Southern African Large Telescope

RSS Throughput Testing

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<th>Date</th>
<th>Description</th>
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<td>Original</td>
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1 Scope
This document describes a plan for testing and fixing of the RSS throughput shortfall.

2 Throughput Shortfall Evidence
Data collected in Nov 2005 – June 2006 during commissioning of the Robert Stobie Prime Focus Imaging Spectrograph show evidence of a throughput shortfall which increases into the ultraviolet. Figure 1 shows some of this data. The bottom panel shows the apparent RSS Optics×Detector efficiency, together with the lab QE of the three detector CCD’s and the FPRD typical and minimum QE for the CCD’s. The top chart shows the “throughput shortfall”: it divides the Optics×Detector efficiency by the CCD #4 QE (the middle chip) and by the expected optics throughput, based on vendor coating efficiency measurements (the blanks are assumed to have 100% throughput). The data were obtained as follows

• 20031030 47 Tuc full field, full mirror imaging, 629 nm filter
• 20051122 EG 21 “burst” (4 segments) imaging, three filters
• 20051204 EG 21 full mirror slitless spectroscopy 3000 and 900 l/mm VPH gratings
• 200603xx 8 stars, 7 filters, imaging burst
• 20060612 HR5501, 340 and 380 nm interference filters, imaging burst

The reduction of this data has assumed a SALT mirror efficiency of 60% (dirty mirrors) except for the June data, which used a clean segment (77%). For spectroscopy, we have removed lab VPH efficiency curves.

The result is that the throughput is below specification, ranging from 95% expected at 900 nm to 50% at 400 nm, then decreasing to < 10% in the UV. The fact that the imaging agrees with spectroscopy verifies that the VPH grating throughput is as expected.
3 Theories

Explanations for the throughput shortfall break down into the following categories:

- Serious absorption ("color centers") in the optical blanks: Fused Silica, NaCl, or CaF₂
- AR Coating deficiency
- Fold Flat coating deficiency
- Detector QE degradation

We have focused on the first alternative so far, since vendor test data exist for the other three. So far, serious absorption in the NaCl crystals has been eliminated by having Janos Inc (the RSS lens manufacturers) polish and measure the transmission of one of the spare NaCl blanks. In Figure 2, the thick line shows the total transmission of the blank, and the thin line removes two Fresnel surface reflections to give the internal transmission. There may be a slight absorption between 300 and 400 nm, but this would be much too small to explain the observations of Figure 1. The total thickness of NaCl in RSS is about 50 mm.

Another possibility which has come to our attention is a process by which the coating of CaF₂ lenses may cause crystal damage (through electrostatic acceleration of ions in the coating plasma into the material). Hans Dekker of ESO reported that this problem occurred with UVES on VLT, and led to very poor UV throughput until it was corrected, by Winlight System of France, through UV flooding of the coated lenses. We have verified this account with Philippe Godefroy of Winlight, and have since found a patent application by two Japanese researchers which tells a similar story. However, we have not found anything similar in the literature. The expected absorption should be similar to color centers caused by irradiation. Figure 3 shows a CaF₂ color center absorption spectrum (A Smakula 1950: Phys Rev 77, 408). One can see a sharp absorption band starting at about 420 nm and peaking at 400 and 340 nm. A secondary broad peak at 650 nm could explain the overall low RSS throughput in the yellow and red, and the absorption does disappear above about 800 nm, as is seen in RSS. The curve does not exactly match the RSS throughput curve, where the sharp absorption begins below 400 nm. However it is possible that the precise shape of the absorption curve is a function of the cause of the damage. Thus this remains a promising lead in the
There are 6 RSS coated CaF$_2$ elements, using three different coatings (see Figure 4):

1) Element 2 in Field Lens: MgF$_2$ coating

2) Element 1 in the Collimator triplet: MgF$_2$/solgel

3) Element 3 in the Collimator triplet: MgF$_2$

4) Element 2 in the Collimator doublet: multilayer

5) Element 4 in the Camera quartet: MgF$_2$/solgel

6) Camera singlet: MgF$_2$/solgel both sides

It seems unlikely that this process would be a problem with the fused silica elements, since fused silica color centers are found exclusively below 250 nm. It is not a problem with the NaCl, since both NaCl elements are the central elements of triplets, and hence uncoated.

We must still keep an open mind on the remaining three theories: coatings, mirror, and detector. The following test process does not assume the CaF$_2$ color center theory. It will test the detector and fold flat theory and if necessary isolate optical elements. If the CaF$_2$ theory holds, it would be confirmed by isolating the problem to multiplets containing CaF$_2$ with common coatings. If it is coatings, we would expect elements with common coatings, but including both fused silica and CaF$_2$.

