Integrated Testing Summary

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1 Introduction

After the thermal testing of the individual FTT mounts was completed successfully, the next stage in the testing process was to put all the components on a baseplate, and see if this ensemble passed the requirements laid out for temperature stability. This full integrated test consists of a test dichroic, a lens, two fold mirrors and a camera. To perform the test, all but the camera are placed on the baseplate inside a temperature controlled chamber, and the temperature is forcibly changed by 5 °C or more over a timescale of a few hours. A laser beam propagated through the system is (intended to be) used as a proxy for the motion of the components, and the spot motion can be compared to the allowable movement in the specifications.

A comprehensive diagram showing the layout for all components during most of the tests described in this document is supplied in figure 1. The most important feature of this test layout is the presence of a beam from the laser that passes straight through the dichroic, before being focussed onto an ancilliary camera by a lens. This reference beam is used to monitor the motion of the laser, which is significant: as the table is locally cooled,[1] it warps, and this causes the laser to tilt. By subtracting the motion of this reference beam from the detected movement of the propagated beam, we believe we are able to separate the effect of the laser tilting from the contribution from the optics moving.

The original integrated test involved a fully populated baseplate, and was conducted in time for the PDR review. This showed a significant failure (failing to meet the specifications by more than a factor of ten), with a characteristic that would become extremely familiar.[2] The instigation of the cooling or warming induces a significant step change in y component of the spot separation (see figure 2). However, for the remainder of the testing period – where the temperature is still changing by several degrees – the spot is extremely stable, easily meeting the requirements.

By the time of the PDR, the general opinion was that this was a calibration error that we would be able to remove in swift order. What follows is a summary of the subsequent tests that we have done, placed in pedagogical rather than chronological order. These tests

[1] Cooling of the table only occurs as a consequence of cooling the chamber resting on the table, but must be considered.

[2] This document only describes the investigation into the y-motion characteristic, not the x-motion instabilities.

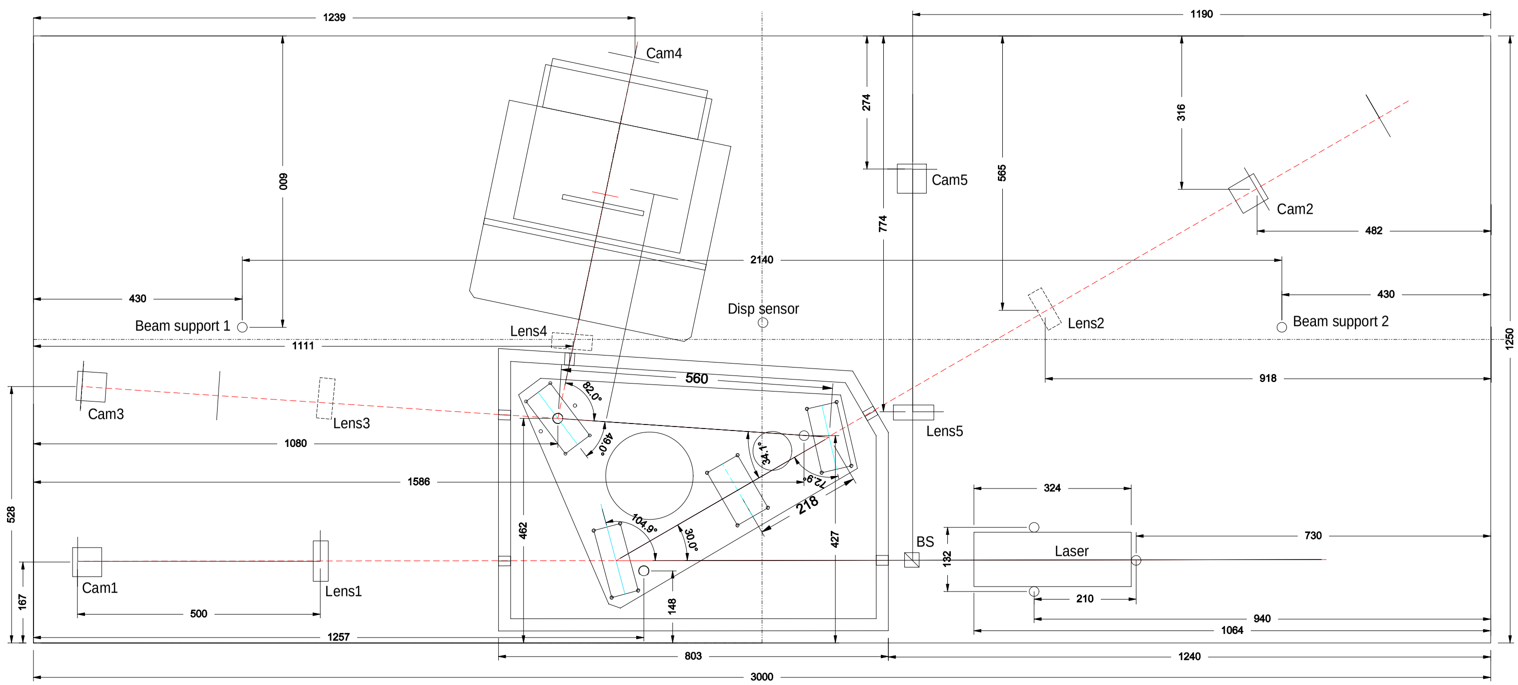

Figure 1: Comprehensive layout for the integrated testing. The beam emitted by the laser enters the test chamber, and is split by our test dichroic. 50 % of the beam goes on to lens 1 and camera 1, and forms our reference beam. The remainder of the beam encounters the lens, is reflected by the first fold mirror and then the second fold mirror. Note that by removing neither, one or two of the fold mirrors, this propagated beam can be observed by camera 2, camera 3 or camera 4. Most often, we have removed the lens and the second fold mirror to examine the propagated beam at camera 3 by using lens 3.

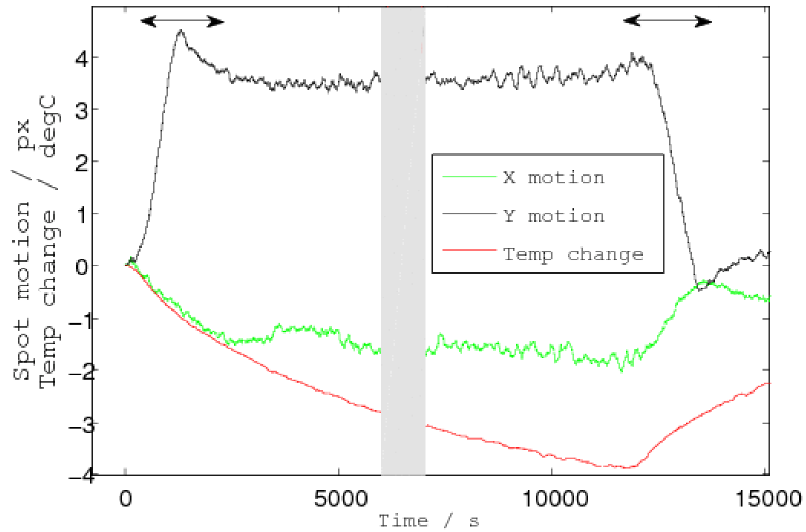

Figure 2: Characteristic failure of integrated test, taken from PDR repot.

primarily revolve around changing a single element of a test before repeating it, observing the effect (if any) on the step, and hence hoping to establish the cause.

2 Reduced Test

This undesireable step-like behaviour was also seen with a 'reduced' integrated test, and so in the interests of simplicity this test arrangement was used for the vast majority of this investigation. For the reduced integrated test, we have removed the lens and the second fold mirror, leaving us with just the dichroic and the first fold mirror on the baseplate. We then use cameras located at the positions labelled 'Camera 1' and 'Camera 3' (see figure 1) to record the laser motion and the motion of the two remaining mounts. This test forms our baseline for many of the subsequent tests described, and with the cameras in these location the differential spot motion between the two cameras in y is almost invariably two pixels. An example result from this reduced integrated test is shown in figure 3.

The temperature profile that the system is exposed to is broadly speaking the same in each experiment. Firstly, the chiller temperature is raised to 27 °C and the system is allowed to stabilise somewhat. Then the chiller temperature is set to 11 °C and held there for around ten hours. Then the chiller is turned off, and the system allowed to return to room temperature simply by equilibriating with its surroundings. The test chamber experiences a temperature change of at least 5 °C during this process, with the exact number depending on the ambient temperature in the laboratory.

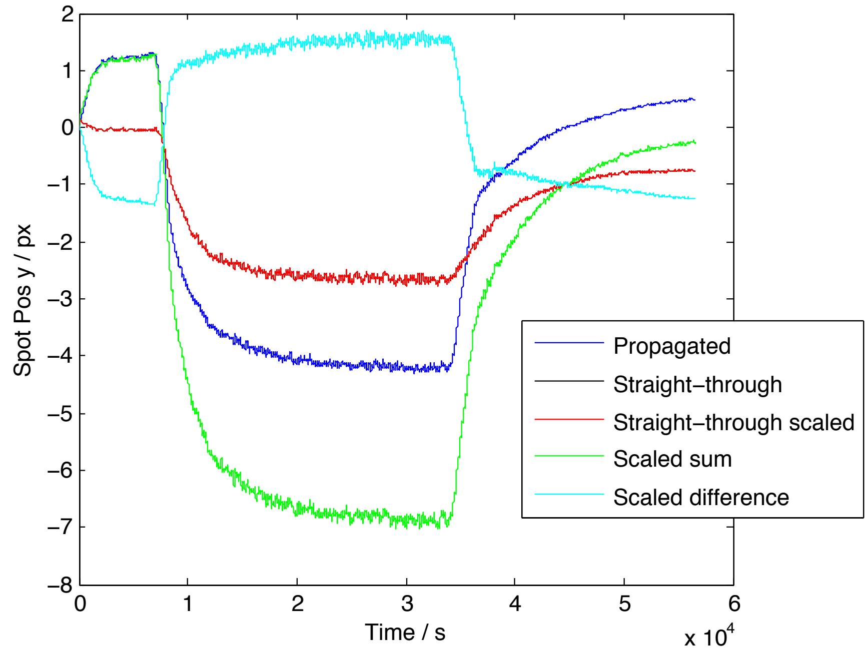

Figure 3: Example result from the reduced integrated test. The 'straight through' beam is the beam detected at position 'Camera 1' and the 'propagated' beam is the beam detected at position 'Camera 3'. Our characteristic step is almost exactly two pixels.

