Apache Point Observatory Optical Imager Proposal
DRAFT FOR COMMENTS

J. Huehnerhoff, B. Ketzeback

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ABSTRACT

The Apache Point Observatory 3.5m telescope has a host of scientific instruments ranging from infrared spectrographs to optical imagers. This suite of instruments allows the telescope to maintain a competitive edge in the astronomical community. One of the first instruments to be commissioned on the telescope, built in 1997, was the Seaver Prototype Imaging Camera (SPICam). SPICam is a general purpose imager with a 2K x 2K (24 micron pixel) CCD. Unfortunately, it does not have correcting optics, only allowing for a 4.78 arcminute field of view. For the past 15 years, SPICam has served the 3.5m members well, but SPICam is no longer capable of competing with newer instruments. The electronics are starting to degrade and, without schematics, it will be difficult, if not impossible, to repair. C.Froning & C.Burrows (2009) investigated some of the available options for a new APO imager. The following paper will try to narrow down the investigation and focus on an imager that could be built at APO with a larger field of view, new electronics, and better sensitivity.

1. Science

Wide field imaging surveys, such as POSS, SDSS, Pan STARRS, PTF, and in the future LSST, provide "industrial" photometry for millions of objects. While this archived data can address many science goals, ground-based imaging on narrower-field 4m class telescopes remains an important capability for followup, including narrow-band imaging and studies of time-varying and transient objects. The primary imager in the optical for the past 15 years on the ARC 3.5m telescope has been SPICam. Table 1 shows a breakdown of the basic science goals for users of this imager. Over the last five years, optical imaging (excluding Agile and GIFS) has been over 10% of total telescope time (table 2).

In every category of science, there are a variety of programs using SPICam as a resource. Some of the solar system programs are imaging planets, asteroids, comets, and trans-Neptunian objects, as well as transient object followups found in the Pan STARRS data. Galactic science includes stellar objects, globular clusters, and even more HST and Pan STARRS followup objects. Extragalactic science has the most diversity which includes follow up observations from radio telescopes (such as VLA, ALMA and Arecibo). Further extragalactic work has involved QSOs, supernovae, dwarf galaxies, WR galaxies, compact galactic group studies, and a photometric redshift survey. SPICam is also used for coordinated observing projects between ground and space based observatories for all the general categories mentioned above.

Photometric studies could be completed with this imager. Special care must be taken in the design so as not to create unwanted light effects. This consideration should be taken regardless of whether the instrument is designed for photometric accuracy. The most important aspect for photometry is knowing all characteristics of the instrument and telescope. This would require extended lab testing and commissioning to properly document.

With such a wide base of user interests, many that cannot be accommodated by the use of survey data as the primary single source for imaging science, having a general purpose medium field imager (with improved capabilities) for users to continue the aforementioned science is a necessity at a respected site like APO.

Table 1:: SPICam Science

Science	Usage
Solar System	25.8%
Galactic	8.2%
Extragalactic	64.1%
Other	1.9%

Table 2:: SPICam Usage

Year	Usage
2008	13.7%
2009	8.7%
2010	10.9%
2011	11.7%
2012	8%

2. Design Requirements

Guiding the design of this instrument are a set of requirements that will determine the overall system performance. These design requirements focus on: throughput, field of view, filter selection, and instrument size.

Throughput will be one of the big drivers of this design. Better throughput will allow imaging of fainter objects making the instrument more scientifically relevant. The biggest sources of throughput degradation include the number of optical surfaces and the quantum efficiency (QE) of the detector. With good AR coatings, the throughput of any optical surface will be greater than

95%. If focal reduction with a minimum of optical surfaces can be achieved, then the instrument as a whole will be more successful.

An increased field of view will allow for different science opportunities and greater capability than what is currently available. To more easily achieve this larger field of view, focal reduction will be necessary. Increasing the field of view will best be accomplished with focal reduction and a large CCD. Focal reducing optics are often easier talked about than designed and is typically done over a small field or band pass. Good performance over a large band pass and field is discussed further in section 3.

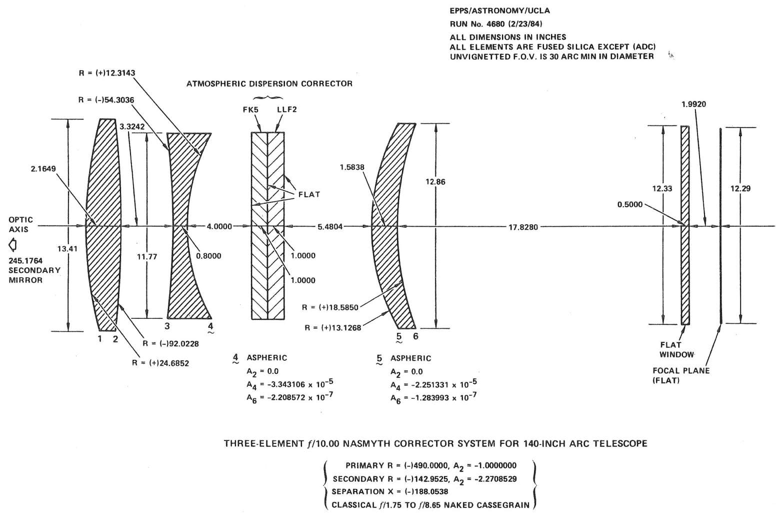
The current APO filter catalog should also be considered in the design of this instrument. APO already has a large host of 3 inch and 2 inch filters. A minimum requirement will be that the use of these filters does not decrease the field smaller than currently on SPICam. This would be approximately a 4.8 arcminute diameter for the 3 inch filters and a 2.5 arcminute diameter for the 2 inch filters.

These requirements will then need to be fit into a small corner port package. The instrument designed will be a compact, sensitive instrument that will allow for quick observations and increased scientific capability.

3. Optical Design

A driving force of the optical design is field flattening and increased field of view. Figure 11a shows the field curvature out to 12 arcminute diameter full field (0.1 degree half field) for the uncorrected 3.5m. With field correction in mind, a corrector can be made to decrease the curvature. The MILT document (E.Mannery & W.Siegmund 1983) discussed two corrector options, one of these is shown in figure 1. With a small field, such as with SPICam, the field is locally flat so no correction is necessary. Outside of a 6 arcminute diameter field, the curvature starts to greatly deviate. As shown by E.Mannery & W.Siegmund (1983) and verified by B.Ketzeback, the radius of curvature is 1389mm. Field correction will only produce a small gain with a conventional CCD. In order to use the entire field with the native telescope focal length, the CCD would need to be nearly 120mm. This is not commercially available, and even if it was, it would be at enormous cost. It was soon apparent that field correction without focal reduction would be unacceptable. Work on focal reducers has shown that there are many tradeoffs that must be dealt with to meet the design specification. A focal reducer is easy if it is a narrow band pass or field, but when the field is from 350nm to 1000nm and the field is greater than 8 arcminutes, it becomes increasingly more difficult. What is relatively easy to do is decrease the focal ratio to f/7 with three optics.