### 4 In-Situ Testing Plan

There are many fault scenarios possible with the above theories. Some of these scenarios would require a major, costly dismantling of the optics to gain access to individual elements, and some would not. We suggest the following in-situ testing apparatus which would narrow down the possibilities sufficiently to determine this. It is relatively easy to place a mirror in three places in the instrument, the filter, the focal plane (a slitmask), and at the 1/4 waveplate slide. Measuring the intensity of a return beam from a sufficiently collimated UV light source placed in the accessible collimated beam (Fig 4) would obtain a ~10% accurate measurement of the throughput (in double pass) of the camera, the collimator, and the collimator excluding the field lens.

Because of the length of the beam, it seems likely that the best light source is a laser, a relatively expensive item. The shortest wavelength CW laser currently available is a 375 nm diode laser,
which is (barely) well enough into the UV drop-off of the throughput curve to be sensitive to the throughput problem. The power available is ~3mW. A possible alternative is a AlGaN UV LED, which can be purchased in 320 and 340 nm versions. This has the advantage that the wavelength is at the bottom of the UV throughput curve, and so would be very sensitive. However, LED’s are poorly collimated, and a simple A-Ω argument suggests that one would get less than 1% of the available power into the return beam. Starting at an LED power of 0.5 mW, this is 3 orders of magnitude down from the laser, and (especially if the optics has poor transmission), it would be very difficult to find the return beam. So we suggest the following apparatus:

- 375 nm laser, CrystalLaser, BCL-005-375, $6450 (lowest of 3 quotes, awaiting a 4th)
- UV Photodiode, OSI Optoelectronics, 1 cm² active area; available on loan from Rutgers.
- 380/25 nm interference filter. Andover, $242 (for stray light rejection)
- Electrometer for photodiode; borrow lab instrument.
- UV converter plate, UVP, 21×26 cm, $245 (for visual alignment of return beam)
- Mirror blank for filter: glass < 8mm thick, < 130x90mm + spare filter holder
- Mirror blank for slitmask: blank longslit or coated microscope slide
- Mirror blank for 1/4 wave slide. Use existing spare blank

The laser and photodiode would be mounted on a fixture that fits into the RSS grating holder (Fig 5). The photodiode would be adjustable up and down, and the RSS grating rotator would be used to adjust the return beam placement in the horizontal plane. A UV to white light converter plate would be used to find the return beam and help with the alignment.

5 Possible Outcomes and Fixes

Figure 6 illustrates the test/decision tree. The in-situ throughput measurement determines whether the problem is in the camera and/or the collimator optics, or in the detector (we assume there are not two independent problems, with the optics and the detector). If there is a camera problem, it will be removed from the instrument (it is relatively accessible), taken to a clean room, and disassembled and tested there. If there is a collimator problem, it may be in any or all of four assemblies, the field lens, main group, fold flat, and doublet. If it is only in the field lens,
a third in-situ measurement with a return mirror at the 1/4 waveplate slide can
determine that. If there are problems in
the rest of the collimator, the doublet, and,
if necessary, the fold mirror can be fairly
easily removed and tested. If there is a
problem in the field lens or main group,
the instrument will have to be partially or
completely removed from the telescope to
gain access. Reassembly and alignment of
the instrument with either of these
elements removed will require the removal
of the instrument for realignment.
Because of the difficulty of the latter, it
may be wise to eliminate or fix problems
in the doublet or fold mirror so that a
repeat collimator in-situ test may be
performed to determine whether any remaining field lens or main group problem is serious
enough to merit the risk.

Bench testing equipment will consist of the same photodiode/ electrometer detector used for the
in-situ testing, with a more flexible UV light source, either UV LED’s, or a fiber light source
loaned from Rutgers. UV LED’s cost about $200.

If the camera or the collimator main group need to be disassembled, this will be done by Alan
Schier of Pilot Group, the original assembler of these optics. We would hope to use the SAAO
clean room. Reassembly and alignment would also be done by Alan Schier. If testing confirms
the CaF$_2$ color center theory, repair will be done in the same clean room, using a mercury curing
lamp as a UV flood, and the UV transmission device as a monitor. The flooding process takes
less than an hour. We would hope to do the flooding process without disassembling multiplets,
though this will be the subject of analysis. The time from disassembly to reassembly in this
scenario should be on the order of a month. If the problem resides in coatings, repair will require
disassembling multiplets, sending them to the manufacturer to have the coatings polished off,
then to the coater, then reassembled. The timescale for this repair would be a minimum of 3-6
months.

