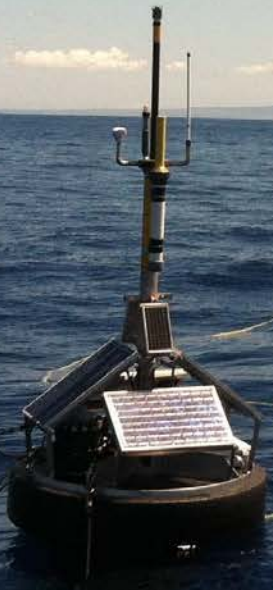


MOBY-Net

Final report presentation
Kenneth Voss (UM), Mark
Yarbrough (MLML/SJSU), B.
Carol Johnson (NIST), Art
Gleason (UM)

10/22/18



Introduction/Outline

- We will go through the system, with tests that have been performed and the results. The general format will be from the back of the system (camera) going forward to the stability monitor and source.

Outline:

- 1) Camera
- 2) Spectrographs
- 3) Fiber splitters
- 4) MOBY Hull
- 5) System tests at sea
- 6) Data acquisition tests
- 7) Stability Source and Monitor
- 8) How did we do with the goals.
- 9) TRL estimates

Cameras

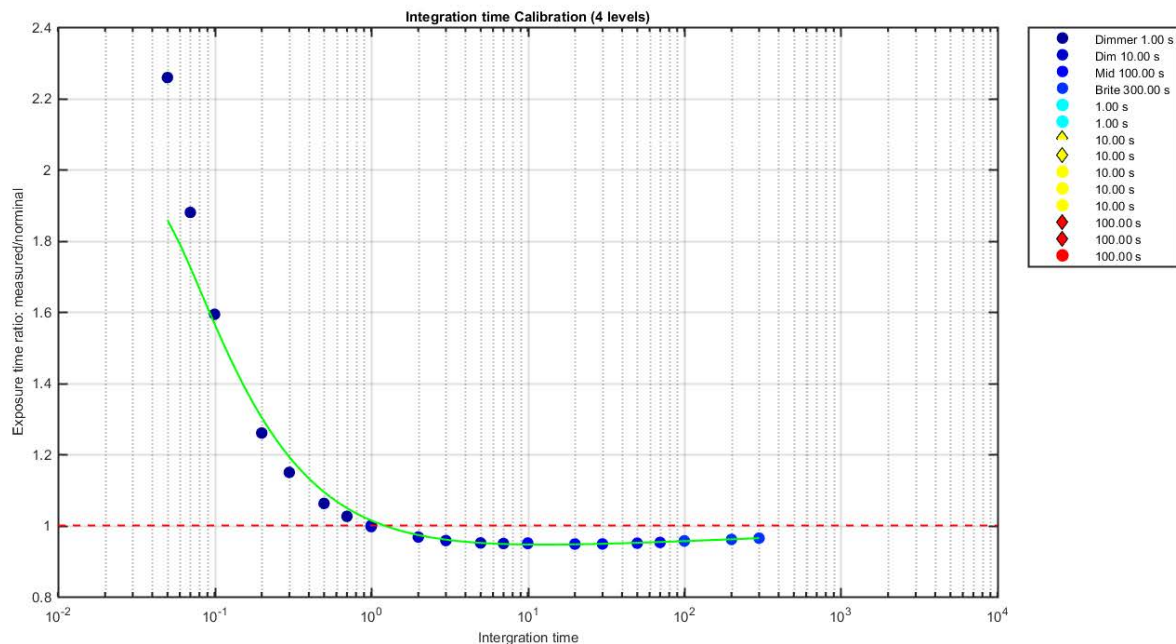
- Started process with Pixis camera, strange jumps in baseline that couldn't be explained...so...
- The camera selected was an Andor iKon-M934 camera
- Mega-pixel camera (1024 x 1024) with the BR-DD imaging chip for both the blue and red spectrographs
- 13 um pixels
- 100,000 electron well depth
- Read noise at 2.9 electrons, with 4 read out speeds (5,3,1,0.05 MHz)
- Back illuminated CCD with deep depletion (thicker active photosensitive area), and fringe suppression to prevent etalon effects

Camera settings

- Many performance tests were done on the camera to test which settings would work best with our application, which uses long integration times (10 s to 1 minute).
- Settings we are using are:
 - Single scan
 - Read full images
 - Horizontal Shift Speed 3 MHz, vertical shift speed 4.250 μ S
 - Gain 4x (Note at the A/D rate, this means approximately 1.2 electrons/count)
 - Cooler at -60 C
 - No baseline clamp

Shutter speed/Calibration

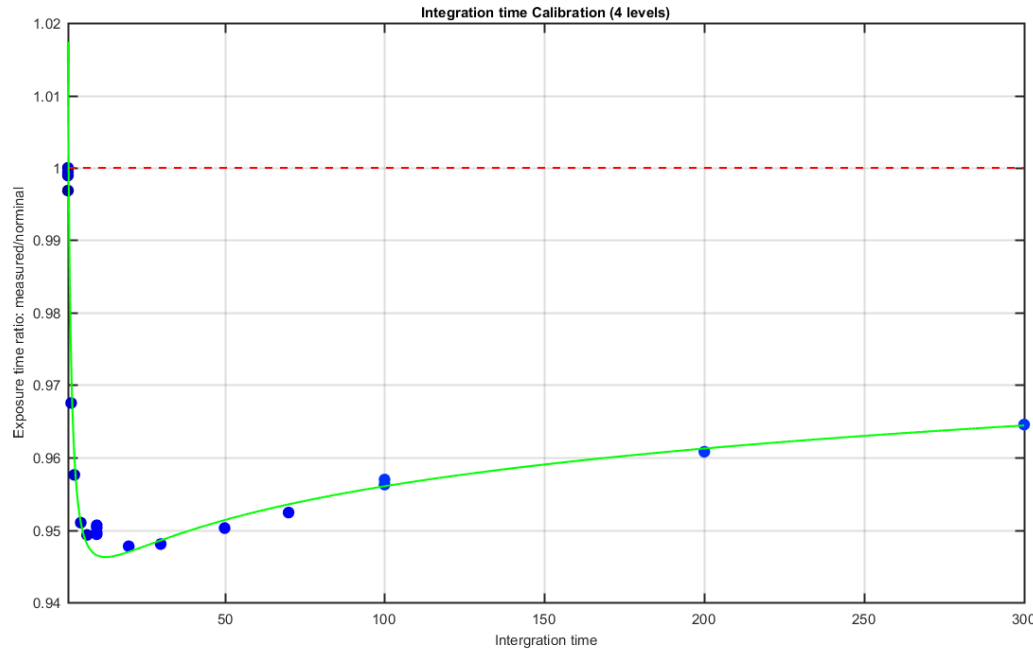
There have been several calibrations of shutter speed/integration time, the example shown here and on the next slide is the post-calibration of the Blue Spectrograph (BSG) on the last deployment.



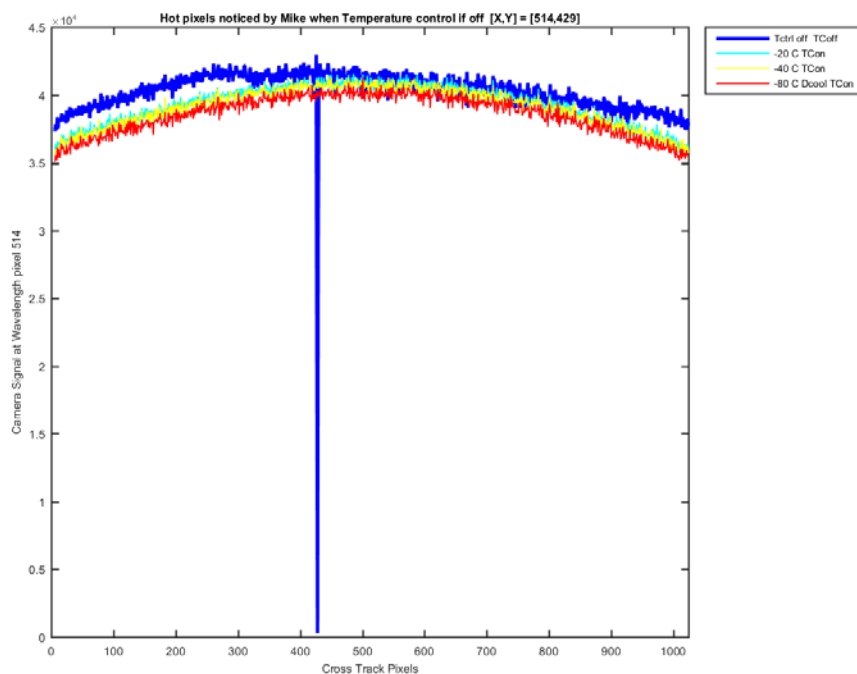
Here one can see the typical rise that happens when an integration time is too short, or the shutter is too slow for that integration time. This result shows that we really want to be using integration times of at least 1 second.

Shutter speed calibration, another view

This expands the scale to more relevant times for MOBY-Net. We typically want to use exposure times of 10-60 seconds to reduce wave focusing (as will be shown later in the presentation), so in this range the normalization for shutter time is quite stable.



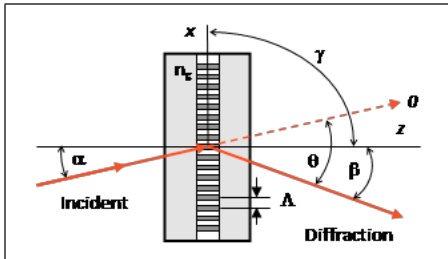
“bad pixels”



While testing the camera, we noticed a few “bad pixels” in the images. These were pixels that the signal was either very high for or very low. We did several tests for this, and the position of the pixels remained the same, so it was restricted to several pixels in each image, for each camera. Many tests were done on this, but in the end we realized that these pixels were only anomalous when the camera was used at room temperature (the blue line), even a reduced temperature of -20 C was sufficient to bring these pixels in line. Since we are operating at -60 C this is not a problem for us.

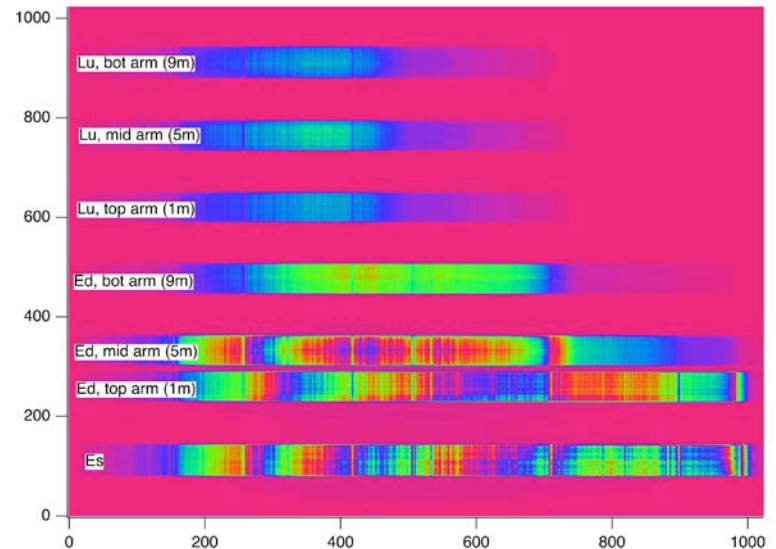
Spectrograph

- The base spectrographs are built by Resonon.
- They are based on Volume Phase Holographic gratings which have very low straylight characteristics and very good imaging qualities that allow us to image many input channels at the same time.



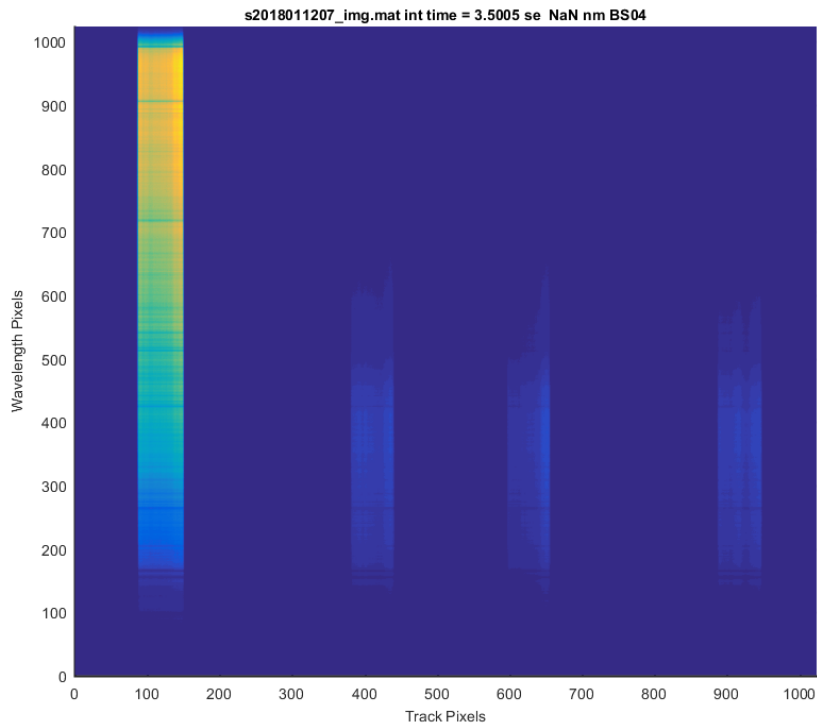
Grating picture on left, Sample image from field on the right showing all optical channels getting signal at once.

From
<http://www.bayspec.com/technical-support/definitions/vpg/>

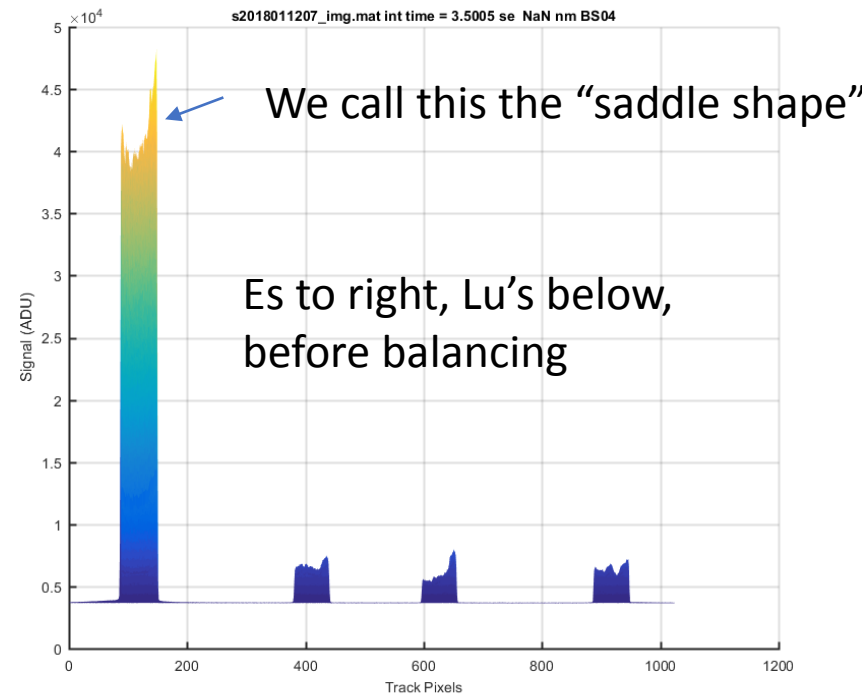


Be best to define the Image layout, and definitions

Wavelengths spread out vertically, each track horizontally spread across. For each wavelength, we average across the track in a single row. Stray light can be thought of as two processes...spectral straylight (spread vertically in this image) and cross track straylight (spreading horizontally from one track to another).