Figures 12 - 17 show possible optical design properties versus the uncorrected properties of the telescope. At this time, it should be noted that this is only a possible design and that further effort must be taken to look into greater focal reduction, tolerances, and ghost analysis.



2.7 Three-lens-element corrector.

Fig. 1.—: MILT Corrector

The uncorrected telescope has very good optical properties, as can be seen in the figures. The biggest problem is what happens beyond 8 arcminutes. The curvature in the focal plane causes the spot size to balloon. Since we want the largest field with the best performance, it is necessary to discuss how that performance will be quantified. A good measure of the performance of any set of optics is the spot size. The spot size is a measure of the aberration control of an optical system by launching rays through the entrance pupil and watching how the rays behave in the focal plane, J.M.Geary (2007). An aberration free system will have a spot size of a single point. In an ideal world, the spot size would fall within the airy disk. This is the diffraction limited region for the optical system. With more complex optical systems, this is not possible and the best that can be achieved is to fall within some regime that is not detectable by the system. In other words, if the light falls within the oversampled region there is no way that the CCD system will know the aberrations exist. This then has to be balanced over the wavelength range and the field.

To determine the maximum acceptable spot size, it is necessary to know the plate scale for a given optical design. Table 4 shows the focal ratio with respect to the ideal pixel size and field of view. The field of view, in arcminutes, is based on a detector that is 60mm for a 4K and 90mm for a 6K square detection area. Since this is the diameter of the field, the corners of the CCD will extend to a slightly larger field.

$$plate\ scale = \frac{206265}{aperture(mm) * f/\# * 1000} \frac{arcsecond}{micron} \tag{1}$$

A Nyquist sample size of 0.3 arcseconds is chosen based on the best seeing conditions at APO.

Equation 1 can then be expanded into equation 2 to calculate the ideal pixel size.

$$ideal\ pixel = \frac{1000 * f/\# * aperture(mm) * 0.3}{206265}\frac{microns}{pixel} \tag{2}$$

Table 3:: Focal Reduction Table

Focal Ratio	Ideal Pixel Size	FOV 4K	FOV 6K
f/10	50.9	5.9	8.8
f/9	45.8	6.5	9.8
f/8	40.7	7.3	11.0
f/7	35.6	8.4	12.6
f/6	30.5	9.8	14.7
f/5	25.5	11.7	17.7

What this means for the design of the instrument is that to be properly sampled, all light must fall within the ideal pixel size calculated. Anything smaller than that will be oversampled and anything larger will cause visible aberrations in the science image (although this is dependent on seeing conditions).

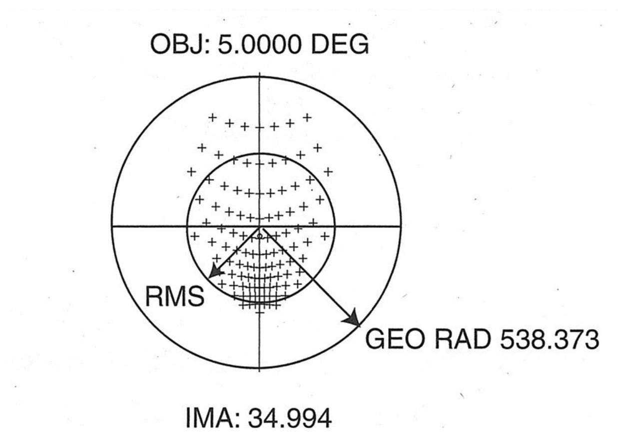


Fig. 2.—: Spot Size Diagram (J.M.Geary 2007)

If the spot size is smaller than $\frac{1}{2}$ the ideal pixel size, then the detector will see no aberrations. To fully understand this concept, it is necessary to differentiate between the RMS and GEO radius of the spot size. The RMS radius is defined as: $RMS = \sqrt{\frac{\sum_i[(x_i - x_c)^2 + (y_i - y_c)^2]}{n}}$ where (x_i, y_i) is (0,0), the central coordinates for our spot system and n is the number of data points. The GEO spot radius is simply the radius that encloses all light rays. Figure 2 is a nice illustration of both the RMS and GEO spot sizes. Figure 13 shows the uncorrected 3.5m and the proposed lens system spot sizes up to the 12 arcminute diameter field of view (note that the field sizes are for the half field).

The figures referenced are for the entire operating wavelength range. For narrowband and even wide-band imaging, the spot size will decrease to below the listed RMS size. Since this is much smaller than the ideal pixel size, all light will be within the sampled region.

Ideally, an optical design will be found to decrease the focal ratio and the spot size. At the current time, it is unclear if this is possible with less than four lenses but a small amount of time investigating the optical design now may prove fruitful to the final instrument.

3.1. CCD

As with any imager, the core of this instrument will be the detector. Several CCD options were looked at, including re-using the Sloan Imager CCDs, but the best option was an off the shelf CCD from e2v. The e2v CCDs offer reliability, maintainability, and high performance. There are several options with regards to the CCDs. Three ideas will be discussed: 4K x 4K, 6K x 6K, and a mosaic array.

The e2v chip that would be ideal for the new APO imager is the CCD231 back side illuminated CCD. It is available as either a 4K x 4K or 6K x 6K CCD with 15 micron pixels. This CCD has low read noise (as low as 2 electrons and no higher than 5 electrons). This is, of course, dependent on readout speed. As expected from a science grade CCD, we would also have low dark current (3 electrons/pixel/hour at -100 Celsius).

The clock speed can be set to readout at the fast, higher noise rate or the slow, lower noise rate. The e2v CCD231 has a four channel readout system, see figure 8. At the fastest clock time, 1MHz, the readout can be completed in just under five seconds. Slow readout will take much longer but may be necessary due to science requirements. The readout time described is for 1x1 binning and will decrease by the binning factor. If even faster readout is required a subregion can be selected for readout in a second or two. The readout rate will be selectable between two options set in the software. These will be user selectable through the TUI interface, see section 7.

Figure 3 shows the electronics noise contribution for a CCD system and electronics identical to what is proposed in the paper. On average the readout electronics add about an electron of noise to the expected CCD noise.

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[1]Figure 3 plots provided by Bob Leach, Astronomical Research Cameras, Inc.