3 Investigation Summary

Each subsection describes the experiments conducted to either eliminate or strengthen the case for some part of the integrated test being responsible for failing to meet the requirements.

3.1 Elimination of Large Interfaces

The two pixel step was unable to be affected by either removing the kinematic seats from the baseplate (leaving its feet – which are steel spheres – resting on the tabletop). Unscrewing the mounts from the baseplate, leaving them resting on the baseplate also had no effect.[3] Changing the length of the legs also had no effect on the two pixel step. This last test indicates that the step is not caused by stresses in the baseplate being induced by the friction between the feet of the baseplate and the table surface.

3.2 Mounts

We do not believe the mounts are causing this step to appear. The interface between the mount and the glass has been tested at the mount testing stage, where the mounts performed adequately. However, the body of the mounts were not tested at that point, and nor was the interface between the mounts and the baseplate; the latter was quickly elimintated (as described in section 3.1), but the former remained a concern.

It was reasonably suggested that as the temperature changes, the mounts may be bending about their horizontal axis, causing the differential motion in the vertical axis on the cameras. This was not tested for at the mount testing stage. If this were the case, then we would expect the mounts to behave in the same fashion regardless of their location in the test chamber. We therefore conducted some tests with a shortened geometry, illustrated in figure 4.

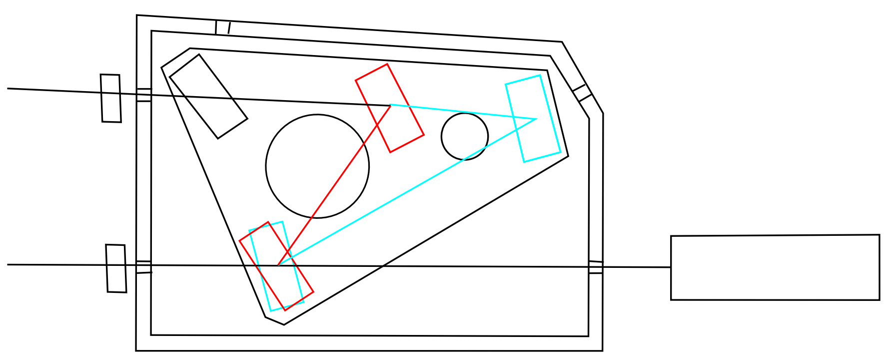

Figure 4: Differing positions of the fold mirror and dichroic, with the usual configuration in cyan and the shortened geometry configuration in red.

[3]Once this was established, we didn't screw the mounts onto the baseplate for future tests. This meant that when we changed the baseplate, perhaps for one that didn't – or couldn't – have screw threads put into it, the subsequent results were more comparable between tests than they would have been otherwise.

We would expect a small reduction in the differential motion with this reduced geometry if the mounts were bending in this fashion, as with the reduced geometry the beam is incident at a slightly more oblique angle on each mirror, and so the bending will deflect the beam slightly less. However, with this reduced geometry, we saw the differential motion reduced far more than we expected, shown in figure 5.

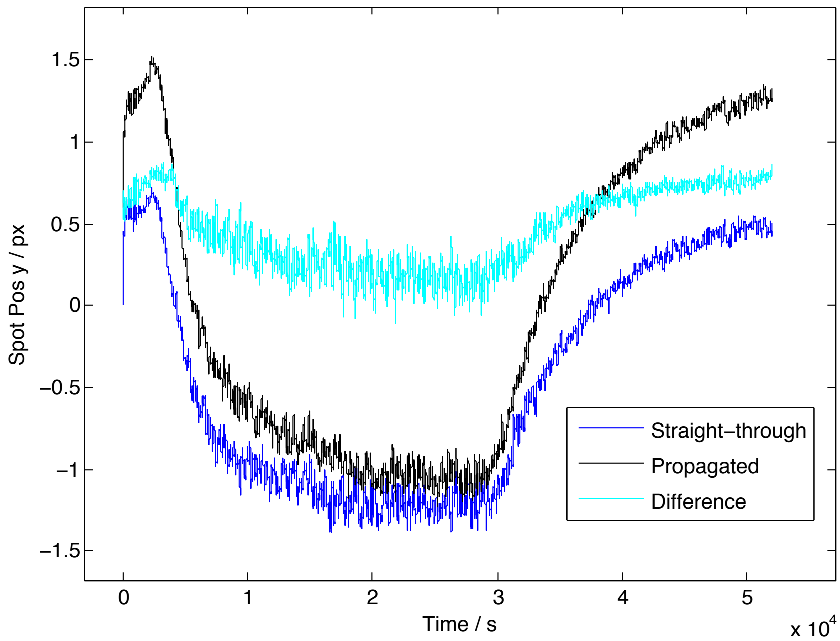

Figure 5: Result from a test with the shortened geometry. The two pixel step has been dramatically reduced in size, simply by repositioning the fold mirror.

This reduction in differential motion with the shortened geometry is too large to be explained simply by the changed angles, so we don't believe that the mounts are bending. This belief is supported by tests with a 4 in COAST mirror instead of the fold mirror, and also by a test where we replaced the dichroic with a glass block. These both showed step sizes of approximately 2 pixels with the normal geometry.

The result from the shortened geometry test could be explained by the camera-lens systems not being focussed correctly, which is discussed and eliminated as a possibility in section 3.4. It could also be explained by the baseplate warping during the test. This possibility is explored further in section 3.5.1. It could also be understood by the fact that the two beams travel different distances in potentially stratified air, but this is ruled out by tests where the feet are repositioned without changing the geometry, also described in section 3.5.1.

3.3 Elimination of Table Motion

We know – via direct measurement with temperature sensors and LVDTs – that the tabletop is cooling when we conduct these experiments, and warps as it does so. We have established that this warping is responsible for the motion of the straight-through beam. We showed this by conducting an experiment where we moved the laser to a nearby optical table in another room, and putting the chiller (which was originally next to this second optical table) in a third room, far from both optical tables in an attempt to mitigate any effects from the heat vented from the chiller. The experiment was then exposed to the usual temperature cycle, and the results are shown in figure 6.

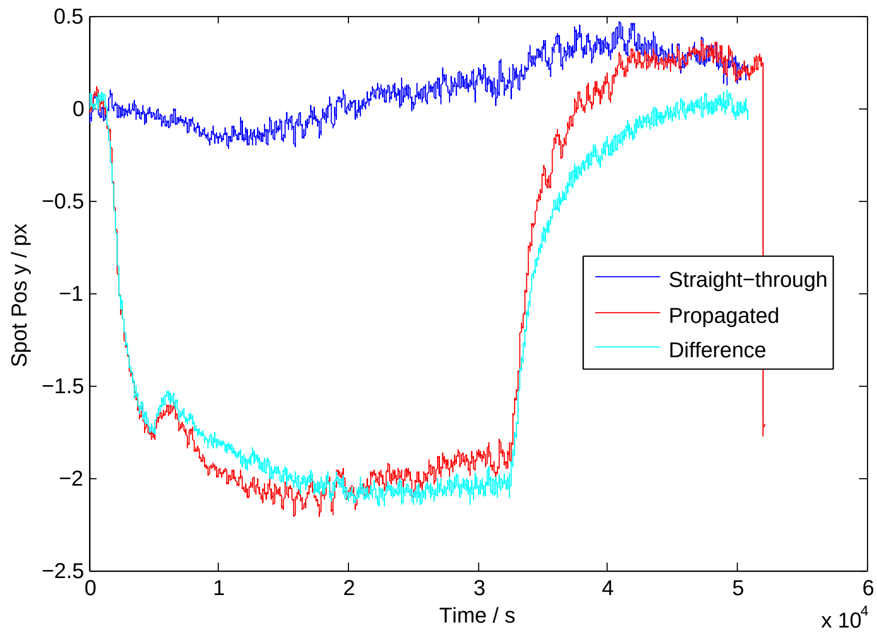

Figure 6: Reduced integrated test conducted with a bath (see section 5.3) surrounding the baseplate and water pipes, which in this experiment are in direct contact with the baseplate. The laser is on a second optical table, and the chiller is separated by two walls from both optical tables involved. The straight-through beam shows no effects suggesting an influence from the chiller, but the differential motion is the usual two-pixel step.

The straight through beam here has been successfully isolated from the temperature variation of the enclosure. While it drifts slightly, it doesn't show any sudden changes correlated with the clear steps in the propagated beam. The propagated beam still shows a clear step of two pixels during both the cooldown and the warm up. Note that the straight through beam spot motion would still be sensitive to relative shear between the camera and the lens being used for observing the straight through beam, but exhibits no signs of this. This suggests to us that the two pixel step of the propagated beam is related to the objects on the baseplate, and not to do with the table motion[4].

[4]This conclusion assumes that the table deformation experienced by each camera-lens pair is the same.

While this result establishes that the step-like motion of the straight through beam we have seen in previous experiments is connected to the table warping and laser tilting, it does not definitively eliminate the table warping as the cause of the differential motion. Further experiments have been conducted in order to achieve this.

The table warping is going to have two major effects on the experiment:

- Tilting the baseplate.
- Shearing the elements of the lens-camera pairs relative to each other and the incident beam.

