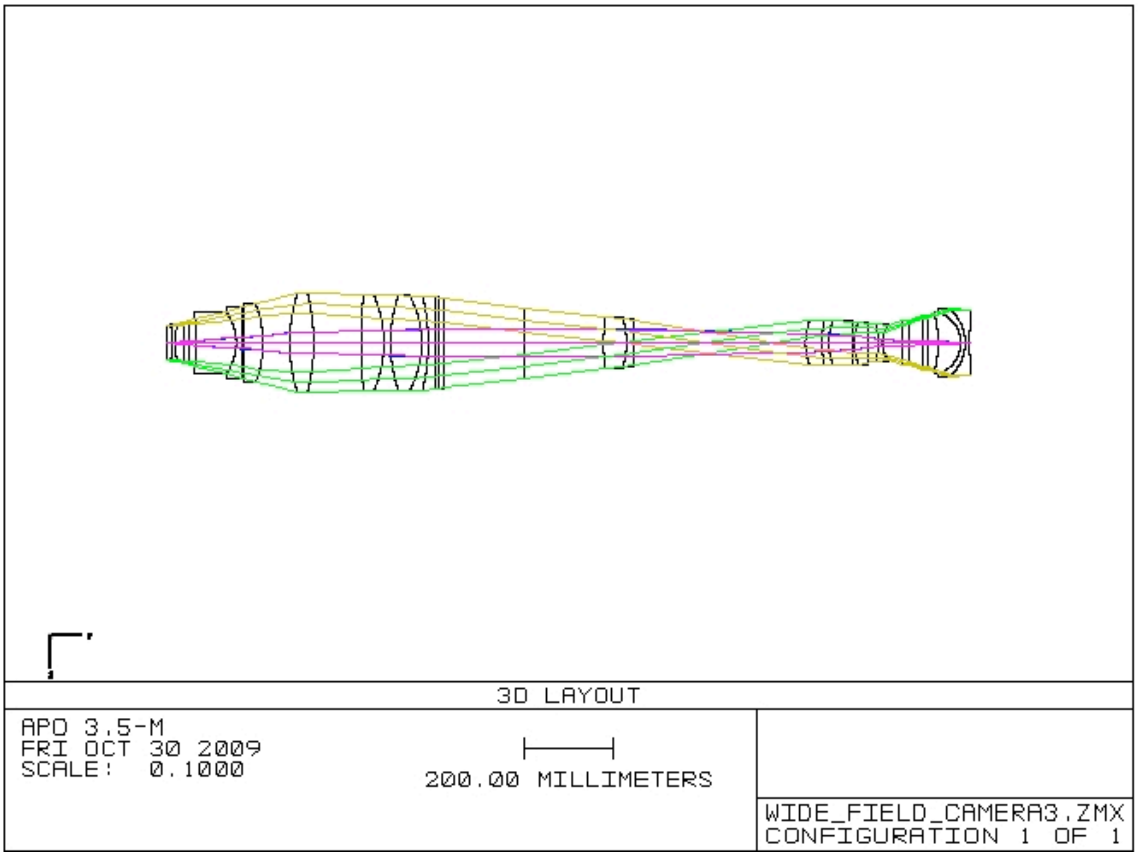

Figure 3: The optical design for the Robert Stobie Spectrograph on the SALT telescope shown for an imaging-only mode.