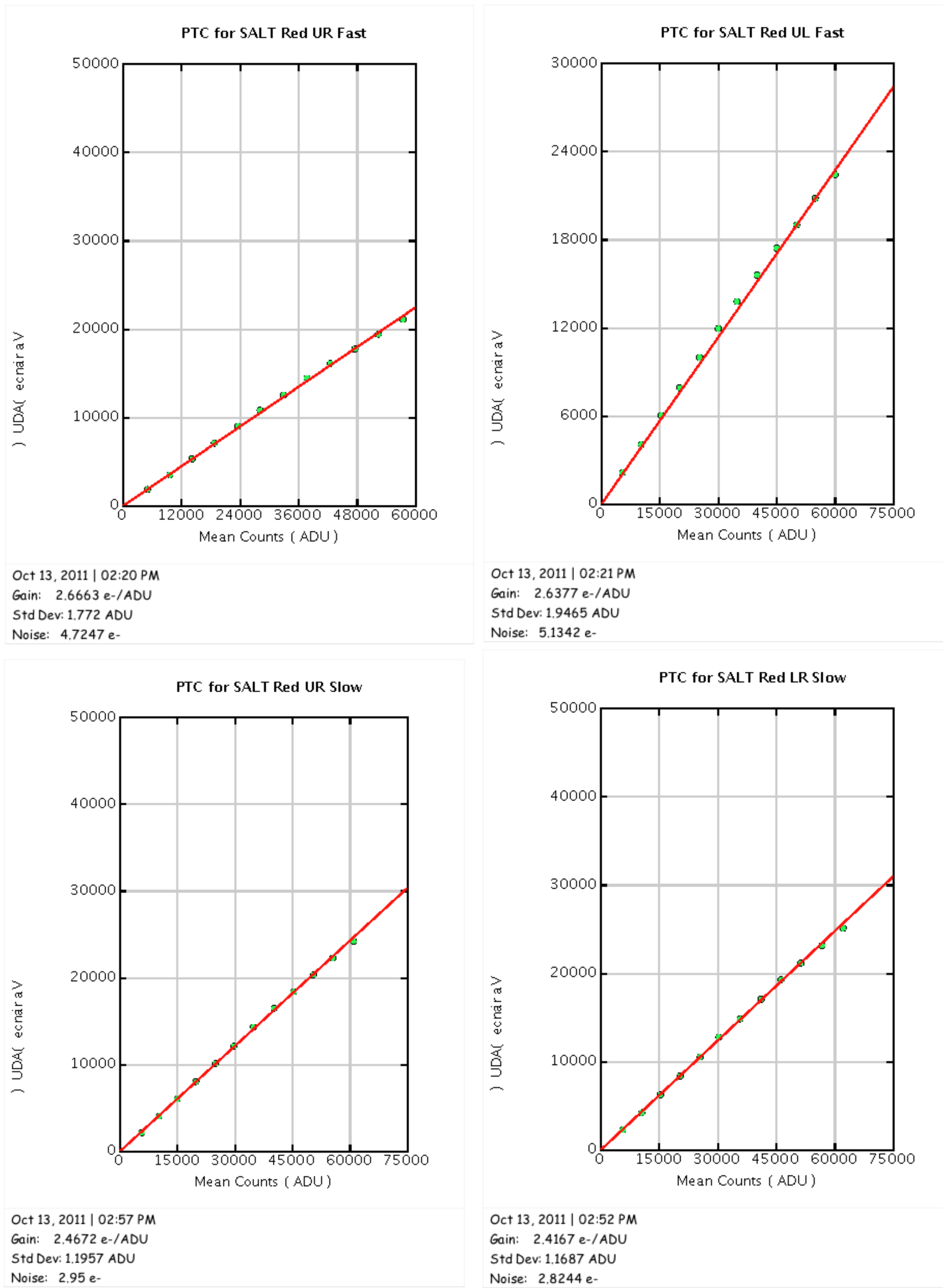


Fig. 3.—: CCD231 Complete Electronics Noise Contributions (top: fast readout; bottom: slow readout)

In table 4 the ideal spot size for an f/7 beam was determined to be 35.6 microns, yet the e2v CCD231 has 15 micron pixels. The detector market has shifted to producing much smaller pixel sizes than when SPICam was first built. A 24 micron pixel, such as in SPICam, would be ideal. The only reason a 60mm or greater sized chip with 24 micron pixels is not being discussed is that they are not available. The largest off the shelf CCD with a pixel greater than 20 microns is 25mm on a side (not necessarily square). As such, the CCD231 will have to be binned to compensate for the oversampling.

The quantum efficiency of this CCD would be high over the entire range if a deep depletion device with the broadband coating is selected, see figure 4 . A peak of 85% in the blue would be seen with the lowest quantum efficiency being about 50% on either end of the spectrum. With an alternate coating a sacrifice in blue quantum efficiency could greatly increase efficiency throughout the remaining range, potentially producing a peak efficiency over 90%.

Deep depletion devices are known to have problems with fringing due to internal reflection of the thinned Silicon. The standard CCD231 has very poor fringing characteristics at wavelengths longer than 750nm. Figure 5 shows that the fringing could be as much as 20% the background level. For an extra 10% the CCD cost fringe suppression can be added. This would decrease the fringe level to a maximum of 2%. Further fringe suppression could be gained by choosing the multi-1 AR coating. This coating will decrease the fringing down to 1% the background level.

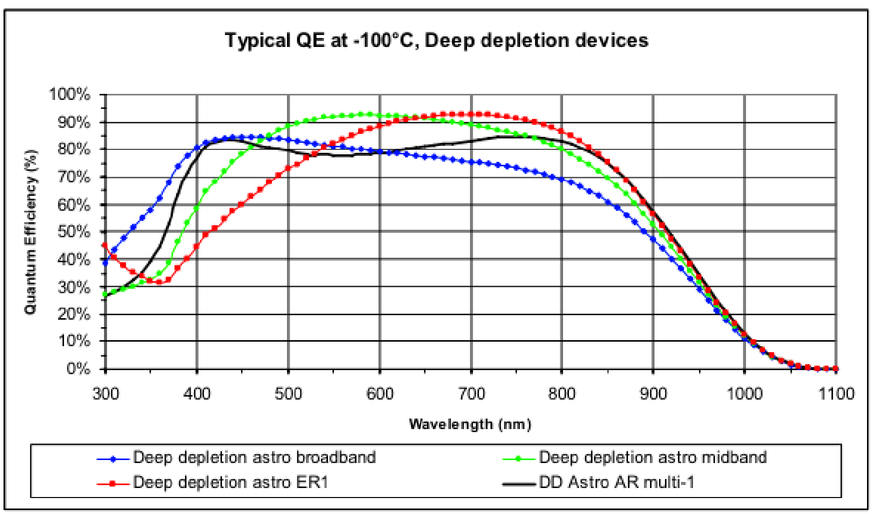


Fig. 4.—: CCD231-84 Quantum Efficiency

The 6K version of the CCD231 is identical in performance to the 4K version. An f/7 beam would yield a field increase from 8.4 arcminute diameter to 12.6 arcminute diameter. Due to the larger number of pixels, the readout time would be increased to 9 seconds in the fast mode. The increase in cost would be about 25% the total instrument and double the CCD cost. An important downside to this option would be with regards to the filters, see section 4.5.

