Describing cross track issues with the BS data by Stephanie Flora
04 Apr 2018

The purpose of this doc is the explain the cross track straylight and UV ghosting issues that need to be solved on the BS data sets.

First a little history. The MOS spectrograph has a straylight problem. But because all the sensors use the same area on one spectrograph the straylight problem is only in the wavelength direction. And we can remove it using laser data to calculate a correction matrix.

In the BS and RS the one spectrograph is broken up into 14 tracks. Which are the equivalent of 14 spectrographs. Each with potentially it's own wavelength calibration, int time calibration, system response, straylight, cross track and UV ghost correction (and probably other stuff like thermal correction). The hope is that the Lus will be able to use one wavelength cal, etc, but this may not be the case for all the corrections.

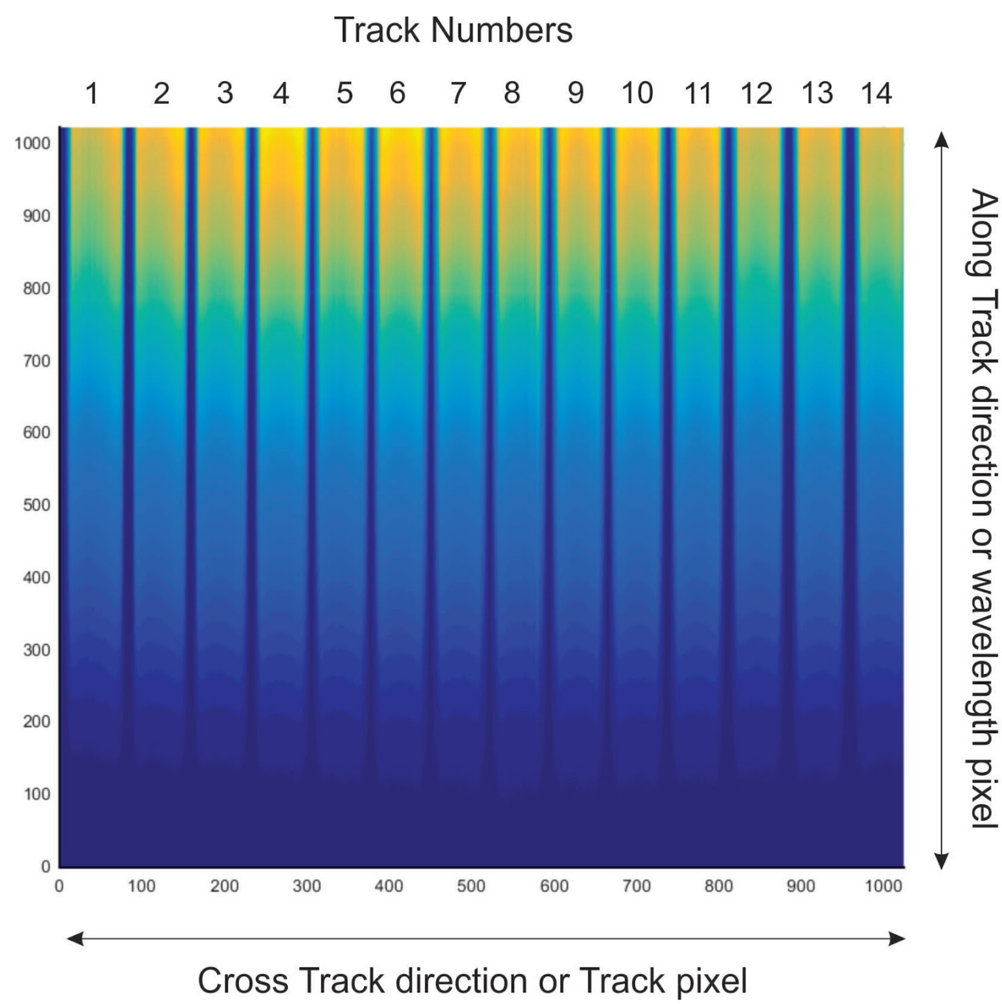

FIgure 1. 14 tracks on the BS resonon spectrograph

Figure 1 shows the 14 tracks available, but we will only use 7 tracks for in-water data and for the current testing (MOBY264) we have been only using 4 tracks (Es, LuTop, LuMid and LuBot). For this document I will be using the MOBY264 BS04 deployment data as the example. So the track definitions will follow that deployments definitions. Also BS04's camera does not have the ½ degree wedged windows and therefore the UV ghosting issue. So that is also included in this document.

Track 2 = Es
Track 6 = LuTop
Track 9 = LuMid
Track 13 = LuBot

I should note that this deployments Es and Lu are not well balanced. So the Es data at the correct level but the Lu's are 10 times lower. For a more balanced system the Lu's might "throw" more light on Es and it's fellow Lu's than they are in this deployment.

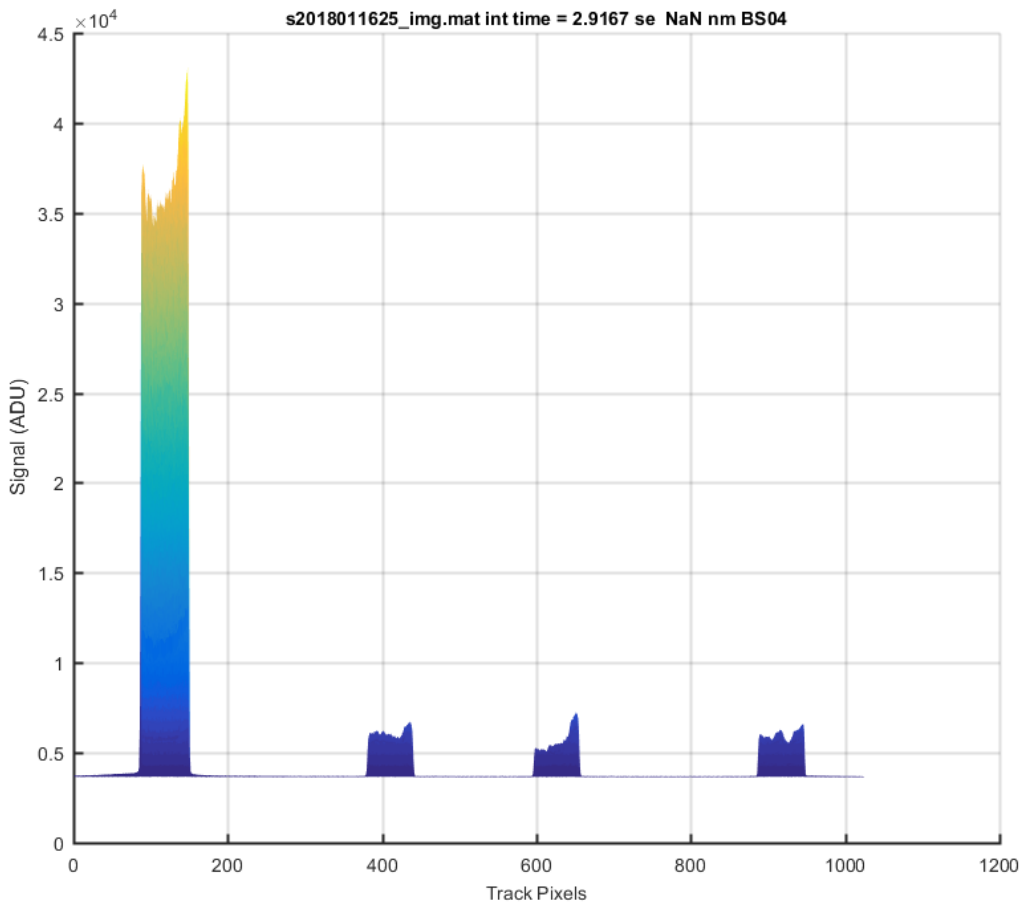

Figure 2. You can see the balancing issue here. The Es is much higher than the 3 Lu's

To get to the website of the MOBY264 data click http://data.moby.mlml.calstate.edu/mobyrefresh/timeseries/characterizations/inital_testing/intial_html.html. Then click the MOBY264 - BS04 link on the blue navigation menu on the left.

To get to the website of the MOBY264 system response data go to the same link above then click L267 - BS04

UV ghosting on mirrored tracks

We first noticed this feature while comparing the in-water Lu data collected with and without Es.