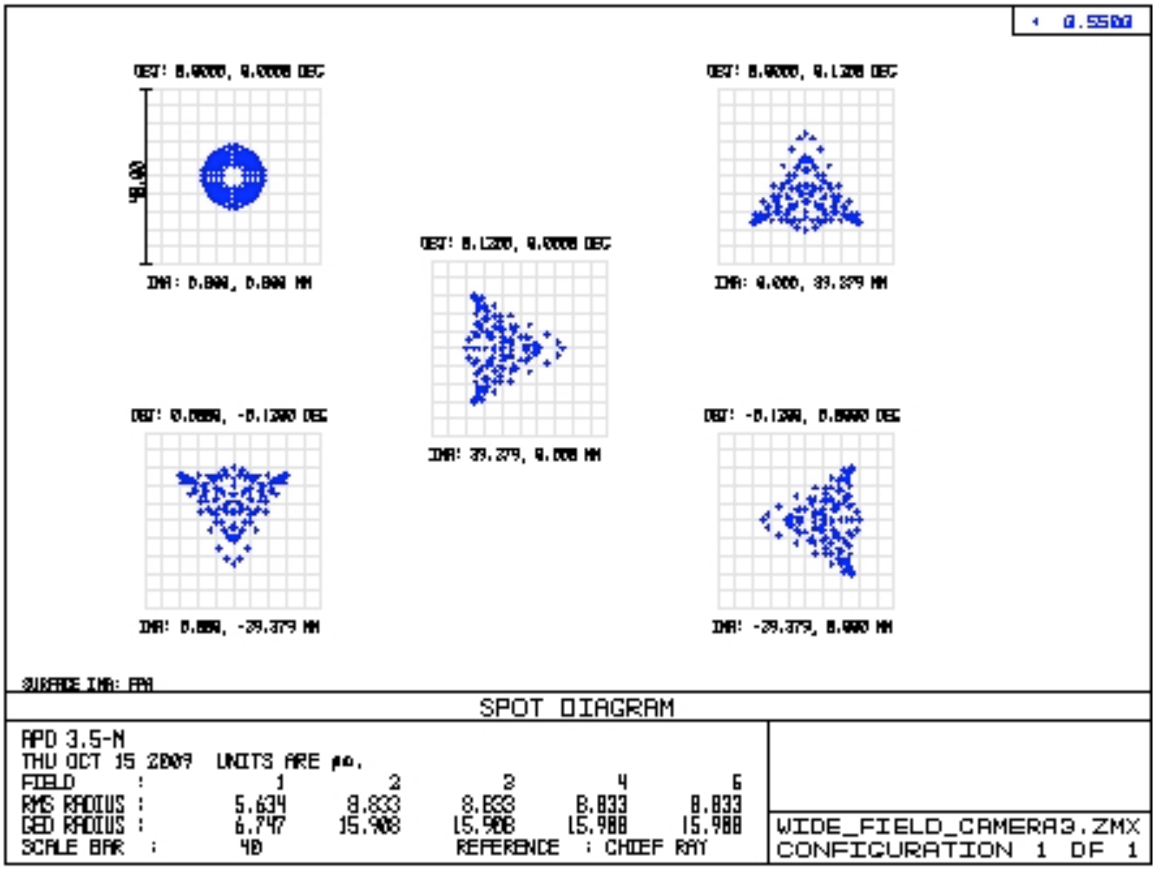

Figure 4: Spot diagram at 5400 Å for the optical camera design presented in Figure 3 when matched to the 3.5-m telescope at APO. The sampling is 0.27 arcsec per pixel, matched to 24 µm pixels. The 40 µm scale shown above corresponds to 0.45 arcsec.

<u>General considerations for a NA2 camera</u>

In 2004, the telescope mirror and NA2 port baffling were redesigned to reduce the amount of scattered light viewed by the CCD in SPIcam. The changes were made in response to a scattered light analysis of the telescope that revealed that the SPIcam focal plane received unobstructed views of multiple scattering surfaces in the telescope structure (Pompea et al. 2003, Proc. SPIE, 4842, 128). The current limiting FOV is set by the baffling inside the NA2 port, which sets a 90% transmission at 0.1 degree diameter, or 6 arcmin. As a result, any camera upgrade that seeks to increase the FOV to >6 arcmin will require removing the NA2 port baffling (the telescope baffling will not need to be removed). The new camera would then require internal baffling at a well-formed pupil to reduce scattered light. The other camera at NA2, NICFPS, is also internally baffled, with a Lyot stop at its pupil (as is TripleSpec), so the effects of removing the baffling should be mitigated by the use of internal stops. However, an evaluation of the effects of scattered light on the NA2 port instruments should be undertaken as part of the upgrade effort.

It is difficult to provide cost estimates for the NA2 camera design examples given above: the designs have not been optimized, do not contain layout information, and have no estimates of opto-mechanical, electronics, or software requirements. We also do not know what resources (particularly human resources) will be available within the ARC consortium to support their construction, or even which institutions and personnel will undertake the work (and how much of their time can be provided at no cost to the project). As a result, we only attempt here to provide the roughest order of magnitude estimates of cost and schedule, with more robust costing models awaiting a full design study for the chosen instrument concept.

We note that the two previous facility instruments developed for the 3.5-m telescope at APO, NICFPS and TripleSpec, were both in the ~\$1.1 – 1.3M price range (though the true costs were higher, as some expenses including labor were borne by the PI institutions). We estimate that the cost of the f/2.07 camera will be at least as much as these instruments but probably more than two to three times as high. The camera will require a complete enclosure (larger than the NICFPS enclosure, though not LN2 cooled), optics, and mounts including a full filter set (broadband plus a few of the more popular narrowband filters, such as Hα), a new CCD and controller, and a filter wheel and focus mechanisms. The detector will be less expensive (~\$50,000 for a 2048^2 optical CCD) than the NIR arrays (\$250,000 for the NICFPS H1RG detector) but the optics in the current design are large (up to 270 mm diameter), have very complex figures, and will be expensive (several hundred thousand dollars total). The hardware costs for the f/5.4 camera will be lower, especially for a simplified optical design, and could probably be constructed for ~\$1M . There are significantly more optical elements in the example design than in the f/2.07 design, but the optics are smaller and easier to build, the packing will be more compact, and some elements can be recycled from SPIcam (most notably the filters and possibly the CCD and controller).

A development schedule should commence with a 6 to 12 month design study to develop science requirements and technical requirements flowdown, optimize an opto-mechanical design, and develop a work breakdown structure with cost, manpower, and schedule determinations. The build schedule from preliminary design review to on-telescope commissioning can be probably be achieved in 2 – 3 years, depending on the availability of personnel and funds (including coordination with NSF funding cycles) and assuming careful up-front project organization to allow for the prompt order of long lead-time items.

<u>Camera for the TR1 port</u>

One attractive option for a new camera on the 3.5-m telescope is to deploy a camera that is permanently mounted on the TR1 port, much as AGILE is on the TR2. The NA2 port on the telescope is crowded, with four instruments currently using it, so a design that could move a new instrument to an unused port would alleviate some of need for frequent instrument changeouts at NA2. The TR ports place some limitations on instrument options, however. The instrument must function under a changing gravity vector and there are volume and mass restrictions: for safety reasons, the instrument must extend <30 in from the port and the weight should be <500 lbs with a center of gravity 24 in from the mounting point. A TR port rotator was designed to work with AGILE but it has only a 5 in aperture, which restricts the FOV to 6 arcmin. As a result, a new rotator would have to be designed for an instrument with a wider FOV. Because the TR port sees the full scattered light profile of the telescope, careful baffling would have to be considered in the redesign of the rotator and may restrict the ultimate FOV available.

To evaluate the suitability of TR1 for a general-purpose optical camera, we have developed a concept for a camera positioned at a TR port on the ARC 3.5 meter telescope. The camera raytrace is shown in Figure 5. The camera uses an off-axis, all-reflective design similar to an Offner relay, with modifications to provide better field control and provide a slightly faster final beam speed. The three optical elements include two ellipses and one on-axis asphere for the pupil mirror. This camera uses roughly half the available field of view of the TR port and lies ~10 inches past the focal plane of Agile (Figure 7). The field of view of the current design is 6 by 9 arcmin using one half of the available field. The second optic is a pupil, permitting baffling in conjunction with the field stop at the focus of the ARC 3.5 meter telescope. There are three optical components and we would anticipate being able to use the existing APO filter set, though there may be some compromise of the narrowband filters due to the faster final beamspeed. The spot diagrams and the rms spot radius over the field are shown in Figures 7 and 8. The design was matched to the existing SPIcam CCD assuming 24 μm pixel pitch. The 90% encircled energy image size is 0.25 arcsec. At the final beam speed of f/5, the camera gives 0.30 arcsec/pixel sampling.