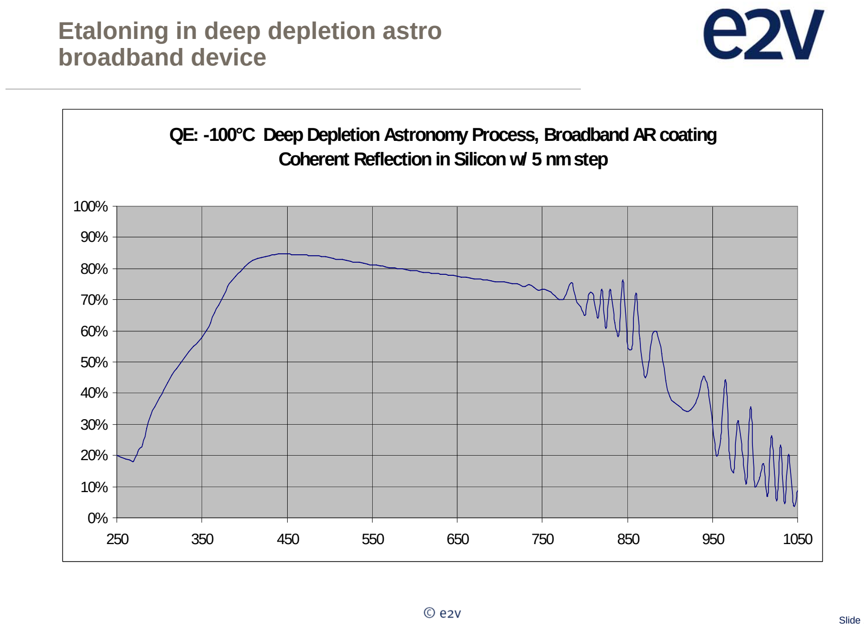


Fig. 5.—: CCD231-84 Fringe Measurement

The third option to consider would be the mosaic of two or more smaller CCDs. If the kinematic system is setup properly, then each CCD could be placed on the tangent of the the curved focal plane in the uncorrected optical path. Each CCD would be locally flat in the focal plane so no optical correction would be necessary. The biggest problem is with choosing a CCD. Most small, 1K square CCDs are not 3 side butt-able, although it might be possible to have them repackaged. With the mosaic 1K CCD option, the electronics could read out four CCDs per set. If a 4K mosaic was setup each CCD would require its own set of electronics. The cost of this option would be as much as a single CCD option with focal reducing optics and would be much more complex.

Usage of an off the self CCD like the e2v detector greatly lends itself to using a Leach controller. Communications with Bob Leach has produced favorable results. He is willing to help design and implement everything necessary to readout the CCD. This would include a pre-amplifier board in the dewar as well as the controller.

4. Mechanical Design

4.1. Instrument Packaging

It has been previously mentioned that the instrument should be on a corner port. This is not a trivial decision. A corner port adds a great deal of complexity to the design of this instrument. The cable management becomes increasingly complex and a new rotator and guider system has to be

Table 4:: CCD Comparison

Spec	SPICam	CCD231
Pixel Size	24μm	15μm
Imaging Area	49.1mm^2	61.4mm^2
Read Noise	5.7e$^-$	2e$^-$ - 5e$^-$
Gain	3.36e$^-$/ADU	2.6e$^-$/ADU
Dark Current	2.5e$^-$/pixel/hour	3e$^-$/pixel/hour
Readout Rate	35kHz	1MHz - 50kHz
Readout Time	120 seconds	4.2 - 84 seconds

Notes. Readout Rate and Time only based on 1x1 binning.

designed. This is at great added cost. While it will increase the total cost of the instrument, it will also clear up a great deal of room on the dome floor. The dome floor has been crowded for years and none of the other instruments are suitable for a corner port. The scientific motivation is the decrease in instrument change time. Currently, the observing specialist must physically mount and unmount SPICam. With a corner port instrument, the swap can occur in a significantly shorter time period.

4.2. Rotator

With the instrument at the TR1 port it will be necessary to have an instrument rotator. The rotator will be similar in design to the one used with Agile on the TR2 port. It will need to be significantly more powerful to handle the increased load. The instrument should weigh less than 350lbs, but that won't be clear until the design work on the instrument housing has been completed. Work may also need to be done to increase the interior space available for the optical path. Elements that should be incorporated on this new rotator that are not on the TR2 port rotator are: rotation brake and magnesensor. The rotator brake is wanted to prevent free spin conditions as are seen with Agile. Proper balancing of the instrument should limit this but it would be a good feature to implement during design, rather than after the fact. A magnesensor for zeroing would also be highly desirable. The corner ports are much more difficult to properly zero and an automatic method for this could prevent instrument usage delays, sometimes seen with Agile.

4.3. Dewar

The dewar design is greatly dependent on the cooling option chosen. Two options are presented. The cryostat can either be liquid nitrogen cooled or cooled with a closed loop system such as

Polycold Compact Cooler (aka Cryotiger).

Liquid nitrogen proves to be complicated for an instrument on a corner port. Due to the changing gravitational vector, it is difficult to control the cooling to the CCD. This itself can be solved but will most likely shorten the hold time of the cryostat. With liquid nitrogen the most likely dewar option would be to use an IR Labs dewar. Since we will be using a large CCD, the dewar will need to be one of their larger models (ND-10 or ND-8). The GFP uses a similar dewar, ND-8, and they have a hold time of barely 12 hours and with a smaller heat load than the proposed system. To get around the problems seen on the GFP (poor fills and hold times), an intermediate transfer dewar with an autofill system would need to be built. This then poses the problem of where to put the 180L LN2 dewar to fill the system. If the imager is on the unused TR port, then it is just above the ECHELLE transfer dewar. Space becomes a big concern and will need to be thought about thouroughly.

The PCC option is very attractive. The cold head in SPICam was recently upgraded, and it has a newer compressor. This would eliminate the cost aspect of the cooling components. The changing gravitational problem is no longer a concern since the cold head is fixed with respect to the thermal strap. Changes in gravity do not affect the closed loop gas circulating through the system. Another benefit of this system is that the dewar can be simple and compact.

With either cooling system, routing of lines will be problematic. They would both require rotatable lines. Steel braided lines that are standard on both systems would work adequately, but a cable tray will need to be made to contain the lines. A large cable tray would need to be installed on the back of the instrument or some sort of rigid containment system could be used along its length. This will need to be designed around the final choice in cooling method.

Some of the base requirements that should be considered for the dewar are: large KF fittings (for a vacuum pump, ion pump, vacuum gauge) and CCD mounting.

A necessity of this dewar should be the inclusion of a KF40 vacuum port. This will facilitate in faster pump down times and could translate into less instrument down time.

An ion pump should also be used with this system although it is undecided if a getter material will be necessary. A new Gamma Vaccuum ion pump and controller was purchased, for SPICam, that can be reused on this new instrument. Even though the ion pump will report a vacuum value, an independent vacuum gauge is also required. This has been very useful on our other instruments when the ion pump is not operational or when the ion pump is turned off when the instrument is being pumped.

