Authors response to Anonymous Referee #1

We thank the reviewer for taking the time to read, comprehend and provide useful comments regarding our manuscript. In this document, the reviewer's comments are in italic, and the authors' responses follow each comment in plain bold text.

General comments

The text sometimes becomes hard to follow, mostly because a lack of clear structure. I recommend ordering the information more hierarchically to avoid raising questions to the reader which only get answered much later in the text, especially in section 3 (Optical feedback). Also, many adjectives used either need to be more precise or put in context, otherwise they provide no distinct information (e.g. good, large, small).
Response: This observation was also noted by Referee #2. Section 3 (optical feedback) has been rewritten in light of these comments. We have also removed or better defined the majority of the adjectives listed. We have appended the revised draft for this section at the end of this document.

Line 115 ff: Re-structure paragraph. First, give the numerical value of the error when declaring it as significant, then describe how you arrived at this value and present your solution strategy last.
Response: We have restructured the paragraph which discusses the parking error. It now reads:

"The single sensor (or coarse flag) used on some rotators to determine mechanical park position can result in significant uncertainty of this important initial reference. For example, we see a parking uncertainty in our design of approximately 0.05° (based upon observation of error offsets resulting from multiple consecutive parking cycles). It may be possible to reduce this uncertainty using a second (fine) flag on the stepper motor shaft that is then ANDed with the coarse flag, resulting in a finer resolution for this position. We have not implemented this solution at present, although we allow for this option in our electronics design."

Line 130 ff: Please describe your alignment process in more detail. What would be specialist tools, or is it the level laser you've used? Why is the movement of 2mm of a 5mm diameter spot difficult to resolve?
Response: The alignment process may well be useful for many readers, although the full description is probably beyond scope of this manuscript. We do have an existing 9-page document which will be available upon request for those who wish to read it. Specialist tools that would make the alignment process easier/more accurate include a large and stable optical bench with adjustable mounts, plus a more accurate laser level with a better collimated beam. The poorly collimated laser level we currently use produces a large blurred image and 2mm of movement is indeed difficult to perceive! We have rewritten the paragraph to partially explain the process and better justify our claim regarding the 0.1° accuracy figure. The new paragraph reads as follows:

"Without access to specialist tools, such as a large optical alignment bench and a well-collimated precision laser level, it may be difficult to accurately align mirrors in a solar tracker. For example, during our alignment process we use a bubble level, with an accuracy of about 0.02°, to initially level the tracker. We then use a self-levelling laser of similar accuracy to set a reference mirror vertical. Only then do we begin to adjust the tracker's mirrors, again using the same laser. The resulting alignment accuracy is an accumulation of the laser and bubble level uncertainties at each step in the process, plus other uncertainties involved using an oil-bath for beam reflection and the stability of ancillary optics used in the process. In-use movement and diurnal thermal cycling may

degrade alignment further. We estimate that overall alignment accuracy better than 0.1° is difficult to achieve or maintain in our experience."

Line 157 ff: The following chapters 3.1, 3.2, and 3.3 are hard to comprehend since the information are badly structured. I'd very much appreciate an explaining sentence on how your feedback system works in the first paragraph. If I've understood it correctly, you are not actively tracking the Sun solely by the optical feedback system but are primarily relying on astronomical calculus. The optical feedback than adjusts the error offset vector in a manner that the astronomical calculations provide a sufficiently precise pointing, which is the state you call "locked". Please introduce your concept in the beginning before going into details.

Response: Yes, you are correct in understanding how the system works, but clearly this section describing optical feedback can be improved. Section 3 (optical feedback) has been rewritten in light of comments from both referees. Optical feedback is now explained in a clearer manner in the introductory paragraph. We have appended the revised draft for this section at the end of this document.

Line 177: How do you approach this trade-off in image size and intensity?

Response: This is indeed a trade-off. Not discussed in the draft is the also the physical size of the complete feedback optics package. A larger image will need a longer projection distance (for the same focal length lenses). In practice, the image size chosen was a function of what optics were on hand and the nature of each existing instrument installation (where there was physically room to fit the optics). The pick-off mirror can be enlarged, reducing the system noise, but at the expense of stealing some of the solar light needed for the spectrometer. Section 3 (optical feedback) has been rewritten in light of comments from both referees. We have included further discussion on design concerning image size and intensity. We have appended the revised draft for this section at the end of this document.

