Tracking Faint Fringes with the CHARA-Michigan Phasetracker (CHAMP)

John D. Monnier^a, F. Baron^a, M. Anderson^a, S. Kraus^a, R. Millan-Gabet^b, E. Pedretti^c, X. Che^a, T. ten Brummelaar^d, N. Calvet^a

^aDepartment of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109;

^bIPAC, California Institute of Technology;

^cScottish Association for Marine Science;

^dCHARA, Georgia State University, Atlanta, GA;

ABSTRACT

The CHARA-Michigan Phasetracker (CHAMP) successfully tracks fringes in 4-telescope and 6-telescope modes when observing high-visibility targets. We have found that our primary targets (Young Stellar Objects) have unexpectedly low visibility fringes (<20%) for most baselines at CHARA, generally below our tracking thresholds. We have undertaken an upgrade cycle in 2011–2012 to re-optimize CHAMP to allow group-delay tracking on the faintest fringes possible. We describe our multi-pronged strategy using special dichroics, new piezo scanners, and our first attempts to explore CHARA J-band made possible by using special metrology-blocking laser filters. CHAMP can now be used with all the combiners at CHARA.

Keywords: interferometry, infrared, fringe tracking, chara, champ

1. INTRODUCTION

Most of today's interferometers have "fringe tracking" capabilities, although this means different things to different people. Because of atmospheric turbulence, the white light fringe is in constant motion, changing up to 100 μm on short timescales. Because most astronomical observations employ wide spectral bandwidth for sensitivity, the coherence length of the combined light is generally 15–50 μm – thus some form of realtime active "fringe tracking" is needed to stabilize the fringes to allow data taking.

Many fringe trackers work in "phase tracking" mode (e.g., PTI, Keck, NPOI); that is, the fringes are stabilized within 1 radian to maintain pure coherence, even allowing long integrations by a science combiner in principle. Now, this mode requires sufficient signal-to-noise within a single coherence time to work, thus limiting sensitivity. In this mode, dispersed light is typically used to determine which fringe one is tracking on to maintain zero OPD.

Another mode is "group delay tracking" (GDT) which merely attempts to keep the optical path difference with one coherence length (typically 10–20 fringes) of the fringe zero OPD. In principle, this mode should be more sensitive since one can integrate for a much longer timeframe for the servo loop and the phase stability requirement are radically reduced (from $<1 \lambda$ to 10–20 λ). In fact, when fringe tracking is occurring at a different wavelength than the science combiner, then pure co-phasing within 1λ may not even be possible due to differential dispersion or multi- r_0 effects for finite size telescopes and GDT is sufficient.

Interestingly, most fringe trackers that have been built so far have simultaneously served as the main science combiners as well. Recently, some steps toward treating the fringe trackers as an auxiliary system (like adaptive optics or tip-tilt system) have been taken, for instance FINITO¹ on VLT and the Keck Interferometer self-phase referencing mode.² For CHARA, we proposed such a split system for the CHARA-Michigan Phasetracker (CHAMP³), where a dichroic delivers IR light to the fringe tracker while allowing science light to be sent to another instrument, exactly like a facility adaptive optics system.

In this contribution, we discuss our lab and on-sky experience with CHARA-CHAMP and some of the limitations we discovered. We also discuss a round of upgrades to CHAMP (v2.0) that has extended the sensitivity. We conclude with some advice for groups wishing to build fringe trackers for practical use on today's interferometers.

Further author information: (Send correspondence to J.D.M.)

J.D.M.: E-mail: monnier@umich.edu, Telephone: 1 734 763 5822

Figure 1. Here we see the average fringe visibility on the MIRC combiner as a function of the adopted coherent averaging time. One can see that fringe visibility monotonically decreases as the exposure time increases due to atmospheric turbulence (dashed line). With CHAMP operating, the fringes are much better stabilized allowing longer coherent integrations on target (solid line).

2. CHAMP V1.0

The goal in building the CHARA-Michigan Phasetracker (CHAMP) was to be able to detect and correct path-length fluctuations due to atmospheric turbulence to allow greater sensitivity for all the various combiners at CHARA. Specifically, the main science goal was to extend a few magnitude sensitivity gain to the Michigan Infrared Combiner (MIRC, Monnier et al.^{4–6}). This would allow MIRC to image the dusty planet-forming disks around nearby young stellar objects.