Our concept shows that a camera with a well-corrected FOV that images twice the area of SPIcam could be likely designed for the TR1 port on the 3.5-m telescope. The camera could recycle the SPIcam CCD and use much the current APO filter set (with the same level of CWL shift and FWHM broadening discussed for the previous NA2 design). The TR rotator would have to be redesigned to accommodate the off-axis FOV and some of the packaging would have to be carefully considered, given the short distance from the focal plane to the dewer edge (2 in) and the option for including a guide camera. However, it will be difficult to design a camera with a FOV much larger than is shown in this concept given the restrictions of the TR port, and the resulting improvement over the current capabilities of SPIcam is modest given the level of design and fabrication work that will be required to realize this concept. The TR ports are well-suited to smaller instruments with specialized designs, such as AGILE, but we do not recommend attempting to deploy a large, general-purpose optical imaging camera at this location.

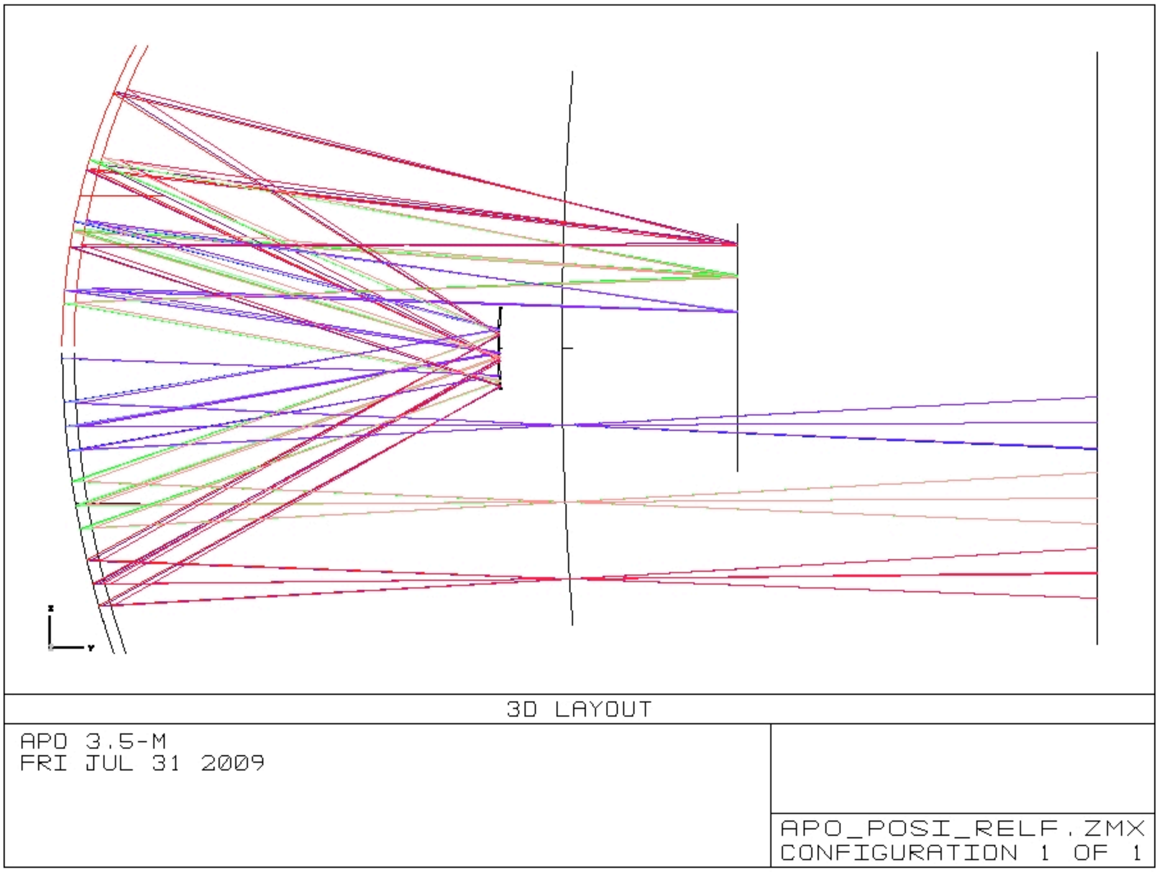

Figure 5: A sample optical design for a camera on the TR1 port of the APO 3.5-m telescope. Light from the telescope enters from the right. The telescope focal plane is in the center of the figure.