Cross track view



Spectrograph testing

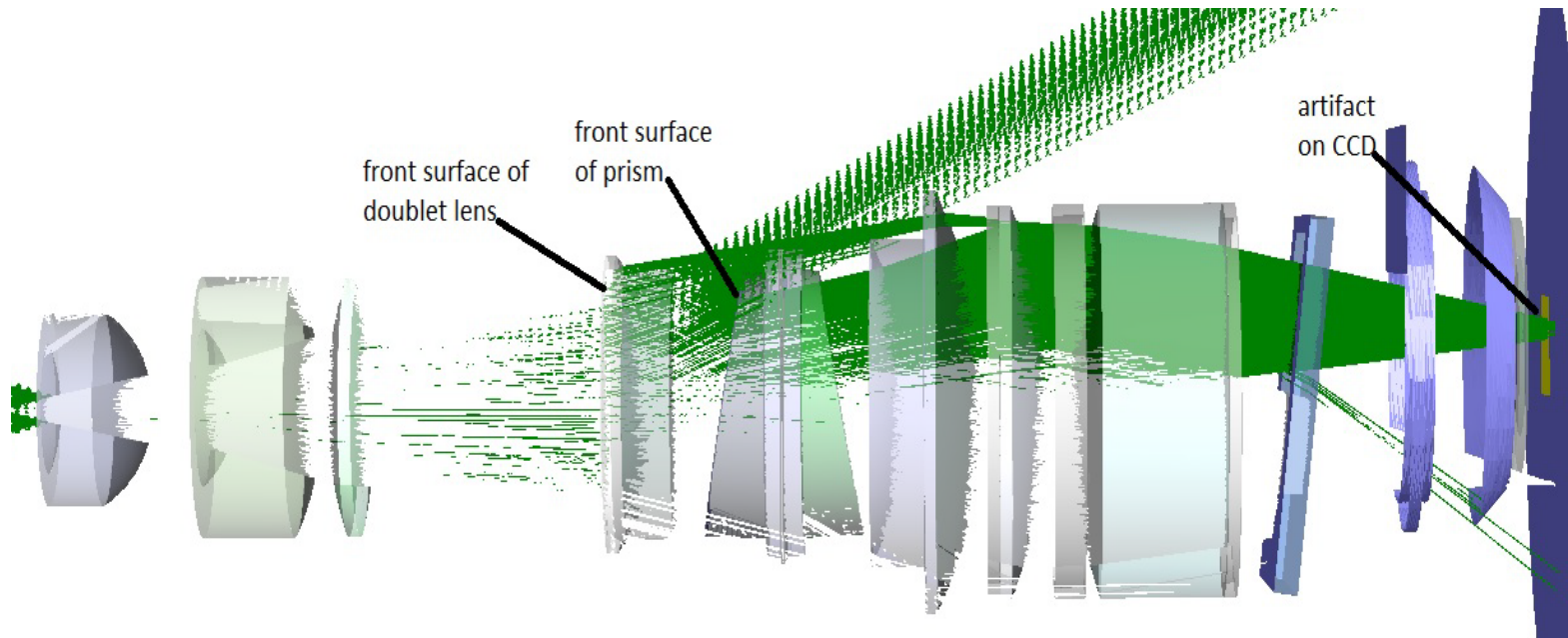
- The Purchase order to Resonon for the construction of the spectrographs (2 each Red and Blue spectrometers) for MOBY-Net was finally processed in Jan. 2015.
- Because we are doing the same base optical system for MOBY-Refresh, we had previously had an order in for additional Red and Blue spectrometers, hence could start testing when these arrived.
- We received our first Blue spectrometer From Resonon in April 2015.
- This first system, while performing well at Resonon, on our closer inspection did not perform as expected. It was sent back to Resonon for further work. In their testing, one problem they noticed was an asymmetric flair in the images, which was suspected to be because of the wedged windows, but this was discounted in further tests...but unfortunately, as will be discussed later, most of the cameras were then ordered with flat windows.
- The flair problem was found to be in the camera software, not a hardware issue in the end.

Blue spectrograph Infrared artifact

- During Resonon testing in May 2015, before returning the BSG to us, they found an infrared artifact that was caused by light above 800 nm (the BSG should only deal with light from 340-700 nm).

There was a filter in the system to block light from 700 nm to 900 nm (shown on left) but let light through at higher wavelengths, so the fix was to replace this filter with one that extended to 1100 nm (will be shown later). This filter is actually put on the face of a prism in the optical system.

Cause of Infrared artifact

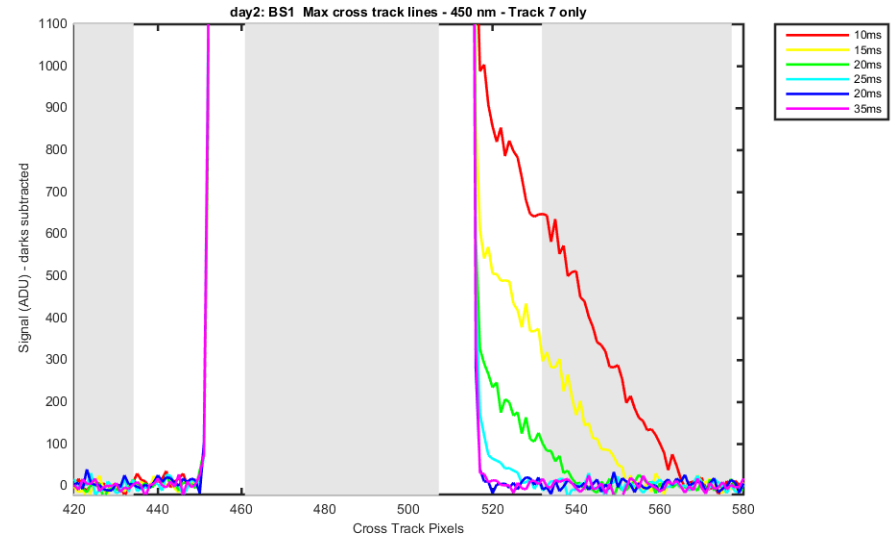


Artifact is a double bounce ghost reflection, first bouncing off filter coating on front face of prism, second a reflection from the front surface of the doublet lens. Solved by eliminating that light (above 700 nm) from system to start with.

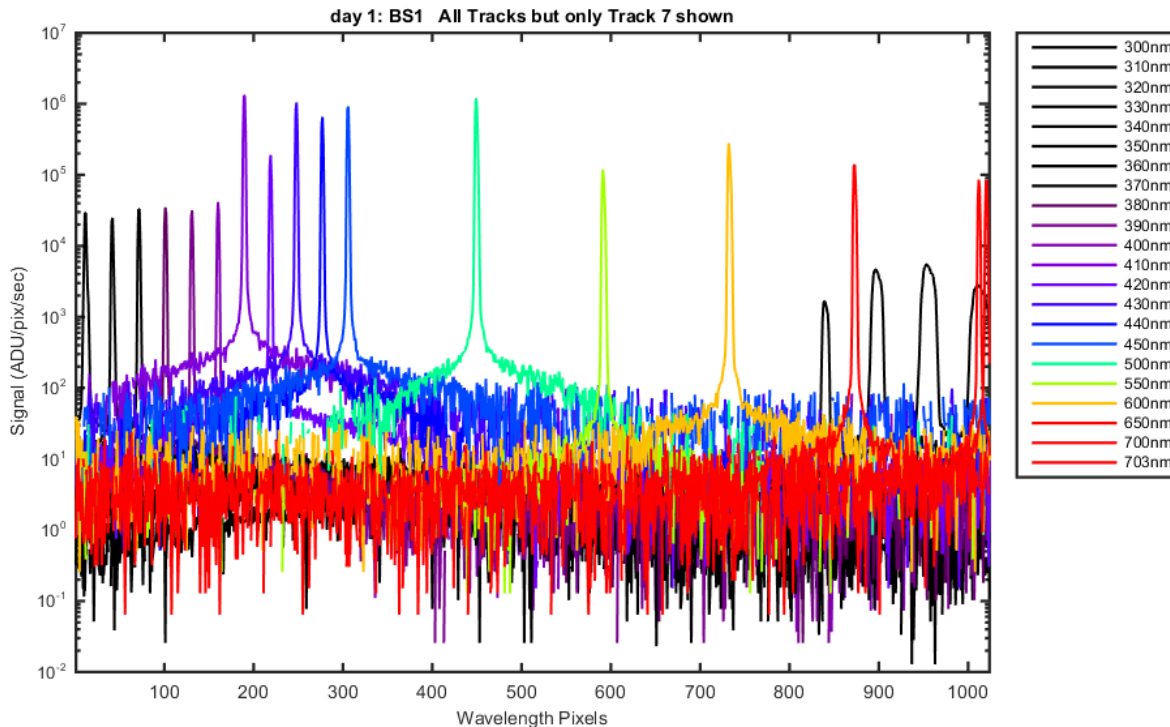
BS1 shipped back to Hawaii

- At the end of May 2015 BS01 was shipped back to Hawaii, without the new filter. The idea was for us to continue testing the other parts of the system, knowing this would have to be retrofitted.

Tests in June found a “shoulder” on each track. After a lot of experiments, it was found to be caused by a shutter delay, (note the blue 20ms should be 30 ms). If the shutter delay was set to 30ms or greater, the shoulder went away. The shutter delay is the time that the system is given after the shutter is told to open, before the integration time is started. If it is too short, the array starts being read out before the shutter is really closed. The shoulder probably comes because the array contents are being shifted while the shutter is open.

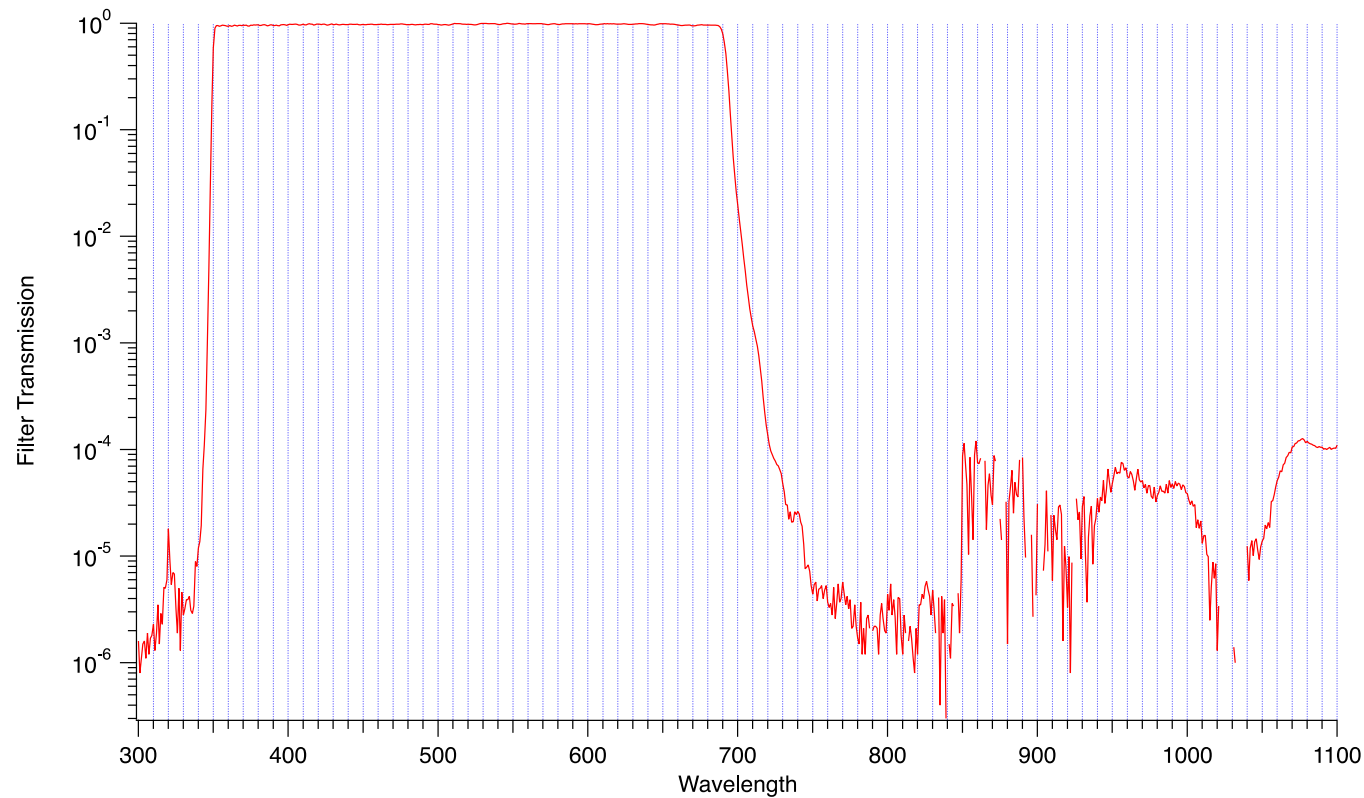


Blue filter required for Blue spectrograph



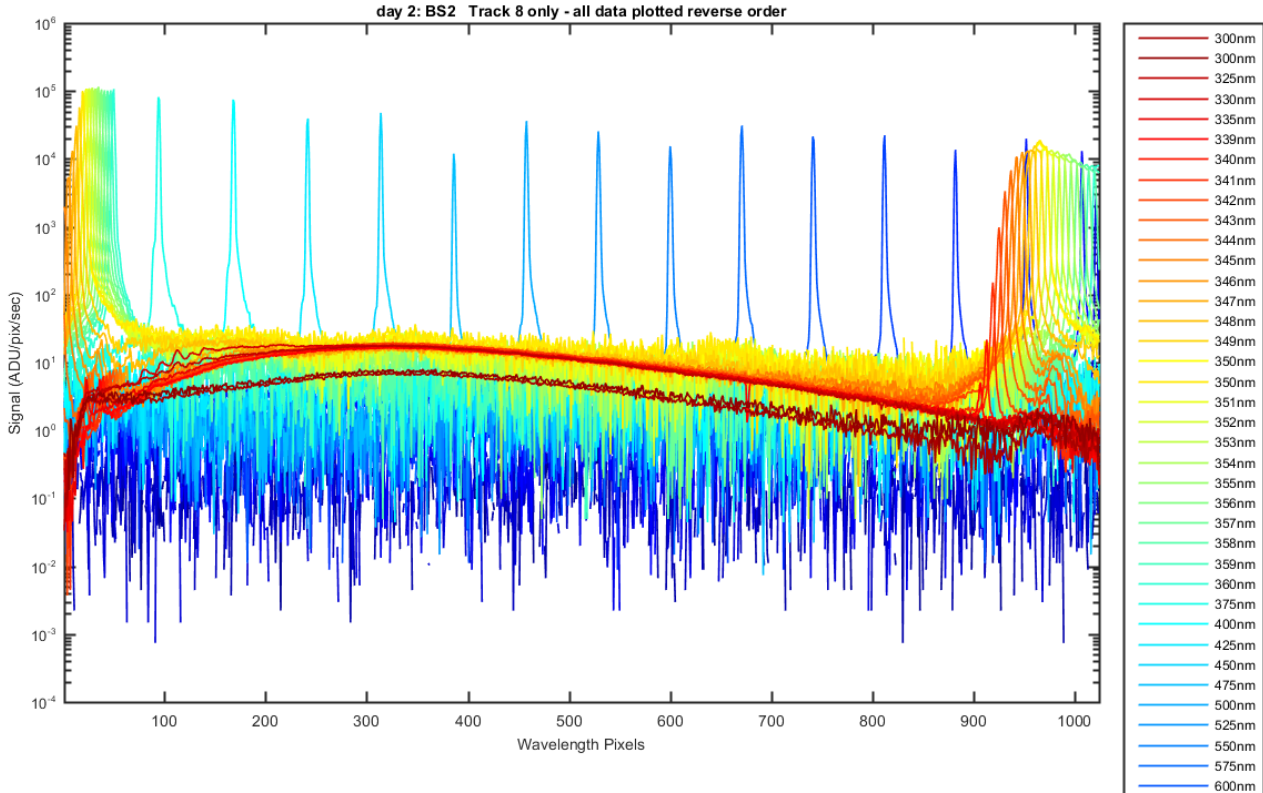
While testing the system for straylight and other effects, we found that the system transmission below 340 nm was much higher than we expected. The 4 black peaks toward the right of the spectrum, shown here, are 2nd order of 330, 340, 350, and 360 nm laser light. Because our 1st order starts at around 340 nm, we would not be able to correct for this in a “straylight” correction. So another filter was required to make light below 340 nm negligible in the system.