The first effect has been demonstrated to not be a concern by taking advantage of one of the significant benefits of the reduced integrated test. With two reflective surfaces, this experiment has an inherent insensitivity to the baseplate being tilted. It is the case that if a beam is reflected from two mirrors with antiparallel normals, then bodily rotation of the mirrors about a common point does not cause the angle of the exiting beam to change (though it does shear the beam). In our case, the normals of the mirrors are not antiparallel, but are only separated by 2°. By placing shims of known thickness under the feet of the baseplate, I was able to generate very controlled tilts of the baseplate about the two axes parallel to the tabletop and compare the resulting motion of the propagated beam to the motion predicted by ZEMAX for this system. These motions were in good agreement (46″ c.f. 39″ and 19″ c.f. 20″), confirming that this system is as sensitive to tilt as we expect. For the table to be causing the differential motion we are seeing, with this level of sensitivity to tilt, the surface of the table that the baseplate makes contact with would need to be changing height by 200 µm during the experiment. The motion of the table we have directly measured is 6 µm across two meters of the table during the experiment, so we are very confident this is not the source of our step.

To further confirm this, we have also done tests with zero, one and two fold mirrors on the baseplate. During these tests, we keep a camera at the camera 1 position (see figure 1) but the second camera is positioned at the camera 2, camera 3 or camera 4 position when zero, one and two fold mirrors respectively are being used. By doing this, we are able to see how much of the differential motion each reflection introduces. If the baseplate were bodily tilting, we would expect the differential motion in the one- and three-reflection cases to be orders of magnitude different from the two reflection case, as those configurations do not share the insensitivity to tilt of the baseplate that the test configuration with two reflections posesses. Upon conducting these tests, we found that the differential motion seen was 1 pixel, 2 pixels and 2.3 pixels in the case of zero, one and two fold mirrors being used respectively. As the two-reflection case is similar in magnitude to the other cases, we are confident in eliminating the baseplate tilting bodily as the source of the step. The ratios of the step sizes between these results is also circumstantial evidence pointing twoards the baseplate – see section 3.5.1.

This assumption seems valid as they were place symmetrically on the table for this experiment, and is further backed up by experiments described later in this section.

The second potential effect of the table warping we must consider is the relative motion between the two elements of each lens-camera pair. The fact that this is not influencing our experiment was confirmed in two ways:

- By moving the entire experimental apparatus from the locations in figure 1 up the table to new locations, such that Camera/Lens 3 and Camera/Lens 1 were either side of the long centre line of the table. If the table were causing the differential motion by shearing the lenses relative to the cameras by different amounts, then by moving the cameras to either side of the centre line from their original positions, we would expect to see a reduction in the differential motion if the table is deforming symmetrically. We saw no change in the differential motion.
- The straight through beam in the experiment with the laser on a separate table showed no sudden steps, even though the straight through beam was still sensitive to relative shear of the CCD and lens. This means that the step cannot be due to such motion.

Having demonstrated that the two main consequences of table motion will have no effect on our experiment, we conclude that the table motion is not responsible for the step we have been seeing.

3.4 Elimination of defocussed lenses

The straight-through and the propagated beams in our experiment travel different path lengths, and so any tilt introduced by laser (which we know is happening) will also introduce differential shears. Ideally, this should not be a concern: shearing a beam passing through a lens does not change the location of the image in the focal plane. However, if the lenses are not focussed correctly, then this is not true, and a shear of the incident beam will cause a movement of the (slightly defocussed) image.

At the time this investigation began, shearing the laser by 3 mm caused a 2.5 pixel motion on one camera and a 4 pixel motion on the other camera. After carefully refocussing the lenses, a 3 mm shear instead gave 0.1 pixel motion on one camera and 0.2 pixel motion on the other. A subsequent repeat of the two-mirror, reduced integrated test showed no change in the step size (see figure 7).

3.5 Discussion of the baseplate

3.5.1 Evidence suggesting the baseplate is at fault

Our best guess for the culprit causing our two pixel step is the baseplate, though the exact mechanism it is using remains elusive.

During the cooldown process, we see a temperature difference between the top and bottom surface of the baseplate of around 0.1 °C. This is ten times the temperature difference assumed to generate figure 8, which is a FEA of the baseplate.

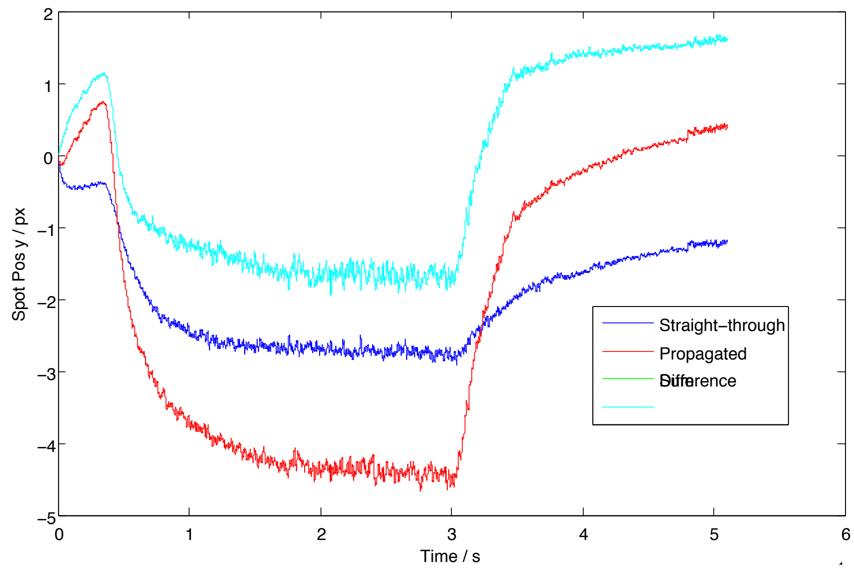

Figure 7: Reduced integrated test after refocussing the lasers. The two pixel step remains, and so we conclude that the slight defocussing of the lenses was not responsible for the step.

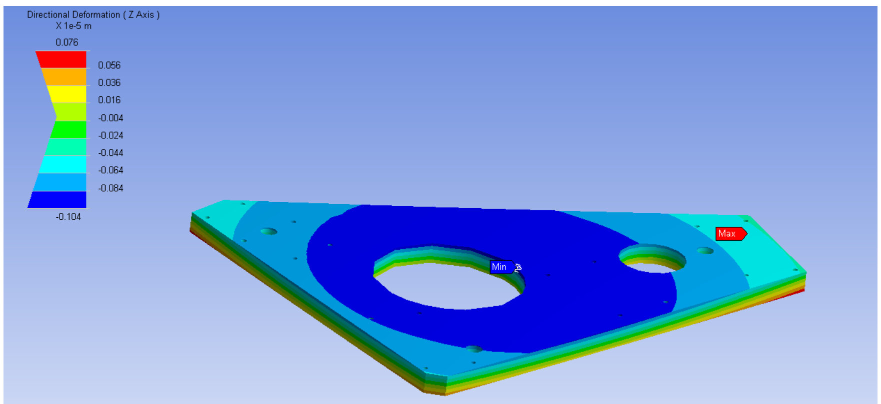

Figure 8: Predicted deformation of the baseplate with a 0.01 °C difference between the top and bottom surfaces.

This FEA, if representative of what is happening, goes a long way to explaining both the results from the shortened geometry test and the results from the one-, two- and three-reflection tests.

- **Shortened geometry:** The substantive difference between the regular reduced test and the test with the shortened geometry is the position of the first fold mirror. If we examine figure 8 in conjunction with figure 4, we can see that this mirror is repositioned from the region of biggest movement at the end of the baseplate to the region of smallest movement, near the centre of the baseplate. This would explain the large reduction in the differential motion seen in the test with the shortened geometry.

- **1-2-3 reflection tests:** The ratios of the differential motion are also explained by the baseplate warping. When we compare the propagated beam detected at Camera 2, Camera 3 and Camera 4, we see differential spot motions sized 1 pixel, 2 pixels and 2.3 pixels. All three reflectors (i.e. the dichroic and the two fold mirrors) are located on the baseplate where it is warping significantly. However, the normals of the dichroic and first fold mirror are pointed towards the centre of the baseplate, whereas the normal of the second fold mirror is closer to being orthogonal to the line joining the mirror to the centre of the baseplate. This means if the baseplate warps, then the dichroic and the first fold mirror will cause the beam to tilt similar amounts, but the tilting of the second fold mirror will have a much smaller effect. This explains the ratios of the differential spot motions seen.

The baseplate is made out of a 1 in thick piece of tooling plate. We also acquired a block of aluminium tooling plate that was two inches thick. Being twice the thickness of the original baseplate, by conducting the same two-reflection experiment we expect to see some improvement here if the baseplate is responsible. The results from this can be seen in figure 9. Note that for this experiment, the 2 in tooling plate was not machined into a baseplate, but only cleaned up, and remained a rectangular slab.

It is clear that this thicker baseplate has had a significant effect on the differential spot motion – it is very different from the usual 2 pixel step that we have seen in e.g. figure 3. It is easiest to believe that the improved performance is simply due to the thicker baseplate being stiffer. This cannot be the whole story, however, as we expect the deflection of a beam under load to go as the thickness squared, but we only saw a factor of two reduction here.

However, because of the increased thermal mass the temperature of the chamber changes much more slowly, and so it is also possible the mechanism causing the spot separation to change has simply slowed. One could argue that in figure 9, the system has not been held cold for long enough for the movement to complete, and so may have ended up going the full two pixels expected if given enough time.

The influence of the incrased thermal mass has been shown to be neglible through another test. This places the dichroic and fold mirror on the 'normal' baseplate for the experiment, but also places the thicker tooling plate in the chamber to greatly increase the thermal mass contained within the chamber. The results are presented in figure 10.