Mounting of the CCD is one of the most complex systems of the imager. It is necessary to have a strong mount that does not move position but is still adjustable. More study is required but a CCD mount of Invar seems the likely choice. Three or five axis adjustment will be necessary but will not be automated outside of the dewar. The axis adjustments should only be required when commissioning the instrument and when invasive CCD work is performed. A five axis adjustment would include tip, tilt, rotation, x translation, and y translation, with focus being integrated into the piston of the tip and tilt. This system will introduce difficulties in creating a stiff, robust mounting assembly. The three axis system will have tip, tilt, and rotation, again with focus as a byproduct of the tip/tilt piston. If the initial alignment of the CCD is close, then an instrument block will compensate for any offset in translation. Making sure the CCD is well centered and properly aligned, with respect to the optical path, is of great importance to instrument performance.

The dewar itself has many options. A standard classic dewar is round, similar to figure 6a, but other options are possible, figure 6b. The benefits of the round dewar are the strong, geometric design preferred in a pressure vessel. The drawbacks are that the length is greatly increased from the rectangular dewar since components must be placed linearly inside the vacuum chamber. All vacuum ports need a machined flat surface that is not inherent in the circular design. Another option is a rectangularly shaped dewar. The wall thickness needs to be increased to account for the pressure differential while under vacuum, but the length of the box can be greatly shortened. A maximum length of 8 inches is possible with the rectangular dewar, while the length of the circular dewar can only be minimized to 11 inches. On the rectangular box, the mounting holes for vacuum ports and electronics also become simple. The strongest proponent of the rectangular box is maintenance. Since the back plate has no components attached, it acts as a large access port. When opened, all dewar connection are visible and easy to maintain. With the round dewar, this is more complicated. To take off the back plate to access the CCD electronics, one of the bulkhead ports would need to be removed and tools carefully threaded into the vessel to remove the cold strap. Only then is the dewar accessible. The machine costs on the rectangular dewar will be more since there is no stock size to start machining. It will most likely need to be made from a solid block and water jetted. The total cost of a rectangular dewar will still be comparable to that of an IR Labs dewar, if not less.

(a) Circular Dewar (b) Rectangular Dewar

Fig. 6.—: Dewar Options Concept

4.4. Opto-Mechanical Design

Several types of lens cell designs could be implemented to properly position the glass elements. A system should be designed to address the thermal expansion seen on the telescope and within the instrument. The lens cells would ideally be made of a stainless steel or a thermal expansion matching material, such as Kovar. A simple lens cell design would probably work 99% of the time, but, given this is a new imager, some time should be put into modeling the expansion of assembly and make sure any offsets are within the tolerance of the lens design.

4.5. Filters

As with any imager, filters are a scientific requirement. With the f/7 design, the APO host of 3 inch filters could be used and would cover the 8.4 arcminute diameter field, which is the entire field if the 4K x 4K CCD was used. If the 6K x 6K CCD was used, then larger filters would be necessary to make use of the entire field (the 6K CCD is 90mm square). Figure 7 shows the dimensions from the focal plane. If the 3 inch filter were placed 2.9 inches from the focal plane the entire field would be covered.

The instrument will need at least one filter wheel. If the 4K x 4K CCD is used, then a filter wheel that contains 3 inch and 2 inch filters will suffice. If the 6K x 6K CCD is chosen, two filter wheels will be necessary. The first will host 3 inch filters, and the second will host the 4.5 inch filters necessary to use the entire field. Purchasing a 4.5 inch diameter SDSS filter set will cost nearly \$20K (as quoted by Custom Scientific, Inc.) and users may need to provide their own filters if they want the full field in specialized band passes.

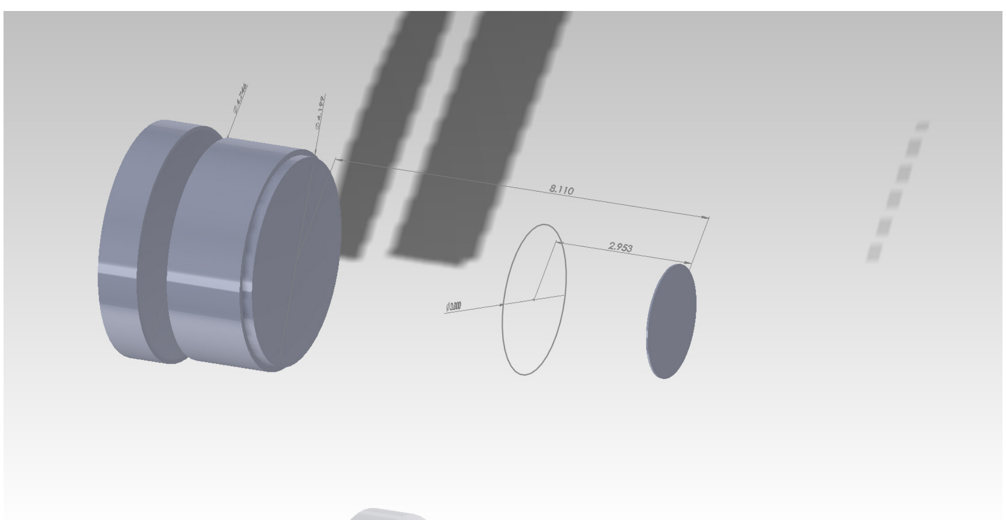


Fig. 7.—: Optical Dimensions

4.6. Shutter

Several shutter types would work with this type of imager. Two of the most likely candidates are: (1) iris shutter or (2) linear shutter.

The iris shutter (1) is the simplest off the shelf option. A 90mm low profile shutter could be purchased for about $4K. These shutters are fast and have a low profile. The downsides are the limited lifetime (typically 100,000 to 500,000 operations) and uneven light distribution on the CCD. The uneven light is due to the nature of the iris. The center section will always open first and close last meaning that more light will fall on the center of the chip than the outside section. Given the very quick activation speed this will be acceptable for most science. Any science that requires precision photometry will be affected.

With a linear shutter a light blocking mechanism is removed from the field in one direction and blocks the field from the other direction. This creates an equal blocking of light over the area of the CCD. A shutter of this type is currently used on SPICam and could easily be adapted or replicated for a new imager. Two alternate methods would be a moving screen on linear slides or a rotating leaf. The linear screen would be more useful in fast time series exposures but the driving mechanism would need to be carefully thought out and implemented. The rotating leaf is the opposite from what is currently used in SPICam. Instead of a hole in a plate that appears, a plate will move into the field whenever light needs to be blocked.

Many of these options are viable, but, given the science drivers, a re-engineered system similar to SPICam's would be the most effective.

5. Guider

Three methods of guiding should be discussed: (1) on-chip, (2) pickoff, (3) additional guiding ccd inside the dewar.

On-chip guiding can take two forms: (1) use the science images, (2) use a section of the chip. The first option is the least effective since a typical science image is up to 20 minutes in length. A guider should ideally make corrections every 10 seconds. The second option would be ideal on the e2v CCD because the chip is read out through four sections, see figure 8, each with its independent amplifier. One of the sections of the CCD could be set to read out independently. A section of the chip would be 1K x 4K and would read out in a second or less. The guider images could also then be co-added to the longer science image and the entire field could be recovered. The Leach controller would require a minimal amount of changes in wiring. The changes would add approximate $2K to the cost of the controller.