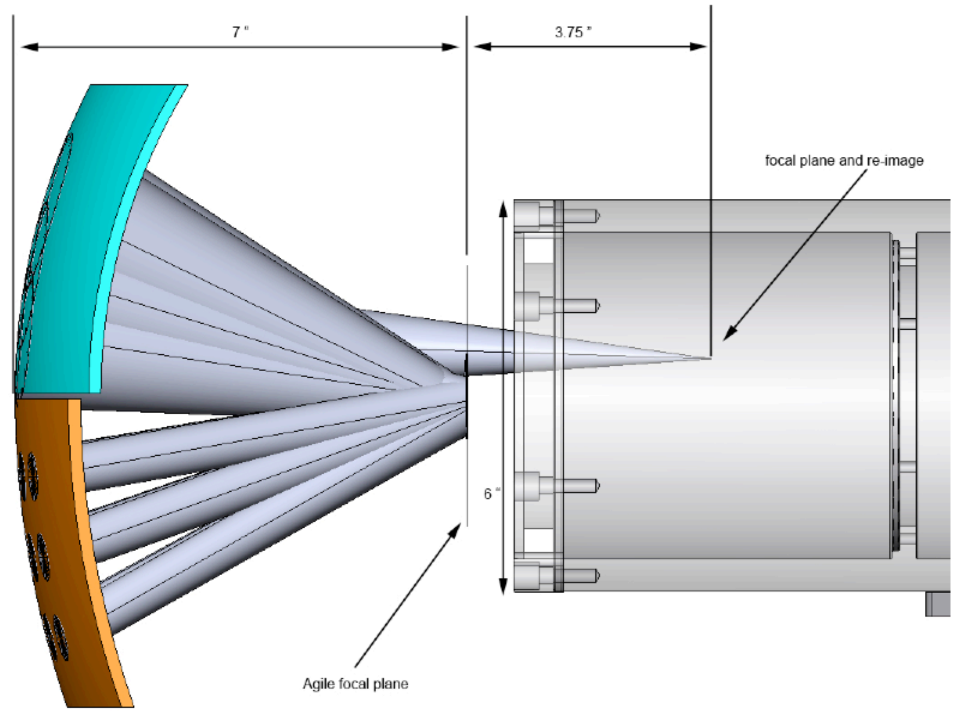

Figure 6: The dimensional layout for the TR1 camera. The locations of the optics are shown with respect to the current location of the AGILE focal plane (on the TR1 port) for reference.

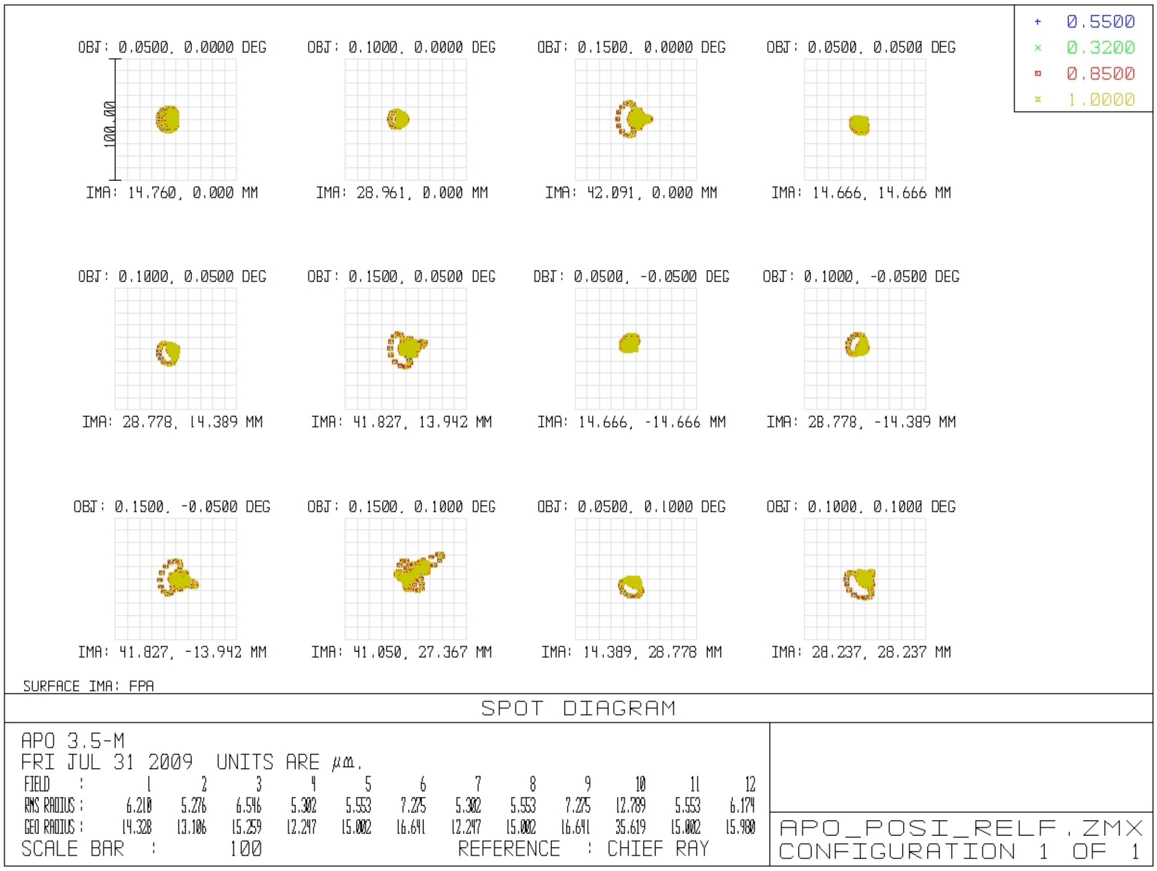

Figure 7: Spot diagrams for the optical design shown in Figure 5. Spatial sampling is 0.3 arcsec/pixel matched to 24 µm pixels.