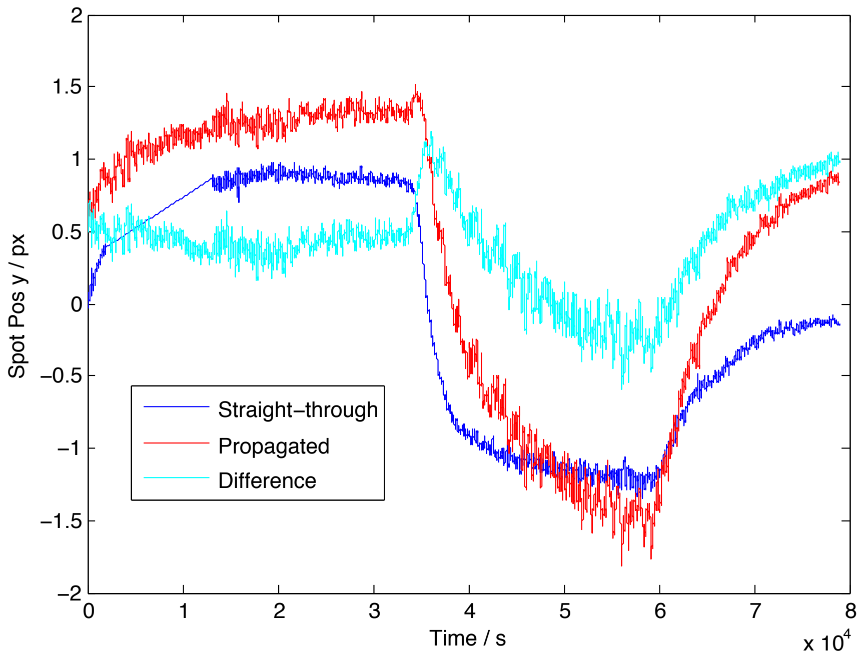

Figure 9: ‘Reduced’ integrated test with two mirrors on a two-inch thick piece of aluminium tooling plate.

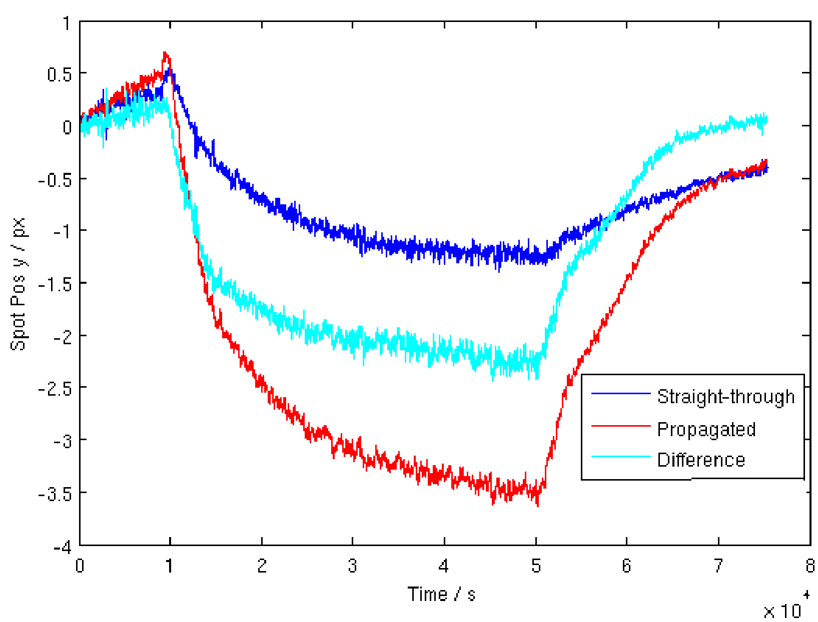

Figure 10: ‘Reduced’ integrated test on the normal baseplate, but with a much higher thermal mass in the test chamber. The two pixel step appears as normal.

In this experiment, we see the two-pixel step, though it is slower than in the usual case. The increased thermal mass seems to have slowed down the step slightly, though it still comfortably completes in the time the chamber is held cold. It is therefore not the thermal mass inside the chamber that governs the step size, but some other property of the thicker tooling plate that caused the improved performance.

A lot of the evidence suggesting the baseplate is at fault presented thus far is reasonably circumstantial, but there are a few experiments that strongly point towards the baseplate being at fault. For the first experiment, we supported the baseplate on ball bearings, but put them much closer to the center of the baseplate than the usual supports; the location of the new supports can be seen in figure 11, and the results from the test in figure 12.

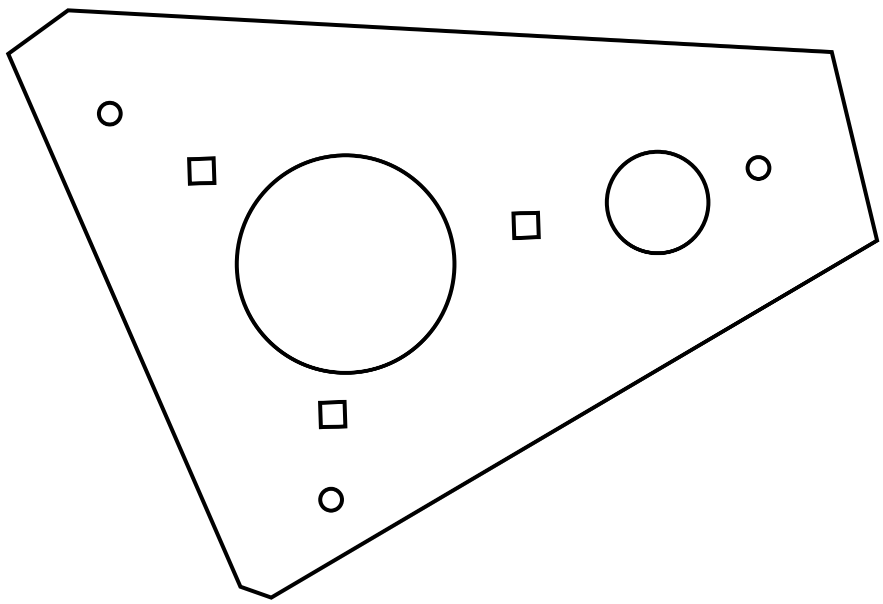

Figure 11: Diagram showing the location of the alternate set of feet for the baseplate. The normal locations are indicated by the three small circles, and the modified locations are indicated by the three small squares. With these modified locations, the pre-stress on the plate is much higher, due to the location of the optics.

We believe the interpretation of the reduced step in this case is reasonably straightforward – the new location for the baseplate's feet do not support the mounts on the baseplate as much, and support the baseplate closer to its center of mass. This causes a pre-stress to be applied to the baseplate and the cause of the step, whatever it is, is unable to lift the mounts as much against this extra force. This causes a reduction in the step size.

The second test that points towards the aluminium baseplate being the culprit is a test we conducted with a steel plate. This is only rectangular, and had not been machined to the shape of the aluminium baseplate, but was the same thickness as the baseplate and was long enough that the two-reflection reduced integrated test could take place. The result from this test is in figure 13.

Clearly, these results show no two pixel step. Two small events can be seen where the

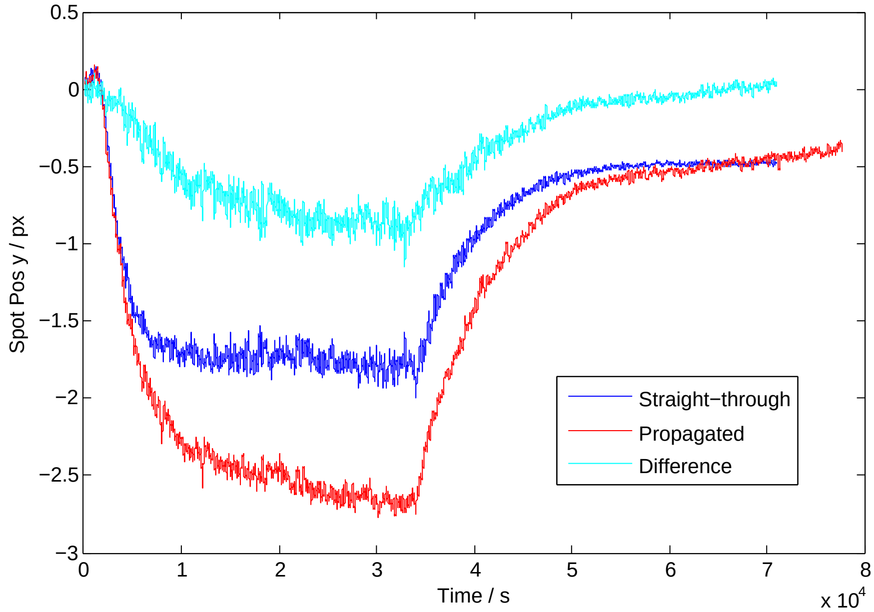

Figure 12: Results from the test with the supports placed closer together. Our two pixel step has shrunk to a only one pixel, and is now much slower.