A guider with a pickoff mirror would be the most conventional route. Similar to the NA2 pickoff, DIS slitviewer, and ECHELLE slitviewer this would be an off the shelf camera (like the

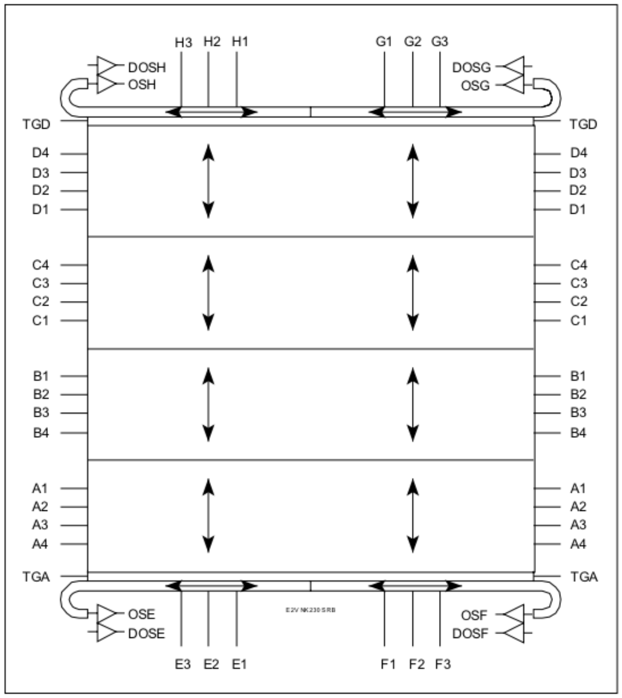


Fig. 8.—: CCD231 Architecture

Apogee Aspen CG77). A right angle mirror would need to be placed outside the main light path and be oriented to direct light to the camera. The biggest uncertainty would be in the field of view of the incoming optical path. The opening of the corner port could conceivably restrict the field to an unusable limit. With this option, no corrective optics would be used so the field would experience a large amount of curvature. The field of curvature over the small region of the guider would not be noticeable. It has been shown, on the NA2 offset guider, that these do not affect the ability to guide.

Another method of using a pickoff guider would be with fiber optics. Similar to the SDSS cartridge guider, an array of large core fibers could be placed at different locations around focus. Linear stages could also be setup to position the fiber bundles into different locations. The guider could then be located away from the instrument for a reduction of heat load on the observing level.

The final option would be to put a separate CCD in the dewar that would be just outside the main CCD field of view. The benefit of this design would be that the chips would still use the corrective optics. A system of one to four small CCDs could be set around the main CCD. If the CCDs used were small, they would each only use a single video card. Since a separate shutter would not be possible, these CCDs would need to be frame transfer/interline type devices. Up to four CCDs could then be used with a single set of electronics. The cost estimate would be only a little more than that of the guider with a pickoff mirror, when total costs are considered.

Another consideration should be the heat released into the dome by the guider. With on-chip and in dewar guiding, this is not a problem as the heat load would be removed by the dewar cooling method. For an offset guider, there would be a great deal of heat released. Liquid cooling is one route to take, but care would need to be taken in shielding the telescope and other critical equipment from glycol leaks, should a line ever rupture. A simpler solution might be to exhaust the heat to the intermediate level. An exhaust trunk could end up being complex given the location of the instrument.

6. Electronics

The electronics for this imager will be similar to those seen on other APO instruments. There will be CCD, robotic, and telemetry electronics. APO electrical engineers have expertise with all of these types of electronics and feel confident in designing an implementing the systems for this instrument.

The main electronics of the system will focus on the CCD controller. As it was referenced in section 3.1, the readout electronics would be controlled through an Astronomical Research Cameras (Leach) controller. The dewar and CCD would be sent to Leach for implementation.

The remaining electronics would be designed and installed separately from the CCD. In the dewar, there will need to be several sensors installed to measure instrument status. These include at least two calibrated temperature sensors, one on the CCD and one measuring the temperature of the cold finger or cold head. A CCD heater will also need to be included in the dewar. The dewar sensors and heater should be connected to a Lakeshore type device to monitor and servo the heater according to the determined CCD specifications.

External to the dewar will be the electronics associated with the filter wheel(s) and shutter. As has been standard practice at APO, a PC-104 controller could be used as the upper level interface. The filter wheel and shutter will most likely be stepper motor based, stepper drivers similar to the IMS drivers used elsewhere on the telescope should be considered.

The electronics chosen above were done so with for very specific reasons. APO engineers have a great deal of experience with electronics in the harsh mountain environment. The devices chosen should reflect this knowledge. They should be robust and maintainable. Custom electronics on a facility instrument are at times necessary but to create a long term maintainable instrument, components were chosen that are known to work well and be quickly repaired.

7. Software

Most instruments at APO have had their Instrument Control Computer (ICC) code written by the instrument builders external to APO. Knowledge of ICC building using Leach controllers is

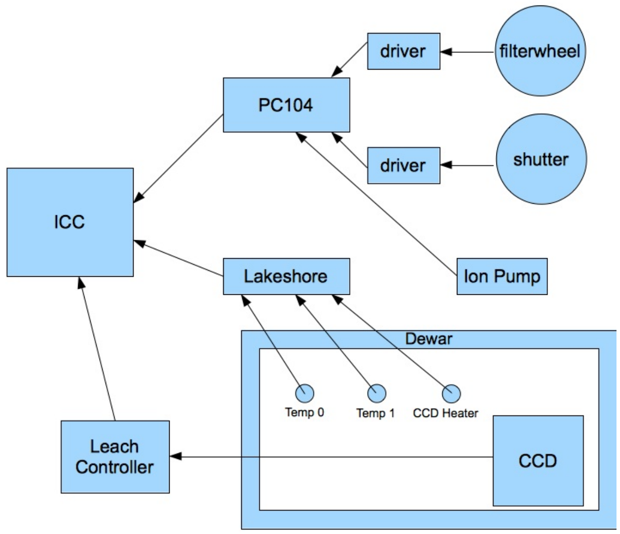


Fig. 9.—: Electronics Block diagram

also well known within the ARC community; TSPEC, NICFPS, and GIFS all use these types of controllers. It was not until the GIFS instrument that APO programmers have taken great strides at programming major components of the ICC. We believe that it is fully within our capabilities to program an ICC and associated controllers.