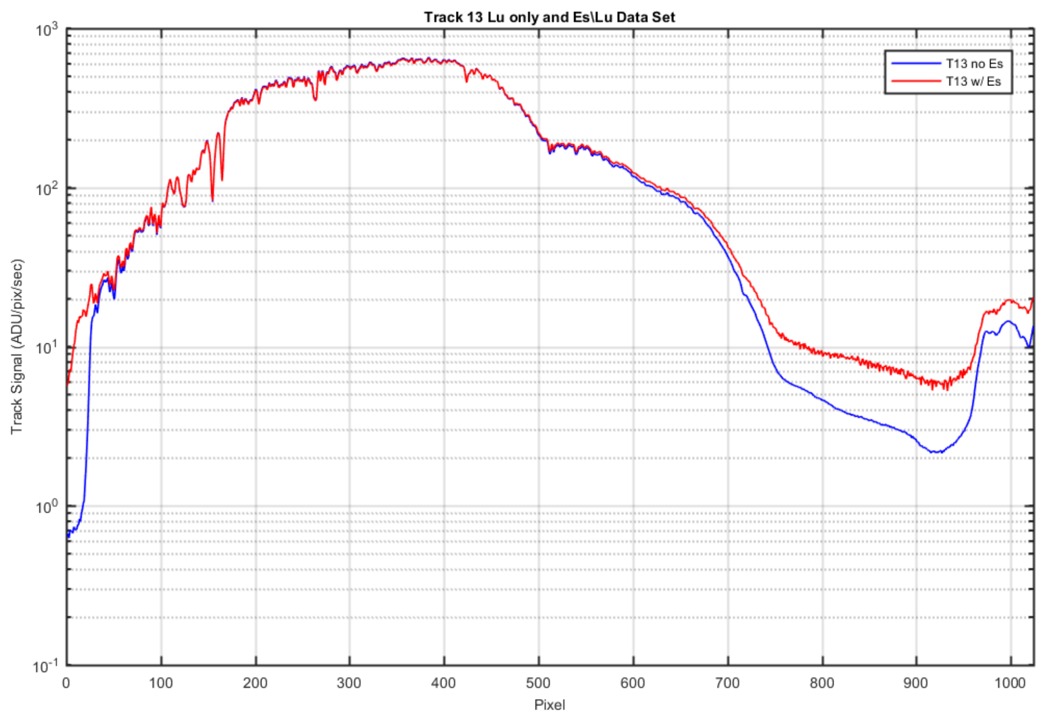

Figure 3. When Es is collected with the Lu data sets the LuBot UV data is much higher than when Es is not collected.

Looking back a older data sets is turns out that all the BS and RS spectrographs without the ½ degree wedged mirror was this UV ghost feature. This feature is only on mirrored tracks. So Track 1 effects Track 14, 14 effect 1, 2 effects 13, 13 effects 2, and 3 effects 12, etc. For the MOBY264 data the interactions are...

Track 2 / Es	effects	Track 13 LuBot
Track 6 / LuTop	effects	Track 9/ LuMid
Track 9 / LuMid	effects	Track 6/ LuTop
Track 13 / LuBot	effects	Track 2/ Es

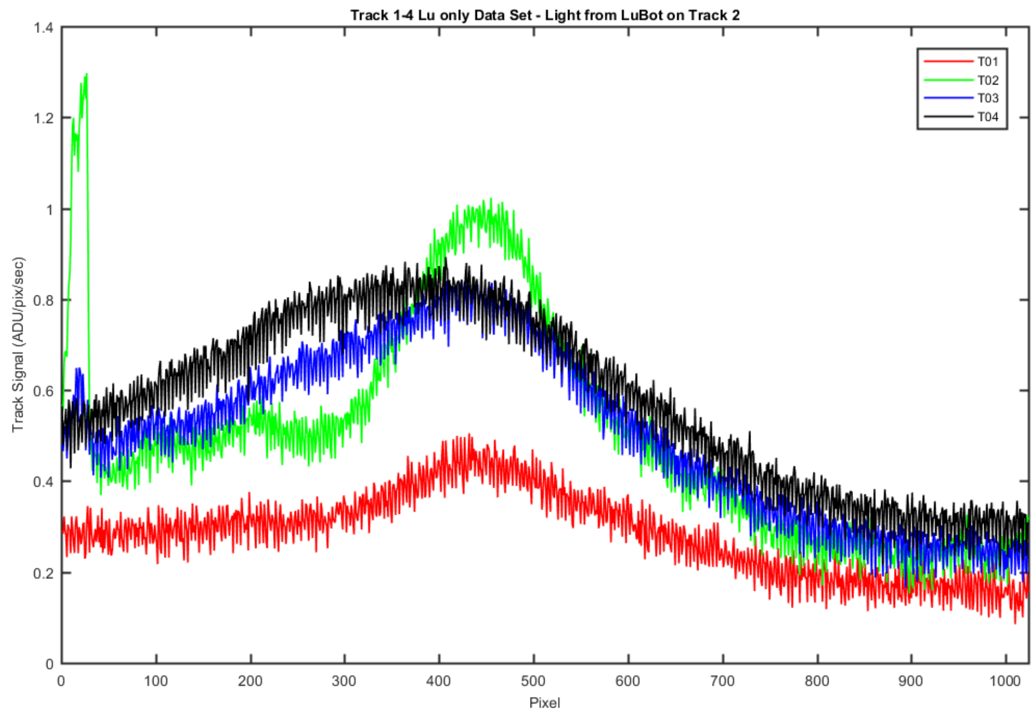

Figure 4. For the in-water Lus when no Es are collected you can see the large UV bump that LuBot (Track 13) "throws" onto Es (Track 2) the green line. When Es and Lus are collected together, then Es "throws" UV ghosts onto LuBot and LuBot "throws" UV ghosts onto Es. So they cross contaminate each other. The other tracks (1, 3 and 4) are the regular cross track. Except track 3 which has a little of the UV ghost on it too. See the small UV spike in the blue line.

To sort this out better Ken asked Art to collected some single track in-water data during MOBY264 at the 22/23 hour times.   Data collection started on 2 Feb and ended on 28 Feb. The data and pages are shown on the MOBY264 - BS04 webpages in the green tables (page numbers 400+).

The data were collected as ...

3 dark, 3 background, 5 light, 3 background, 3 dark track 2 only
3 dark, 3 background, 5 light, 3 background, 3 dark track 6 only
3 dark, 3 background, 5 light, 3 background, 3 dark track 9 only
3 dark, 3 background, 5 light, 3 background, 3 dark track 13 only

In the figure below you can see the characteristic shape of the UV ghost. It had a large bump in the UV, pixel 0-30 and another wider bump in the middle of the array. This bump is taller and pointier than the regular cross track stray light (we will discussion soon). Note also that for the

Tracks 6 and 9 the UV ghost data are also contaminated by regular cross track stray light. So for those tracks there are two different sources of contamination. This is because 6 and 9 are close enough to each other to have regular cross track light problems in addition to being mirrored.

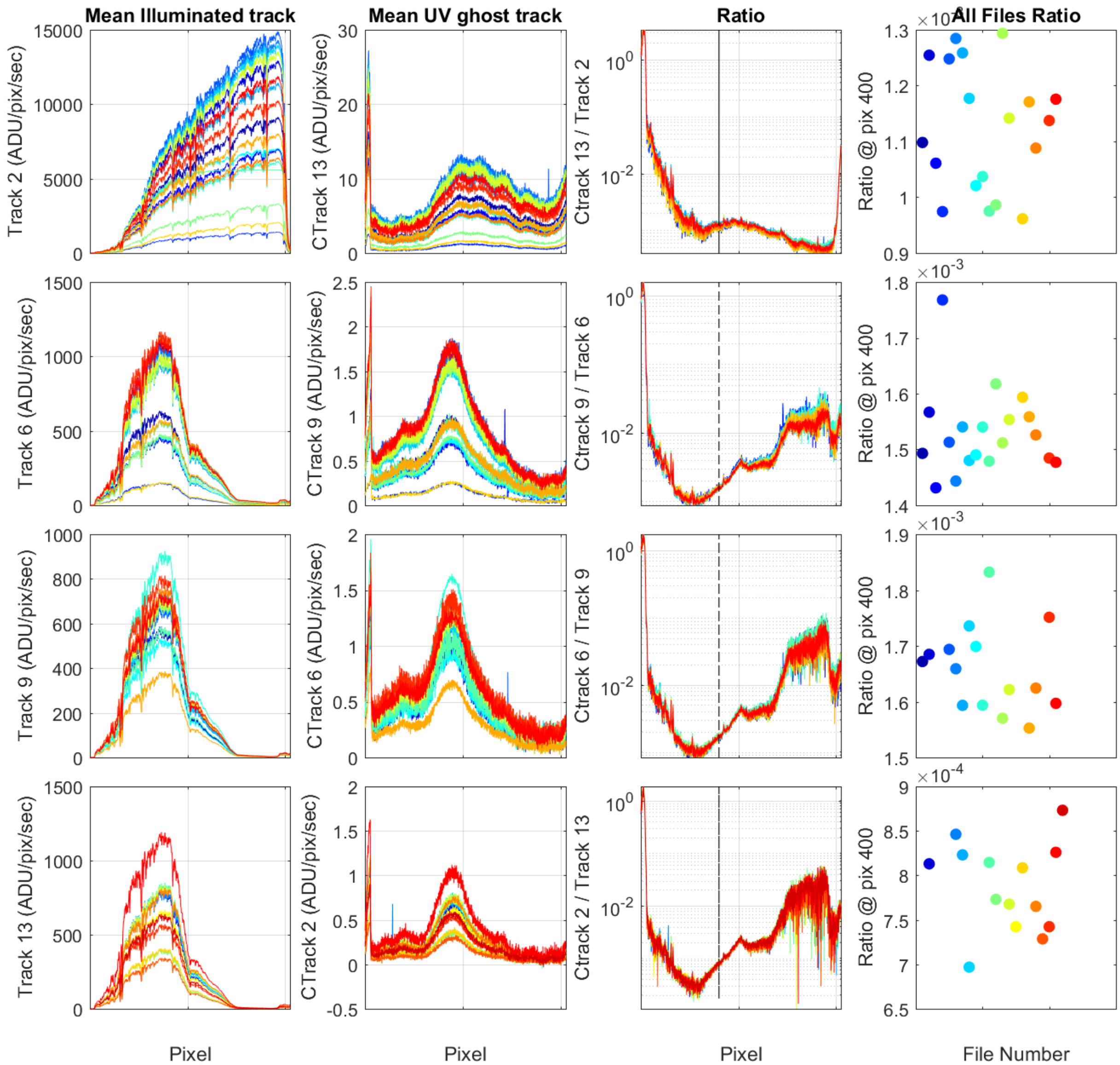

Figure 5. All the in-water single track data sets, the UV ghosted track and the ratio of UV ghosted track / illuminated track.