This filter was added to the blue spec, took care of both the infra-red artifact and the Light below 340 nm. Cuts on between 340 and 350 nm, off starting at 690 nm. The first system with this new filter was delivered in Feb, 2016.



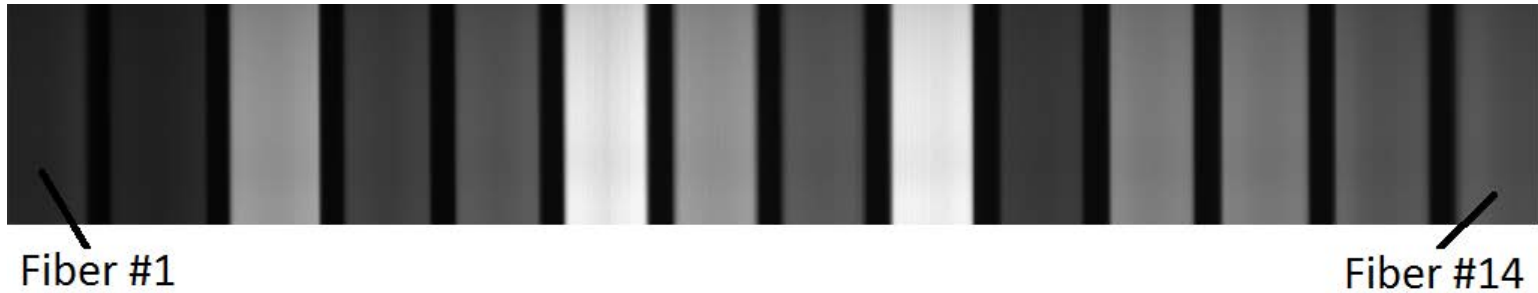
Note y axis is log transmission.

Preliminary data with this system indicated we were getting the correct bandwidth (<1nm), spectral sampling (approximately 0.3nm/pixel), and that the off-CCD 2nd order had been cut off.



Red spectrometer

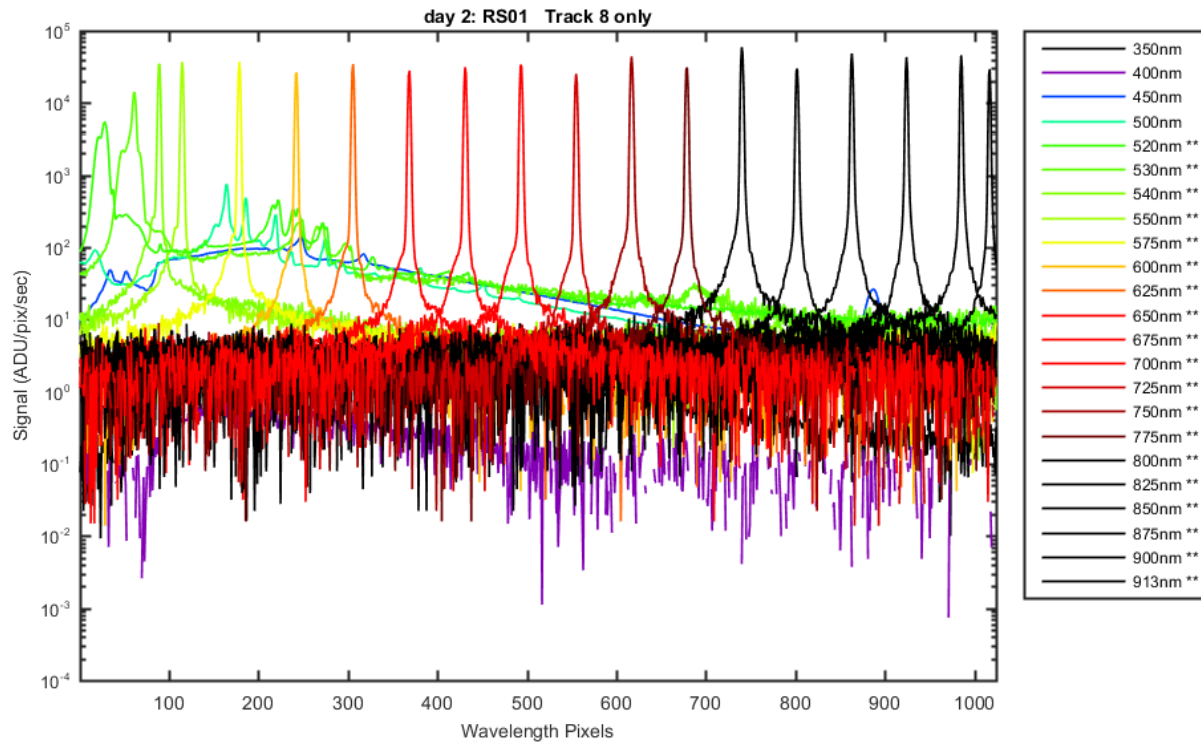
- The initial build of the red spectrometer at Resonon (Sept 2015) ended up with the image of the 14 fibers too large for our camera array (tracks 1 and 14 did not fit on array)



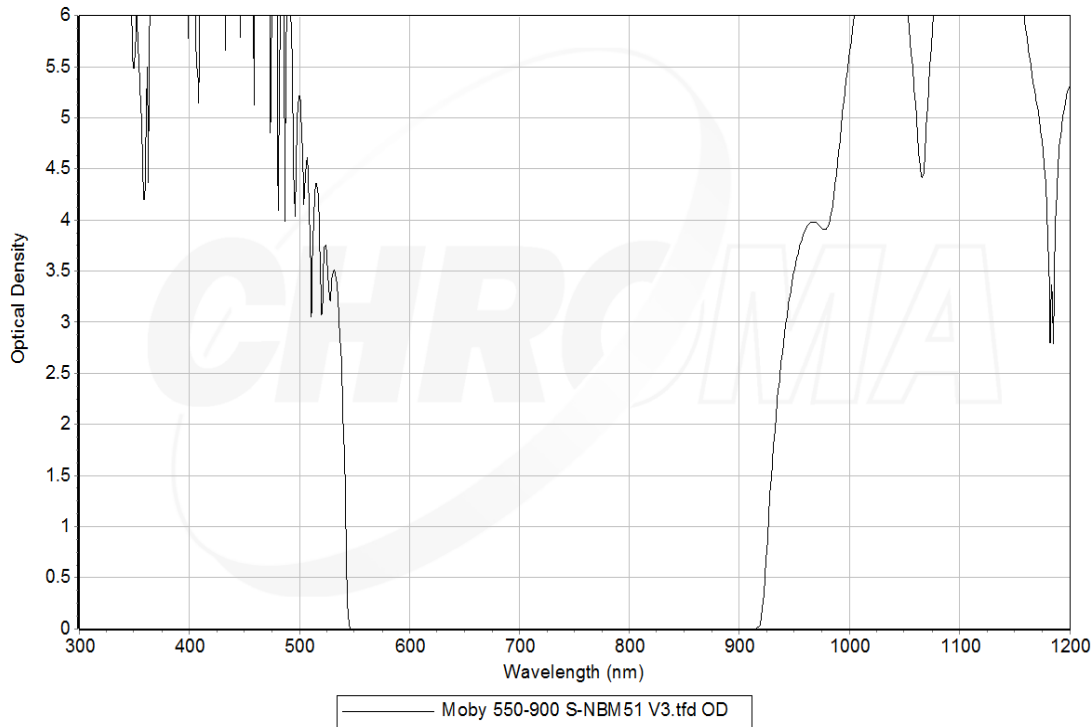
The solution to this was to have two of the custom lenses in the spectrometer remade (there are 7 lenses in total in this system). (Determined October 2015). New lenses were made and the first red spectrometer was assembled December 2015.

Issues were found with the fiber optic bundle that provides the input to the spectrometer. These issues were corrected and the first Red spec shipped to Hawaii and arrived April 2016.

Preliminary data with Red Spectrometer looked good. There were funny wiggles on the 520 and 530 nm lines (explanation next page). bandpass around 1.2 nm, spectral sampling 0.4 nm/pixel. Note almost no 2nd order on this spectrograph.



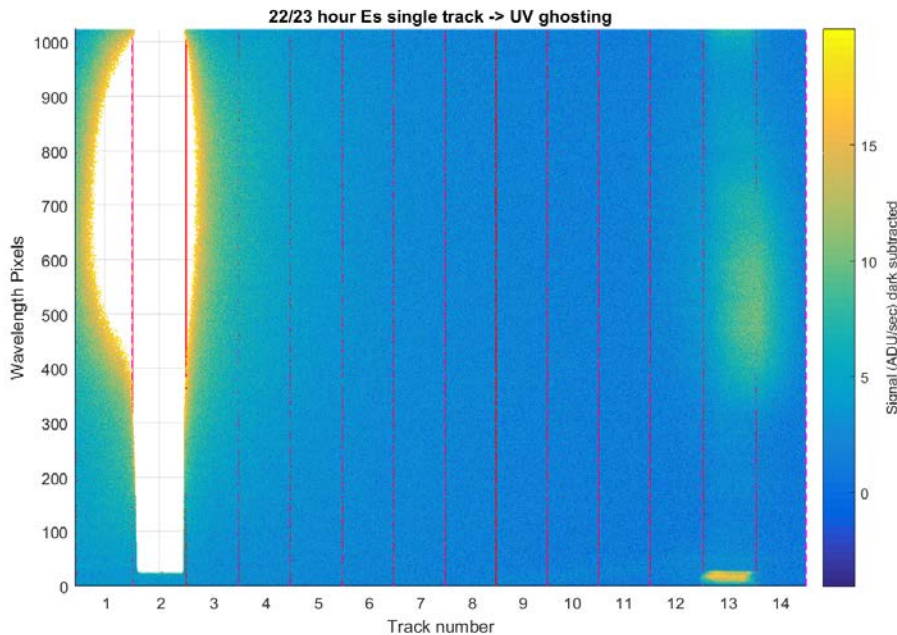
If one looks at the filter that is installed on the Red spectrometers, it explains the wiggles.



Note that between 500 and 540 nm, there are wiggles in the optical density. Given that the power of the laser would have to be very high to see a signal at the peak there, these wiggles would then show up at longer wavelengths.

Final issue (with both Red and Blue systems)

- While looking closely at field data from M264, Stephanie Flora noticed some small features that she called “UV Ghosting” in the images.



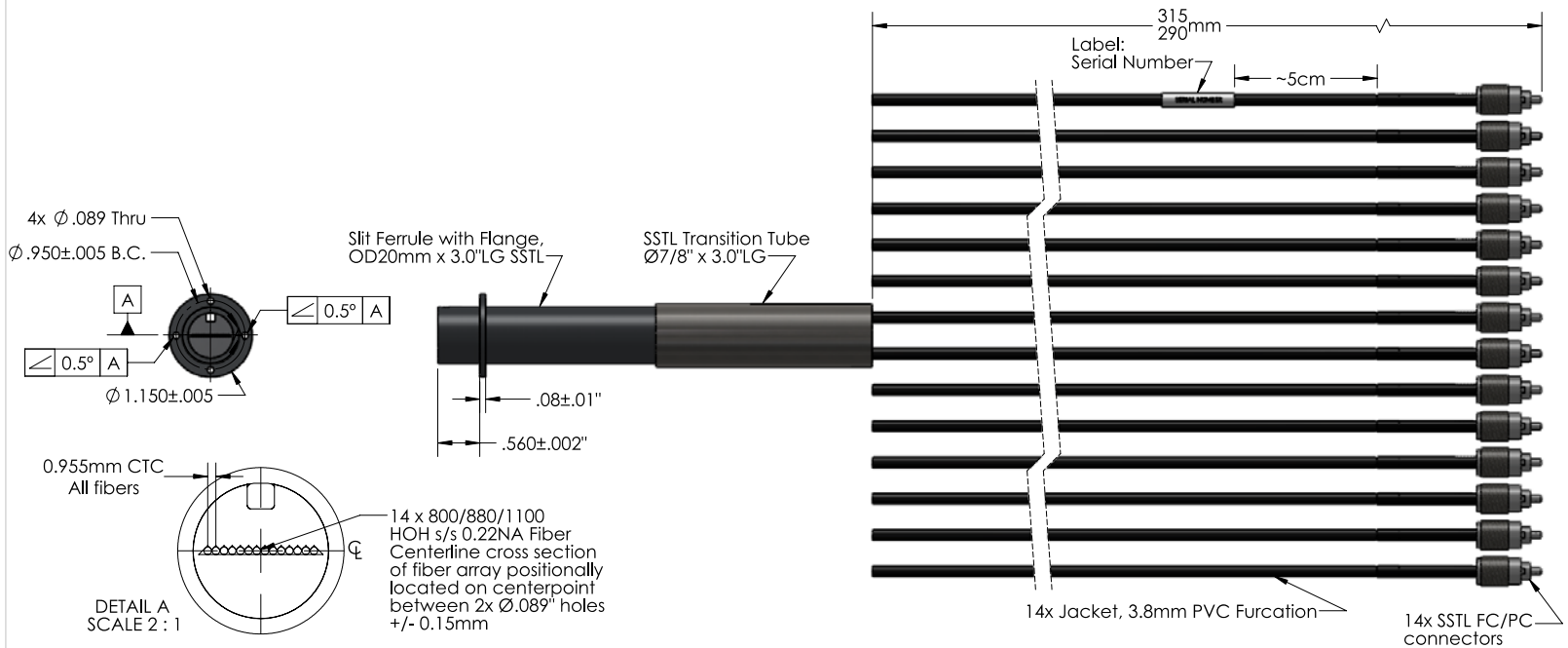
This is with one channel (Es) illuminated. Note that signal from track 2 shows up in Track 13. This effect consistently moves light from an illuminated track to the mirror location (2 to 13, 4 to 11, and vice versa). It is not a spectral mirror...i.e. signal in the UV comes from other wavelengths. It is also small (note <15 ADU while Es is very high...in the $+10,000$ ADU), but after much further investigation we found that it is in all of our systems that have parallel windows on the cameras, rather than wedged windows.

The cameras that had parallel windows (8 out of 12) were sent back to Andor for window replacement in July 2018, we are waiting on return shipment.