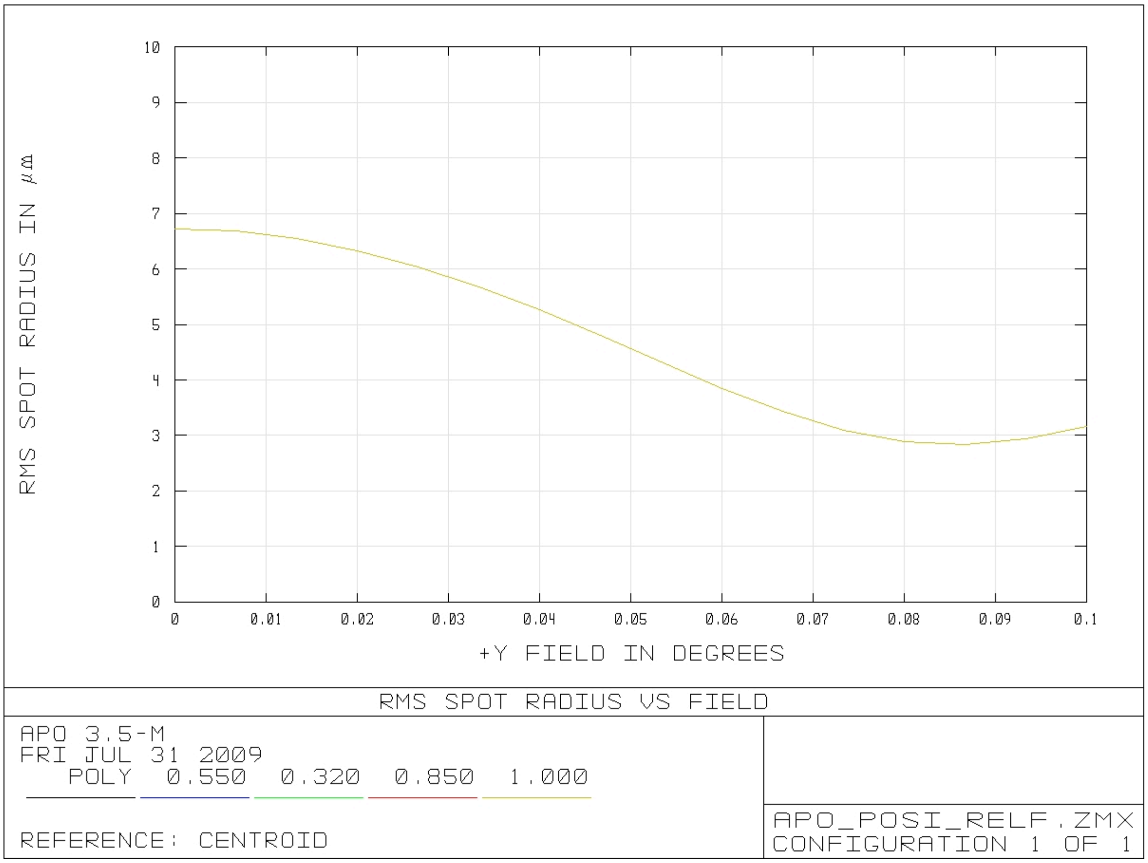

Figure 8: RMS spot radius over the field for the optical design shown in Figure 5.

B. Simultaneous Multicolor Camera

In addition to exploring general-purpose camera upgrade options, we also examined potential new instruments that could provide the 3.5-m telescope with a unique capability. One intriguing option is the use of dichroics to provide color separation to feed five cameras for simultaneous UBVRI imaging. The authors' interest in this concept derives from a conceptual design study for a high resolution optical spectrograph for the Thirty Meter Telescope project in which a dichroic tree was proposed for spectral separation to feed a bank of first-order spectrographs (Froning et al. 2006, Proc. SPIE, 6269, 61; Osterman et al. 2006, Proc. SPIE, 6269, 95) and from work on developing the NMSU High Speed Photometer, a simultaneous multicolor photometer for the New Mexico State University 1-m telescope (Harrison et al. BAAS, 211, 1119).

A comparable instrument has recently achieved first light on the 1.5-m Kanata telescope in Japan (Doi et al. 2008, Proc. SPIE, 7014, 14). Their instrument uses 14 dichroics to feed 15 CCDs, resulting in a 15-channel imager covering the 3900 – 9300 Å over a 4.5 arcmin FOV with 0.27 arcsec/pixel sampling. They were able to achieve ~80% transmittance through their dichroic system (which also included leak cut filters to limit response in each band to the desired range).

Although they had a limited observing run with the instrument, it showed good co-alignment between channels on the telescope, stable focus positions, and limited ghosting.

What we propose here is a multicolor camera that uses four dichroics to divide the light into five visible wavebands (UBVRI or Sloan ugriz) feeding five independent cameras. Using the NICFPS spare, engineering-grade detector, the camera could also extend into the non-thermal infrared with a J-band channel. Ideally, each camera channel would include a filter wheel so that both broadband and narrowband imaging could be supported. Because each channel would be independently operated, multiple combinations of broadband and narrowband imaging could take place simultaneously (e.g., undertake a long integration in one waveband where the target is faint while cycling through broadband and/or narrowband filters in other channels).

Such an instrument would be a powerful tool for visible band imaging on the 3.5-m telescope at APO. Simultaneous, multiband imaging is particularly attractive for observations of transient and variable targets, including gamma-ray bursts, supernovae remnants, compact binary systems, asteroids, etc. The camera would also serve as an outstanding survey instrument for projects that require multi-waveband colors, such as determinations of photometric redshifts (where a J-band channel would be particularly useful) and stellar population studies. As large survey projects such as PAN-STAARS come on line, the ability to efficiently follow up on interesting targets, particularly transient detections, will be an attractive capability for a moderate size telescope.

However, a simultaneous multicolor imager will also be useful for observations that only require imaging in a few wavebands. Because each camera will only observe over a limited portion of the visible waveband, the cameras can be designed to maximize throughput for each channel through targeted choices of optics and CCD coatings. This will be particularly important in the blue and red channels, where specialized CCD coatings can improve the QE values by a factor of 2 or more over broadband coats. The camera optical designs will also be less challenging when the need for very broadband performance is eliminated. If we adopt conservative throughput estimates of 80% for the collimator and camera optics and 80% for the dichroics and assume new CCDs with optimized coatings in each band, the new instrument would achieve mid-band (~6000 Å) throughputs comparable to SPIcam but exceed the current SPIcam performance by 20% or more in the blue (~3500 Å) and red (~9000 Å) extremes.

In the interest of minimizing cost and instrument size, the FOV of the cameras would likely be smaller than the single camera option: 5 – 6 arcmin per channel. (In this case, the NA2 port baffling would not need to be modified, though we would still recommend internal instrument baffling to further control scattered light.) The current APO filter set could also be recycled for this instrument (though if the filters need to be readily accessible because they are shared with other instruments, the location of the filter wheels for each camera will have to be carefully considered in the design). Although the FOV for each camera would not be much larger than the current SPIcam FOV, the simultaneous multiband observations would provide a multiplexing advantage of 5 over the single camera.