Row 1 is shows the ghosting of Track 2 (Es) onto 13 (LuBot).
Row 2 is shows the ghosting of Track 6 (LuTop) onto 9 (LuMid).
Row 3 is shows the ghosting of Track 9 (LuMid) onto 6 (LuTop).
Row 4 is shows the ghosting of Track 13 (LuBot) onto 2 (Es).

Remember each of the single track Es and Lu data sets where taken at different times (one track at a time). The first column shows the illuminated track. The second column is the signal from the illuminated track onto the mirrored/ghosted track. The third column is the ratio of the ghosted track over the illuminated track. This would be the shape you would multiply by the illuminated track in the normal in-water data to get the amount of light to subtract off from the ghosted track. The fourth column shows the value of the ratio at pixel 400 for all the files.

**Note that filter tests Mike ran showed that the light appearing on pixels 0-30 is not coming from the UV portion of the illuminated track (L276 - BS01). So Track 2 pixel 1 is not producing the UV ghost light on Track 13 pixel 1. I.E the UV ghosting light is not spectrally mirrored. This will be important later when we try and apply a correction.

Regular Crosstrack

With MOS we know what straylight is. But for MOS we only have to deal with straylight in the wavelength direction. For the BS the straylight is in the wavelength direction but also in the track direction. So the light from each track is not contained within its track. It spreads out in a delta shape from the illuminated track. I should also note that because we will be doing track definitions as “full” track where the edges of the tracks bump up again the edge of the next track the crosstrack levels will be higher than if we used the narrower track definitions. The figure below is from when we used the narrower definitions.

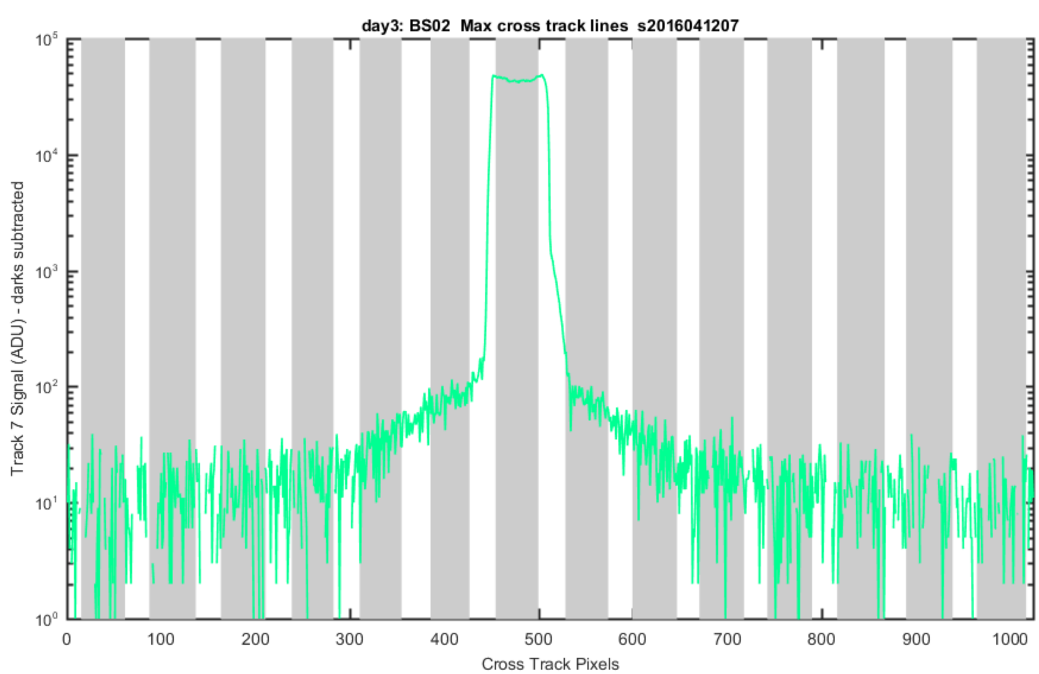

Figure 6. Hawaii-2016-01 BS02 page Num 4.01 showing the single track solar data. Does a good job of showing the cross track straylight delta shape. And many tracks the cross track straylight effects.

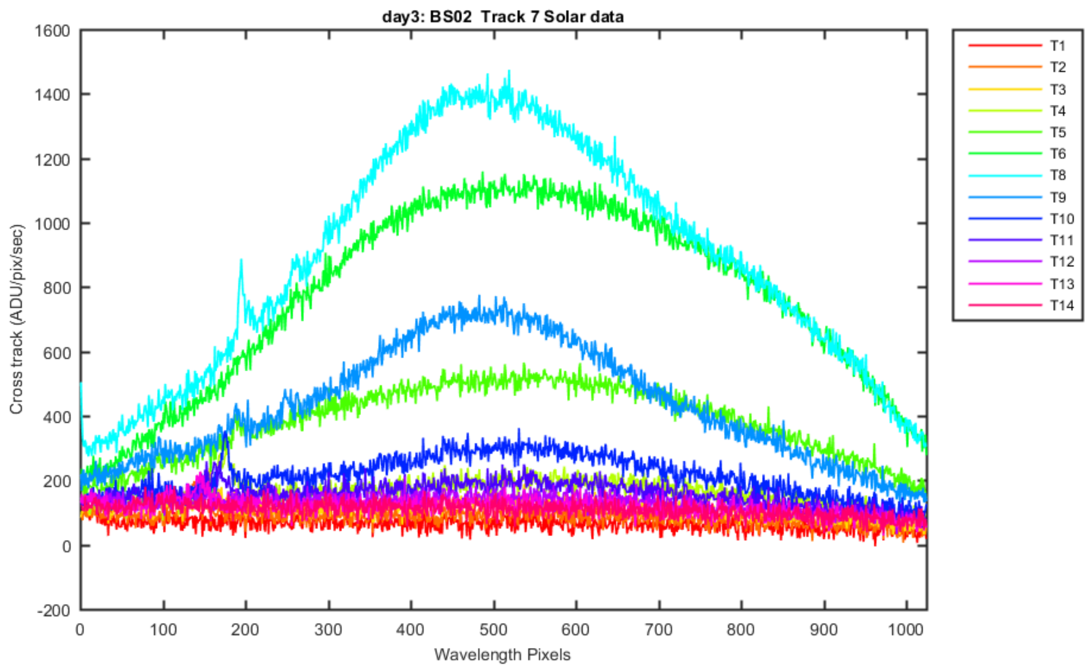

Figure 7. What the cross track straylight from track 7 looks like when binned into the tracks.

You can see in the cross track graph once you are 3 tracks away the light contamination is very small. These numbers will be higher for the wider “full” track definitions we will use in the future.

Note also that for this straylight pixel 1 of the illuminated track “throws” the most straylight onto the next closest track at pixel 1 but also on the other pixels around pixel 1 to a lesser degree. Imagine a delta shape and then spin it around to get a circle (see following figure 8). You can see that one pixel effects many other pixels in the neighboring tracks. I am not sure what this means for a correction but it could complicate things. When we get laser data it will be more clear where the light is going in the cross track direction.