Fiber bundle required to input the 14 different signals onto the spectrometer

Customer: Resonon

Part Number: 096484 Customer



- Notes:
- Fiber faces will be polished to a scratch-free finish at 40x Magnification.
 - Fiber breakage not to exceed to 2%.
 - Non-Displaced and Non-Occluding cracks do not constitute a broken fiber.
 - Maximum operating temperature of this assembly is +85°C.
 - Minimum bend radius is 200x the fiber diameter for single fiber assemblies and 400x the individual fiber diameter for multi-fiber assemblies.

Signing this document signifies that it has been carefully reviewed in all aspects and can be used as a controlling document for the product depicted.

Customer: _____

LEONI Fiber Optics, Inc.
 FiberTech - RoMack
 209 Bulifants Blvd., Williamsburg, VA 23188
 PH: 757-258-4805 FAX: 757-258-4694
 contact@leoniinfo.com

Checked: Michael Carr	Approved: Derick Scherberger
<small>Digitally signed by Michael Carr DN: cn=Michael Carr, o=LEONI Fiber Optics, Inc., email=Michael.Carr@leoniinfo.com, c=US</small>	<small>Digitally signed by Derick Scherberger DN: cn=Derick Scherberger, o=LEONI Fiber Optics, Inc., email=Derick.Scherberger@leoniinfo.com, c=US</small>

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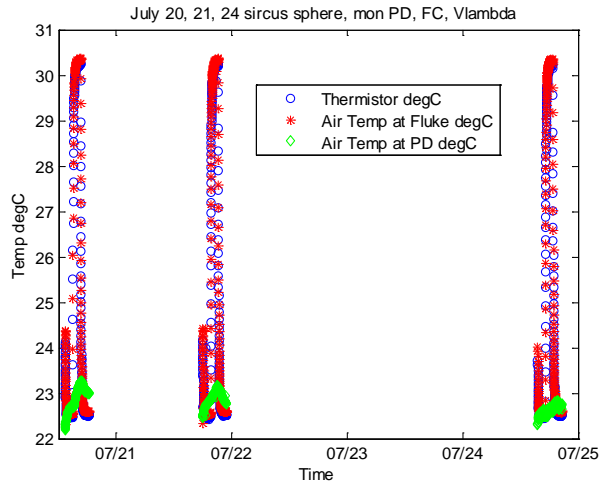
Fiber bundles

- There is a fiber bundle which delivers the light to the slit of the spectrometer. These are made by Leoni, and in 2016 the delivery of these were beginning to be a bottleneck in the process.
- We kept hearing, from Leoni, that they were having many break during the process of building them, so the yield was very small.
- In May 2017 they asked and we allowed them to change the design slightly (5cm longer, the drawing shown on previous slide), which was apparently enough to make the easier to build. All of the spectrometers needed to accommodate this change in length, as the bend radius of the fiber is fairly large.
- Now we know....

Fiber splitter

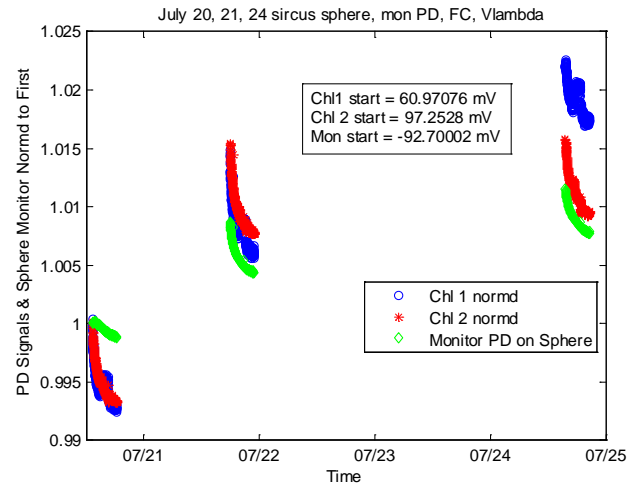
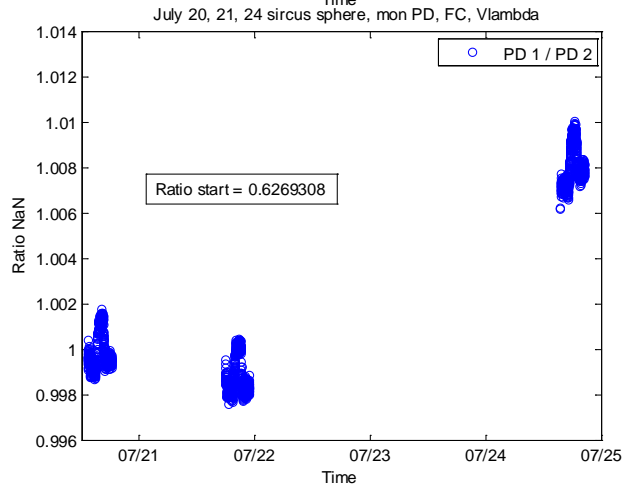


- In July and August 2015 we spent time testing a pre-delivery fiber optic splitter to make sure that the splitting ratio was stable with differences in illumination that we might expect. All of our tests indicated that the devices would be stable for this, so we went ahead with designing the system around these Fibersense fiber splitters, and ordered the set for MOBY-Net
- In September 2016 we received all of the splitters, and started a thermal test of their stability. In the range from 23 C to 43 C, the splitting ratio varied between 0.7353 and 0.7315, in a regular fashion, so it seemed the splitters were working, however the one we were using completely failed.
- We then started working through seeing if more rugged splitters could be made by Fibersense (because of the failure) and getting quotes for these.

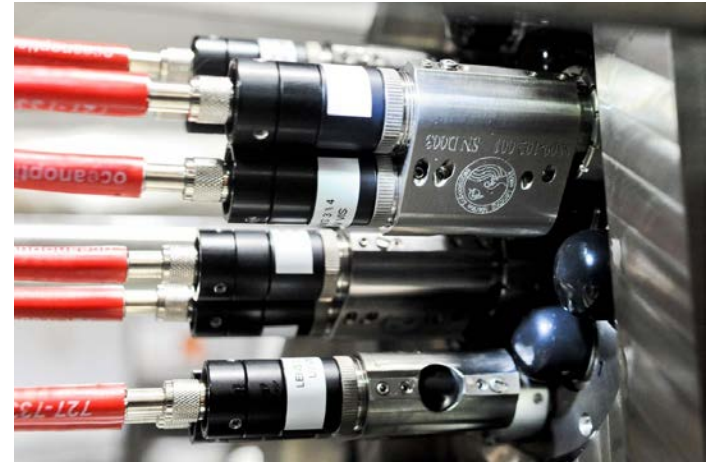
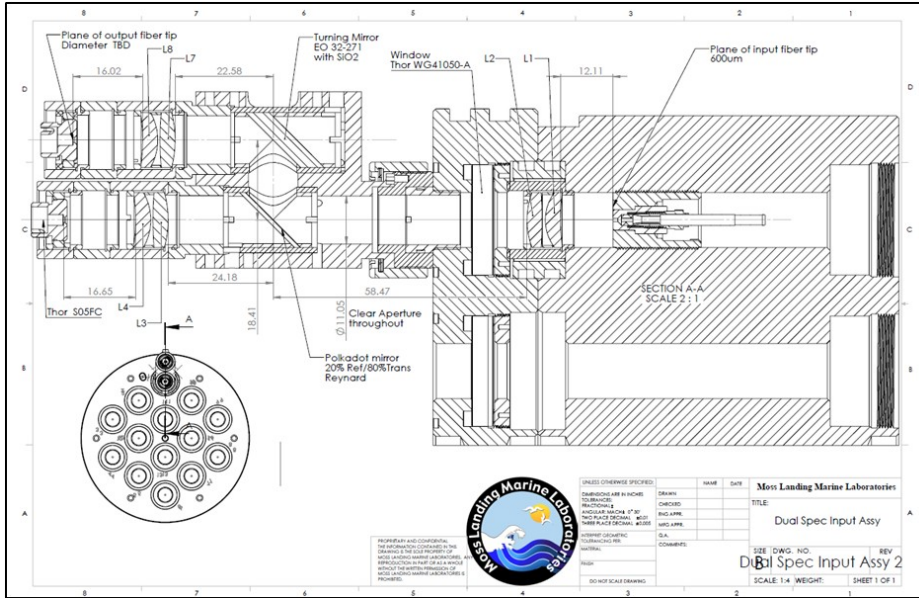


Left: Summary of three days with the Fibersense Splitter. The temperature cycled between about 22 and 30 deg C. The ratio of the flux in the two output channels varied with temperature, which we could in principle develop a correction function for, but the ratio was not consistent from run to run as seen in the lower left plot.

Below: Summary of three days showing the throughput of the two channels is not reproducible, varying more than the changes with temperature.



Switched to a new design using a polka-dot mirror: spectrally flat, stable response

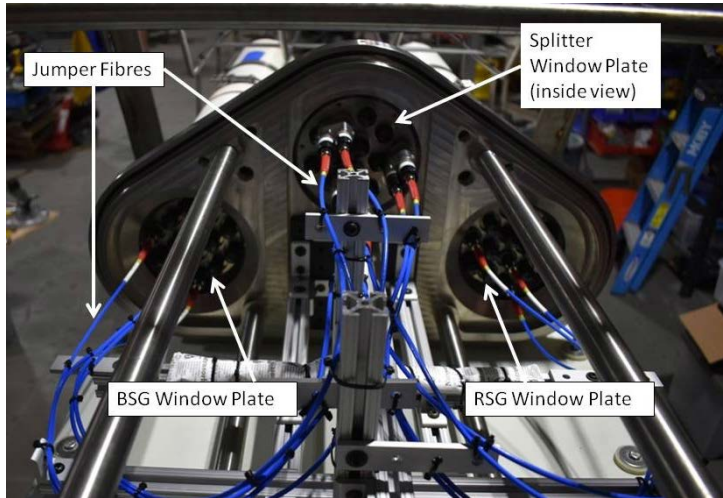


Optics designed by Clarence Zarobila

Pictures: Top, inside splitter housing, beam splitter assemblies.

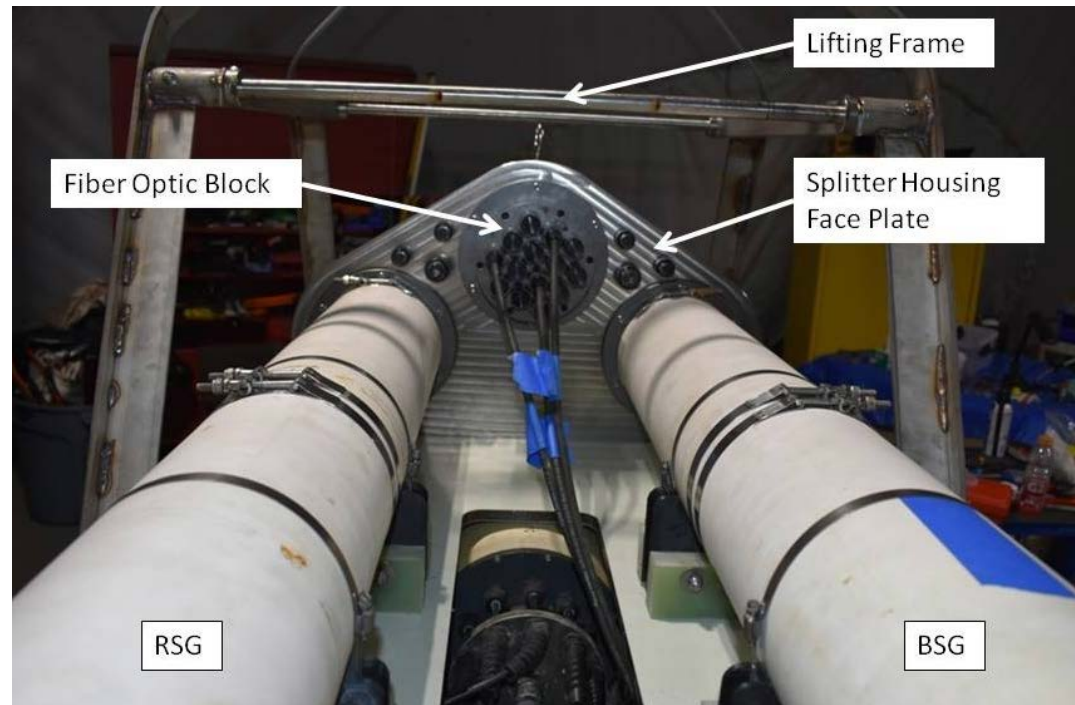
Bottom: outside, showing where fibers come into the beam splitter housing. Also shown is temporary PVC housing for spectrometers.

More Splitter pictures

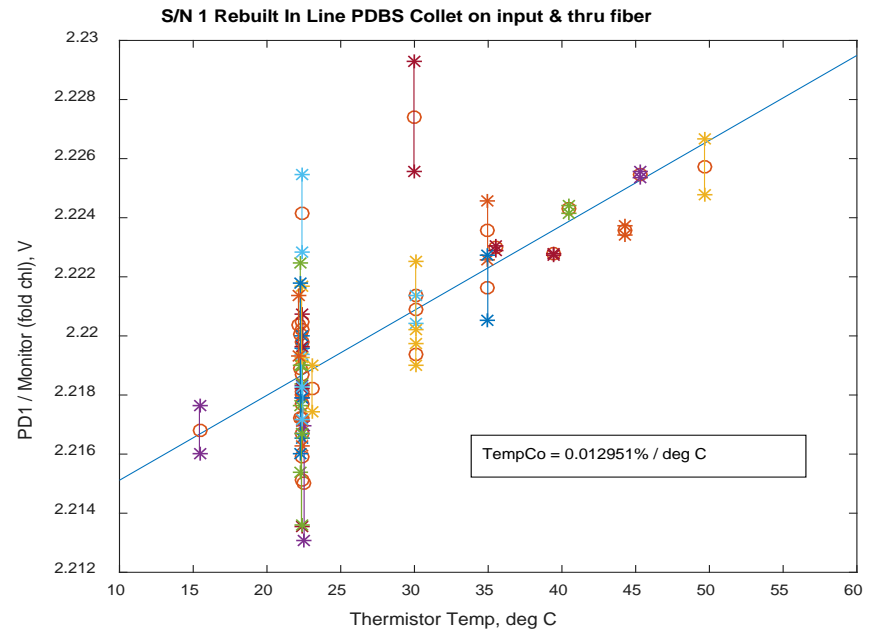
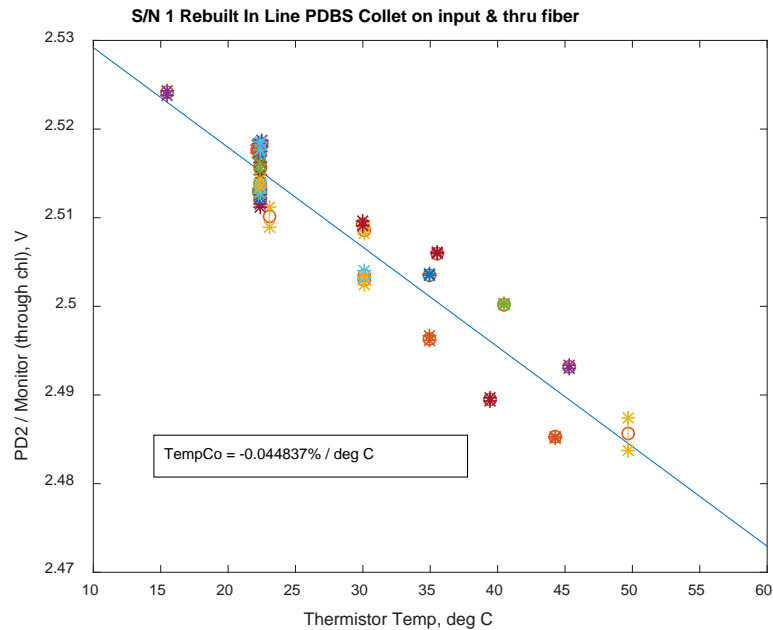


Above, inside Splitter housing

Below outside view, fibers coming in and both spectrometers, lifting frame serves two purposes, moving system around during assembly, and roll/protective cage while deployed with MOBY-Heritage.



