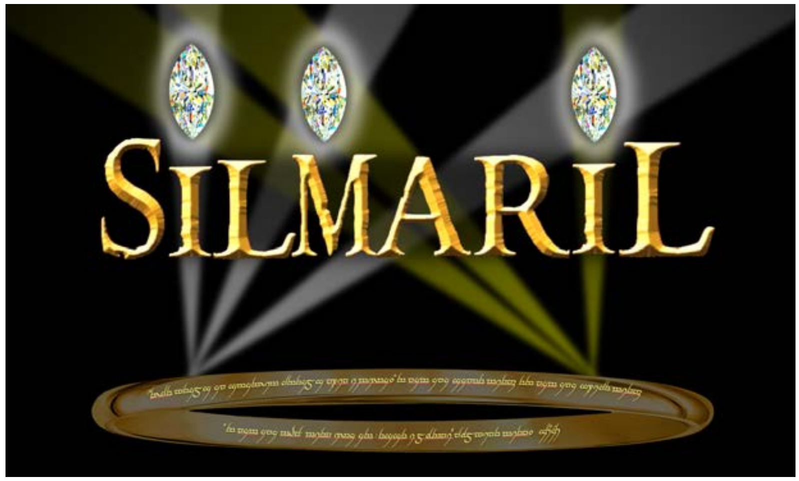

SILMARIL: Commissioning and First On-Sky Tests

CHARA Technical Report #122

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1.0 INTRODUCTION

This document is a description of the first official on-sky tests of the new CHARA Beam Combiner Silmaril (See TR105, TR112, TR113, and TR114 for technical details) performed on the nights of July 4th and 5th 2023. Silmaril is a three-beam image plane combiner designed for sensitivity, that is, many things often used in beam combiners have been compromised to achieve the best possible sensitivity. The number of optical components has been kept to a minimum, there are no fibers, no photometric channels, and there is only a single low-resolution spectrograph used in the design. Silmaril will use the same CRED-1 detector system used by MircX and MYSTIC, but with a much smaller input aperture in the cold stop and a custom built "edge filter" (TR114) intended to separate H and K band light and reduce the background light reaching the H band channel.

Unfortunately, the CRED-1 camera was not available for this run due to a leak found in the vacuum system by First Light Imaging, the company manufacturing the camera. Instead, we used an engineering grade CRED-2 camera on loan from Lowell Observatory. This camera has much more noise and is restricted to H band only. Since this time a second leak has been found in the CRED-1 which has been repaired and the camera is currently being baked. We hope to receive the camera in Los Angeles in late August or early September and test it on the sky as soon as possible after that. Nevertheless, the on-sky tests were very successful, with fringes being found quickly and easily tracked. This gives us confidence that the system will function as expected once we have installed the CRED-1 detector system.