As with the single camera options, we can only attempt a rough estimate of cost here by comparing costs with other systems and without attempting to cost out labor (which requires a full work breakdown structure and knowledge of the team undertaking the build). Given those caveats, we estimate that such an instrument would cost \$3 – \$5M, particularly for a full, facility-level instrument (as opposed to a less user-friendly visitor-level instrument such as the Doi et al. first light system). New hardware would include a (large) enclosure, collimating optics, a dichroic bank (4 dichroics), five cameras, five CCDs, one to two controllers, five filter wheels, and filter wheel and focus mechanisms. There would probably be some cost savings from ordering multiple copies of the CCDs and camera components (e.g., TripleSpec received a 30% discount on its opto-mechanical assembly by ordering three units; Wilson et al. 2004, Proc. SPIE, 5492, 1295). The complexity of the concept will require careful attention in the design phase to questions of packaging (can the instrument be made compact and mobile enough for ready mount/demount to the NA2 port?), long-term maintenance (e.g., avoid having five separate dewars to fill), alignment and stability (can you focus in one band each night and maintain constant, stable focus offsets in the other five bands?), and user support (an exposure time calculator will be useful to plan observations before the run and data reduction tools would maximize efficient use of the data received).

We do not have the space in this white paper to fully explore the design options for a multicolor camera. If the ARC community is interested in pursuing this concept, we recommend that the next step be the commencement of a preliminary design study, which would probably take 6 – 12 months, depending on availability of personnel. As with the single camera option, the participation of ARC observers in such a study would be essential to develop sample science use cases and requirements derived from the scientific goals. For this concept, careful study of opto-mechanical design, layout and packaging, and electronics and software requirements will be particularly important to determine exactly how such an instrument can be deployed on the 3.5-m telescope. The design study could lead directly into a proposal to the NSF for funding support for the instrument. If funded, we believe the instrument could be designed, constructed and commissioned in 3 – 4 years.

C. QUOTA Camera

Many of the users polled for this white paper expressed an interest in improved spatial image quality for the 3.5-m telescope. Full adaptive optics solutions for achieving diffraction-limited imaging at visible wavebands remain many years off, but some simpler solutions can be implemented for improving image quality in the visible, including implementing tip-tilt systems or using frame-transfer CCDs to correct image distortions on-chip.

To investigate the image quality improvement we might expect if some form of tip-tilt correction was implemented, several series of images taken with the high speed Fastcam camera were analyzed. These frames were taken at 100 frames per second. Each of the time series was split into chunks of 1000 frames (10s), and coadded frames were constructed from both the raw frames and from frames shifted by the centroid position of the previous several frames to mimic tip-tilt correction. Results of the "raw" image quality vs. the "tip-tilt corrected" image quality are shown in Figure 9 (lines are for 0, 0.1, 0.2 arcsec improvement). Overall, improvements of 0.1-0.3 arcsec can be seen. This is comparable to image quality improvements reported by KPNO/WIYN for implementation of tip-tilt on their 3.5m.

We did not examine tip-tilt options in detail in this white paper. Tip-tilt systems can correct for telescope vibrations and guide errors and can improve R and I-band image quality by 10-15% over native seeing. However, they also can be expensive to implement on large telescopes (the WIYN Tip-Tilt Module cost >$1M, for example), correct over a limited FOV, and can lower throughput in the visible (as part of the light is picked off to feed the error sensor). If the ARC community has a strong desire to see tip-tilt implemented on the 3.5-m, we recommend a thorough consideration of specific science cases that would benefit from its use to allow for a more quantitative trade study between cost and performance.