Polka Dot beam splitter temperature tests



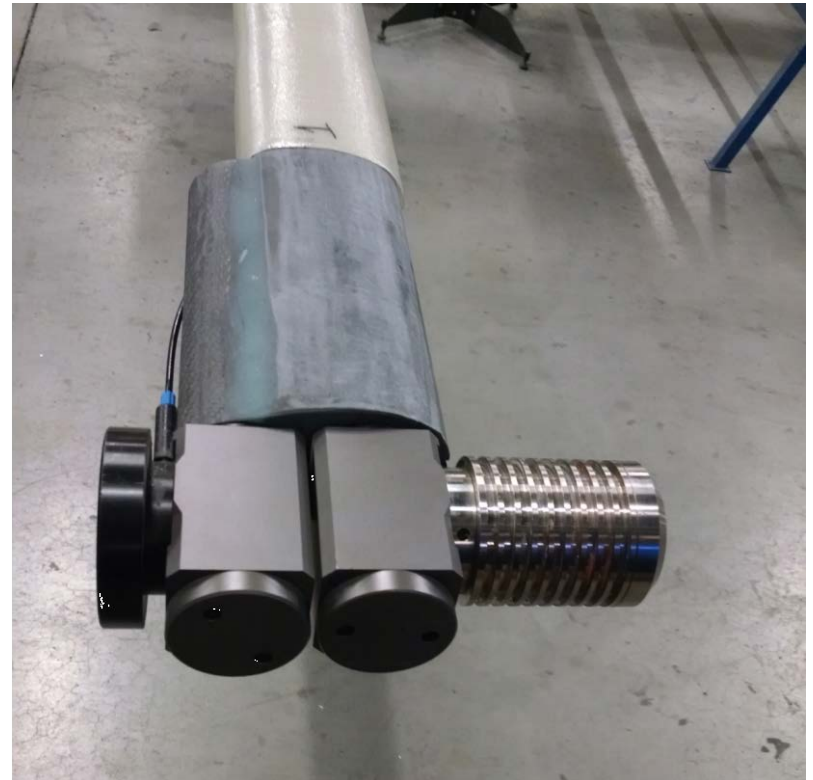
Compilation of many of the temperature tests done on several different days. Thru channel on the left, and fold channel on the right. While there is more apparent spread in the fold channel, the scales are different and the overall change is a factor of 4 smaller than the thru channel.

MOBY Hull

- With MOBY-Net we maintained the 3 arm configuration of the heritage MOBY system. While some may complain about the lack of profiling, there are many advantages to this configuration:
 - Arms allow us to get farther from the main instrument hull (reducing self shadowing).
 - 3 arms over 2 arms offers redundancy:
 - We have had the top arm damaged during deployments, the extra arm allows continued operation.
 - Occasionally a calibration will drift in one or other arm, with three arms we can see this by comparing the derived KL from different arm pairs, and can eliminate the bad arm measurement.
 - 3 arms allows 3 different KL pair measurements which can be used to track relative calibration
 - Arms at fixed depths allows long integration times (30-60 seconds) and repetitive measurements to eliminate wave focusing variations.
 - (not as important for Calibration) simultaneous measurements with the three depths will allow measurement in less optimal broken cloud situations.

MOBY Hull

- The important feature for MOBY-Net is the ability to remove the optical system (fibers, collectors, and spectrometer) intact for calibration in another location.





MOBY Net Hull in Falmouth before shipping

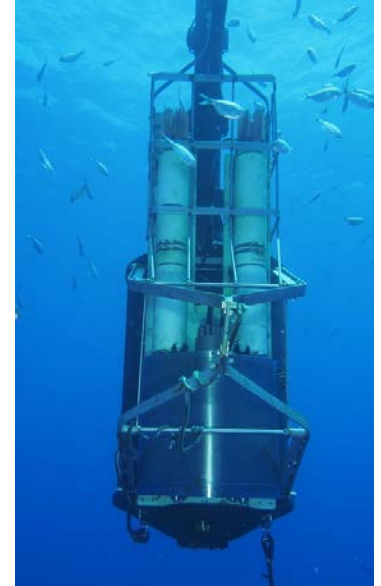


Top floats inside container.

Shows the lower instrument housing



System tests at sea

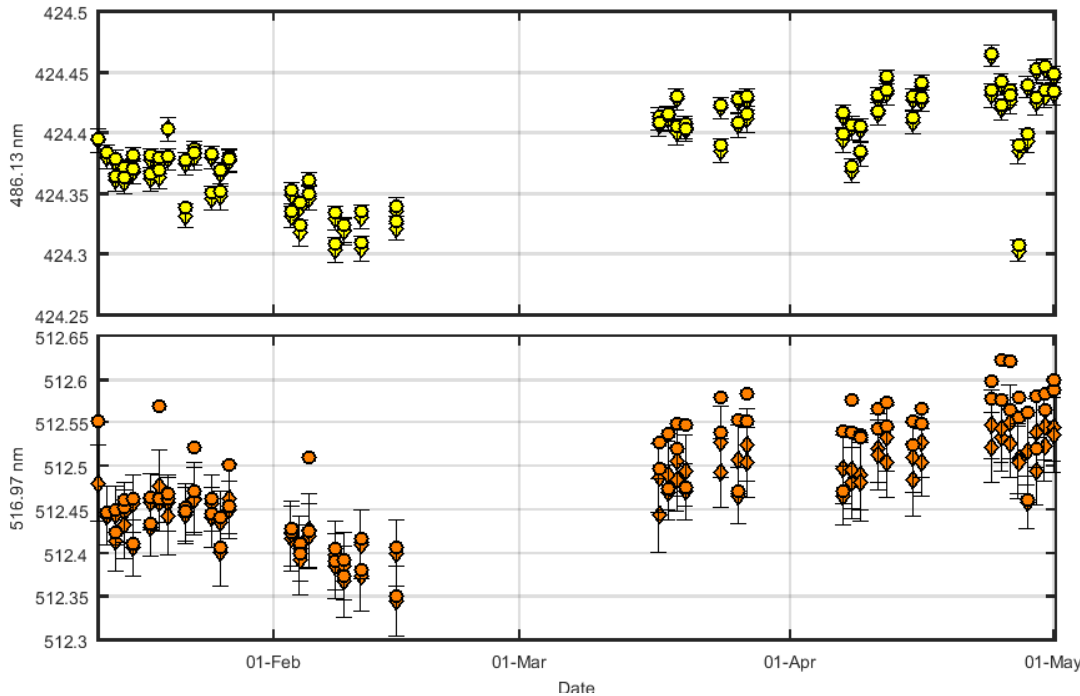


- We have had 4 deployments of the Blue spectrometer
 - M261, August 2016 – February 2017 (top arm sheared off)
 - M262, February 2017-August 2017 (mooring broke free)
 - M263, August 2017 – December 2017
 - M264, December 2017 – May 2018
- One, very short, deployment of the red/blue spectrometer
 - M265, May 2018 – July 2018 (MOBY broke free)

These deployments have allowed us to test the stability of the spectrometer in real deployment situations, do experiments to test different operational situations, and work on the optimal data collection strategy

Spectral Stability, Blue spectrograph

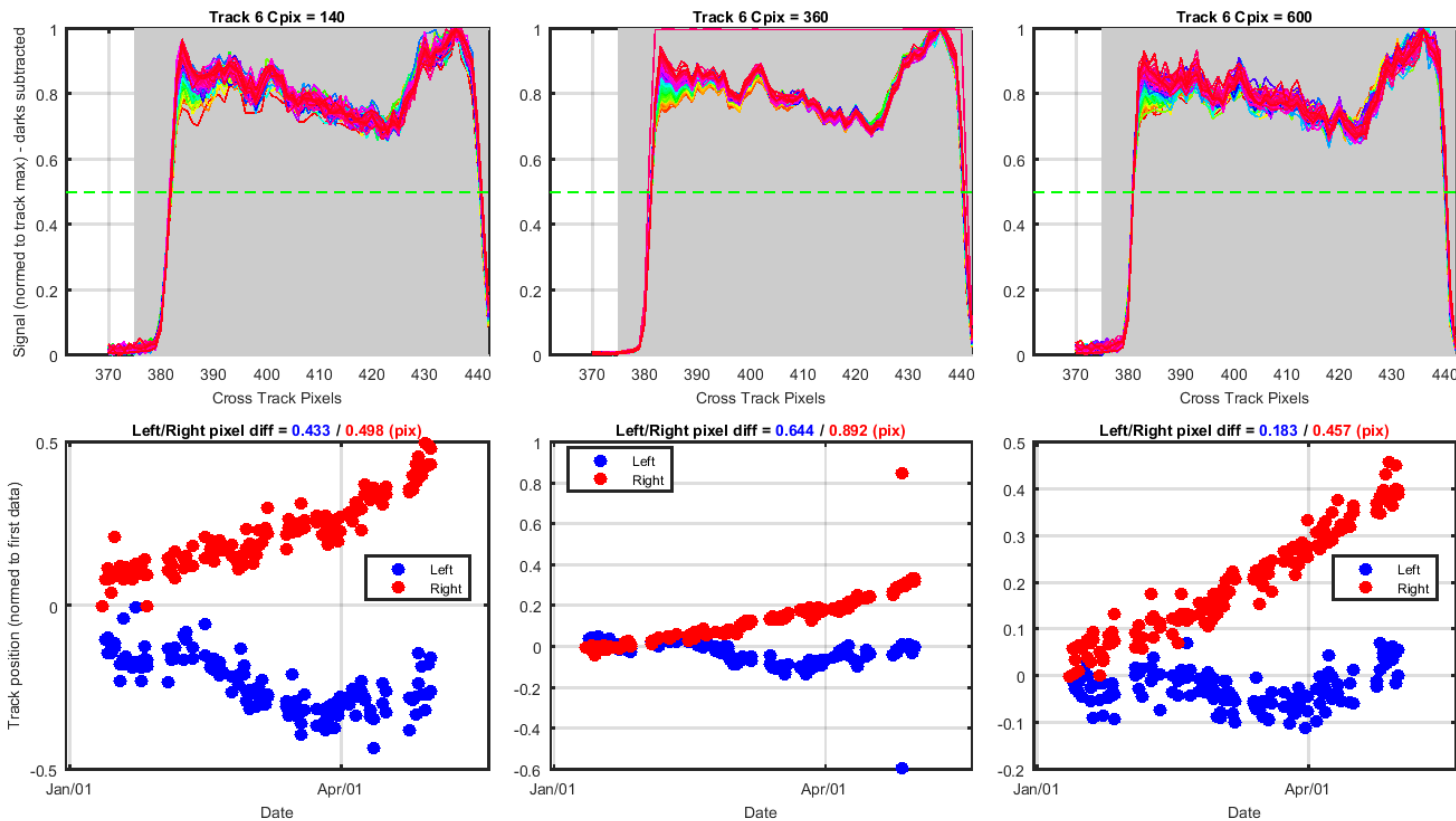
We can measure the Spectral stability through the deployment by measuring the Fraunhofer lines in each image.



A good deployment, typical of 3 out of the 4 deployments. The drift is within 0.2 of a pixel over the 4 month deployment, approximately 0.07 nm. This is probably close to the accuracy of our automated procedure to estimate the center of the gaussian fit to the Fraunhofer line.

In the one bad deployment, the drift was 1 nm, over the 6 month deployment but this deployment was problematic as MOBY was deployed twice (the break in data) because the mooring failed.

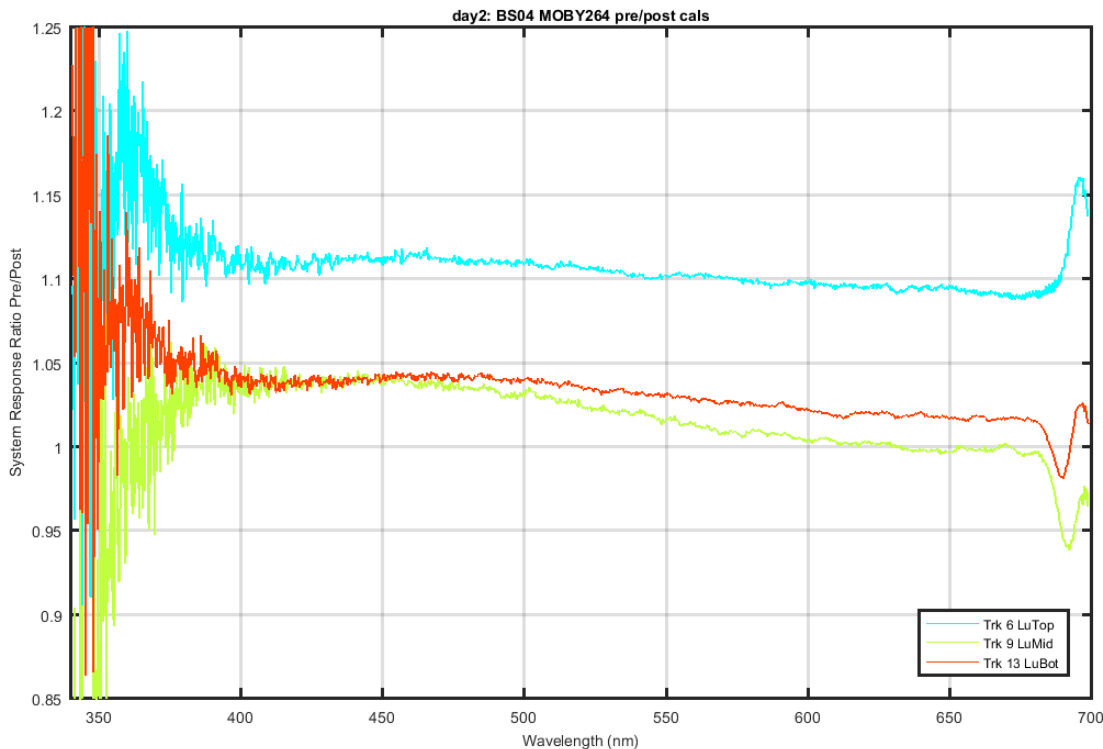
Track location stability



Typical result (this one for M264) for 3 out of 4 of the deployments. Less than half a pixel shift in track location. Very small change in track width (showing worse case). We oversample track by 3 pixels, so this shift not important. Track location shifts, and spectral shifts are important as each camera pixel is not the same, so cannot just move calibration to match shift. The one anomalous case, M262, shifted around 6 pixels during deployment.