The design specifications and on-sky commissioning runs of CHAMP have been documented in earlier SPIE proceedings.^{3,7,8} Here, we briefly summarize the major design features. CHAMP operates at the astronomical J, H, and Ks bands using an engineering-grade HAWAII-1 detector. CHAMP uses all 6 beams from CHARA, combining beams in a nearest-neighbor pairwise scheme implemented in bulk optics (6 simultaneous fringes between beam pairs 1–2, 2–3, 3–4, 5–6, 6–1). The fringe tracker uses piezo-electric OPD modulation on every other beam after a dichroic split so that science combiners do not see the fast OPD modulation. Closed-loop operation is made possible by talking to the CHARA delay line realtime (vme) computer using a dedicated ethernet connection (latency ~ 1 ms). CHAMP successfully tracked on one baseline in 2009, 4 baselines in 2010, and all 6 baselines simultaneously in 2011. Figure 1 demonstrates the performance of CHAMP successfully “phasing up” the MIRC combiner – showing a $>6\times$ increase in the coherence time during commissioning in 2010.

Figure 2. This figure illustrates the scanning philosophy of the first version of CHAMP. Here we see a K band fringe along with a window showing the stroke range of the first edition PZT scanner. For high signal-to-noise, the 5-fringe scan length is adequate to both determine the phase and group delay, however the group delay estimator fails at low SNR, limiting faint-fringe sensitivity.

In the original design, a very stiff, flexure stage piezoelectric mount was used in order to have the highest possible resonance frequencies, based on the concern that moving a 1 inch mirror at tens of hertz might cause large uncontrolled resonances and spoil the OPD modulation scheme. This choice led to the PZT with only $8\mu\text{m}$ stroke, allowing maximum of approximately 5 K-band fringes to be observed (see Figure 2). While we successfully tracked on-sky fringes using this mode, we had limited sensitivity because the relatively short stroke did not allow us to estimate the group delay accurately enough for the faintest fringes. Another problem we found is that the open-loop PZT we used had to painstakingly calibrated with internal fringes to obtain a linear stroke and avoid hysteresis, and the calibrations drifted with time which caused a headache for practical use. Thus, while we commissioned an excellent "phase tracking" interferometry for relatively bright targets, we were unable to use this system for observing our highest priority science targets, the young stellar objects.

3. CHAMP V2.0

With the primary goal to improve sensitivity for faint fringes, we began an upgrade cycle for CHAMP in 2011–2012: CHAMP v2.0. Inspired by the high sensitivity of the other CHARA near-infrared combiners (CLASSIC, CLIMB^{9,10} reaching $K=8.5$), we chose to purchase longer stroke ($100\mu\text{m}$) PZTs. Figure 3 shows an example fringe for a young stellar object using the long-scan pupil plane combiner CLASSIC. One can easily see the fringe packet, even at fairly low signal-to-noise ratio. Figure 4 shows a cascade plot with time on the y axis and scan OPD on the x axis. One can see the fringe packets jumping around $\pm 50\mu\text{m}$ during the data acquisition sequence. With a slightly faster update rate, we expect to track fringes to within $\pm 20\mu\text{m}$, allowing the fringes to be always within the coherence length of the MIRC combiner.

Figure 5 shows our new scanning mode in-action. We have adjusted our previous sawtooth scanning to a symmetric triangle waveform. We choose roughly 4 samples per fringe in order to continue to use our dewarped ABCD phase/envelope estimators in our current control software. We can see in this figure that a debiased matched filter does an excellent finding the group delay and on-sky tests were successful.

We took our new system on-sky in 2012 June. We modified the control algorithm to use the matched filter algorithm and implemented code for debiasing and auto-thresholding. After co-phasing CHAMP with MIRC in the lab, we went on sky and were able to easily track all 6 fringes while observing with MIRC (see Figure 6 – which also shows a picture of the old and new PZT scanning modules as installed).

Another aspect to our upgrade was to include a new J band mode. Previously we obtained a J/K Reflect, H Transmit dichroic filter that allows MIRC to see the H band while sending J and K to CHAMP for fringe tracking. However, the J band contained metrology laser light at $1.319\mu\text{m}$ which made observing on-sky impossible. We

Example from CHARA/CLASSIC

Figure 3. This figure shows a real fringe of the young stellar object v1295 Aql made using the CHARA CLASSIC combiner. We have modified CHAMP to have a longer stroke to allow a similarly slow, yet high sensitivity, tracking mode.

determined that we needed a OD 4.5 filter at $1.319\mu\text{m}$ in order to observe J band and, after much discussion with vendors, agreed to purchase a short pass filter by Brinell Vision – see Figure 7 for measured transmission curve. We obtained first CHARA fringes at J band in 2012 June during our engineering run. Note that facility work at CHARA within the past year has reduced the metrology background by factor of 100 – this lower level of background might allow a custom “notch” filter (instead of the short-pass) to be used that could retain more of the J Band while still suppressing the laser contamination.

4. LIMITATIONS FOR CHARA-CHAMP

The new upgrades to CHAMP did increase our sensitivity and led to successfully tracking of YSO fringes with four telescopes on MIRC. However, we have more work to do to make CHAMP v2.0 a robust facility instrument and to allow observing of many other YSOs.