Line 183: The partly illumination of the photodiodes is important to get the basic idea of the feedback loop, mention it earlier.

Response: Yes indeed. Section 3 (optical feedback) has been rewritten in light of comments from both referees. The partial illumination of the diodes is now discussed earlier, and the sentence now reads:

"The diodes are positioned to be partially illuminated by the edge of the image, thus ensuring a high response to any movement of the image across their surface.".

Line 190 ff: Algorithm description hard to comprehend. Please introduce in a clear way

- *what's the threshold and hysteresis parameter?*
- *how does the algorithm steer the motors and what happens if parameter bounds are crossed?*

Response: Yes, the threshold and hysteresis parameters need further description and the steering process described in more detail. Section 3 (optical feedback) has been rewritten in light of comments from both referees. These threshold and hysteresis parameters are now clearly introduced early in a renamed section 3.2 "Feedback decision algorithm". We have appended the revised draft for this section at the end of this document.

Line 218: Name the parameters you use for the feedback correction and explain why they are sufficient.

Response: Addressed below

Line 230: Again, you use "the parameters" without naming or explaining them. This would help a lot following your characterization approach.
Response: Yes, we need to name the translation parameter (it was never named!) and introduce it and the rotation parameter earlier. Section 3 (optical feedback) has been rewritten in light of comments from both referees. Specifically, the translation and rotation parameters are clearly named and explained in the renamed section 3.3 "Image translation and rotation algorithm". We have appended the revised draft for this section at the end of this document.

Line 318 ff: Give manufacturer and description to each compartment, e.g. Bluetooth module
Response: The make and model of the major components are given in the figures (e.g. Fig. 7). Some parts such as the Bluetooth serial dongle and AC power supply modules are quite generic, are easily swapped with alternative but functionally equivalent versions. We currently use more than one brand amongst our existing trackers. Including such detail in the body of the manuscript risks disrupting the flow of the description. No change has been made to manuscript.

Line 393: On which stations are these Trackers?
Response: These at Lauder, New Zealand. Unfortunately, the Arrival Heights (Antarctica) spectrometer is not capable of TCCON near-IR measurements so we cannot assess tracker accuracy using the TCCON S-G shift method. It is possible to diagnose the S-G shift using MIR spectral fits, but this feature has not implemented yet. We have further identified the location of the spectrometers (and Tracker1 and Tracker 2) in the paragraph by appending:
"…, based at Lauder, NZ".

Line 404: Description of parameters must be given in algorithm chapter.
Response: I assume you are referring to the "offset error variables". Unfortunately, we used "error offset variable/s" 3 times in the preceding text. We have now corrected this, standardising on the "error offset" version for the manuscript.

Figure 13: How long are the averaging periods?
Response: The periods are quite variable, but we decided that a minimum of 1 hour of "likely" continuous clear sky was needed, per point, to be meaningful. On perfect blue days, in summer, this point might represent up to 12 hours of measurements. The 1-hour duration was chosen so we could plot more days (those that were largely cloud-affected) even though the data might be more variable. We have added this information to the caption by editing the line to read:
"Each point is a daily average value for TCCON spectral measurements taken during days that experienced at least 1 hour of continuous clear sky. "

Specific comments

Line 12/13: Use of "simple" and "just" unnecessary.
Response: We agree that "just" is unnecessary, and this has been removed.
"Simple" remains an important characteristic of this design, so it remains.

Line 48: Can you provide the reflectivity range of the mirrors?
Response: Sure – mirror reflectance (or rather the mirror coating chosen) will need to match the requirements of the spectrometer used with the tracker and the longevity required of the mirrors. We settled on using protected aluminium, which gives a good response from the visible out to about 20 microns. We added the following sentence to discuss our choice:

"Their reflectivity matches the typical wavelengths used for our spectrometers and the protective surface is hard-wearing, allowing for some limited cleaning.".

Line 59: Chapter 2 only covers mispointing of passive solar trackers, please add this.
Response: Thank you, we have added the word "passive" to make this clear. We have also added "…of a passive solar tracker" to the title of section 2.1.

Line 67: Define "vital" role, sth. like "Our trackers enable direct sun observations at sites XY..."
Response: We think "vital" is not needed, so it has been deleted.