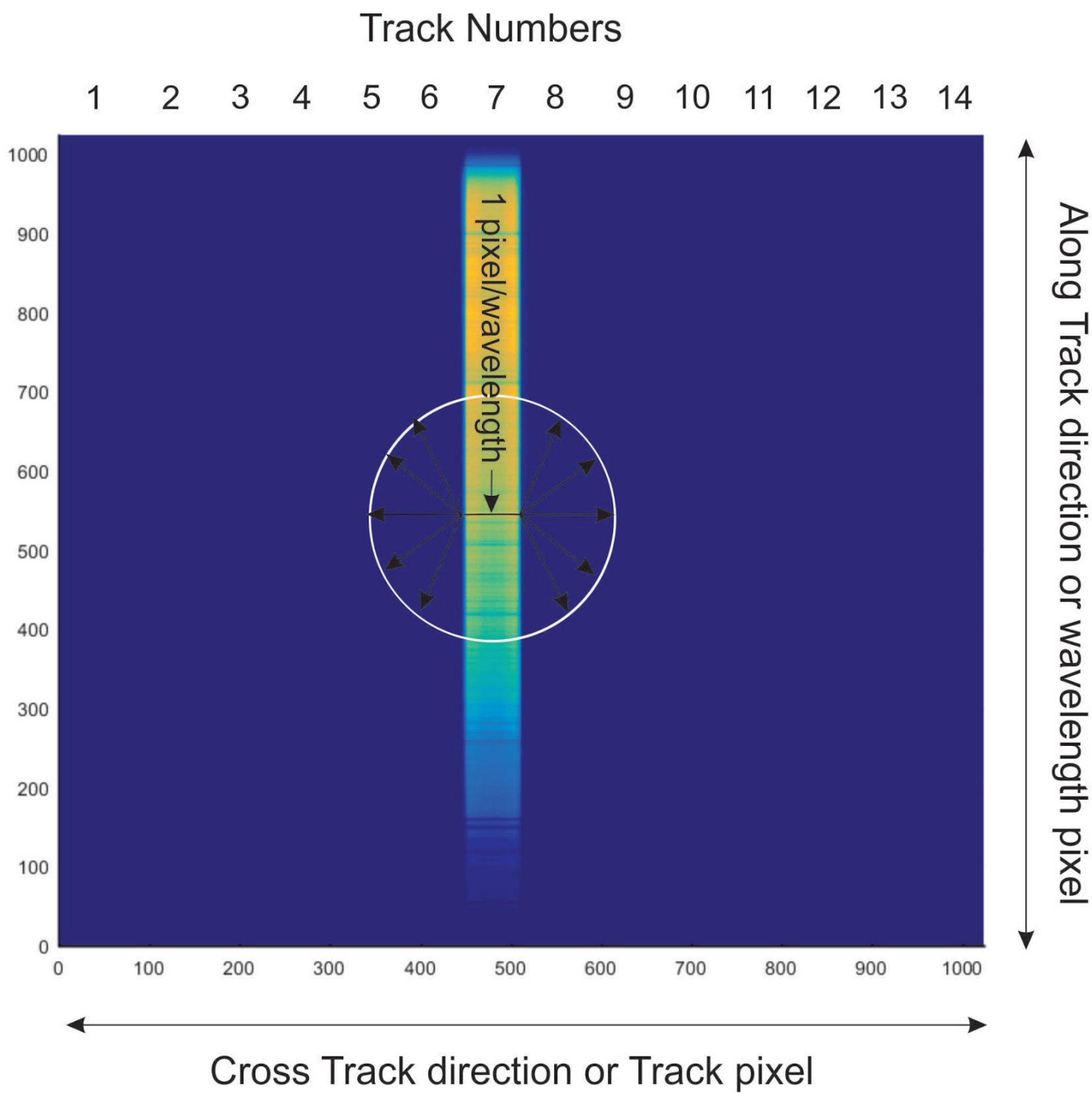

Figure 8. Illustration of the cross track straylight from 1 pixel. The white circle is the edge of the delta shape created by one pixel (not to scale). That one pixel "throws" light in all directions. The along track light is the stray light we already know how to deal with from MOBY/MOS laser data. The light "thrown" in the cross track direction is the new problem. And as you can see the light from pixel x does not only affect the same pixel in the neighboring tracks but affected the pixels around them.

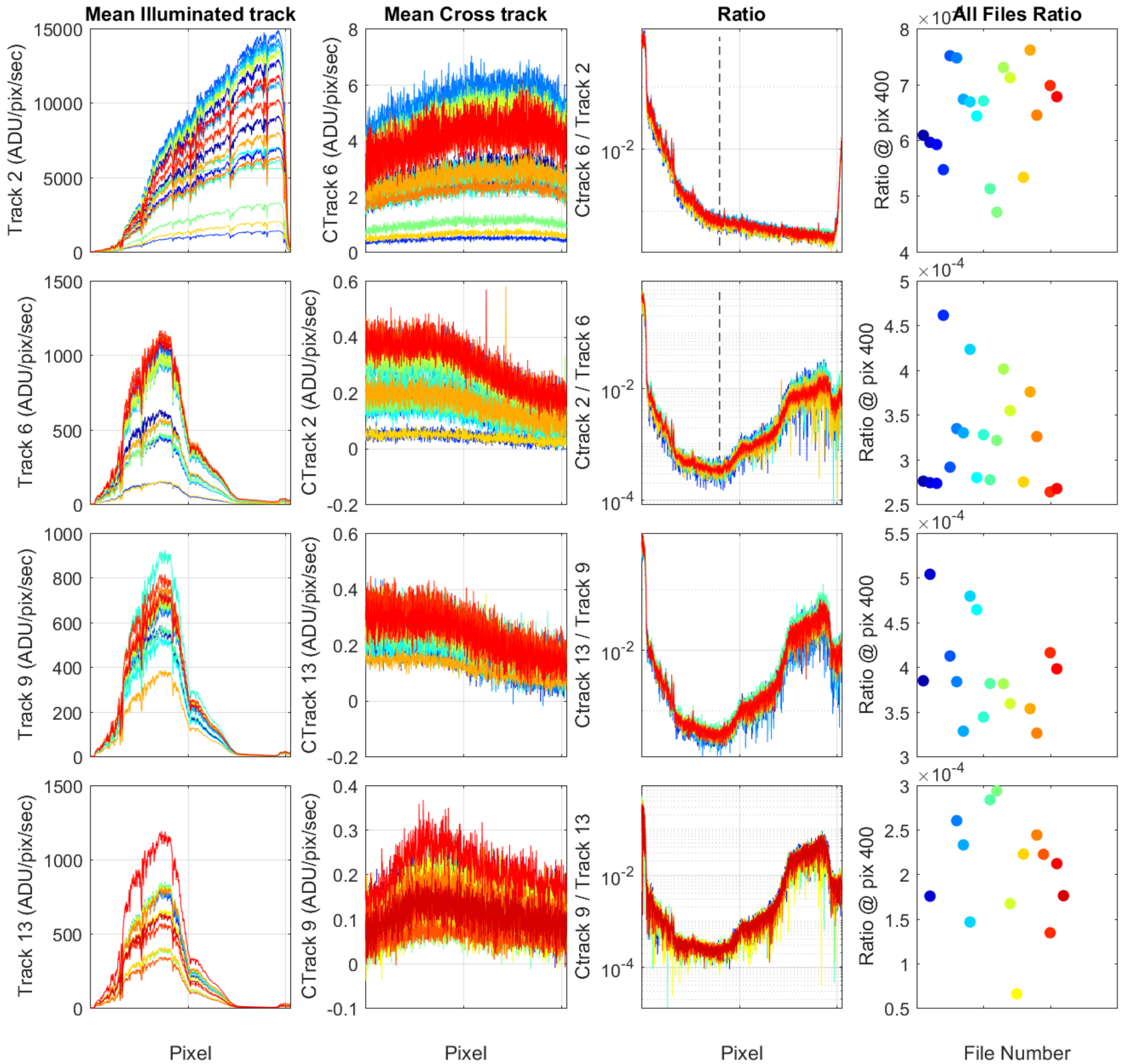

Figure 9. All the in-water single track data sets, the regular cross track (closest track) and the ratio of crosstrack straylight track / illuminated track.

Row 1 is shows the ghosting of Track 2 (Es) onto 6 (LuTop). LuTop is the closest track to Es. But I think the values are so low we may be able to ignore them???
Row 2 is shows the ghosting of Track 6 (LuTop) onto 2 (Es). Es is the closest (non-ghosted) track to LuTop. But I think the values are so low we may be able to ignore them???
Row 3 is shows the ghosting of Track 9 (LuMid) onto 13 (LuBot).
Row 4 is shows the ghosting of Track 13 (LuBot) onto 9 (LuMid).

Remember each of the Es and Lu where taken at different times (one track at a time). The first column shows the illuminated track. The second column closest track to the illuminated that that does not have UV ghosting. The third column is the ratio of the cross track over the illuminated track. This would be the shape you would multiply but the illuminated track in the in-water data to get the amount of light to subtract off from the cross track effected data. The fourth column shows the value of the ratio at pixel 400 for all the files.

Correcting for cross and uv ghosting

Figure 9 does not show all the cross track combinations but Figure 5 does show all the UV ghosting combinations. For the MOBY264 in-water data all the track/cross-uv ghosting combinations are…

```
                                Matrix of ratio combos
Es     (2)  illuminated    |    2/2     2/6     2/9     2/13
LuTop(6)    illuminated    |    6/2     6/6     6/9     6/13
LuMid(9)    illuminated    |    9/2     9/6     9/9     9/13
LuBot(13)   illuminated    |    13/2    13/6    13/9    13/13
```

The top number is the "affected" track and the bottom is the illuminated track. The bolded ratios are will be 1 because they are divided by themselves. The ratios in the red boxes are the UV ghosting ratios column 3 of figure 5. The ratios in the blue boxes are the cross track ratios shown in column 3 of figure 9. The ratios in the orange boxes we have not shown yet. They are also more than 3 tracks from their illuminated track and so the effect is very small.