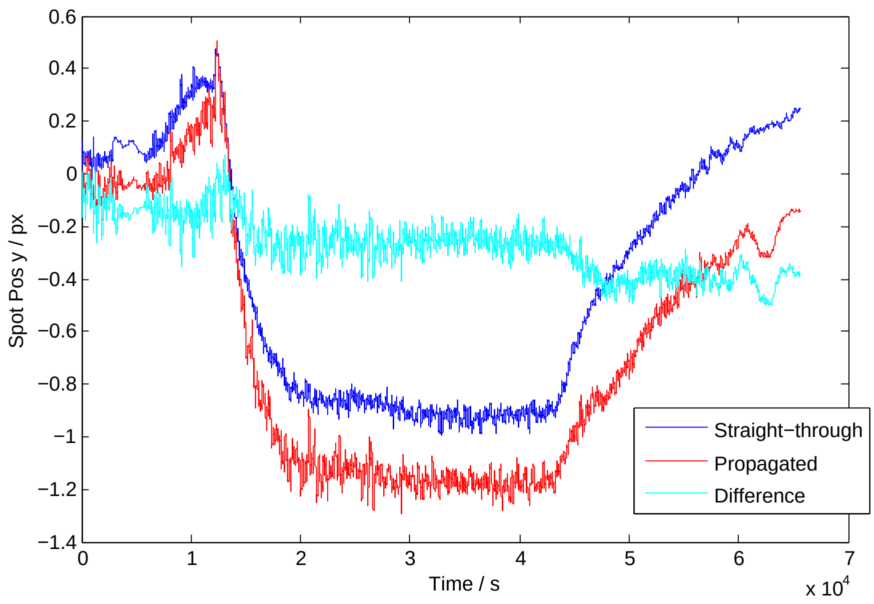

Figure 13: Results from the test with a steel baseplate. Note that for clarity, a constant slope has been subtracted from both the propagated and the transmitted beams; we believe that this was due to the laser setting, and has no impact on the differential motion. Clearly, there is no large step to be seen.

cooling started and ended, but the degree of improvement when compared to the aluminium baseplate is striking. The steel baseplate is heavier and stiffer, and also posesses a much smaller thermal conductivity, than the aluminium baseplates; perhaps one of these differences is responsible. It is difficult to draw a conclusion as to which of these properties, or another not mentioned, is responsible without knowing the mechanism that is causing the step.

Using a steel baseplate does not solve our problems, as it is heavier than the aluminium baseplate and also introduces interface issues between the aluminium mounts and the steel baseplate, with materials of different CTEs in contact. We would prefer to stiffen the aluminium baseplate. An initial experiment to this end has been conducted, by attaching a large aluminium bar (with a square cross-section approximately 50 mm by 50 mm) to the baseplate, and then conducting the usual reduced integrated test. The result from this test are shown in figure 14.

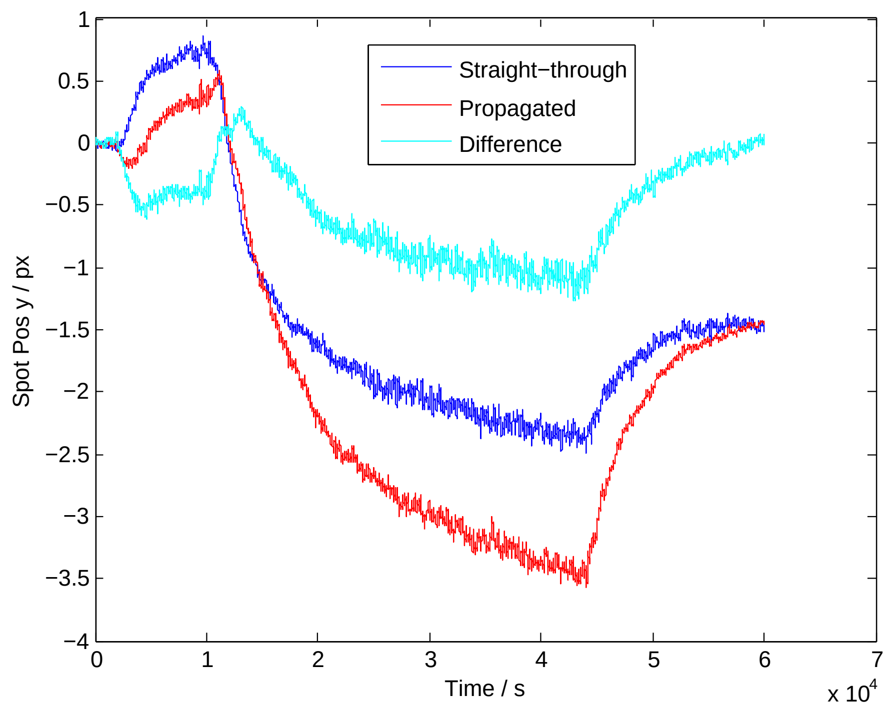

Figure 14: Result from the test with a stiffened aluminium baseplate. It is clearly very different from the same test with the same baseplate without the stiffening bar, and bears a striking resemblance to the test with the thick aluminium baseplate.

Clearly, the large aluminium bar we've attached to the baseplate has stiffened it (as the overall excursion is much less than the two pixel step we usually see), but has caused it to behave very much like the thick aluminium baseplate (see figure 9), including the initial rise on cooling. We tentatively attribute this to a thermal equilibriation process that we are not giving time to settle out at the start, but does over the course of the experiment, explaining why a similar bump is not seen when the system begins to warm. At this juncture, we believe that using a thinner stiffening bar would retain the majority of the gains in stiffness, but eliminate this thermal effect.

We have also explored reducing or increasing the load on the baseplate. One test was run after putting an 11 kg mass on the center of the baseplate, and another was run after putting supporting springs under the baseplate, in similar locations to where the feet were moved to (see figure 11). In the case of the 11 kg mass, the initial addition of the mass caused a substantial deflection (more than 20 pixels), and then we exposed the system to the usual temperature cycle, the result of which is shown in figure 15. The result from the test with the supporting springs is shown in figure 16.

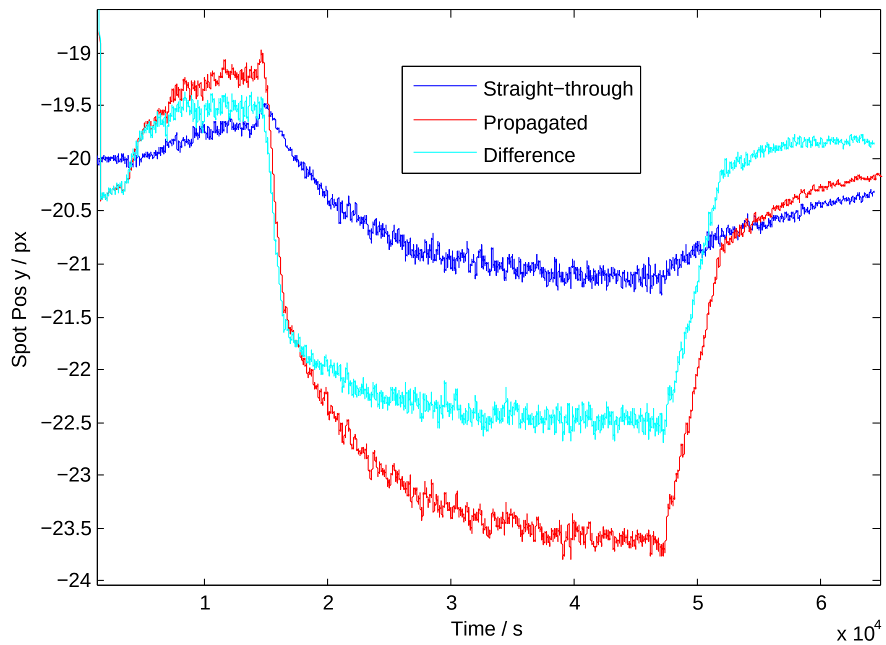

Figure 15: A slightly enlarged step size (by about 0.5 pixels) is seen when the baseplate has been additionally loaded with an 11 kg mass.

By increasing the load on the baseplate, we get an enlarged step size, and by reducing the load on the baseplate (or rather, increasing the support provided to the baseplate), we get a reduced step size. This seems to indicate that the effect, whatever it is, has a magnitude dependent on the load that the baseplate must support intrinsically. However, it is only triggered by a change in temperature.

These tests described in this section all indicate that it is the baseplate that is responsible for step. Further compelling evidence comes from our tests where we cool only the baseplate, where we still see the step. These tests are described in more detail in section 5.2.

3.5.2 Evidence pointing away from the baseplate

It would be remiss to present the above evidence without also presenting results of investigations that seem to suggest the baseplate is not at fault.

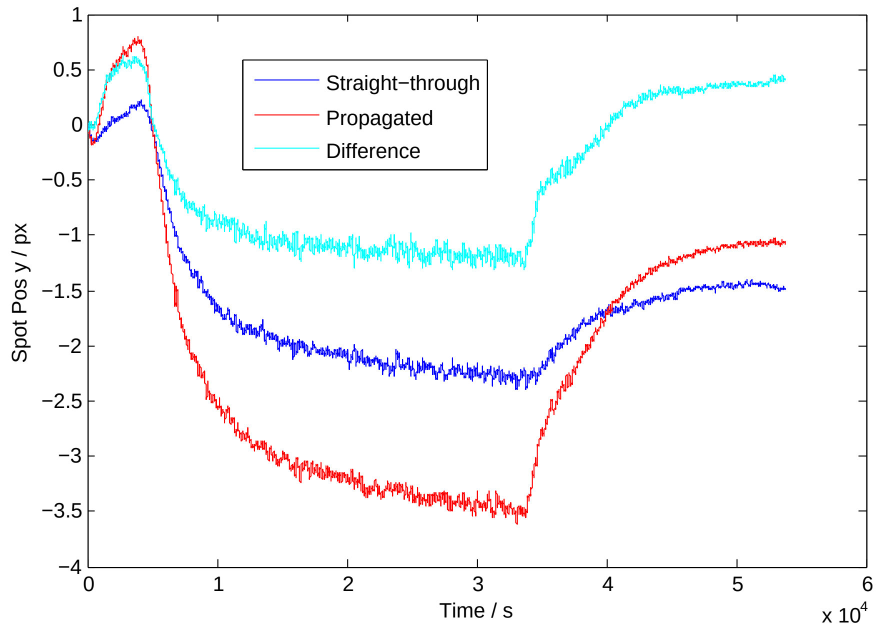

Figure 16: A slightly reduced step size (by about 0.5 pixels) is seen when the baseplate has been additionally supported by springs.

The most straightforward theory for what would be driving the bending of the baseplate is a temperature differential between the top and the bottom surface – indeed, the FEA presented in figure 8 suggests that only a very small temperature differential is required before warping occurs. If the baseplate warping is due to this, however, we have been unable to influence it.