Line 76: Define "small changes"
Response: We have added the line:
"For example, to improve our understanding of the carbon cycle we require a measurement precision of about 0.25% (e.g. Rayner and O'Brien 2001).".

Line 78: Add "passive" to the chapter title
Response: Thanks, yes clearly needed. We added "…of a passive solar tracker" to the title of section 2.1.

Line 97: "required" instead of "needs used"
Response: Thanks, change made.

Line 139/40: remove "simple" and replace "good" with something more descriptive
Response: We're reluctant to imply that no passive solar trackers could achieve better than 0.1% accuracy – and we imagine some skilled, well-resourced designers have achieved this. Hence, we use the word simple, which covers our design. We agree that "good" is better replaced by "acceptable". This change has been made.

Line 158: Either remove "large" or put it into context
Response: We have revised the sentence to read: "…edge detection using four silicon diodes spaced evenly around the perimeter of a focused solar image of approximately 60 mm in diameter."

Line 169: Remove "very"
Response: This word was removed.

Line 173: "[...] adjustments performed by another mirror." The figure caption calls this the alignment mirror, since it, as explained later, is used to adjust the optical axis onto feedback plane. Be consistent with naming and explain parts at first occurrence in the text.
Response: This word "another" was replaced by "the alignment".

Line 186: What's an adequate diode size relative to image?
Response: The larger size solar images (~60 mm or perhaps greater in diameter) probably benefit from the active diode area being around 7 mm^2, which is the area of the diodes we use. The larger area gives are less noisy signal if the image is not so intense (compared to a smaller image). But also, the larger images have a less defined edge – and we feel this is better suited to broader detection surface area. Smaller images (less than 20 mm diameter) may require smaller diodes to truly edge-detect. Perhaps 1 mm^2 would be the smallest practical diode size although we have not

tried this yet. Like much of the design process, there is this trade-off in total optics size, image size, pick-off mirror size, and also diode size (and placement in relation to the image edge).
with an active surface area chosen to suit the solar image size. During the rewrite of section 3 we clarified this point with the following text:
"…with an active surface area chosen to suit the solar image size. In our examples we used diodes with about 7 mm2. The diodes are positioned to be partially illuminated by the edge of the image, thus ensuring a high response to any movement of the image across their surface"

Line 213: Sentence structure is weird, either introduce both approaches using colons or neither one, I'd go with the latter.
Response: We agree this is messy and have rewritten the paragraph for better clarity. We have appended the revised draft for this section at the end of this document.

Line 231 ff: Mention that you move the image on the feedback plane. Also, describe in further detail how you determine the angular offset.
Response: Section 3 (optical feedback) has been rewritten in light of comments from both referees. Specifically, we add "...at the diodes" to help identify the reference plane, and we have clarified how the rotation offset is determined.

Line 239: "consecutive" implies successive days, but 6 month lay in between, I'd recommend another adjective.
Response: "Consecutive" behaviour was a useful adjective to retain when discussing pre-correction. We have added "...as do plots six months apart" to make the reference to figure 12 more valid.

Line 259: Can you give a notion how reliable the software has proven to be, e.g. a number of failures during the 11 year period?
Response: The paragraph including this line discusses trackers in general, not our design in particular. However, your question is best answered in section 6.2 (Reliability achieved), where the value of "many months" is used. As a further guide, we don't recall ever having a software failure on one of our systems, yet another system might suffer a software crash as often as every 3 months or so. Of course, we are dealing with different computers and different versions of Linux OS so finding the exact cause is difficult. We made no changes to the text.

Line 261: Maybe give examples, see e.g. Heinle and Chen (2018) (doi: 10.5194/amt-11-2173-2018)
Response: Thank you. We have referenced this example.

Line 277: remove "simple"
Response: This word was removed.

Line 284: make clear what you're comparing to with "greater".
Response: We have edited the text to read "In addition to enhanced reliability over other methods of power transfer…".

Line 327: Define why the modules are "Good"
Response: The word is probably superfluous, as there is no reason to use poor quality (cheap) units in an instrument such as this. The words "good quality" are removed.

Line 390: remove "very"

Response: This word was removed.

Line 444: Your title poses a question, give a decisive answer in the following paragraph.
Response: The title poses a question because the answer is subjective. What period defines longevity? To help answer this we now modestly add the sentence "We believe our design demonstrates longevity.".