Here is a list of improvements we are pursuing to increase tracking sensitivity:

- Better co-alignment of CHARA beams with internal CHAMP alignment system. CHAMP diroics transmit too little of the CHARA alignment laser through our system and we rely on an internal laser for detailed beam alignment. More work needs to be done to avoid vignetting because of slight mismatch between the beams.
- Reduction of photometric cross-talk. For low visibility fringes encountered for YSOs, variations in the flux can mimic a fringe signal and non-gaussian fluctuations (“spikes”) limit our ability to track faint fringes. We would like to reduce our cross-talk through optimizing tip-tilt performance (see CHARA-AO upgrade, ten Brummelaar et al. in these proceedings) and also through better pixel focus alignment. We can also use detection on both sides of beam splitter as a discriminator in some cases.
- Cold pupil on CHAMP needs a detailed alignment with the image-slicer pyramids.
- More sophisticated algorithms to track in “lucky fringes” mode without being confused by spikes due to cross-talk.

Scanning mode for GDT

Figure 4. This figure shows a “cascade” plot, showing fringe scans of a calibrator and of a YSO. The y-axis is time and the x-axis is the fringe scanning direction (OPD). We can see the fringes jump around tens of microns during data acquisition under good seeing. By tracking fringes using this kind of mode, we hope CHAMP will extend its sensitivity enough to allow tracking of YSOs and stabilizing the packet for data acquisition with MIRC.

- Implement dynamic sweep adjustment using the new PZTs. This would allow the scan length to vary dynamically to try to minimize the time off the fringe and to adjust for varying seeing. Our current software paradigm does not allow this because our camera readout is triggered by a static waveform generator driving the PZTs and also our linux drivers are not flexible. We envision an OS upgrade cycle to bring the control computer up to new version of the linux kernel and this would necessitate updating the DAC board drivers.

Of course, some problems are endemic to the facility and our choice of targets and can not be improved through hardware. Our targets are highly resolved and not bright (low surface brightness from dust emission). A 6-telescope system like CHARA is necessarily missing a central station and thus poses severe problems for bootstrapping, made more difficult by the nearest-neighbor architecture of CHAMP which minimizes redundancy. While it is straightforward to switch beam order at CHARA, in practice this lowers observing efficiency and we try to avoid it.

5. CONCLUSION

Following successful coherent phase tracking of CHAMP in 2009-2011, we carried out a major upgrade of the PZTs to optimize group delay tracking for faint targets. We have demonstrated full 6-beam tracking with the new system and even observed with MIRC and CHAMP simultaneously on a young stellar object (4 beams). CHAMP can already support all the current combiners and is a strong basis for future development of a 6-beam visible-light system.

New Scanning Mode

Figure 5. Here we illustrate the steps of our new group delay tracker (GDT). The top left shows lab fringes showing the lowest possible signal-to-noise ratio fringes we might track. We are scanning now with a triangle wave – constant slope up and constant slope down. We calculate the envelope function based on an ABCD decomposition. The bottom left shows the result from applying a matched filter using the expected fringe packet width from known bandwidth of observations. The right panel shows actual on-sky fringes using the new long-stroke PZTs.

Based on practical experience, we would advocate a few design features for future fringe trackers in the optical/infrared.

1. Despite the allure of greater sensitivity by using minimum number of spanning baselines, we advocate combiners that give all the baseline pairs to maximize best flexibility in fringe tracking and baseline bootstrapping.
2. Simple and easy alignment is a big advantage for quick on-sky commissioning. Our small group has spent a lot of time dealing with alignment and calibration of open-loop PZTs – time that would have been better spent optimizing algorithms.
3. Scanning modes using closed-loop PZTs are very flexible, give large capture range, and can be used in both phase tracking and group delay tracking modes. It is not clear if dispersion is really needed although useful for phase tracking application since one may not want to scan more than one fringe. Do not slave your camera readout to the PZT waveform.
4. If near-infrared detectors improve to the point of a few electrons read-noise, it might be possible to painlessly disperse light more on the science combiner which would greatly reduce the demands on the group delay tracker.
5. A future instrument might combine simultaneous H and K band detection in one system. This could allow a very flexible bootstrapping for group delay tracking, allowing either H or K band fringes to be used.

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Figure 6. Here we see the main control gui for CHAMP populated by six fringes (see red box). In addition you can see the realtime estimation of the group delay from based on the fringe envelope along with the FT offsets being sent to the delay lines. As an inset, we include a photograph showing both the old flexure stage PZT and the new long-stroke PZT in place at CHARA in neighboring beams.

Figure 7. As part of our upgrade, we worked with Brinell vision to create a filter to suppress the $1.319\mu\text{m}$ laser light from the CHARA metrology to make J-band observing possible. We show a short pass filter that suppresses the laser light by OD 4.5, allowing first on-sky J-band fringes at CHARA (see top right panel for fringe snapshot from control gui and the bottom right for the envelope estimate).

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