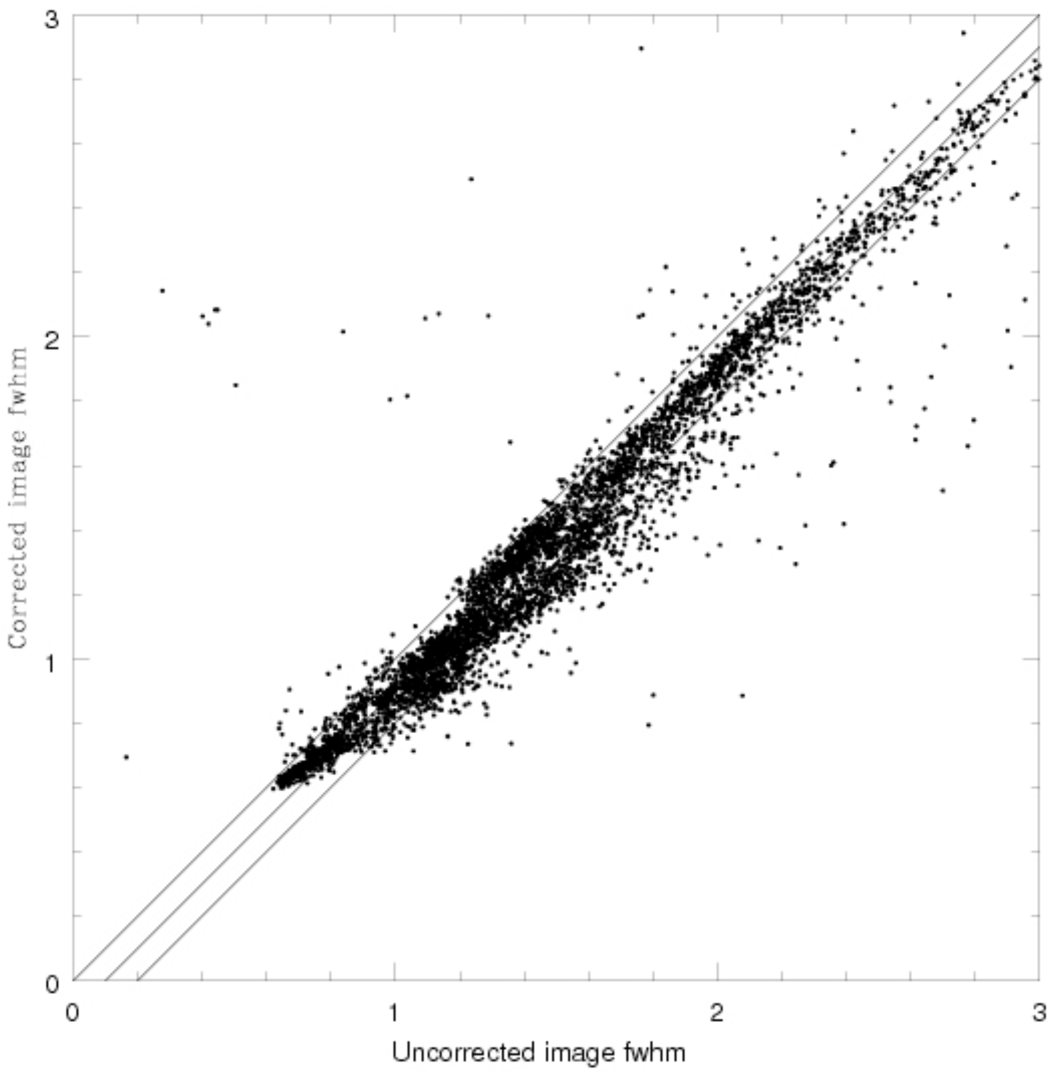

Figure 9: FASTCAM observations on the APO 3.5-m telescope showing the expected improvement in image quality over raw images.

Alternately, we can consider image quality improvements using Orthogonal Transfer Arrays (OTAs) for on-detector corrections. In late April 2009, we were contacted by NOAO/KPNO to see whether we had any interest in making use of their QUOTA instrument at APO. QUOTA (QUad Orthogonal Transfer Arrays) was built for the WIYN 3.5m as a prototype for their new ODI (One Degree Imager) which is under construction. QUOTA was supposed to serve as the primary WIYN imager for several years during ODI construction, but QUOTA was delayed because of chip delivery issues. It has had several engineering runs on the WIYN telescope, but at this point, ODI is near enough to completion that NOAO has decided not to invest further in QUOTA, hence their desire to find a use for it somewhere else.

QUOTA consists of 4 OTAs, each 4Kx4K, with 12 μm pixels. Each of the OTAs is split into 64 cells. Within each cell, charge can be transferred both vertically and horizontally during an exposure; with this capability, there are necessarily small gaps between the cells. The control electronics has the ability to read a subset of these cells (8) at a high rate (30 Hz). The anticipated mode of operation is to choose cells for fast readout that have moderately bright stars in them, use these to track motions of these stars, and shift the other cells accordingly to sharpen images. Having multiple fast readout cells with the OTA capability allows for different regions of the field to be shifted by different amounts, an important consideration if one wants to track atmospheric motions over a wide field, since the isokinetic patch is generally only a few arcmin or less.

Implementation at APO

The ARC 3.5m differs from the WIYN 3.5m in that our focal ratio is F/10, as compared with WIYN's F/6. As a result, the pixel size and field of view are correspondingly smaller at APO. At 12 microns, the pixel size at APO would be about 0.07 arcsec, with a total FOV about 10 arcmin on a side; because of gaps between arrays and between cells, there will be gaps within the FOV. NOAO claims that the OTAs can be binned, but they have not experimented with this capability, and it is not totally clear how it interacts with the charge-shifting operations during an exposure.

The current CCDs in QUOTA are not thinned, leading to lower QE overall, and particularly low QE in the UV/blue. Thinned OTAs are now available, and thinned devices will be used in ODI. Apparently, there will be spares and there is a possibility of getting thinned chips for QUOTA from NOAO as part of some "deal"; purchase of such devices directly would be at an estimated cost of $60 -- $70K. The chips have readout noise around 6 electrons for the "science" readout cells, and about 20 electrons for "guiding" readout cells.

The large focal plane requires a corrector in front of the detectors. We have obtained the optical prescription of the corrector used at WIYN, and preliminary analysis suggests that it will provide adequate correction at the ARC 3.5m as well (although this would need to be confirmed before proceeding).

The instrument includes a large shutter and filter wheel that are mounted in front of the detectors. The filter wheel uses ~6 arcsec filters and a few (TBD) would be available with the instrument (others are shared with other NOAO imagers).

At APO, QUOTA would be mounted at the NA2 port to accommodate the large field. The NA2 baffle would need to be opened up to allow illumination of the full field, presumably at the cost of increased scattered light. The instrument is relatively compact, weighs ~100 lbs, and the focal plane is not too far behind the front mounting surface (~5 inches), so it could probably easily be accommodated at NA2 with the construction of an interface plate.

The instrument uses a Cryotiger to cool the detector and a Lakeshore controller for the temperature control; this could presumably be kept at the intermediate level. Interface to a control computer is by fiber optic, so the instrument computer could be located essentially anywhere.

Graphical software has been developed for instrument control, including selection of guide stars. Currently this has to be done manually; this would be an area for potential improvement. An interface to obtain telescope information for image headers would need to be developed (probably be fairly straightforward). A method of providing guide information to the telescope (for long scale drifts, to keep the amplitude of the charge transfer down) would also need to be developed. Developing entirely new control software, e.g., for use through TUI, would likely be fairly time-intensive, but the existing GUI software could probably be used remotely.

NOAO staff has indicated that they would probably be willing and available to come to APO with the instrument to help get it implemented. Scheduling of such of visit is still TBD and likely will not be trivial!

Performance/issues at APO

Implementing QUOTA at APO would provide a larger field of view than currently exists, along with the “tip-tilt” correction allowed by the OTA arrays. The basic scientific improvements would be in larger FOV and modestly improved image quality. With the current detectors, we would suffer a significant throughput loss compared with SPICAM, but if we upgraded the detectors, the throughput would be comparable or better.
Another application that OTAs have been used for is the “square star” observing mode which allows bright stars to be spread out over more pixels, allowing many more photons to be collected and corresponding lower errors per measurement. The high-speed readout cells in the OTA could also enable high speed time-resolved imaging.