We have tried covering the top surface of the baseplate with cardboard and then subsequently a layer of the same insulation used to build the test chamber. This had no noticeable effect on the two pixel step. We also used this insulation to cover the cooling plates of the chamber, so that none of the components had line of sight to the cooling plates, removing much of the radiative cooling. Again, this had a negligible effect on the step size. The general feeling is that if the baseplate is warping due to differential temperature between its top and bottom surfaces, then we shoud have been able to influence the step size through at least one of these modifications to the experiment; even if not prevented, the rate at which they appeared should have been changed.

The most drastic change we've explored with the baseplate is having it anodised. The entire baseplate was treated in this manner, including the screw threads. It was then exposed to the traditional temperature cycle, the result of which can be seen in figure 17. The two pixel step remains, and the anodising process seems to have had very little impact other than turning the baseplate black.

A lightweighted baseplate, with many more holes in it has also been manufactured. The intention here was to increase the surface area and reduce the mass of aluminium present, causing the plate to thermalise more quickly. Unfortunately, it gave exactly the

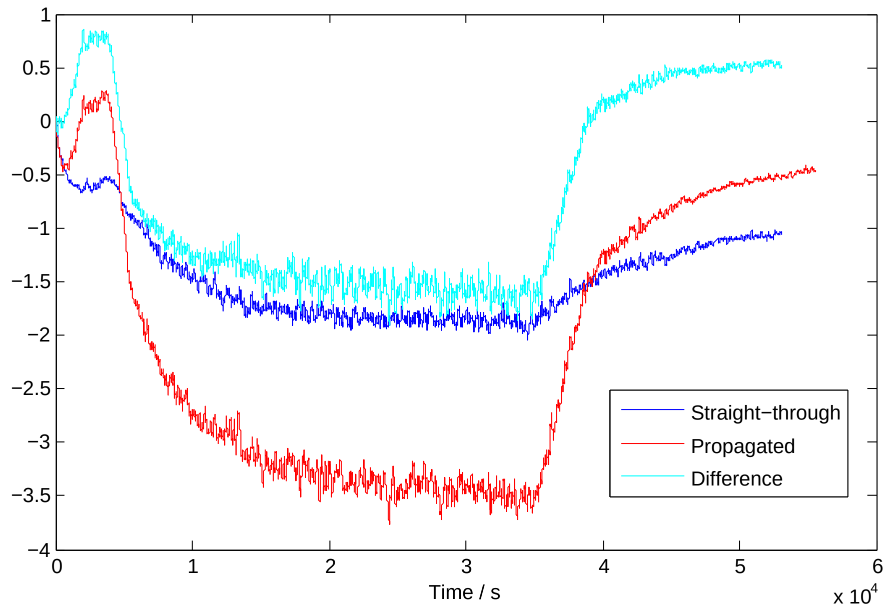

Figure 17: 'Reduced' integrated test with two mirrors on an anodised aluminium baseplate. The two-pixel step is perhaps a little larger, but broardly speaking it has not changed.

same performance as the original baseplate. Sending the original baseplate to be destressed and then repeating this experiment also had no discernable effect on the 2 pixel motion.

A somewhat radical experiment that we conducted was to replace the aluminium baseplate with a granite base. This did result in a change in the step, though only in its recovery speed, not its size. The result from this test is shown in figure 18.

The differential motion being two pixels, but recovering more slowly, is extremely odd. A natural interpretation is that this points away from the baseplate – the size of the motion hasn't changed, but some other property of the baseplate has caused the recovery to slow because e.g. the granite is a much worse thermal conductor. This result remains unexplained if the baseplate is the responsible for the two pixel step, other than simply being a coincidence of material properties.

4 Temperature Profile Investigation

Reasonably confident that we are dealing with a problem with the baseplate, one approach used to attempt to get a handle on the mechanism causing the two pixel step was to vary the temperature profile that the system was exposed to, and see how this caused the step to alter its behaviour. The first test conducted along these lines was to change the temperature of the chiller by one degree at a time until the spot separation started to change, at which point it was held at a constant temperature. A temperature change of three degrees was required before significant motion was seen, at which point the chiller temperature was changed no further; the results can be see in figure 19.

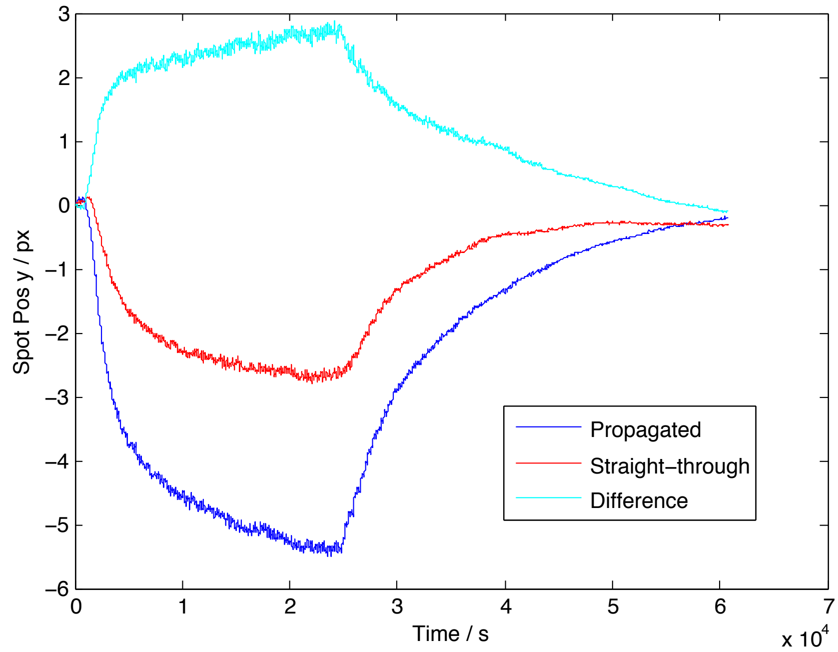

Figure 18: ‘Reduced’ integrated test with two mirrors on a granite baseplate. The step size is still two pixels, though the subsequent recovery is much slower.

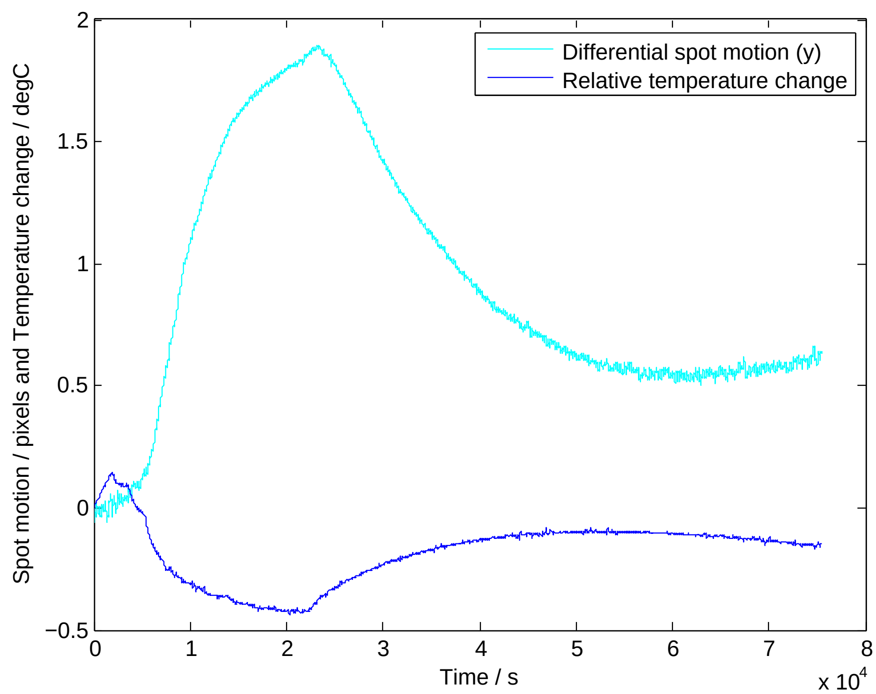

Figure 19: ‘Reduced’ integrated test with very small temperature change of the test chamber. In spite of this much smaller temperature change, we still see (most of) the full two pixel step.

As we still see the full two pixel step, it seems that the mechanism causing the spot separation to change isn't related to the absolute temperature, but to the event that causes the temperature change happen. In addition, the fact that the differential spot motion changes very smoothly in both directions suggests that we're not dealing with a stick-slip mechanism, where we would expect bursts of movement followed by periods of relative benign behaviour.

Two further temperature profiles have been tried, shown in figure 20 and figure 21. In figure 20, the chiller temperature was set to 27 °C and the system allowed to settle. Then, the chiller temperature was reduced by 4 °C, the spots were allowed to settle, and then the chiller temperature was reduced by a further 12 °C and held cold. After many hours, the chiller was switched off and the chamber allowed to warm back up to room temperature.