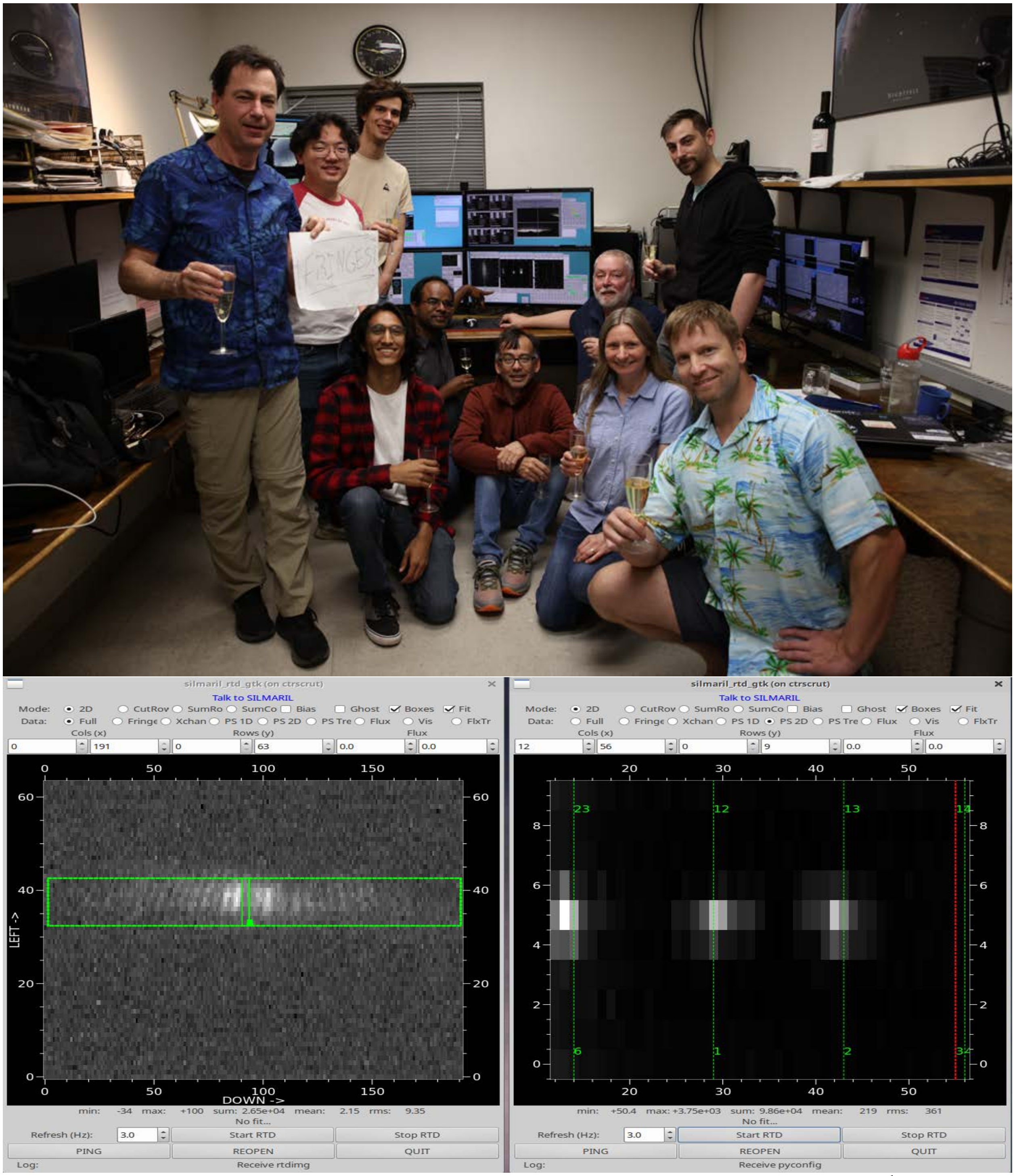

Figure 1. _Top_: CHARA crew celebrating first fringes on sky with Silmaril July 6th 2023.
Bottom: Screen shot of fringes (left) and their power spectrum (right).

2.0 ON-SKY TESTS

The first night of July 4th was primarily used to:

1. Perform some photometric tests. There has been some doubt about the relative quality of the first, long focus, cylindrical mirrors as one of the beams has always appeared fainter than the other two during lab source experiments. It is unknown if this is due to the source itself or the Silmaril optics. Data were collected on each beam, one at a time, and with each telescope placed on each beam. These data have yet to be reduced but on-line estimates of beam intensity indicate that the issue is primarily due to the lab light source and not the cylindrical optics. More analysis is required to confirm this preliminary result.
2. Obtain internal fringes using the STS lab source on both MYSTIC in K band and Silmaril in H band. This ensured that the two system were co-phased and MYSTIC could be used as a fringe finder and fringe tracker if necessary.
3. Obtain fringes on-sky with Silmaril and use the group delay tracking software of Silmaril to keep the fringes in position. There were some bugs found in the Silmaril software, but these were corrected and group delay tracking with Silmaril performed well.
4. Many experiments with the alignment of Silmaril were performed and we took a large amount of data to test for beam drifts and how long the alignment would remain stable. These data have yet to be fully analyzed but the anecdotal evidence during the night was that the stability was good enough to collect at least one bracket of on-sky data and no worse than CLASSIC or CLIMB. We found that fringes were hard to find and track if the beams were not well centered and the AO systems were not properly optimized.