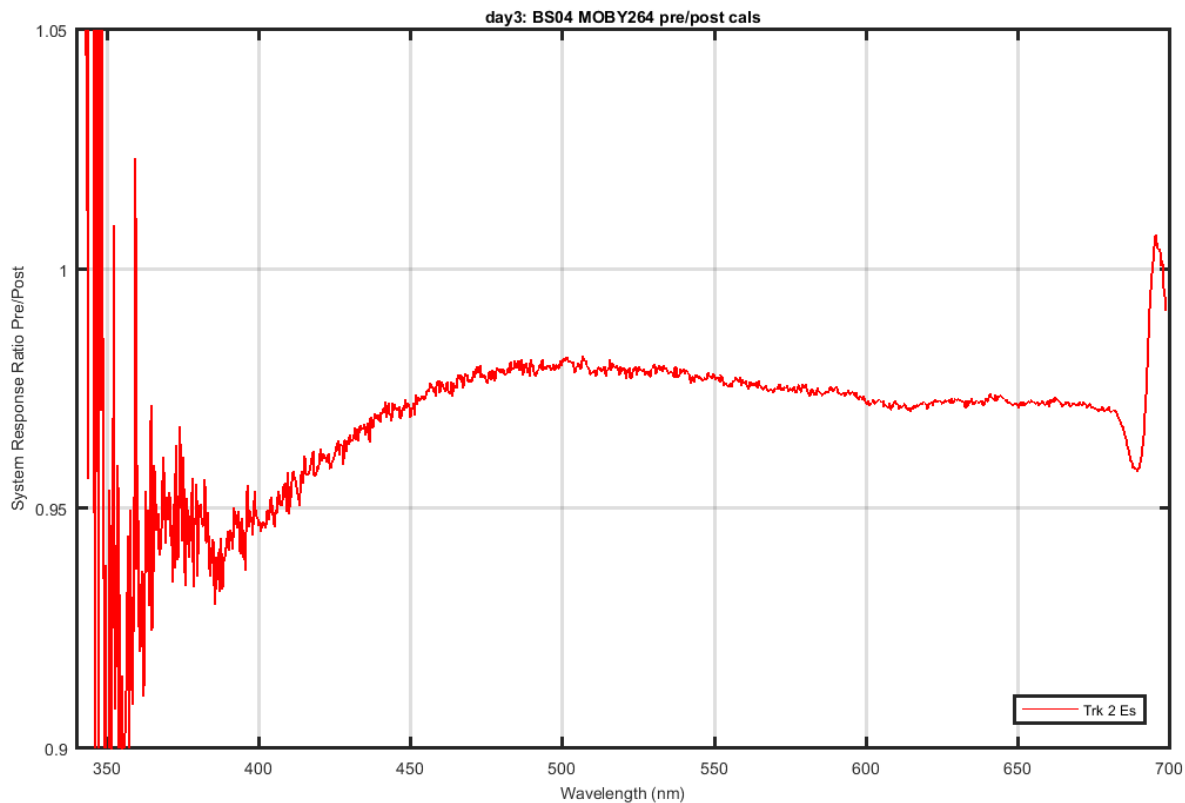
Radiometric Stability

- Several ways to look at this, but still a work in progress. We will concentrate on M264, most recent Blue spec deployment
- First way, Pre/post calibration data.



Lu arms Pre/post deployment. Mid and bottom arms are reasonable, however top arm shifted by 10% over deployment it appears from this data.

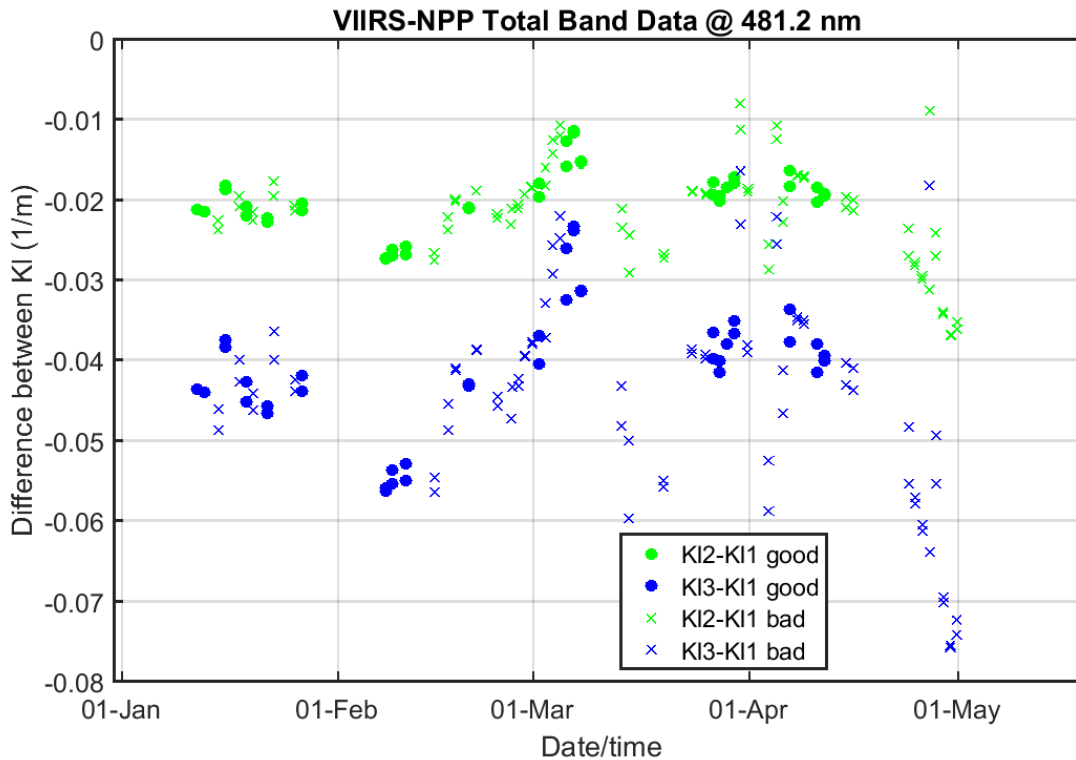
Pre/Post deployment Es



Pre/post deployment calibrations reasonably consistent here. Note that in the pre deployment, the instrument was calibrated, the spectrometer removed (separated from fibers), then reinstalled and no additional calibration was done....so this is quite good.

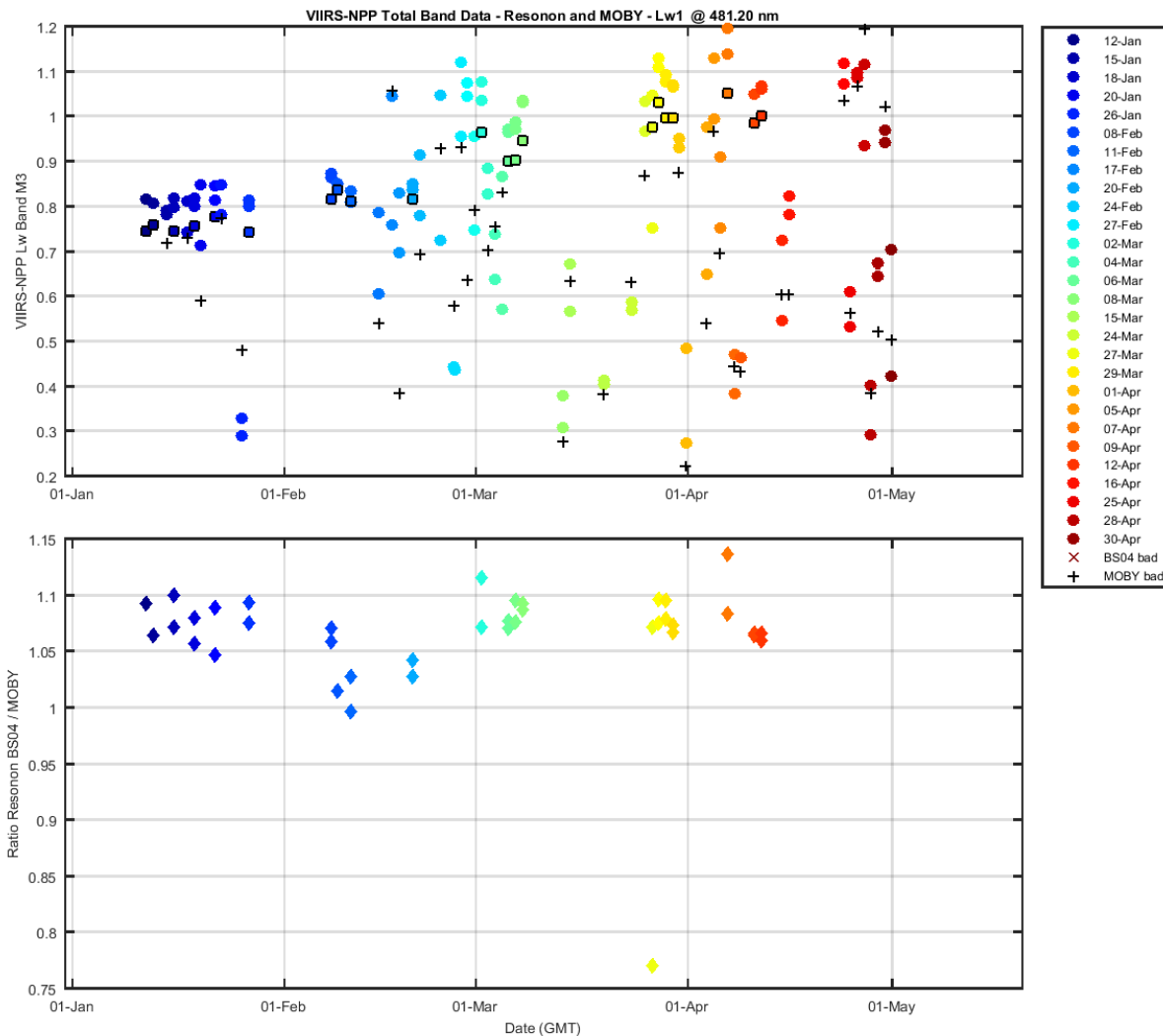
Radiometric stability during deployment

This can be checked with the different KL's to look at different arm pair comparisons:



Relative stability can be monitored by looking at KL from different arm pairs. Focusing on the good data (circles) it appears the relative differences are stable over the deployment. Interestingly, the KL's can be made to match up very well with an 8% change to the LuMid arm measurement (not the one that was different pre/post calibration).

Radiometric stability during deployment

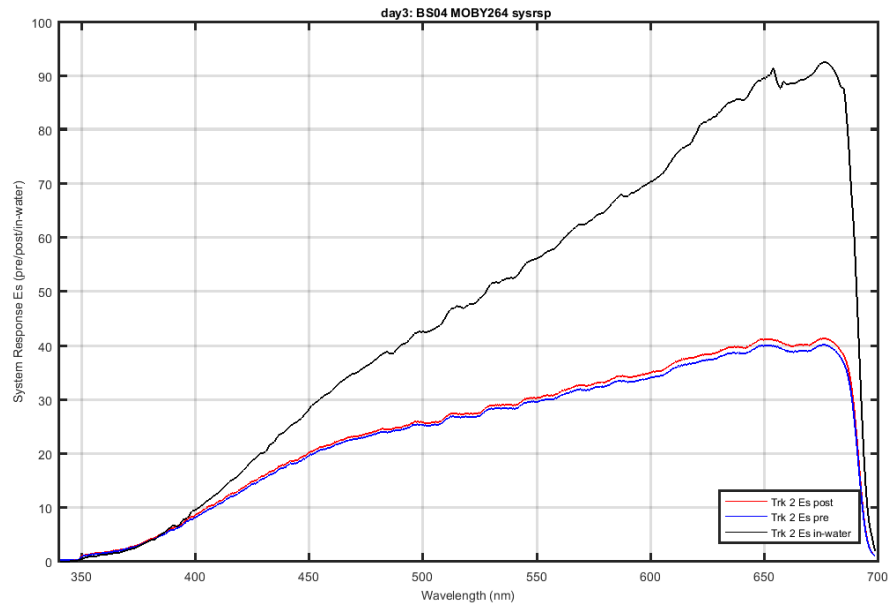


- We also can compare with MOBY measurements, which are close, but not simultaneous (10-20 minutes different). Stable comparison for Lw1 (top arm Lu with Kltop-mid arm), but strange as contradicts pre/post calibration comparison.

Radiometric stability

- Compare Es measurements with MOBY....while pre/post calibrations are good, measurements in the field are significantly different.

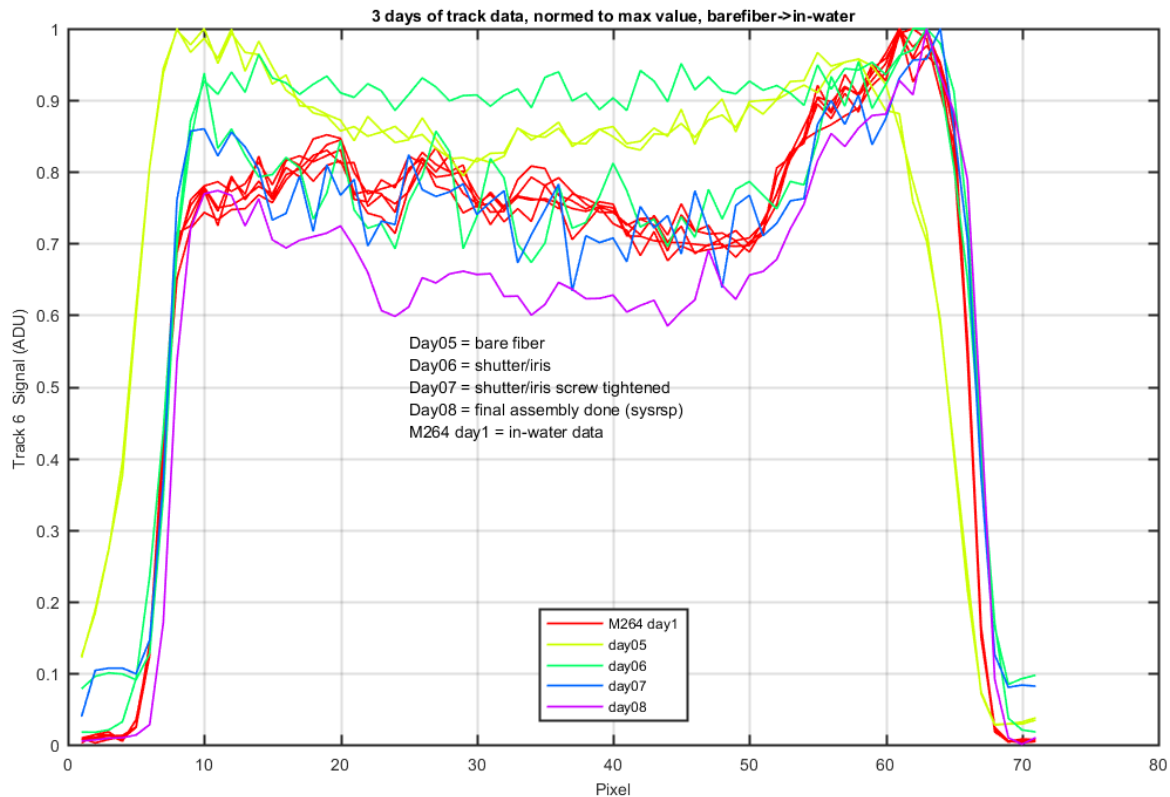
Es response derived from vicarious calibration with MOBY Es significantly different from lab calibration??



Here suspicion is on small apertures used to “slow down” Es to make better balance with Lu measurements, but still in testing phase.

Main suspect for radiometric issues are collimators used in system to go in/out of window barriers.

Saddle shapes vary during instrument assembly, as collimators are added. Currently working with Resonon to work towards a better collimator optical design.