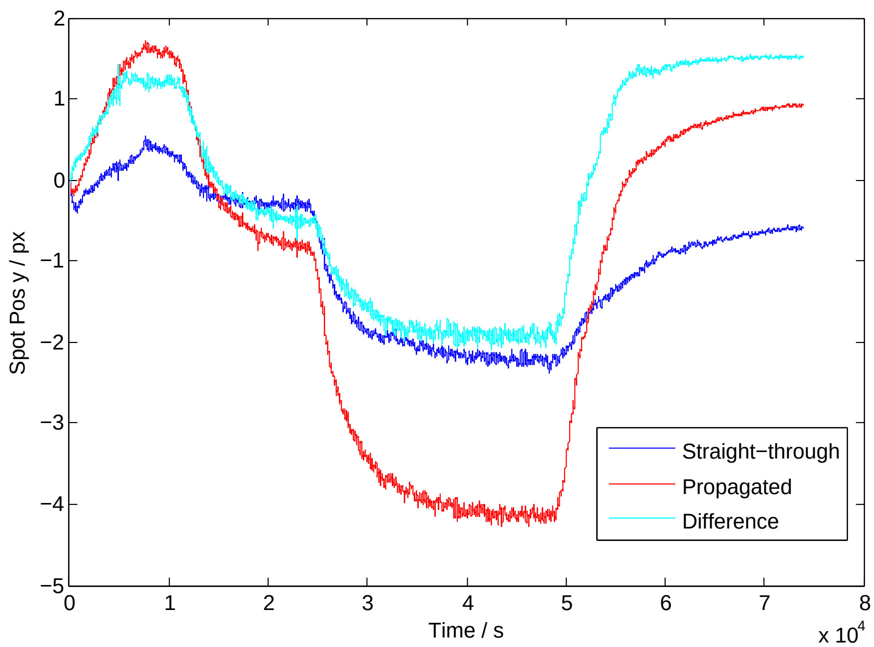

Figure 20: 'Reduced' integrated test with a temperature change on the chiller of 4 °C originally, followed by a change of 12 °C. test chamber. The initial, smaller temperature change gives a larger step (1.6 pixels compared to 1.3 pixels.

These results seem to suggest that once the event – whatever it is – has occurred, it is difficult to get it to happen again, though still possible. These data also seem to suggest it is a little easier to get to happen again if the temperature changes by a larger amount.

5 Changing Temperature Delivery

As well as using the thermal test chamber, some alternate methods of changing the temperature have been used in an attempt glean further information about the process we are observing.

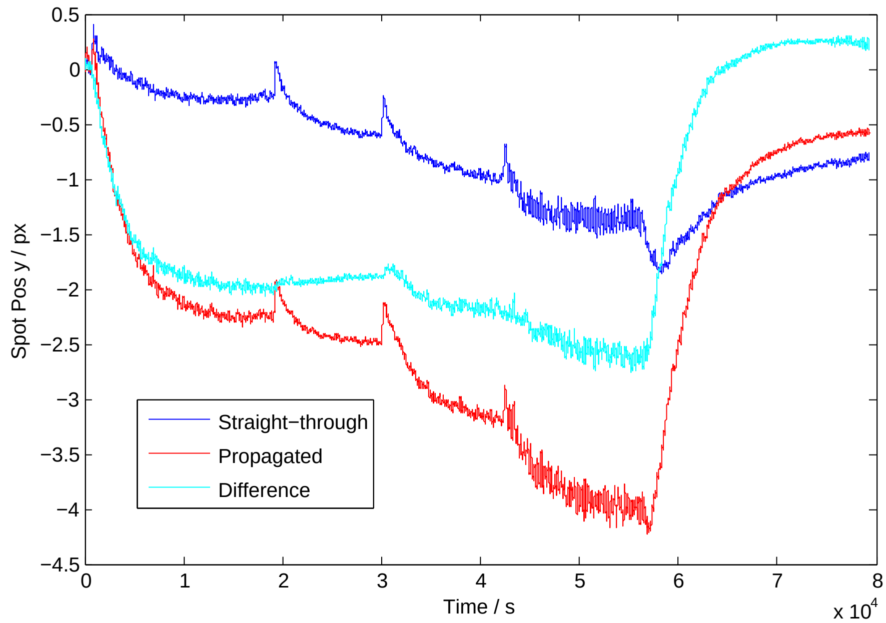

Figure 21: 'Reduced' integrated test with the temperature on the chiller being changed in 4 °C steps. The first step shows a step of nearly two pixels. The subsequent three steps give about another 0.5px of motion.

5.1 No chamber, air conditioning

Taking advantage of the air conditioning in the optics lab was an obvious approach to changing the method of cooling. While this means that we are cooling all of the apparatus being used in the experiement (such as the lenses and cameras), it means that we are cooling the optical table uniformly. The result of the cooldown can be seen in figure 22; the two-pixel step remains. This experiment does have the benefit of showing the good cancellation between the propagated beam and the calibrated beam – the absolute motion of both is much larger than than the two pixel step, but the cancellation is clean. We believe this large common motion is due to the laser tilting as the table cools, despite the uniform nature of the cooling.

5.2 No chamber, pipes on plates

The second alternative approach to cooling was based around putting cooling pipes in direct physical contact with the baseplate, in order to change the temperature of the baseplate only. This stemmed from trying to achieve the opposite of using the air conditioning, where we were explicitly trying to cool everything involved in the experiment uniformly

We conducted this test with both the normal baseplate (figure 23) and the two-inch thick tooling plate (figure 24).

The normal baseplate behaves as it nearly always has – a two pixel step. The thicker baseplate behaves very differently from how it behaved with the chiller, with the step occur-

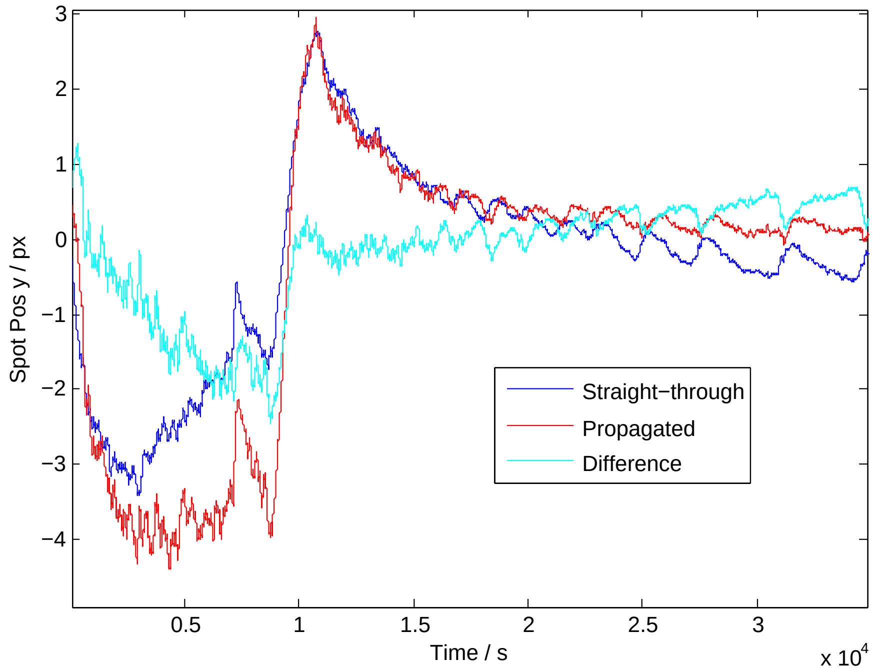

Figure 22: 'Reduced' integrated test with the temperature being driven by the air conditioning installed in the lab. The air conditioning was heating until just before 10 000 s, at which point it was switched to cooling. A two pixel step is very clear.

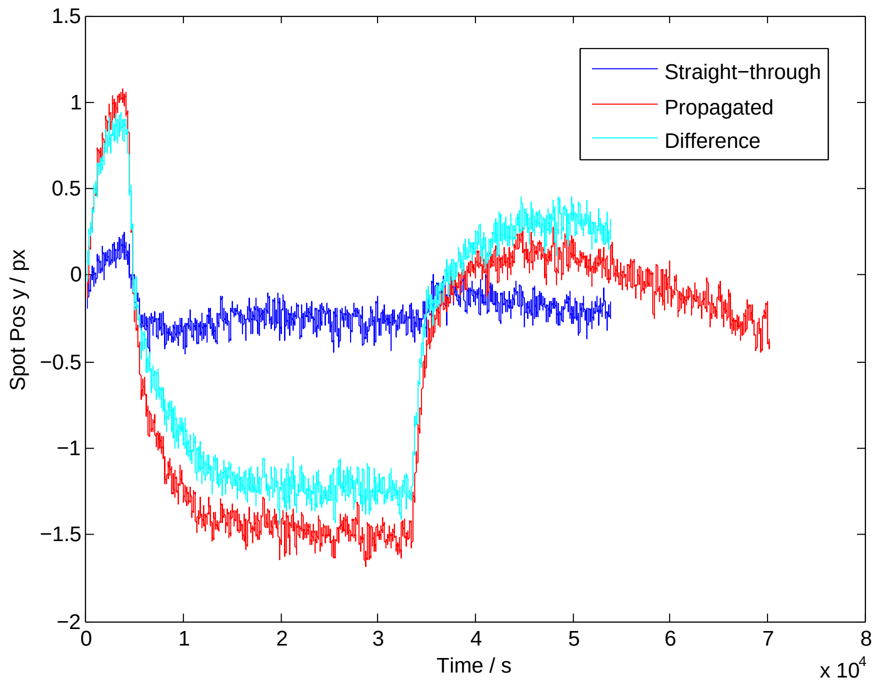

Figure 23: Cold pipes on top of normal baseplate. Even when only the baseplate is being (directly) cooled, we still see a two pixel step.