To correct for the UV ghosting and cross track you need to calculate all the combinations above and put them in a 4 by 4 by 1024 matrix. Where k is the pixel number

```
M = [Es(k)/Es(k)      Es(k)/LuT(k)     Es(k)/LuM(k)     Es(k)/LuB(k)
     LuT(k)/Es(k)     LuT(k)/LuT(k)    LuT(k)/LuM(k)    LuT(k)/LuB(k)
     LuM(k)/Es(k)     LuM(k)/LuT(k)    LuM(k)/LuM(k)    LuM(k)/LuB(k)
     LuB(k)/Es(k)     LuM(k)/LuT(k)    LuB(k)/LuM(k)    LuB(k)/LuB(k)]
```

You then invert the 4 by 4 matrix M for pixel k and matrix multiply is to the matrix of the [Es(k) LuT(k) LuM(k) LuB(k)] for pixel k. You repeat this for all 1024 pixels. The result should be the [Es(k) LuT(k) LuM(k) LuB(k)] with the cross track and uv ghosting contamination removed. (In Matlab you do is with the left matrix divide rather than inv and matrix multiply).

This correction assumes that the cross track and UV ghosting light on pixel 1 of the track effected comes from pixel 1 on the illuminated track. But Mikes tests show this is not true for the UV ghosting. So the correction will not work on spectrographs with UV ghosting.

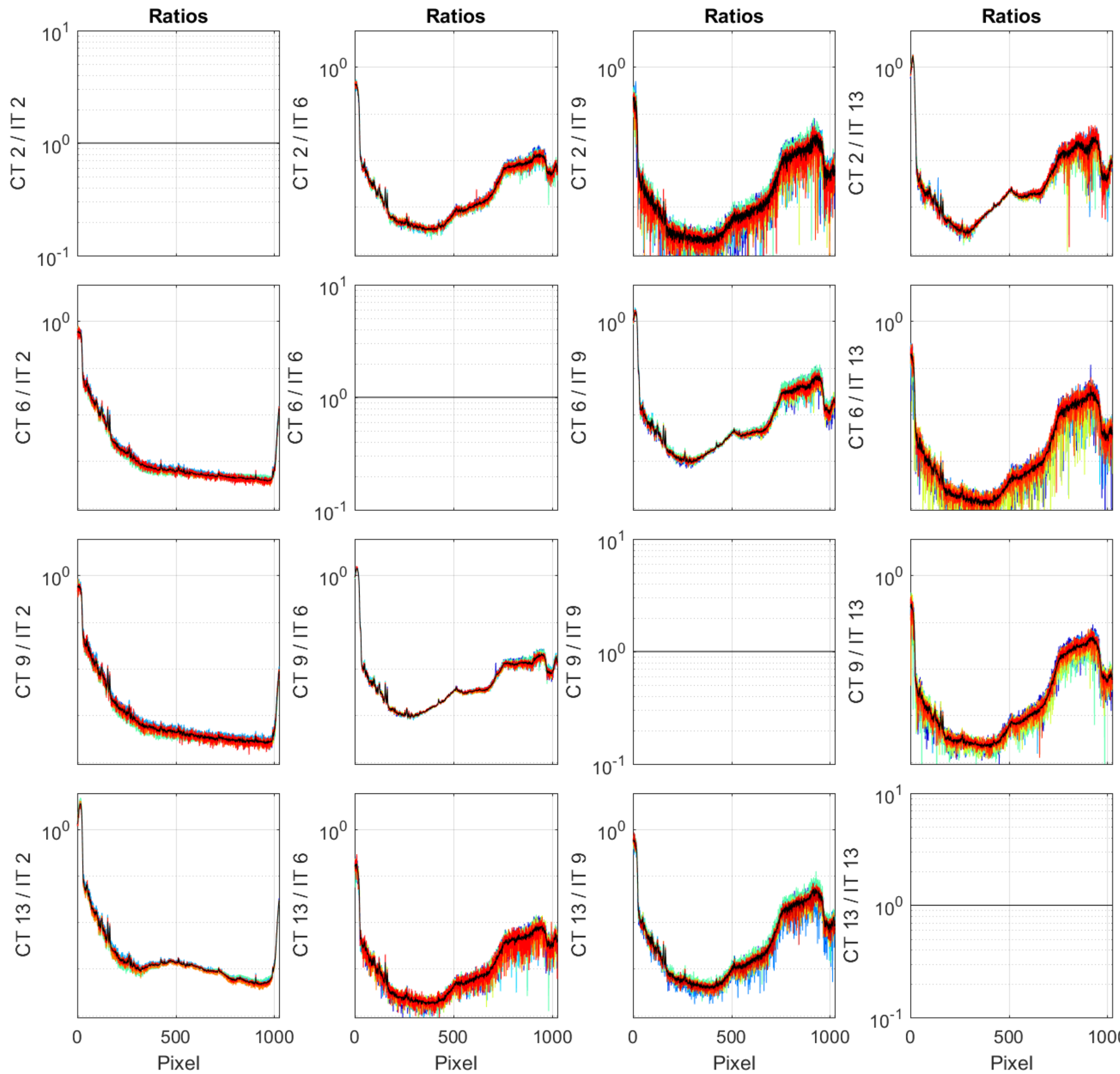

Figure 10. Shows all the 22/23 hour single track data's ratio combinations in the same order as the matrix of combinations above.

The above matrix shows the ratio combinations used to apply the correction. Pixel k is on the x-axis.

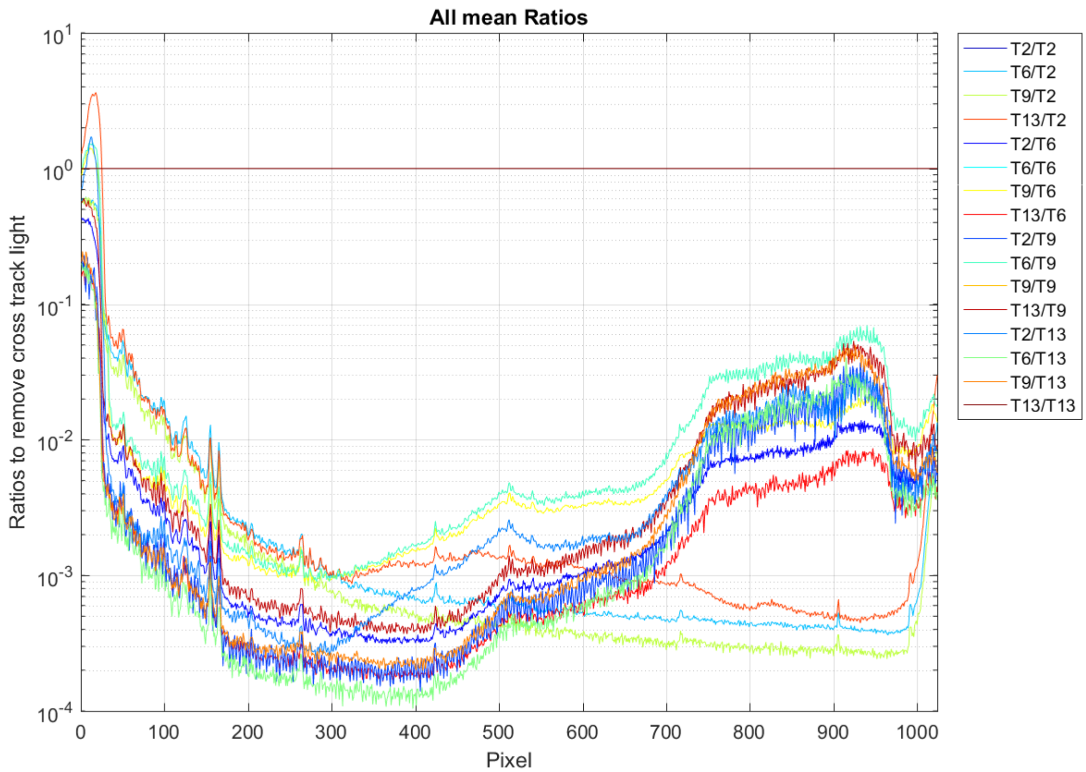

Figure 11. All the ratios on one graph

You can apply this correction to the single track data, or the in-water data where we collect Es and Lu at the same time or the system response data. First I will apply it to the single track data collected on 22/23 hour, which where used to create the ratios above.

Figure 12 below shows the single track data corrected. I tried to correct this data first because when only Es is illuminated (row 1) the other tracks have only the cross track and UV ghosting. So if the correction is working the tracks not illuminated should be pulled down to near 0. Ditto with each of the other rows. Remember that for Figure 12 each row was taken at separate times. So for row 1 the [Es(k) LuT(k) LuM(k) LuB(k)] matrix is the red lines from the 4 axes in row 1. Ditto for Row 2, 3 and 4

Originally the ratio matrix combinations where in the wrong order. Now that they are fixed the corrections applied to the single track data work very well, except in the UV (See figure 12). This is probably because the UV ghosting light is not coming from the UV area of the illuminated track and so the correction breaks down. Hopefully laser data or lamp data with different filters will tell us where the light is coming from.