The drawbacks of QUOTA at the ARC 3.5m include: 1) we would have to remove some of the NA2 baffles to allow the larger FOV, with resulting increase in scattered light; 2) there may be significantly larger overhead for running QUOTA compared with SPICAM because of the setup time required for getting the fast guiding started; 3) additional time would be required to image continuous fields because of the many gaps in the focal plane between detectors; 4) the filter set is very limited, and to buy additional large filters will be expensive; 5) the chips/detector controller is a complex system, and any issues that may develop will have to be worked out in conjunction with NOAO staff. Apart from these technical issues, there is also the "political" issue that we will likely have to arrange some sort of “trade” to get use of the instrument, e.g., we may have to give up some telescope time in exchange for use of the instrument.

D. Other options

It is not possible within the confines of a single white paper to examine all of the possible upgrade options that fall under the broad umbrella of visible band imaging capabilities. We chose to concentrate on those options that appeared to provide general capabilities broadly matched to the desires of the ARC community. However, we note here a few options that we did not pursue in detail, but that may be of interest when considering future instrumentation at APO.

A camera using a Lucky imaging system (Mackay et al. 2004, Proc. SPIE, 5492, 128) to improve image quality could readily be deployed on the TR port of the 3.5-m telescope using the existing AGILE TR rotator design. Lucky imagers use low noise L3CCDs to rapidly read out frames (>10 per second) and then retain and co-add only those frames that meet the desired image quality criterion (with the option to trade off sensitivity and spatial resolution). Lucky imagers have been tested on ground-based telescopes and shown to provide "near diffraction-limited" images under good seeing conditions and improvements in angular resolution of 2.5-4 when the seeing is poor (e.g., Law et al. 2006, A&A, 446, 739). The L3CCDs currently run to 1024^2 active pixel regions, so the camera would be used over relatively small fields of view. For example, a 0.03 arcsec/pixel sampling (to Nyquist sample the 0.06 arcsec diffraction limit of the telescope in the I band) would give a FOV of 30 arcsec. Matching the two-pixel sampling to the V-band diffraction limit would give an 18 arcsec FOV.

We also did not consider imaging spectroscopy options in this white paper. The Goddard Fabry-Perot spectrograph is available as a visitor instrument and upgrades to the instrument (such as incorporating an integral field spetrograph) have been considered. Other ARC consortium members have expressed an interest in combining specialized slit masks with grisms to enable imaging spectroscopy in combination with current cameras or the DIS spectrograph at APO. Another option is the use of programmable microshutter arrays as proposed by Mike Pearce in the NIR. If an imaging spectroscopy option is desired for future cameras, it should be considered during the design phase to ensure that the upgrade path remains readily available.

V. Conclusions and Future Work

The purpose of this white paper is to outline some of the options available for upgrading the visible light imaging capabilities of the 3.5-m telescope with the ultimate goal of replacing SPIcam with a more powerful camera. It is intended to provide the ARC community with information about potential upgrade options, summarize community preferences for camera performance, and indicate areas where telescope modifications may be necessary to achieve certain capabilities. Ideally, the white paper provides sufficient information to the ARC community to help it prioritize its future instrumentation development plans and shape the science requirements that will ultimately flow down into a complete design study for a new instrument. Indeed, we strongly recommend the development of a science user's group as part of the design study who can help shape the requirements, as we found during the course of this study that there is a large parameter space to consider and it challenging to make the correct design trades in the absence of specific science drivers.

The ARC observing community is interested in an upgrade to SPICam that maintains the diverse broadband and narrowband imaging capabilities but with a larger FOV and improved sensitivity and image quality. The most straightforward upgrade for the telescope is to replace SPIcam with a general-purpose camera with better performance. We presented two example optical designs for a ~10' FOV camera for the NA2 port as proofs of concept and to examine trades between performance, complexity, and cost. They showed that a substantial increase in FOV over SPIcam can be achieved with a completely new camera while a more cost-effective design can be pursued by trading off the FOV and throughput performance. We also examined placing a permanently-deployed camera at the TR1 port of the telescope, but the volume and weight restrictions for this port limited the potential designs to ones that were not considered interesting improvements over SPIcam.

Another direction to pursue when upgrading the optical camera is to provide APO with a unique instrument that would provide a competitive advantage to optical imaging on the 3.5-m telescope. The example provided here is to build a multicolor camera that uses dichroics to spectrally divide the optical light to feed 5 cameras that provide simultaneous imaging in UBVRI. The NICFPS spare, an engineering-grade Hawaii-1RG array, could also be used to extend the imaging into the non-thermal infrared and provide a J-band channel. Such a camera would provide APO with a powerful instrument for the observations of transients and target of opportunity and large survey programs. Due to packaging requirements at the Nasmyth ports, this concept would likely have a smaller FOV than the camera upgrade option, but would include both a multiplexing advantage (x5) and the potential for significant improvement in sensitivity (as each camera and detector could be optimized for its waveband).

The user community has expressed an interest in improving image quality on the telescope. Options include the design of a tip-tilt system or the use of orthogonal transfer array (OTA) CCDs to allow on-chip correction. For the latter, NOAO has expressed interest in providing QUOTA, their prototype camera for the WIYN One Degree Imager, to APO. QUOTA uses four OTA CCDs to cover a 10' FOV. QUOTA provides an attractive option for improving spatial imaging performance at APO, but it is unlikely to act as a complete replacement for SPIcam, as it requires special, large filters, has gaps in its FOV, will suffer from scattered light contamination, and is somewhat complex to operate. For both tip-tilt and OTA systems, the improvement in image quality is typically of order 10-15% over native seeing in the R and I bands, with the improvement decreasing with distance from the tip-tilt guide star (although multiple stars can be used with QUOTA, improving the full-field correction).

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