![Figure 6. Test/decision tree](image-url)
6 In Situ Testing Results

Nordsieck and Burgh traveled to SALT on September 16 - 30 to perform optical tests related to UV throughput and the “ring ghost”. Figure 7 shows the test apparatus mounted on the grating rotator in the RSS collimated space, set up for the camera subsystem throughput measurement.

6.1 Throughput

Ten separate throughput tests were made of various optical subsystems within RSS using the 375 and 635 nm lasers and corresponding photodiodes, together with mirrors placed in the filter slide, the slitmask slide, the waveplate blank, and just above the collimator main group:

<table>
<thead>
<tr>
<th>#</th>
<th>Subsystem</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Camera (- filter and field flattener)</td>
<td>Mirror in place of filter</td>
</tr>
<tr>
<td>2</td>
<td>Collimator</td>
<td>WP blank in, mirror in place of slitmask</td>
</tr>
<tr>
<td>3</td>
<td>Collimator/ WP’s</td>
<td>HWP, QWP in, mirror in place of slitmask</td>
</tr>
<tr>
<td>4</td>
<td>Collimator/ HWP/ QBL</td>
<td>HWP, QWP Blank, mirror in place of slitmask</td>
</tr>
<tr>
<td>5</td>
<td>Collimator/ no Waveplates</td>
<td>no WP or Blank, mirror in place of slitmask</td>
</tr>
<tr>
<td>6</td>
<td>Collimator/ no Field lens</td>
<td>Mirror in place of WP blank</td>
</tr>
<tr>
<td>7</td>
<td>Fold + Collimator Main Group</td>
<td>Doublet removed, mirror in place of WP blank</td>
</tr>
<tr>
<td>8</td>
<td>Fold</td>
<td>Doublet removed, mirror on top of Main Group</td>
</tr>
<tr>
<td>9</td>
<td>Waveplate Blank</td>
<td>WP Blank on bench (double pass)</td>
</tr>
<tr>
<td>10</td>
<td>Collimator Doublet</td>
<td>Doublet on bench (single and double pass)</td>
</tr>
</tbody>
</table>

In addition, the collimator doublet and waveplates blank were removed from the instrument and measured for both transmission and reflectivity on the bench. For reference, the signal reflected off each mirror alone was used. In addition, the laser stability was monitored by periodically placing a reference jig over the apparatus which reflects the laser back into the photodiode off 2 flats. The measurements appear to be internally consistent to within 5 - 10% of the signal. Table 1 lists the reduced throughput measurements, and compares these with the expected throughput, based on the number of coatings of each kind and on each substrate. Under “Total”, the “measured” number is based on data from Figure 1.

<table>
<thead>
<tr>
<th>Coating</th>
<th>Substr</th>
<th>375</th>
<th>635</th>
<th>Total</th>
<th>Cam</th>
<th>Coll</th>
<th>Coll/ WP’s</th>
<th>Coll/ HW/QBL</th>
<th>Coll/ no WP</th>
<th>Coll/ no FL</th>
<th>Mir+</th>
<th>Mir</th>
<th>WP</th>
<th>Coll</th>
<th>Blank</th>
<th>Doublet</th>
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<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>MgF2 SPT</td>
<td>CaF2</td>
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<td>0.9805</td>
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<tr>
<td>MgF2 SPT</td>
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<td>0.9805</td>
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<td>1</td>
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<tr>
<td>MgF2 CC</td>
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<td>0.9765</td>
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<td>1</td>
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### Table 2. Inferred Subsystem Throughput

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<th>HWP</th>
<th>QWP</th>
<th>QBL</th>
<th>FL</th>
<th>WBL</th>
<th>MG</th>
<th>MIR</th>
<th>DBL</th>
<th>CAM</th>
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<tr>
<td>LLNL Fold</td>
<td>0.965</td>
<td>0.97</td>
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<td></td>
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<td>1</td>
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<tr>
<td>MgF2 SPT CaF2</td>
<td>0.9634</td>
<td>0.9805</td>
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<tr>
<td>MgF2 SPT Sil</td>
<td>0.9634</td>
<td>0.9805</td>
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<tr>
<td>MgF2 CC Sil</td>
<td>0.9817</td>
<td>0.9765</td>
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<td>ML CaF2</td>
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<td>ML Sil</td>
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<td>SG Sil</td>
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<td>0.9942</td>
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<td>6</td>
<td>1</td>
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**Nominal**

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<tr>
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<th>0.9564</th>
<th>0.9564</th>
<th>0.9801</th>
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**Measured**