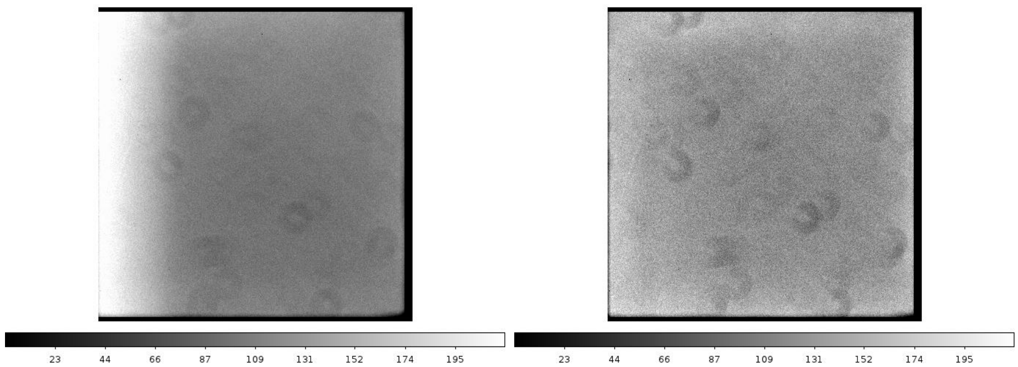
A TUI widget will also need to be written. This widget may be a little more complicated that the current SPICam widget since there could be the option for multiple filter wheels, special flat lamp options, and on chip guiding selection.

8. Integration

Integration of the imager onto the telescope is one of the more critical tasks as all elements described above must come together into a complete and functional instrument. It is possible to integrate the different pieces over an extended time scale to decrease the final rush as assembly is completed.

8.1. Calibration

Changes in the calibration system for the telescope, specifically the flat field lamps, will need to be implemented. As it has been determined with Agile the TR ports experience unwanted scatter from the flat field lamps. Testing has shown this to be attributed to the angle of incidence of the flat lamp. Figure 10 show that disabling the lower lamps corrects the problem for the upper TR ports (TR1 and TR2). This does not cause an uneven illumination in the flats, as might be expected (see figure 10b) since the scattering painted surface of the flat field covers disperses the light evenly from the single lamp. Special lamp controls will need to be integrated into TUI to control the lamps individually. It may also be worth investigating the addition of lamps at different locations on the truss.



(a) Two Lamp Flat Field   (b) Single Lamp Flat Field

Fig. 10.—: Flat Field Test Images

Flat fielding in the extreme ends of the bandpass, especially blue, will not be a problem. This is currently done with SPICam, which has a much poorer blue response than the proposed imager. The current quartz lamps are much stronger towards the red but do have some blue output. For comparison, SPICam can take an MSSSO B flat field in about 17 seconds with the bright quartz lamps. A similar exposure time is needed with only the dim quartz for a good MSSSO I flat field.

Considerations must also be taken to account for scattered light. The tertiary baffle was designed to block out a good portion of stray light. There will still need to be baffling on the instrument section of the optical path. Since the optical design is pure focal reduction there is not a field stop, which is the ideal place to baffle. Without a field stop, baffles will need to be placed just outside the usable field. A system of six to eight baffles would be able to handle any stray light. The interior of the instrument structure should be grooved/threaded to cause scattered incident light, inside the housing, to bounce off at high angles of reflection. The interior should also be painted with Aeroglaze®, a light absorbing paint manufactured by Lord. This will ensure that the few unwanted photons will make it to the detector.

8.2. Schedule

A new instrument will take a great deal of resources in the form of personnel. Below is an estimate of the time required to to complete each task. The times are listed in terms of full time work.

1. TR Port Testing - 1 man week

   (a) Determine focus empirically, verify baffle structure with model. Past evidence shows that optical reference from mounting port is incorrect.

2. Optics finalization - 1 man month
3. Mechanical design - 3 man months
4. Electrical design - 1 man month
5. Software - 4 man months
6. Lab Testing - 2 man months
7. Integration - 2 man weeks
8. Commissioning - 1 man week (split into two blocks)

Total Time Effort: 12 man months

8.3. Budget

1. Cryostat Dewar - $15K
2. Optics - $100K
3. CCD - $110K (200K)[2]
4. Mechanics
   (a) instrument structure - $20K
   (b) opto-mechanical components - $5K
   (c) shutter - $5K
   (d) rotator - $30K
   (e) detector support systems - $5K
   (f) guider systems - $30K
   (g) Filter Wheels - $5K
5. Electronics - $50K
   (a) Readout Electronics
   (b) CCD Pre-amps
   (c) Power Supply's
   (d) Robotics control

(e) ICC

Total Costs (approximately)+10% overage: \$385K + \$38K = \$423K (\$522)[2]

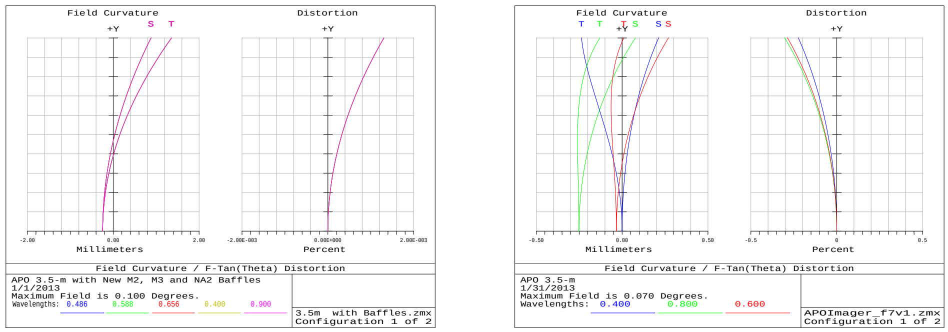
9. Conclusion

Outlined in this paper is a path to build an new imager for the Apache Point Observatory 3.5m telescope. Several decisions still need to made to narrow down the focus of this instrument. These include:

1. Optical Design. Is f/7 enough focal reduction? What field and performance specifications should be set? Is the decrease in throughput worth the increased field?
2. CCD. Should a 4K square or 6K square CCD be selected? The 4K will be less costly but at the expense of 50% the field area of the 6K CCD. Is the increased cost worth the scientific gain?
3. Cooling Method. Liquid Nitrogen or Cryotiger? Are the continued maintenance costs of a PCC worth the increased complexity of the liquid nitrogen system?
4. Shutter Type. Linear shutter or Iris shutter? Will this be a photometric capable instrument? Is the increased cost of a custom shutter worth the decreased error in light distribution?
5. Guiding Method. On chip, pickoff, or secondary CCD? Should the guider be based off the science detector, completely separate, or a separate detector integrated in the dewar? Should a combination of these guiders be chosen?

With the discussion and approval of this imager, APO will continue provide the telescope users with current instrumentation to maintain a competitive edge in the scientific community.