During this first night, or at least the first half of it, it was clear that the AOB alignment process being used was not producing a fully optimized AO correction. The beam size was twice what was expected making it difficult to properly align the beams and find fringes. The first few hours of the second night were spent experimenting with the alignment scheme and trying a few extra steps including recentering the WFS boxes on the beacon, and more carefully ensuring the beacon and starlight were well centered on the hole in the acquisition mirror. This worked well making it possible to achieve the beam size as predicted in the original design and very stable fringes. This new procedure should become standard for on-sky observing and has already been described in the wiki pages. For completeness I will describe the procedure in detail in section 4.0.

The remainder of the second night was used to collect on-sky data brackets on Iota Peg, the interferometrist's favorite binary star, for science verification of the instrument. These data are yet to be reduced but this will be completed before the next annual report on Silmaril to the NSF.

3.0 MAGNITUDE LIMIT TEST

Since the primary goal of Silmaril is to achieve the best possible magnitude limit it was important for us to try to determine what this limit will be. We went as faint as we could with the CRED-2 detector and found that it was possible to easily find fringes on HD 191195, a magnitude 4.50 star in H band with an exposure time of 50 mS. Later analysis showed that the signal to noise ratio (SNR) of these data was 50 or higher. At this SNR the fringes are clearly present by eye, and our experience with the MircX instrument shows that it is possible to track fringes reliably at an SNR of 5. Experiments using blind fringe tracking using the CLASSIC beam combiner show that in good conditions and with care it is possible to obtain useful visibility amplitude data at an SNR of just over 1.

We can write the signal-to-noise (SNR) of a single measurement of the fringes in one spectral band as

$$SNR = \frac{ENV^2}{\sqrt{EN + N_p(2 \times \sigma_R^2 + E^2\sigma_B^2)}}$$

Where E is the exposure time (s), N is the mean number of photons expected in one second, V is the visibility, σ_R is the read noise (e/p, included twice as each frame requires two reads), and σ_B is the background noise (e/p/s). Most of these are known from the specification of the cameras as set out in table 1.

For N we fit a simple model to data collected during the run, as shown in Figure 2, which turns out to be

$$N = 6.0 \times 10^7 \; 10^{-M/2.5}$$

Where M is the magnitude of the object. This is for the CRED-2 detector which cuts off at 1.7 microns so it has only 60% the light of the full H band. Furthermore, the CRED-1 system will have the full H band as well as K band, each of which will have 1/0.6 more pixels than the CRED-2 and 1/0.6 more light. We will work out the SNR in each of these separately and then combine them:

$$SNR_1 = \sqrt{SNR_H^2 + SNR_K^2}$$

Table 1.

Parameter	CRED-2 H	CRED-1 H	CRED-1 K
E	0.050	0.050	0.050
V	0.9	0.9	0.9
Pixel Size	15 microns	24 microns	24 microns
N_p	$7 \times 180 = 1260$	$\frac{15^2}{24^2} \times 1260/0.6$	$\frac{15^2}{24^2} \times 1260/0.6$
σ_R	30	0.96	0.96
σ_B	600	178	1232

The values for the CRED-2 are taken from the First Light Imaging technical specifications while those for the CRED-1 are those measured on our camera. This model gives an SNR of ~50 for the CRED-2 for a magnitude of 4.5, which matches our on-sky measurement. The resulting comparison of the SNR for the two cameras is plotted in Figure 2. The CRED-2 SNR reaches 5.0 for a magnitude 7.03 object, while the CRED-1 this is magnitude 9.72. This estimate is based on a single measurement on a single night, but it does indicate that Silmaril should easily reach magnitude 9.7 and it matches our predictions in the original proposal and our subsequent modeling. This is without further optimization. For