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<th>0.915</th>
<th>0.977</th>
<th>0.855</th>
<th>0.920</th>
<th>0.900</th>
<th>0.628</th>
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<td>0.894</td>
<td>0.911</td>
<td>0.911</td>
<td>1.032</td>
<td>0.930</td>
<td>0.768</td>
<td>0.950</td>
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**Measured/Nominal**

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<th>0.957</th>
<th>1.021</th>
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<th>0.991</th>
<th>0.9418</th>
<th>0.667</th>
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<tbody>
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<td>0.947</td>
<td>0.930</td>
<td>1.073</td>
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<td>0.821</td>
<td>0.979</td>
<td>0.949</td>
<td>0.856</td>
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</table>

Substantial UV throughput losses (50 - 70% of expected throughput at 375 nm) were found in three subsystems, the collimator main group, collimator doublet, and the camera (solid boxes in table 2). Smaller visible wavelength throughput losses (75 - 80% of expected) were found in the
collimator main group and camera (dashed boxes). Multiplying the throughput of all measured subsystems together to obtain a system throughput yields 14% and 53% of expected throughput for 375 and 635 nm, compared to the measured on-sky results of 27% and 61% of expected, respectively, so it is likely that all significant efficiency issues have been accounted for in these measurements. The collimator field lens doublet, waveplates, waveplate blanks, and fold mirror throughputs were within errors of the expected throughput. Figure 8 summarizes these results, where filled symbols are 375 nm and open circles are 635 nm results, and large symbols represent direct measurements. The coating types for each subsystem are shown along the bottom.

Since there is no coating type in common among the three subsystems with throughput problems, it seems likely that at least two coating-related problems are involved. The involvement of the collimator main group, which is inaccessible with the instrument installed, means that the instrument must be removed from the telescope to disassemble and repair its elements.

### 6.2 Reflectivity

In addition to the above transmission measurements, selected reflectivity measurements were performed on three elements that could be removed to the bench, the waveplates blank, the collimator doublet, and the field flattener/ dewar window. All were coated with multilayers, the waveplates blank by OptoSigma, the doublet by Spectrum Thin Films, and the Field Flattener by SPT using a “humidity-resistant” process. Table 3 summarizes these results:

<table>
<thead>
<tr>
<th>Coating</th>
<th>Substr 375</th>
<th>635</th>
<th>WPBL</th>
<th>Doublet-Si</th>
<th>Doublet-CF</th>
<th>Fltnr-Frnt</th>
<th>Fltnr-Back</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML</td>
<td>CaF2</td>
<td>0.9900</td>
<td>0.9899</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ML</td>
<td>Si</td>
<td>0.9900</td>
<td>0.9899</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
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<td>Nominal</td>
<td>375</td>
<td>0.0200</td>
<td>0.0100</td>
<td>0.0100</td>
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<tr>
<td></td>
<td>635</td>
<td>0.0202</td>
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<tr>
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<td>Measured/Nominal</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>635</td>
<td>0.84</td>
<td>0.79</td>
<td>0.99</td>
<td>7.91</td>
<td>0.59</td>
<td></td>
</tr>
</tbody>
</table>

• The waveplates blank reflectivities appear to be completely nominal, while the total...
transmission (0.90, 0.93 at 375 and 635 nm) laser measurements are marginally low compared with the expected $1 - \text{reflectivity} = 0.98$. (Both the front and back side reflectivity were measured together, since these reflections could not be separated). Because of this discrepancy, this element was removed from the instrument and its transmission subsequently measured using a monochrometer. Figure 9 shows these results (monochrometer: small points; laser: large points). These show the visible performance to be as expected, but the UV transmission is up to 8% low down to 320 nm. While this element is clearly not a major player in the UV throughput shortfall of the instrument, it does reinforce the possible contribution of coating absorption below 450 nm. The substrate is fused silica, so is not susceptible to the CaF$_2$ induced color center effect discussed in section 3.

• The collimator doublet is a lens fluid-coupled pair consisting of fused silica and calcium fluoride with multilayer coatings on the two air-glass surfaces. The reflectivity of both the silica and CaF$_2$ surfaces and the total throughput are consistent with the coating specification at 630 nm, but at 375 nm the reflectivities are 5 and 7%, respectively (specification < 1%), and the total throughput is 50%. So not only are both coatings out of specification for UV reflectivity, but there must be additional absorptive losses to account for the UV throughput being less than one minus the sum of the reflectivities. The absorptive loss here could be due to induced color centers in the CaF$_2$ element, but the out-of-specification UV reflectivity for the coating on both substrates points to at least some of the underperformance being due to the coatings alone.