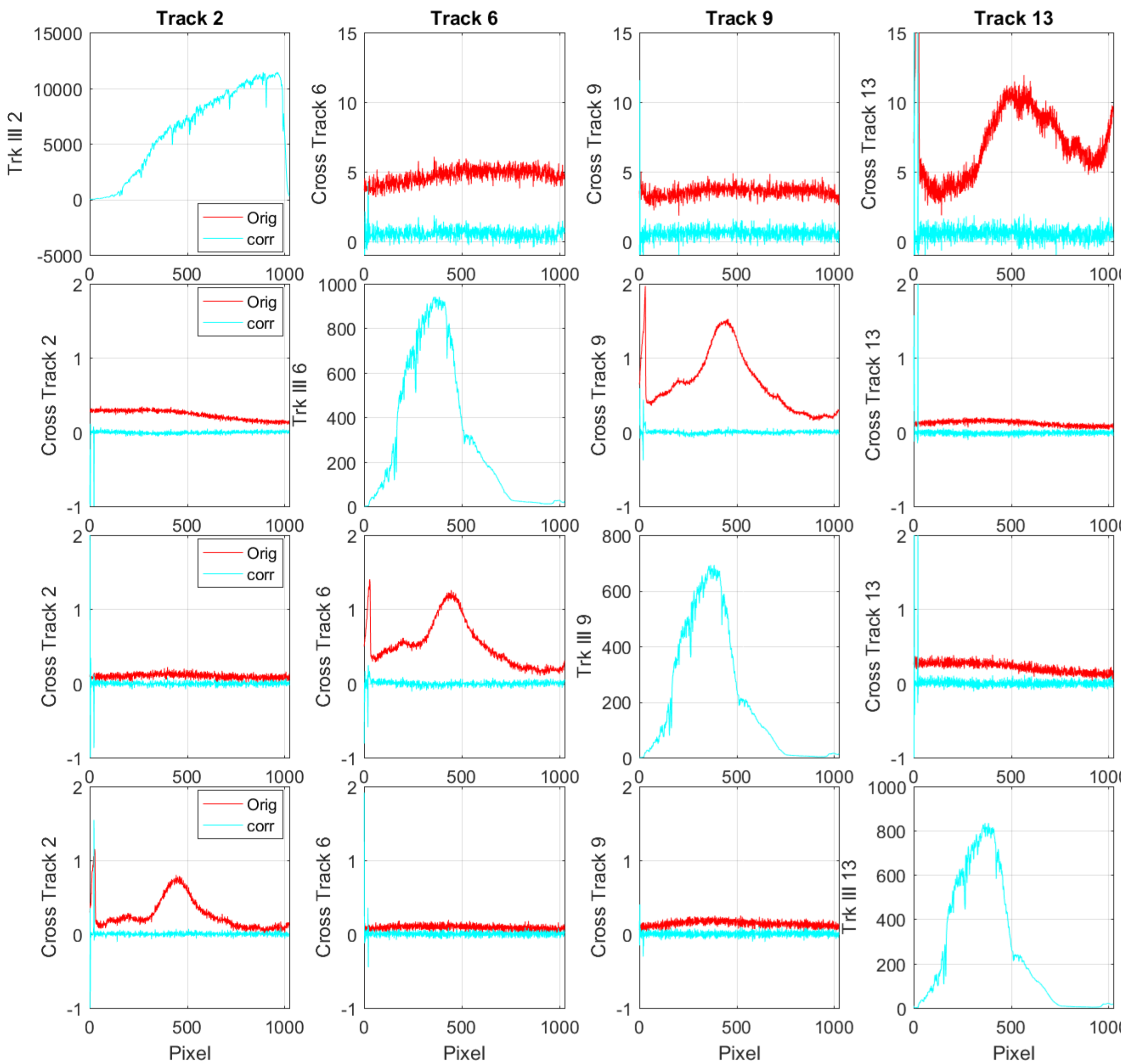

Figure 12. Linear plots of single track data corrected for cross track and UV ghosting

After correcting the single track data I tried it on the in-water 00 hour files when we collected Es and Lu together. Figure 13 shows the results got one days data when Es and Lu was collected together. The top row is the logged graphs and the bottom row is the linear graphs of the same data. There are lots of over corrections for the Lu data. I should do this again when only Lu data are collected (no Es) to see if the corrections are better (see section below called "Applying corrections to in-water 00 hour files when NO Es was collected", after Figure 17)

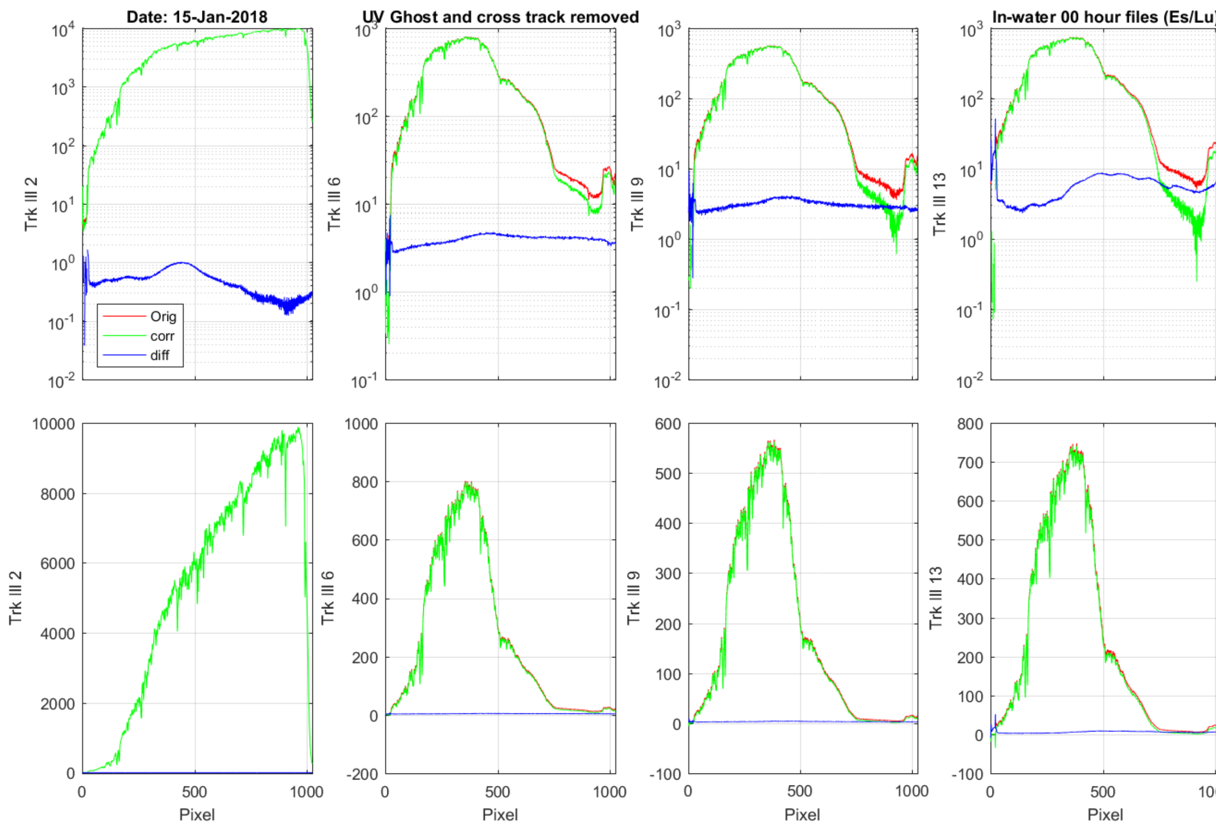

Figure 13. Linear and logged plots of in-water Es/Lu data sets corrected for cross track and UV ghosting. Blue line is the amount subtracted from the red line to get the green.

Ratio changes with spectral changes

The ratios shown in Figure 10 where calculated using the in-water 22/23 hour single track data. So the illuminated signal was Es and Lu data. But when Mike takes system response calibrations he collects single track data that can be used to calculate the same ratios but the spectral shape of the illuminated track is very different. So I calculated the same ratios using the system response data from L267 - BS04.

Figure 14 shows the comparison of the ratio for cross track light calculated using the in-water Lu single track data and the system response single track data for track 6 (LuTop). You can see on the left panel the illuminated tracks shapes are very different and this causes a very different ratio on the right panel. I think this means that the along track stray light is large enough to have a large effect on the cross track straylight. The other 2 Lus tracks had similarly large difference in the ratios from the 2 methods.

I need to do these graphs for the UV ghosting as well.