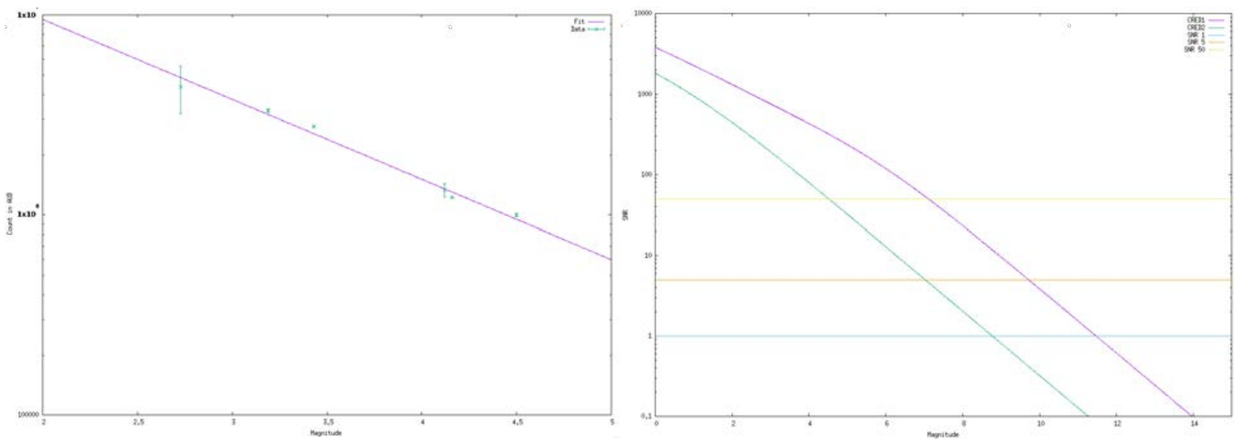

Figure 2. *Left*: Fit to photometric Data.
Bottom: Predicted SNR for the CRED-1 and CRED-2 Cameras

example, the number of pixels read out could be much less, on good nights we could use longer exposures, and the techniques employed by Matt with CLASSIC on AGNs could be used. This model predicts that the SNR will reach 1.0 for the CRED-1 at magnitude 11.47, so it is not unreasonable to expect to observe objects fainter than magnitude 10.5 in good conditions.

4.0 ALIGNMENT PROCEDURE

This procedure is based on an email sent by Gail on July 12^{th}.

At start of the night: This could also be done again during the night, but the intention is to ensure everything starts in a known and repeatable position. I use here TWFS for the telescope wavefront sensor and LWFS for the lab wavefront sensor. Similarly, I use TDM, LDM, TAO, and LAO

1. Stow the telescope. It has been suggested by Norm that since changes in elevation affect the alignment of the AOB optics this should be done with the elevation at a position other than zenith, say 60 degrees. It isn't important what position is used so long as we use the same position each time.
2. Put M7 in the default position as determined at the last Coude alignment.
3. Check the M10 alignment.
4. Load default boxes on TWFS (DEFBX on obsgtk).
5. Load the default flat on LDM (LD DEF on obsgtk)
6. Load default flat on TDM (LD DEF on obsgtk).
7. Use blue starlight boxes in TWFS and align the beacon flat using the red beacon.
8. Check that the beacon is centered on the hole in the acquisition mirror. This may mean moving the boxes.
9. Change the exposure of the TWFS to 5 msec (default 2 msec; 10 msec on W1) and make sure you see all spots on TWFS. Make sure to change back to standard observing values once you are done. There may have to be some iteration or compromise between this and step 8. Having the beacon well centered on the hole in the acquisition is more important.
10. Align blue beacon on the LWFS using auto align dichroic.