[2]parenthesis refer to the 6K x 6K CCD option



(a) 35m (b) f/7

Fig. 11.—: Field Curvature and Distortion

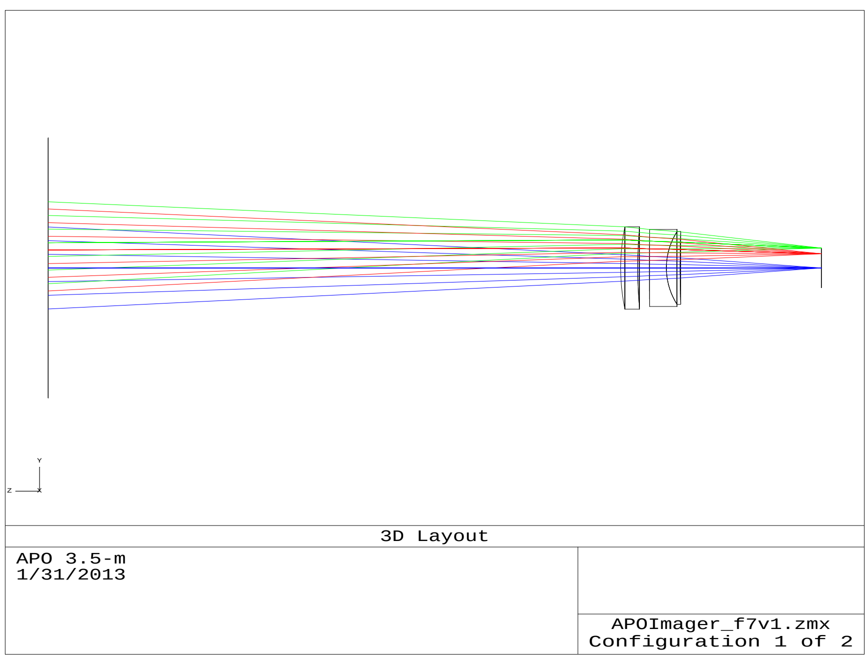
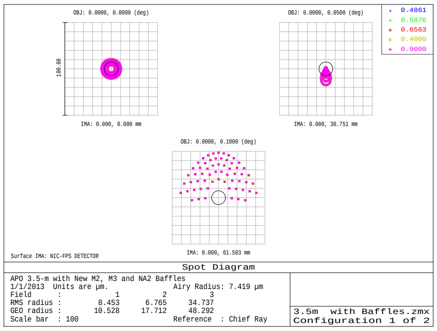
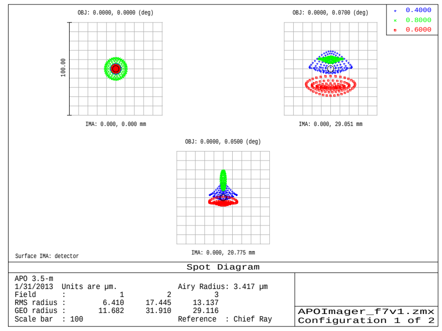


Fig. 12.—: f/7 Optical Layout

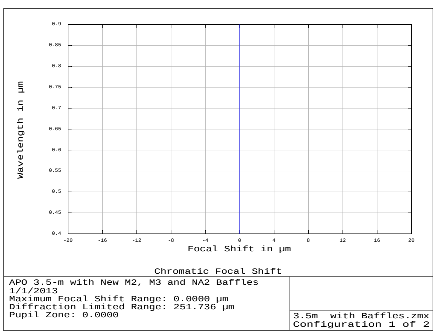


(a) 35m

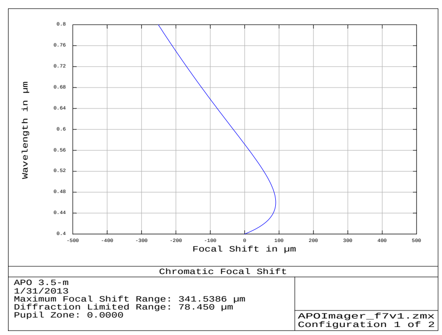


(b) f/7

Fig. 13.—: Spot Diagram

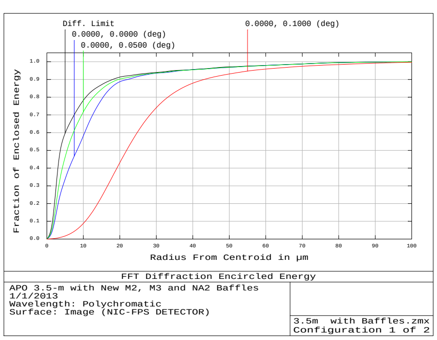


(a) 35m

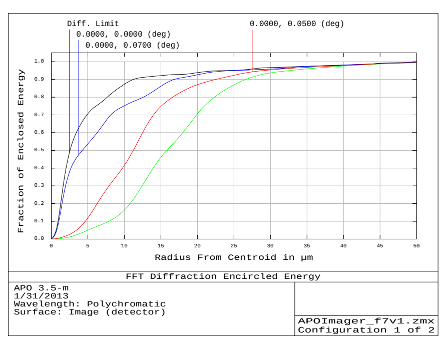


(b) f/7

Fig. 14.—: Chromatic Focal Shift

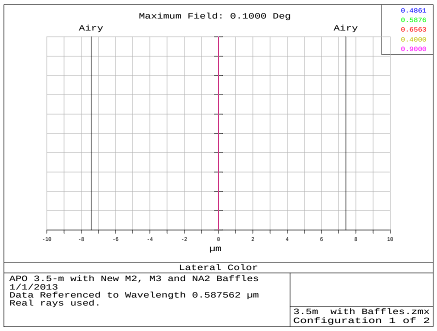


(a) 35m

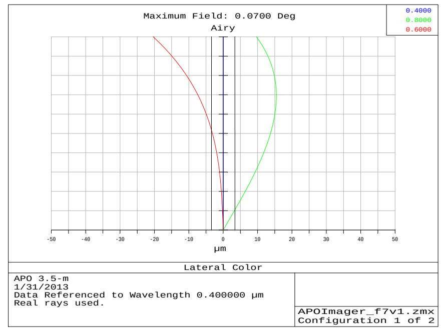


(b) f/7

Fig. 15.—: Diffraction Encircled Energy

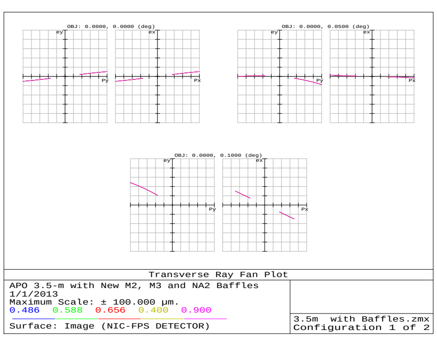


(a) 35m

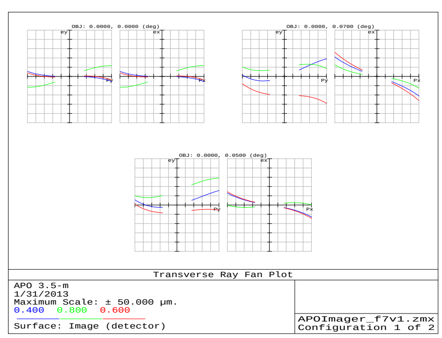


(b) f/7

Fig. 16.—: Lateral Color



(a) 35m



(b) f/7

Fig. 17.—: Ray Fan Plot

REFERENCES

C.Froning, J.Holtzman, M., & C.Burrows. 2009, Optical Camera Upgrade White Paper

E.Mannery, & W.Siegmund. 1983, Multiple Instrument Large Telescope (Seattle, Washington: University of Washington)

J.M.Geary. 2007, Introduction to Lens Design (Richmond, Virginia: Willmann-Bell, Inc.)