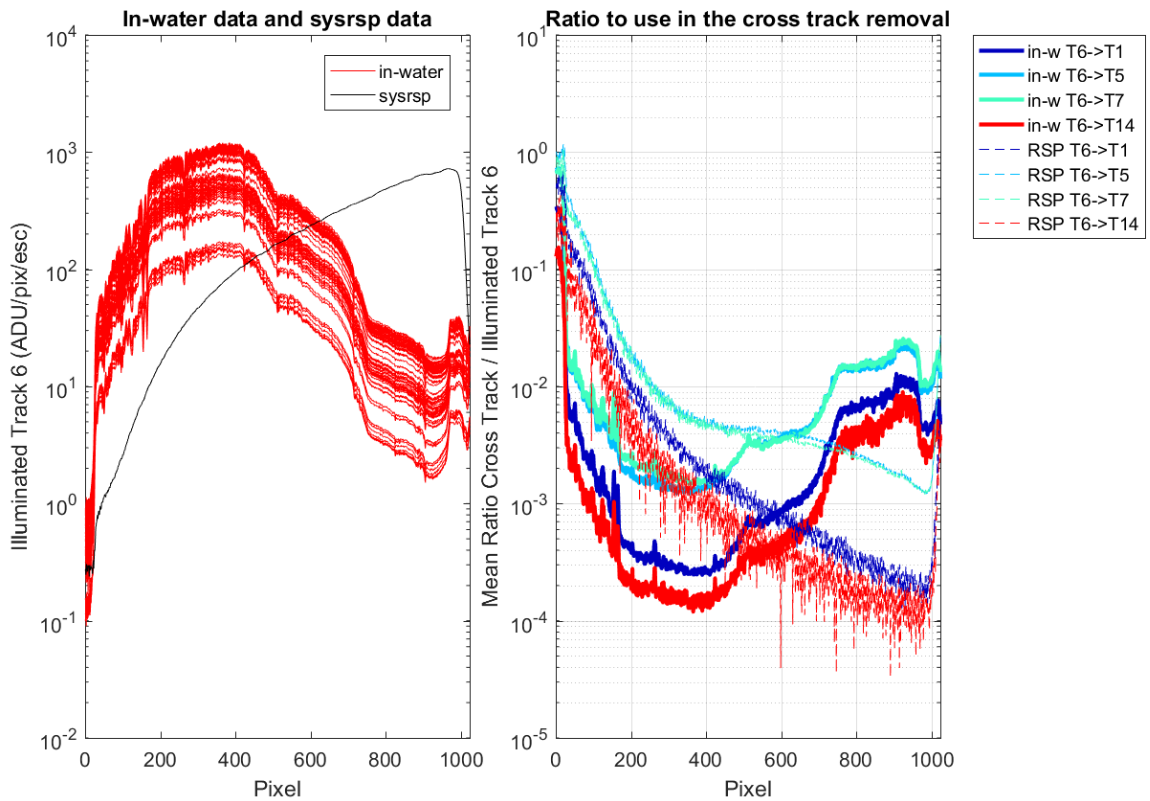

Figure 14. Comparing the cross track straylight rations from system response and in-water single track data sets. There is a large difference.

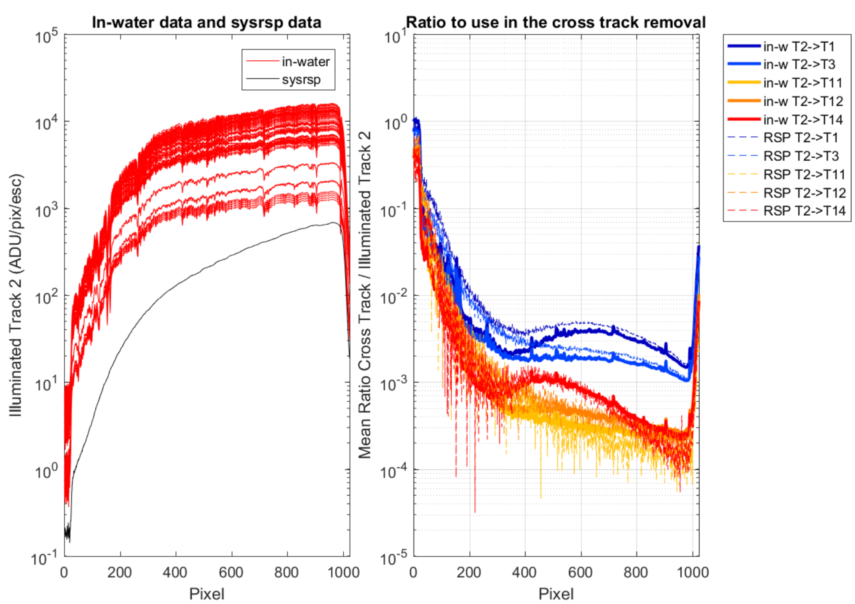

FIgure 15. Cross track straylight ratios for track 2

You can see in Figure 15 when comparing the Es and system response lamp that when the illuminated tracks spectral shape is similar the ratio is similar. Since Es and Mikes cal lamps have a similar spectral shape the ratios are similar because the along track stray light is similar.

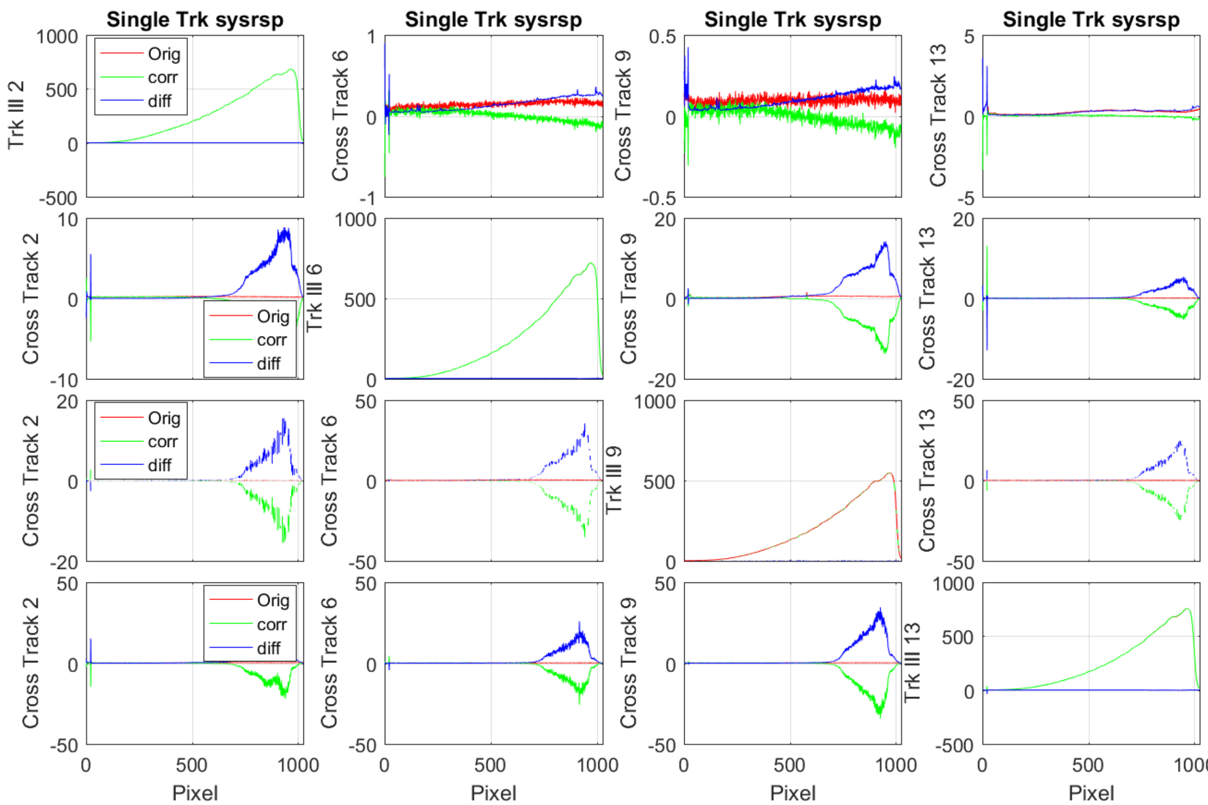

Figure 16. Correcting the system response single track data with the in-water ratios.

You can see when applying the in-water ratios to the system response data is over corrected on the red end of the spectrum. You can see from Figure 17 that a lot of light from the UV laser data ends up on the red side of the spectrograph. This is likely the cause of the bump on the red side in Figure 16 (the over correction).

So because the in-water and system responses have such different straylight profiles you must get either a ratio for each different light source or get one with no straylight (from laser data).