11. The blue beacon is very unevenly illuminated and, in some scopes, oversized. This makes it easy to overlook an error of a full WFS box or more. To avoid this, look at the red beacon on the LWFS and find the center of the beam. Make sure all the spots are in the correct boxes. If not, manually move the telescope dichroic to get the spots into the correct boxes. You can then look at the blue beacon to see what the pattern should look like. Note that the blue/red beacons are offset by about half a box. If you did have to move the dichroic manually, you need to re-center the spots in the boxes with the automated procedure moving the telescope dichroic.
12. Focus the blue beacon on the LWFS.
13. Focus the TWFS by looking at the red beacon on TWFS.
14. Recenter red/blue beacons again.
15. Check the higher order terms - look at "TOG ABER" plots (on WFS/TT tab for wfsgtk, on ALIGN tab for labao). Soon there will be a small GUI that will show these plots. It may also be helpful if obsgtk displayed at least astigmatism.
16. If they are large it means that these same aberrations will be imposed on the starlight, which is not what you want. To fix this, you need to redefine where the boxes should be. For now, use "ZERO CENT" on telescope wfsgtk (-E for engineering version), or ZCEN on obsgtk to zero out higher order terms. It may be a good idea to do this more than once during the night as the temperature changes. It is also likely to be affected by large changes in elevation. This should probably be a button on obsgtk.

After slewing to a star:

1. Align the red beacon on the TWFS by moving the beacon flat. It is worth rechecking at this time that it is still well centered on the hole in the acquisition mirror.
2. Align the blue beacon on LWFS by moving M7.
3. Check the focus of both beacons.
4. Turn off the blue beacon and lock the star on tiptilt only.
5. Move TWFS boxes (use BOXES button obsgtk) to ensure the star is centered and evenly illuminated on the acquisition hole. This should also mean that the starlight evenly illuminates the TWFS boxes. As above, some compromise between these two may be necessary. Having the starlight go through the middle of the hole is most important.
6. Lock TAO and LAO.
7. Save a flat on both AO systems . The AO servo uses the flat to guide the optimal correction so this is important. If you notice that the AO performance is poor it's always worth doing this to see if it helps.
8. Center star on STST. This is done by STST by moving the beacon flat. The LAO system then offloads large tilts of the LDM by moving M7.
9. Check the aberration plots. If X/Y terms are not going to zero, try stopping all servo loops, recentering alignment, and turning back the servo loops back on. If X/Y and higher order terms are still not going to zero after checking alignment and making a new flat, then this likely means a new reconstructor needs to be made. You should notify charatech about this. You can try the on-sky reconstructor measurement, but only do this on a bright object. There should probably be a button on obsgtk for this.

10. FUTURE IMPROVEMENTS

A new proposal to support Silmaril activities will need to be submitted in November (for an AAG) or December (for an ATI) and this will need to include some hardware upgrades, salary support, and some travel money. Work should begin on this proposal soon. I am happy to help with this, but it would be inappropriate for me to be the PI or even CoI. This proposal could include funding for:

1. The blue beacon is very unevenly illuminated and this needs to be fixed. It may be a function of the coating on the dichroic, the beacon optics themselves, or likely a combination of both. One thing that can be done in the short term is to check that the beacon optics include an aperture stop that is 5 inches in diameter.

2. Expanding the system to be able to use all six beams. This means another set of fold and long focal length cylindrical mirrors. It may also require obtaining a second or larger fold mirror.

3. The addition of a narcissus mirror. In the short term an experiment should be done once the CRED-1 is installed with a spherical mirror with no holes in it just to check that this reduces the background counts at all.

4. The addition of photometric taps on the beams. One method would be to use the CLASSIC/CLIMB beam paths. If the first fold mirrors in the system is replaced by dichroics that reflect H and K while allowing J band to pass through we could use the J band light as a photometric signal. This would require placing the beam splitters in CLASSIC and CLIMB on kinematic mounts so they can be removed easily, but this is already true of one of them in CLIMB2. This way we will have six beams on NIRO to monitor beam intensity without disabling CLASSIC or CLIMB. It is probably a good idea to check that the J band scintillation is a valid measure of what happens in H and K band. Rather than a dichroic we could have a grey split on the fold mirrors so that a small amount of H and K reach NIRO. A trade off study for these options will be required.

5. Automated beam alignment. The beams do drift and beam alignments are necessary in the same way that as it is required for CLASSIC and CLIMB. If we do use NIRO for monitoring the six beams, we could use 4 pixels (2x2) on NIRO and obtain a tiptilt signal for each beam on the same table as Silmaril. This could be used to adjust the beacon flat using a long average, or even to send Tiptilt offsets to either TWFS or LWFS.