• The RSS detector was removed and the dewar window was inspected and measured for reflectivity. The front surface of the window is the leading suspect for the origin of the “ring ghost”, which has the unfortunate property of imaging the pupil onto the detector, so that ghost light from all field angles is stacked up. Laser measurements (table 3) at 635 nm find the reflectivity of the rear surface to be 1% (consistent with specification) and the front surface to be 8%, clearly out of spec. The eyeball-judged color of the reflected light is also different for the two surfaces - blue for the rear surface, and yellowish-green for the front surface (Figure 10). Using the observed ghost intensities in the different RSS interference filters from 380 - 870 nm, together with a model of the filter reflection efficiency after a reflection off the dewar window, we can construct a predicted reflectivity for the dewar window as a function of wavelength (Figure 11, diamonds). This is consistent within errors with the 635 nm laser measurement (square), and its shape, which drops
from a peak of 20% at 540 nm to much lower values below 480 and above 650 nm, is consistent with the yellowish-green tint of the reflection. Thus we are now almost certain that the ghost has been identified and that it can be remedied by repairing the dewar window coating. This coating problem does not appear to be related to the UV throughput problem, and the implied transmission loss has not been included in the system throughput model of section 6.1. Taking transmission = 1 - reflectivity, it would imply a ~8% loss at 635 nm and a negligible loss at 375 nm. However, one would expect a ~20% transmission loss centered on 540 nm. Figure 1 does suggest such a transmission feature.

6.3 Inspection

A detailed inspection was made of the camera assembly by viewing it from the collimator side and from the detector side in the presence of a strong light. By comparison with a similar inspection before the instrument was mounted on the telescope, we see that there has been some degradation in either coatings or the lens fluid coupling during the one year interval. Figure 12 shows two disk-shaped areas of higher reflectivity which were not previously seen. One is probably a reflection of this area off the interference filter at the other end of the camera, so there is likely a single area, which does not occupy the full aperture of the camera. This may or may not be a major contributor to the camera throughput loss.

6.4 Summary and Prognosis

The picture so far is that the RSS throughput problem is not the result of a single issue, but of the sum of several problems. In terms of the decision tree of section 5, the problems reside in three optical subsystems, the camera, the collimator doublet, and the collimator main group (Figure 13).

Reviewing the possible throughput loss contributors (section 3), the fold flat and the detector QE have been exonerated. There remain three possible contributors, and they are all coating-related:

• Out-of specification AR coating reflectivity. This has been demonstrated in the collimator doublet in the UV and in the dewar window in the yellow.
• AR coating absorption. This is seen at a low level in the waveplates blank below 400 nm.

• Coating-induced color centers in CaF₂ substrates.

There is clearly absorptive loss in the collimator doublet in the UV, but it is not clear whether this is due to coating or CaF₂ substrate absorption. So while possible, the UV color center theory put forward in section 3 has not been unequivocally demonstrated.

Which coatings and coating processes are to blame? So far, all the elements with only MgF₂ coatings (the waveplates and the collimator field lens) have been exonerated. Multilayers have been shown to be a problem in the collimator doublet and the dewar window. There are at least two separate problems here because of the different spectral signatures. Also, the dewar window "humidity resistant" process is somewhat different from the other SPT coatings. The SolGel coatings are not exonerated because the collimator main group, which does have a problem, has SolGel and MgF₂ coatings only: if MgF₂ is not a problem, then SolGel must be. It is also worth noting that the two subsystems with visible degradation, the camera and the collimator main group, have only SolGel coatings in common. So we see four possible coating-related problems, with a minimum of three involved:

1) Multilayer yellow coating (dewar front face, but not the rear one).
2) Multilayer UV coating (collimator doublet, Silica and CaF₂).
3) Multilayer CaF₂ color centers (possible, but not required, in collimator doublet).
4) Solgel coating, visible and UV. This could be a CaF₂ color center problem.

It is noteworthy that none of the problems 1-3 are seen in the SALTICAM coatings, which were the same SPT "humidity resistant" coatings applied to the dewar window.

The next steps require further disassembly of the camera and collimator main group to isolate the bad coatings, an investigation of what went wrong with these coatings, and repair of the coatings. A proposed repair scenario is as follows:

• Remove camera, collimator doublet, and collimator main group.
• Disassemble camera and collimator main group to multiplet level.
• Measure detailed transmission curves of multiplets.

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**Figure 13.** Decision Tree, as traversed
• Attempt a UV flood (color center repair) of any bad multiplets containing CaF$_2$, remeasure.
• Disassemble if necessary remaining bad multiplets to element level.
• Measure coated elements.
• Ship bad elements to coating vendor(s) for forensics.
• Polish off bad coatings.
• Recoat, either with original coating, or with a fall-back.
• Remeasure.
• Reassemble optics.