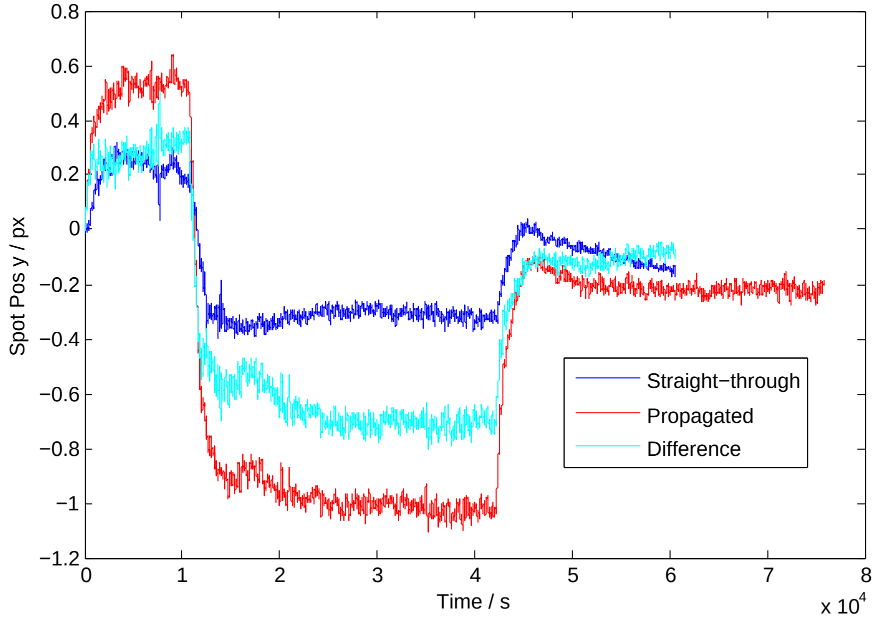

Figure 24: Cold pipes on top of thick tooling plate. We see a one pixel step, similar to when the thick tooling plate is tested in the thermal chamber. However, the speed of the step is significantly increased by being in direct thermal contact with the pipes. In addition, we do not see an initial rise in the differential spot motion as we do when this tooling plate is tested in the thermal chamber.

ring much more suddenly. We attribute this to being in direct contact with the cold pipes; as the thinner baseplate cooled quickly already, we don't see as large a speed up with the thinner baseplate.

In an effort to change the sign of the the step we see, we also tried reversing some of the elements involved in this test – firstly by cooling the baseplate, but with the pipes under the baseplate (figure 25), and then heating the baseplate with pipes underneath it (figure 26).

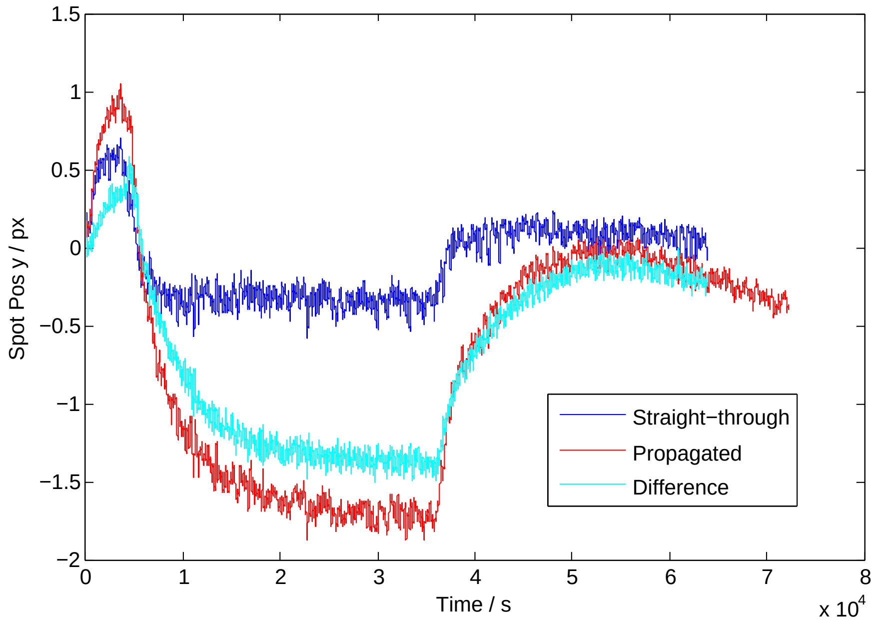

Figure 25: Cold pipes under normal baseplate, with insulation underneath.

We see a two pixel step in both cases,[5] and in all cases the step is down when the system is cooling and up when the system is warming.

The most perplexing result here is that the side of the plate being driven makes no difference – the same sign of step is seen if the top or the bottom side of the plate is cooled, where one would expect to see the direction of the bending change when the side of the plate being cooled was switched if the motion is due to differential expansion and contraction of the two sides of the plate. This remains unexplained.

5.3 Cold bath

After the above experiments with the water pipes in direct contact the baseplate, there was still some concern that the table was being signficantly exposed to the change in temperature, in spite of the steps taken to prevent this. To mitigate this further, a 'bath' was

[5]We do not see a significant step at the start of the hot pipes under the normal baseplate. I believe this is because the system was not 'primed' in the way that the cooling tests are. The cooling tests are originally heated to 27 °C before being cooled. This test was just heated from room temperature without being cooled beforehand. In the very early tests, it was found that if the system was not primed in this fashion, then we mightn't see a step at the start – though we always would at the end.

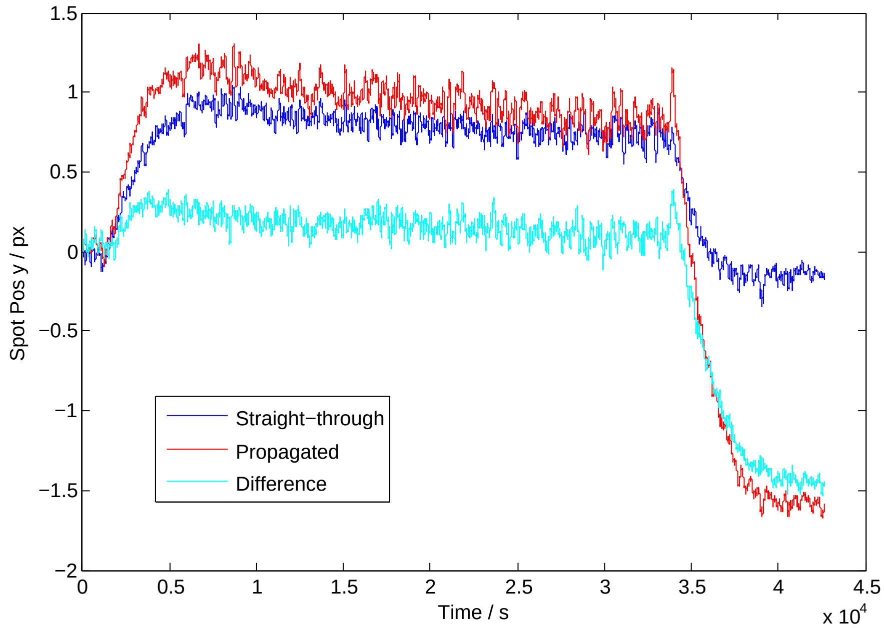

Figure 26: Hot pipes under normal baseplate, with insulation underneath.

constructed for the experiment, with insulation under the plate (save for three holes to allow the baseplate's legs to contact the table) and walls of insulation a few inches high around the experiment. The intention here was to have the bath contain the cold air, at least long enough to separate (temporally) the influence of the cold air on the baseplate and the table. A result of these tests can be seen in figure 27.

Most notably from figure 27, the two pixel step has remained. However, the straight through beam does not have a large step at the start, as we very often see, but instead changes much more smoothly. This suggests that we have at least been moderately successful in preventing the cold water from influencing the table. However, once the chiller turns off, there is a sudden step at the end, which suggests that while we are able to delay the onset of the table chilling at the start we are not doing so at the end. We understand this if at the start, we are delaying the cold air flowing onto the table and then as the bath fills up with cold air, it slowly spills over. Then at the end, the cold water stops flowing, which near-instantly stops the cold air flowing onto the table.

6 Conclusions

The consensus at this point is that there are two major directions we can go:

- Stiffen the aluminium baseplate with fins, and aggressively lightweight it.
- Move to a steel baseplate, which appears to perform better as it is.

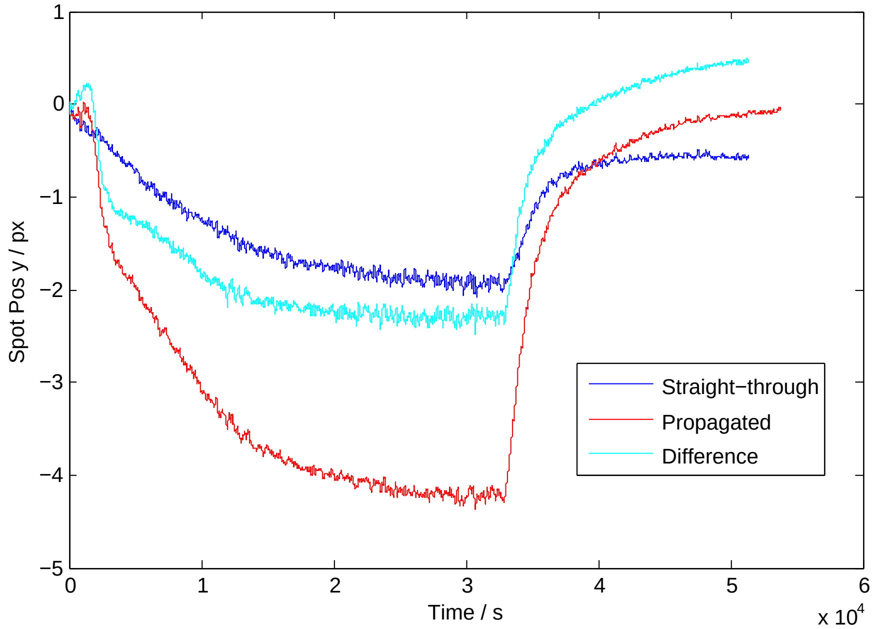

Figure 27: Reduced integrated test conducted with a bath surrounding the baseplate and pipes in contact with the baseplate.

We believe that we should exhaust the possibility of the former working before moving onto the latter, primarily due to the additional interface issues that moving to a steel baseplate would introduce between the baseplate and the aluminium mounts. We propose constructing a baseplate that only has a contiguous thickness of 12 mm to 15 mm, but attaching lots of thin stiffening fins top and bottom, in an attempt to give the system a vastly increased stiffness, without greatly increasing the thermal mass.