Have performed various tests with the data. Two will be described here

- 100 point test to see how averaging should be done on data.
- Test to see whether cross track light can be corrected.
- Other analysis have been
 - into effect of small wavelength variations between channels on KL.
 - What happens when track or spectra response drifts
 - Etc...

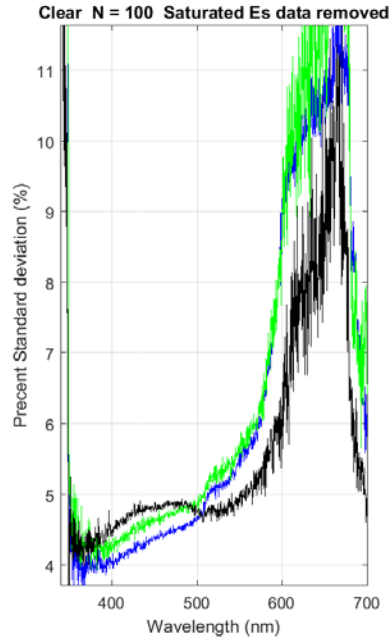
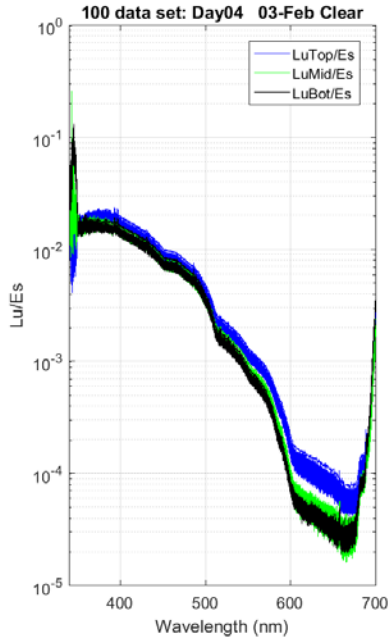
Data Acquisition test, how to average?

Rapidly take 100 data sets sequentially, experiment run for 60 days, short integration times (2s), 5 s between each set. Taken during M264.

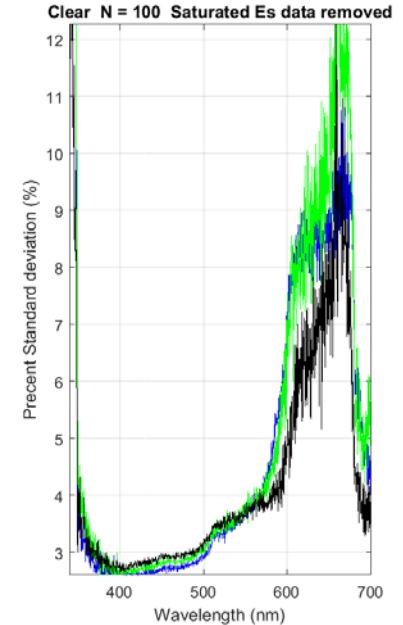
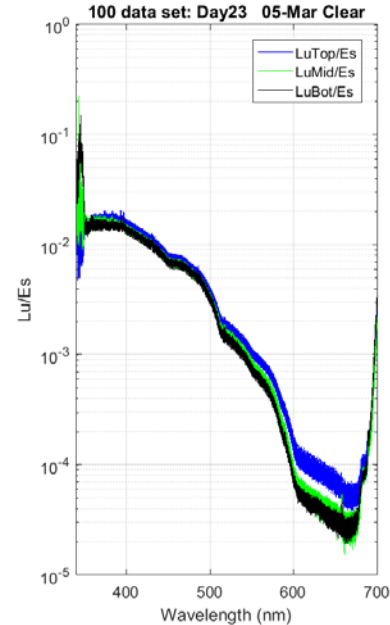
Pick two days to focus on, typical high wind (11 m/s) and low wind (1.7 m/s).

First % standard deviation over the 100 pt. data sets. Higher wind, lower % standard deviation. Light field more “mixed up”.

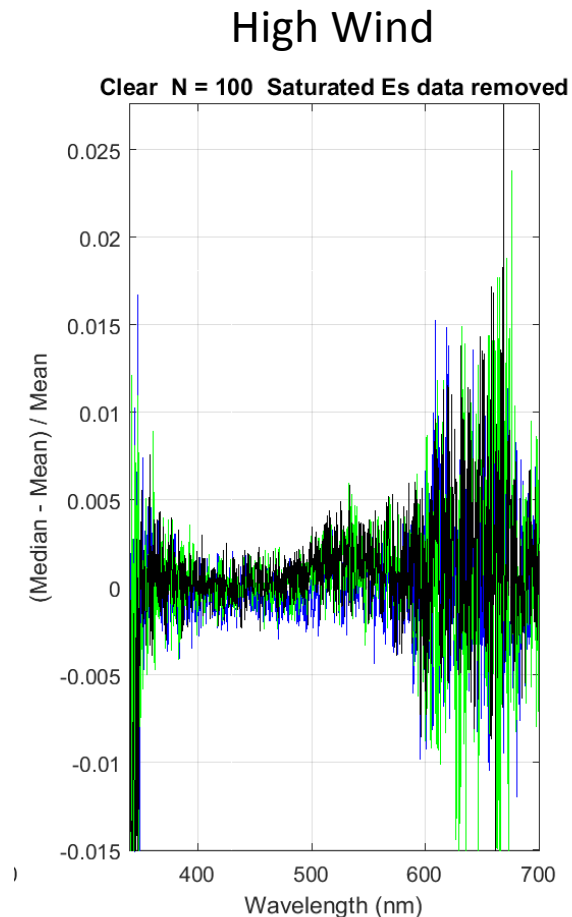
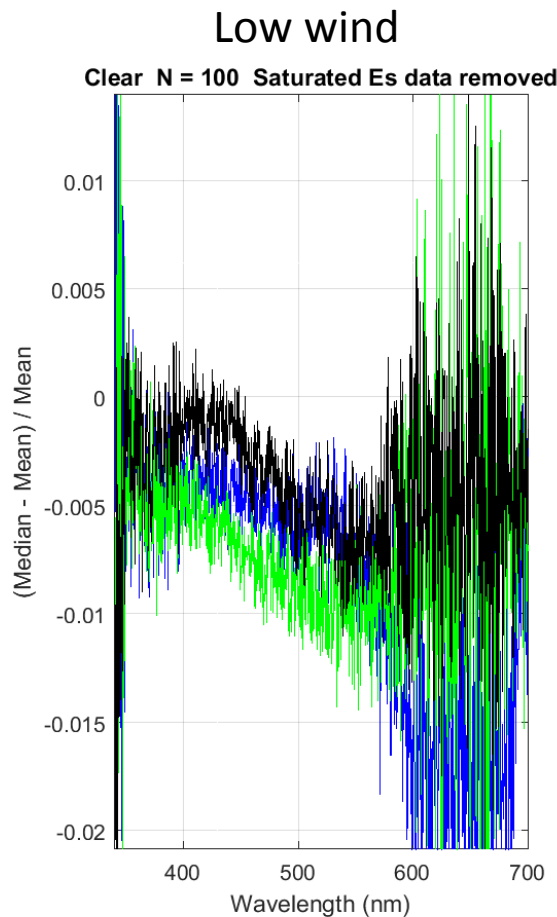
Low wind



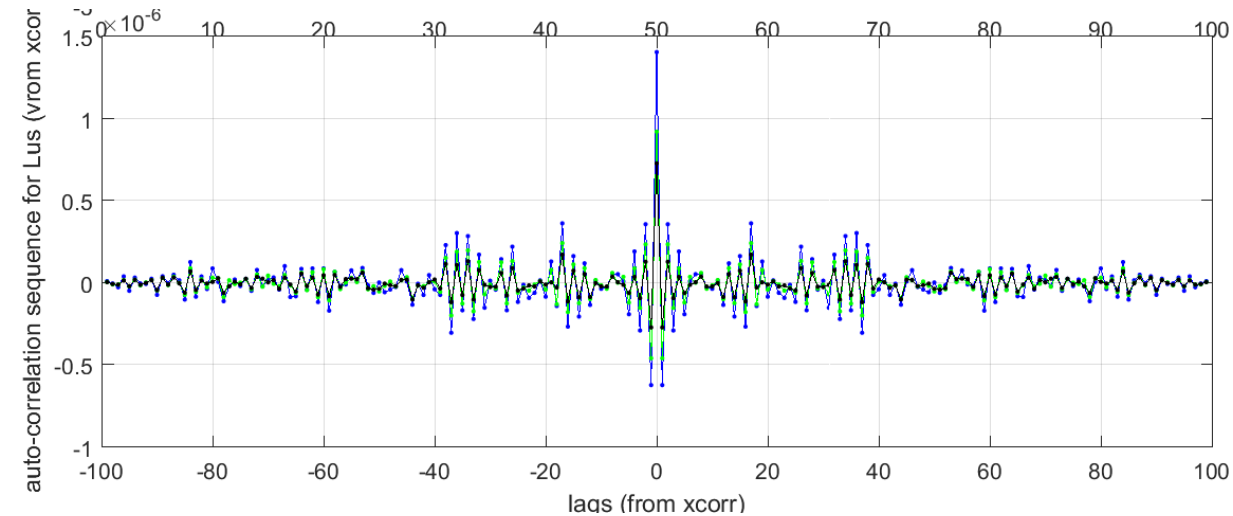
High wind



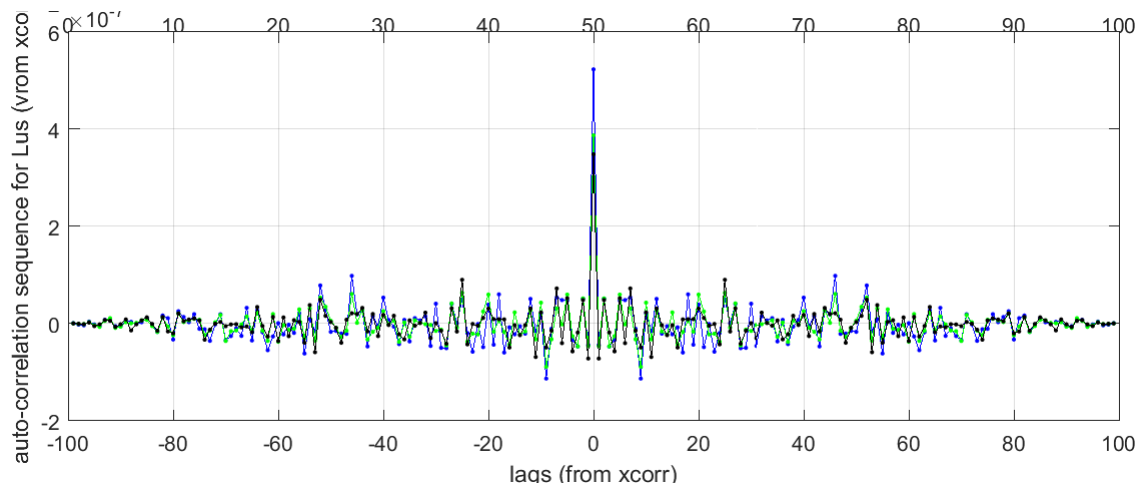
100 pt. set, is mean and median same?
Definitely for high wind, not quite as
good for low wind (but close).



What time frame do you have to average over?



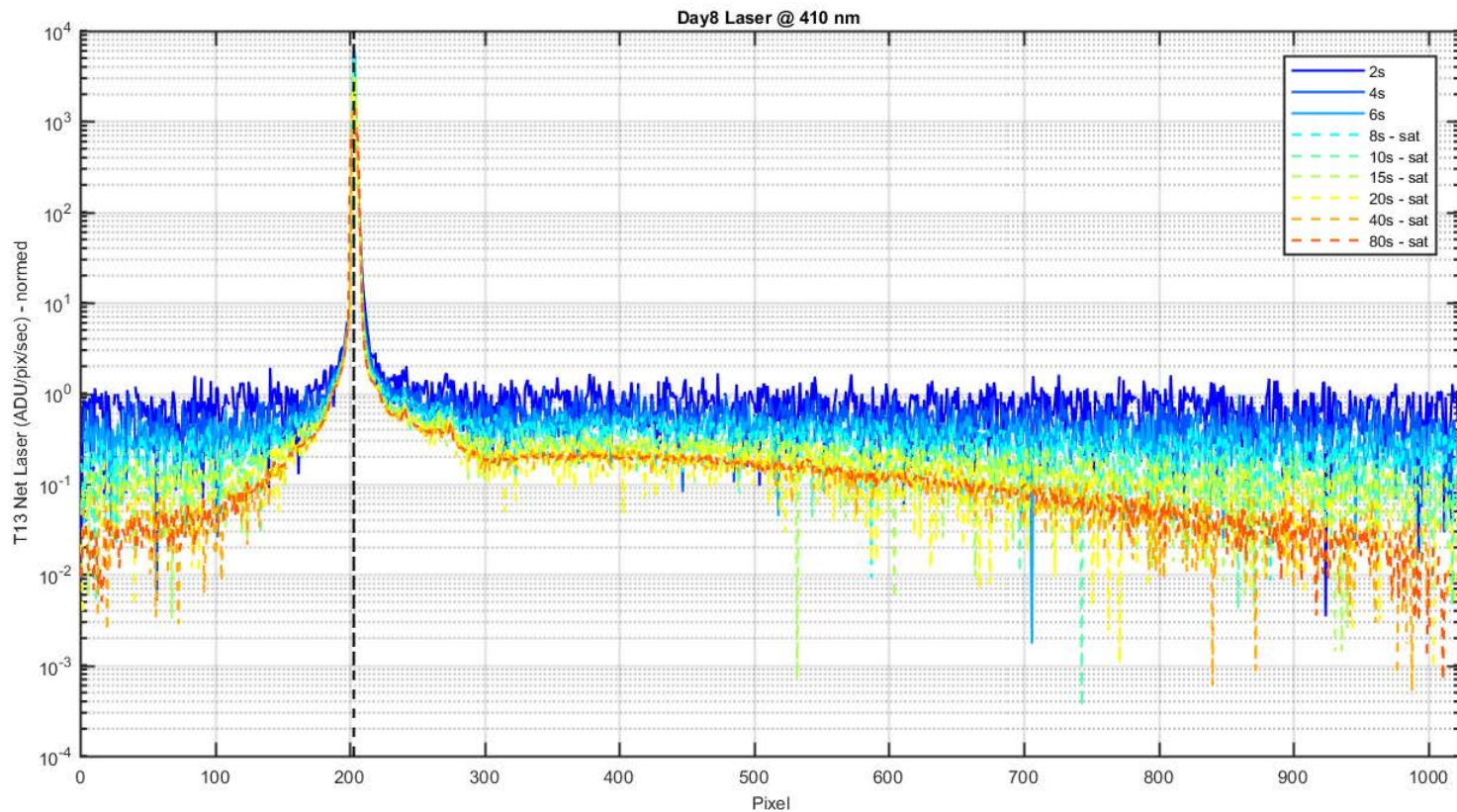
Low wind, auto correlation peaks at about 90 seconds.



High wind, no real peaks in the auto-correlation.