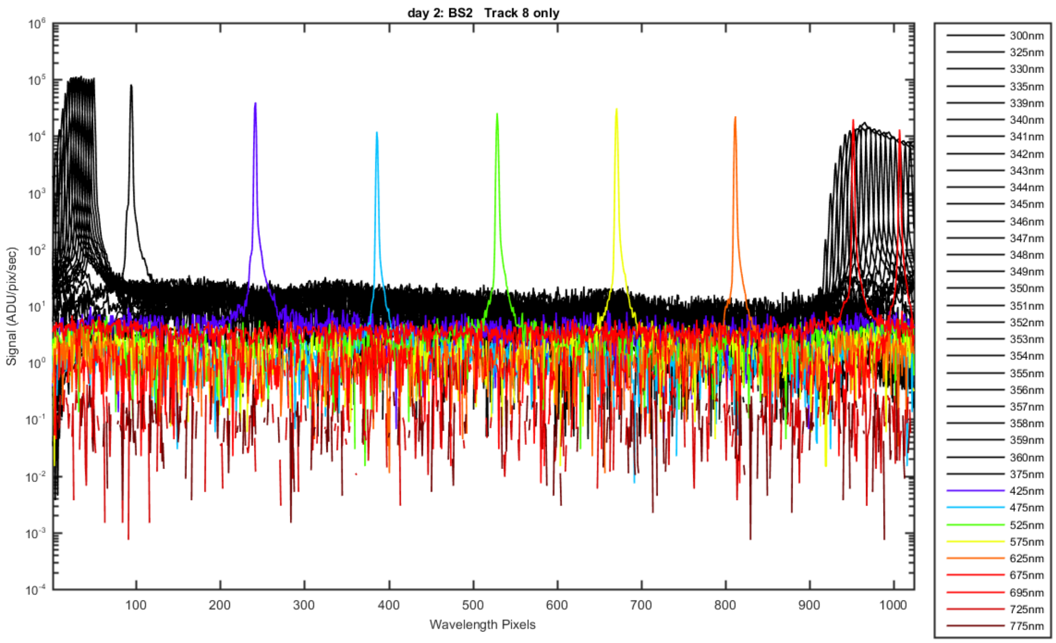

Figure 17. Showing the laser data collected on BS02, Track 8 on day 2 of Hawaii-2016-01

Applying corrections to in-water 20 hour files when NO Es was collected

Figure 13 above showed the correction for the in-water data collected at the 00 hour when Es and Lu data are collected at the same time. I wondered what the correction would look like if I used the Lu only data set. I.E. only the 3 Lu tracks where on, no Es data where collected. So for Figure 18 I used the Lu only 00 hour data set. The matrix was not a 3x3 and the

			Matrix of ratio combos		
LuTop(6)	**illuminated**	|	**6/6**	6/9	6/13
LuMid(9)	**illuminated**	|	9/6	**9/9**	9/13
LuBot(13)	**illuminated**	|	13/6	13/9	**13/13**

You still invert the 3 by 3 matrix M for pixel k and the matrix multiply is to the 3x1 matrix of the [LuT(k) LuM(k) LuB(k)] for pixel k. Rather than the 4x1 matrix [Es(k) LuT(k) LuM(k) LuB(k)]. So this will show the effect of the Es track on the data set and the correction.

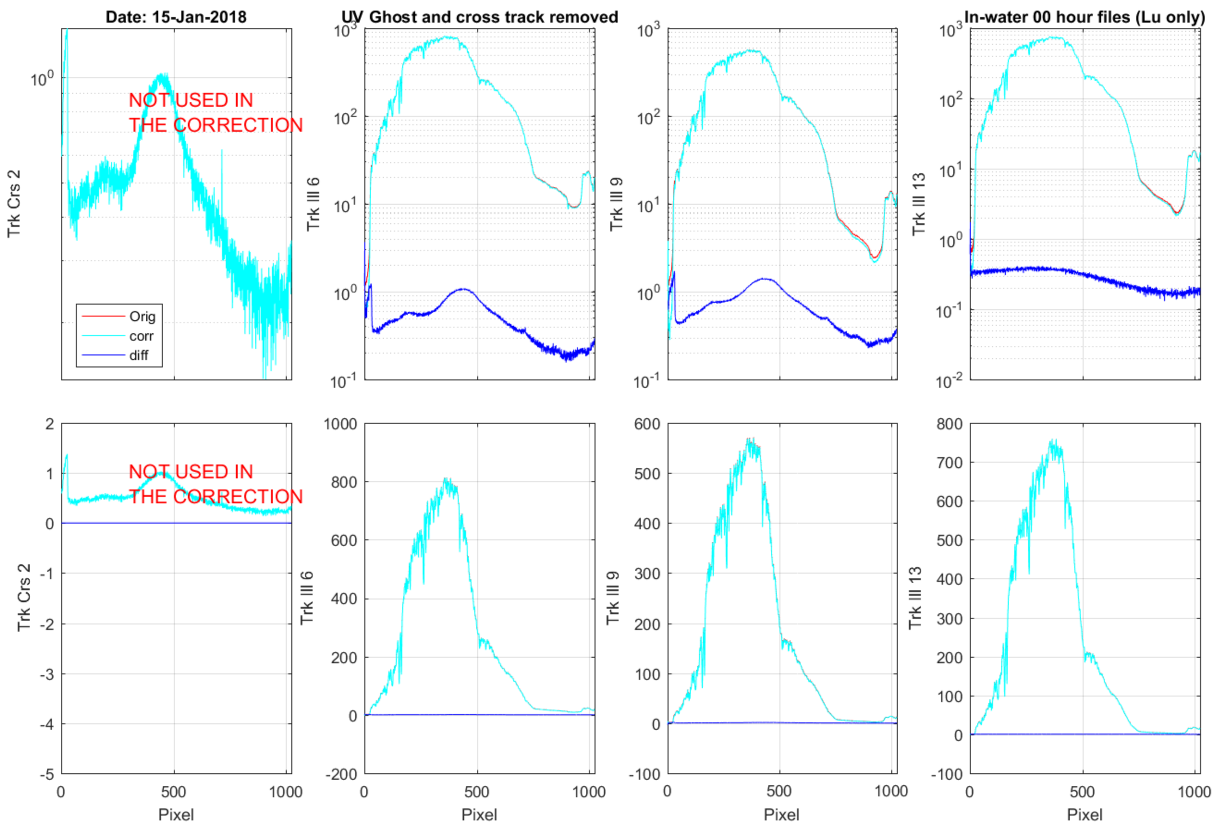

Figure 18. Linear and logged plots of in-water Lu only data sets corrected for cross track and UV ghosting. Blue line is the amount subtracted from the red line to get the cyan. The Es track was not included in the matrix math to get the correction values. So orig and corr are the same number for track 2.

You can see the corrections are much smaller in this data sets. It shows just how much light Es is contributing to the cross track and UV ghosting problem.

In Figure 19 below you can see the comparison of the EsLu amount subtracted and the Lu Only amounts which are about and order of magnitude lower.

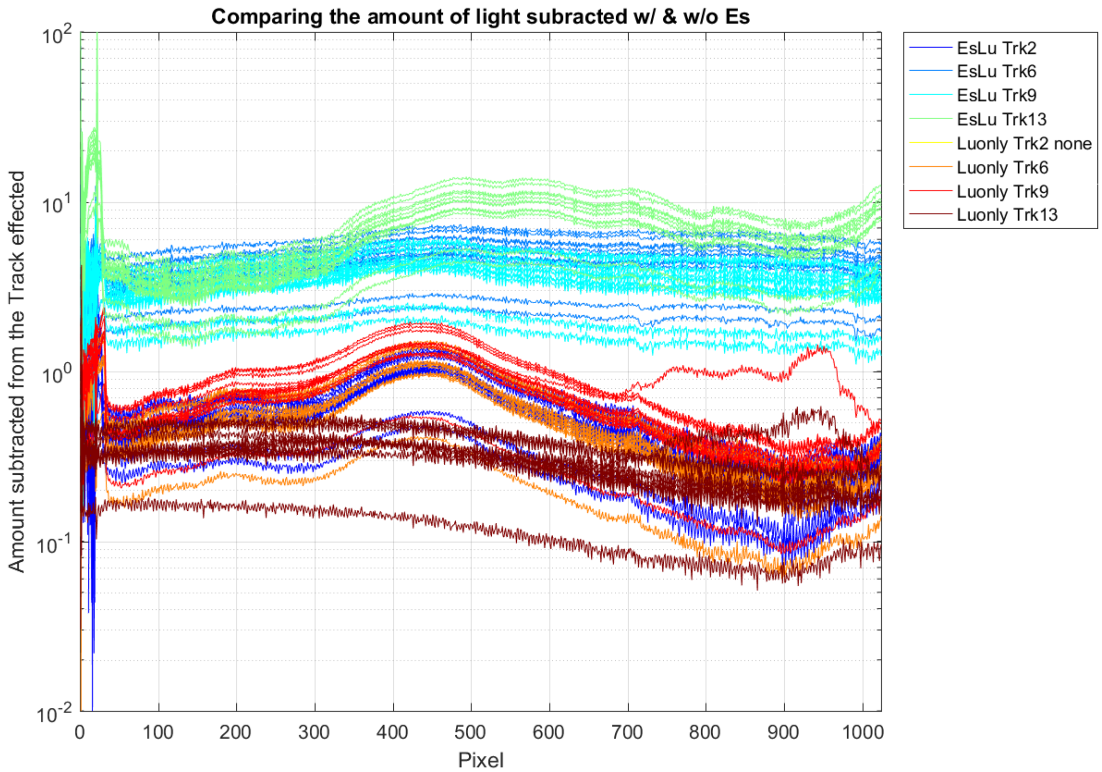

Figure 19. All the light subtracted for data sets with and with out Es