Stray light and Cross track

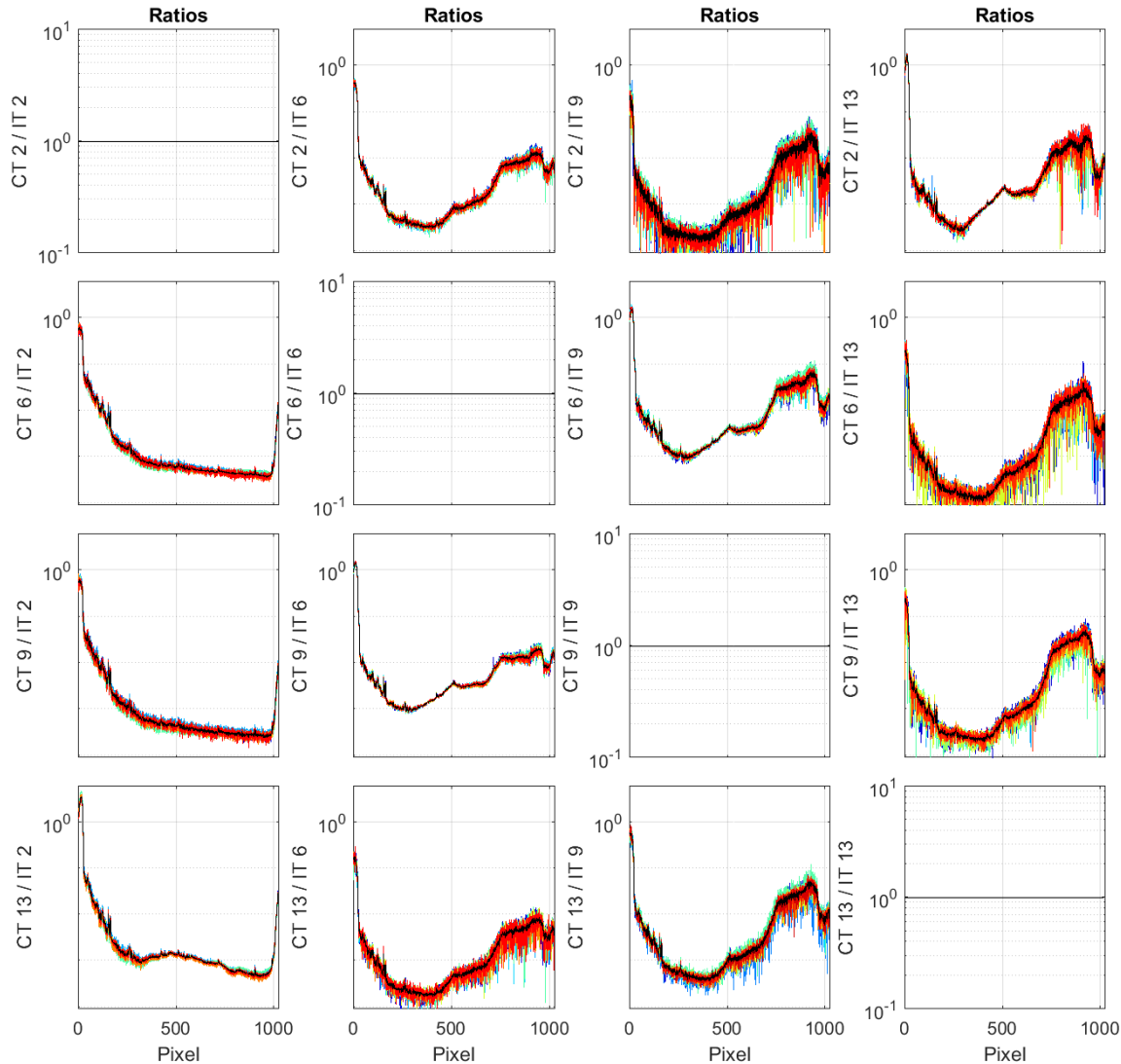
- The spectral stray light in the system is small (as we have said previously), but will have to be corrected for.



Stray light and Cross track

- Because we extended the low end of the spectrometer to 350 nm to accommodate PACE, we also have to correct for 2nd order light through the spectrometer, as shown earlier.
- Once these are corrected (or simultaneously) we should also correct for cross track light caused when using the system in simultaneous measurement mode.

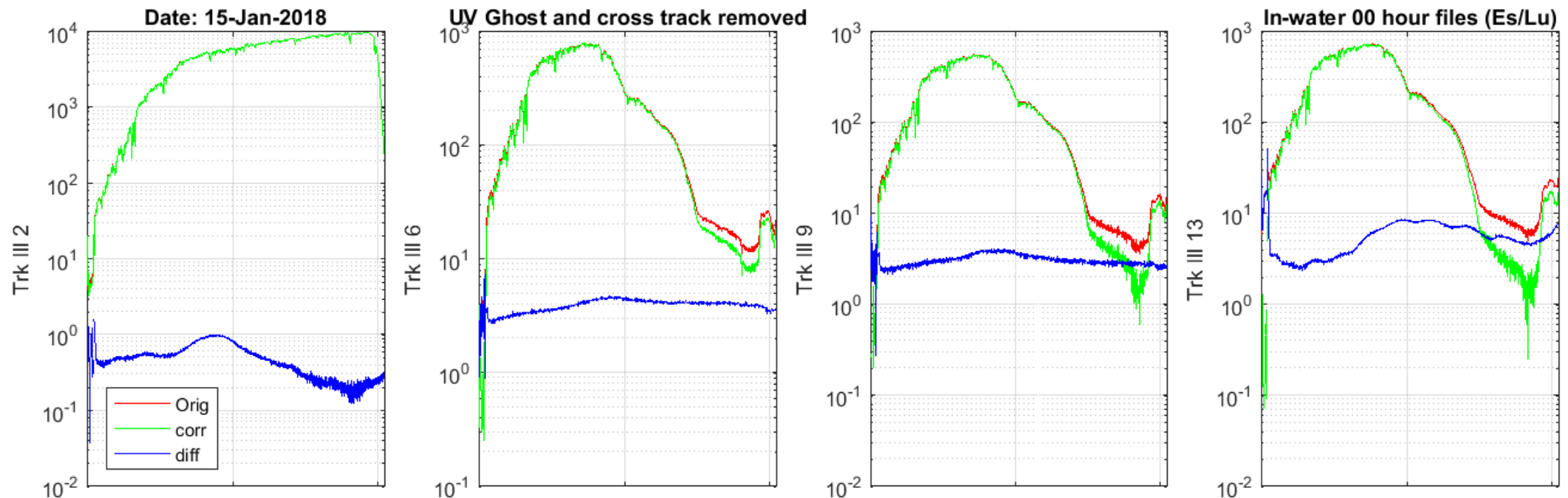
Cross Track correction



- The cross track signal is not large. Below shows data we acquired in the field by turning on one track (say E_s) and measuring the signal in the other tracks. Below is the matrix formed. Horizontal pixel is wavelength. Y-axis is normalized counts. First column is illuminating track 2 and signal into tracks 2, 6, 9, and 13

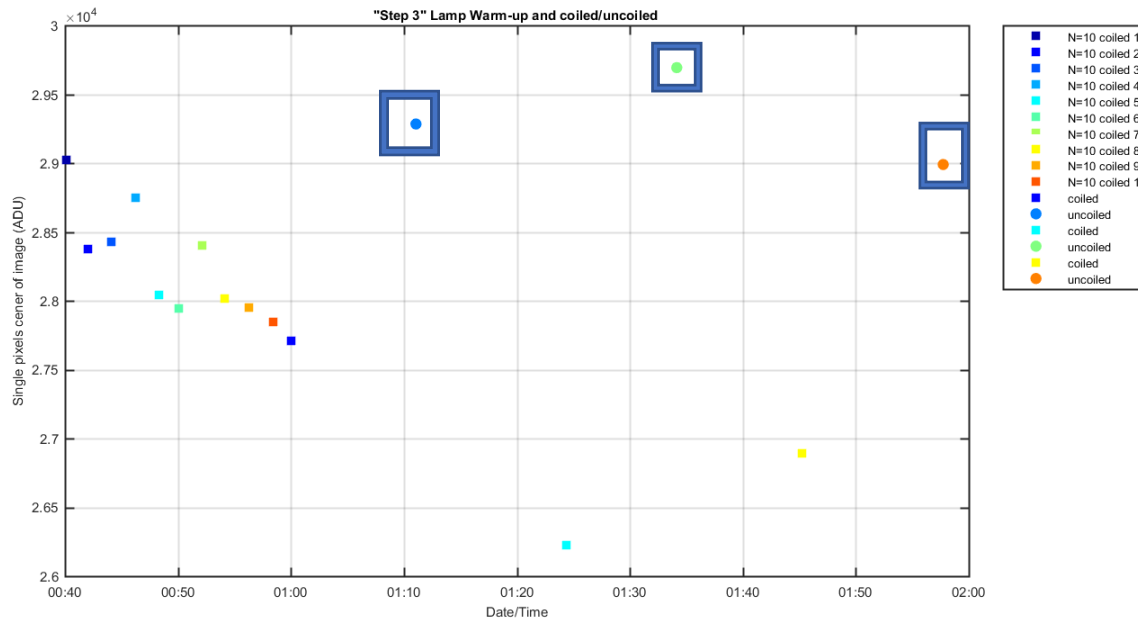
Cross Track

The matrix in the previous slide can be inverted to get the correction matrix. Below shows an example of applying this correction to a data set in M264. As the green graph is the corrected data, the blue is the difference between corrected and uncorrected. As can be seen, through most of the spectra it is irrelevant, but predominantly in the red wavelengths it can be a large effect. Fortunately MOBY-Net also has a red spectrometer which overlaps with this blue spectrometer to help verify these corrections in the overlap region.



One other test, relevant to MOBY-Net

- We will need to coil/uncoil the fiber for MOBY-Net during shipping. A quick test was done to see how this would work:



The three boxed points are when the fiber has been uncoiled after being coiled up. While there were big changes between being coiled and uncoiled, the differences between the extreme of these three points are less than 2%.

MOBY NET Stability System

Carol Johnson, Tom Larason, Stephanie Flora, Ken Voss



How did we do with our goals.

Target	Achieved
Spectral range 350-900 nm	350-900 nm
3nm resolution	Predicted and achieved 1nm FWHM, 0.3-0.4 nm spectral spacing
Radiometric uncertainty <4% blue, 5% red	Not yet, good comparisons with MOBY at 5-10% but other problems
Stability 1% per deployment	Not yet
Capability of Autonomous field operation	Yes, controller has been working for many years.
Capable of maintaining calibration through 3-5 year period	Planned on 6-12 month redeployments, never 3-5 years
Built for sustainability and field maintained	As modular as possible. System rugged with some redundancy and features to limit damage
Laboratory and field characterized with NIST	Have been doing this consistently
Fully autonomously deliver data to NASA	Never thought this was correct. Should be delivered with short latency (days) to allow QC.

Stability System– Repeatability & Reproducibility

- Independent of Lu or Es foreoptic – COV's about the same
- Short term repeatability (over ≈ 2 min) is comparable to the long term repeatability, as long as the only thing you do is turn the CAS off and on, flex the fiber bundle, and, in the case of Lu, realign the optic about the vertical axis
- The NPR is a bright and stable source, and we get comparable values for repeatability of SQM – says SQM is stable and CAS has adequate SNR
- Reproducibility (“changed conditions of measurement”) is about 4x the repeatability using this COV method (probably an underestimate)
- The reproducibility changes are spectral
- The SQM internal monitor photodiodes are not as repeatable as the CAS Lu

TRL table

Portion of project	TRL in	TRL goal	TRL achieved	Explanation
Control system	2	7	7	Controllers operating in field for several years
MOBY Hull	2	7	5-7	2 hulls have been built, they have not been operated in the field
Optical System	2	7	5-7	The systems have been operated in the field. We still have issues to resolve
Stability System	5	6	6	The systems have been operated in the field, but not with MOBY-Net optics

SQM Paths Forward

- Keep or start new?
 - Pros: Stable, easy to use, now have nice DAQ and analysis programs
 - Cons: heavy, large, old internal processors, little UV, current diffuser results in non uniformity, lamps very difficult to replace (in series, so one lamp of eight is failure), not a good spectral match to Lw, monitor detectors aimed the wrong way, not a big seller at YES
 - At a minimum, replace bead-blasted quartz diffuser with Diffusil product
- If new, start from scratch or modify a commercial source?
 - Commercially available (e.g. SpectralLED from Gamma Scientific)
 - Will require modifications for stability source aka SQMs, both software and hardware
 - Vendor does not support all the LEDs we'd want (380 nm is lowest advertised)
 - Spectra not smooth
 - Custom source
 - Combination of temperature stabilized LEDs and TQH lamps
 - Could mate the CAS directly to the source
 - We'd have control of DAQ programs

CAS Paths Forward

- Keep or consider other options?
 - Pros: UV option available, compact, CCD detector, wide dynamic range, very repeatable under “static” conditions, fiber coupled
 - Cons: reproducibility needs x2 improvement
 - At a minimum, track down source of variability (thermal, Lu head design, ?)
 - For TRL 7 step, may have to implement thermal enclosure for CAS
- Options other than CAS
 - Commercially available
 - Fiber coupled spectrographs (ASD, SEI,...)
 - Lu or Es hyperspectral instruments (SeaBird, Bio Spherical, RAMSES,...)
 - Custom radiometer(s)
 - Filter radiometers aka SLM-II
 - Custom spectrographs (e.g. a MOBY NET copy or prototype)
 - Either would require a similar investment in software, testing, characterization, and time series

Follow On Activities

- SQM
 - Replace diffuser and characterize
 - Fabricate adaptor for MOBY NET foreoptics (Es/d & Lu; attached or free from the MOBY frame)
- CAS
 - Re write processing software to be compatible with MLML Mldbse structure
 - Perform missing characterizations (stray light, ambient temperature, integration time, linearity, internal filter transmittances)
 - Derive necessary correction functions
 - Investigate with vendor getting access to actual dark counts
 - Re process data, perform correlation investigations, write paper
 - Implement temperature controlled housing if necessary

Recommendations

- BOUSSOLE experience
 - They had an SQM but stopped using it because the time invested did not match the knowledge they felt they acquired
- So,
 - Before investing a lot in a new SQM or alternative to the CAS, we should
 - Keep existing SQM but improve the uniformity
 - Keep existing CAS but attack the reproducibility problem
 - Deploy MOBY NET and use the Stability System as planned, evaluate reproducibility
 - If the reproducibility is greater than $\approx 1\%$
 - Motivation to use stability system may be impacted

What is the next stage for rest of system

- Improve the radiometric stability, we believe the key is the different collimators in the system but also maybe related to the small apertures we are using to slow the system down.
- Do an experiment where we calibrate a system in Hawaii, ship to Miami and/or NIST, set up on “mock” buoy, and take off and send back to Hawaii for recalibration...running stability system along the path. At this point save money and do not ship a buoy hull, so experiment would be measurements on land.
- Find a location where we can work with a group to install a mooring and the buoy and start a remote site. Examples might be:
 - Puerto Rico if infrastructure is there, and suitable “secure” site could be found. Shipping would be relatively easy (customs free).
 - Australia, David Antoine has experience in these types of programs.
 - European site? Eumetsat currently has two groups working on developing cal/val site. One is the Boussole group proposing a reworked (by CIMEL) optical system, the other is a group focused on using a MOBY-Net system, a possible location for this system is Lampedusa, but two other possible European sites will be investigated

Not NASA's issue, but other operational issues during this period

- Tether was cut 3 times (8 times total in 20 years)
- Mooring broke free...first time ever
- Top arm broken off (has happened one other time in 20 years)
- Boat hits top arm but doesn't break it, (happened twice before in 20 years).

Last 4 years have been anomalous in terms of operational distractions.