Line 467: "works very well" ! e.g. "surpasses precision requirements"
Response: We have altered the text to read "…feedback is effective".

Line 469: replace "good"
Response: This word was replaced with "useful".

Technical corrections
Line 55/56: space between numbers and units "2 mm", please add the space everywhere in the text.
Response: Thank you. All instances of this error have been corrected.

*Line 128: horizon*t*al*
Response: Corrected.

*Line 287: so *IT* is ready*
Response: Word added.

Line 291: present tense "use"
Response: Replaced by "use".

Line 326: "of" should be an "a"
Response: Changed, thanks.

*Line 330: "[...] inside *OF* the [...]"*
Response: Word added.

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3 Optical feedback

When the solar tracker is operating in the dead-reckoning or passive mode, the sun's position is continuously calculated, and the tracker mirrors are adjusted to direct a stable image of the sun into the laboratory below. The process of optical feedback adds an additional loop of control by electronically monitoring a focused image of the sun at the reference position or plane. By using control algorithms, the feedback system makes fine corrections to the rotating optical stages to precisely maintain the position of the image at the plane. The corrections made by the feedback are in the form of small error offsets which are added to the passive control reference positions for each of the two rotators. Thus, the basic passive tracking process is still occurring in the background, with fine control being contributed by the optical feedback (also known as active mode).

With optical feedback, a sample from the tracker beam is picked off by a small mirror prior to entering the spectrometer. Traditionally, this sample is focused onto a quadrant detector (a 4-element photo diode device) located on the reference plane. The four signals are analysed by the algorithm, and any imbalance detected between quadrants is used to correct the pointing. The optics for this method can be quite small, perhaps even mounted within the tracker itself. Signal levels are quite high because of the large surface area of the brightly illuminated quadrant detector. This method can be used for fast (sub-second) control, so is useful in mobile measurement systems such as balloons, aircraft or vehicles.

More recently, excellent results have been achieved using a miniature digital camera to analyse the solar image at or near the spectrometer entrance aperture (Franklin, 2015; Gisi et al., 2011). This has the additional advantage of coupling the tracker optical axis directly to the spectrometer, mitigating any error caused by movement of the spectrometer relative to the tracker. The camera can be installed within the spectrometer, but only if there is adequate space available.

3.1 A solution using solar edge detection

We chose to use a different solution for our optical feedback design: edge detection using four silicon diodes spaced evenly around the perimeter of a focused solar image of approximately 60 mm in diameter. This method was chosen primarily because the major sources of pointing errors are uncertainty in alignment and poor levelling. By their very nature, these errors appear as a slow changing function, often sinusoidal, with a wavelength measured in hours. We don't want information from the bright solar image itself because there is a possibility that this could make the system too sensitive to rapid intensity changes caused by passing clouds. The real information instead comes from the high contrast of the intensity gradient found at the perimeter of the solar image.

The size of our focused image is large compared to that used with a typical quadrant detector. The larger image requires longer optics (for the same focal length lens). Each of our installations is different. We've used a variety of solar image sizes ranging from 20 mm to 60 mm, depending upon the lenses available at the time, and the size and location of the free space available to mount the optics. The edge detection diodes are nominally named as left, right, up and down (L, R, U and D), with an active surface area chosen to suit the solar image size. In our examples we used diodes with about 7 mm^2. The diodes are positioned to be partially illuminated by the edge of the image, thus ensuring a high response to any movement of the image across their surface. The diode signals are lower in level and exhibit more noise compared to those from a quadrant detector. This is partially due to the low intensity of the solar image. They are also sensitive to image "jitter" caused by atmospheric turbulence and by constant movement of the mirrors by the tracker itself. If necessary, diode signals can be improved by increasing the size of the sample mirror – but at the expense of using some of the light available for the spectrometer. Diode signals are further improved with an adjustable gain op-amp circuit near the diodes and the jitter is somewhat smoothed in software using a running average of 10 samples.

Despite the differences in solar image size, intensity and sample pick-off size, each installation appears to perform similarly. This indicates that the edge detection concept is robust in response to the various trade-offs in design parameters.

Figure 3 shows an example of our feedback optics. Firstly, a small (~2 mm^2) front-surface mirror (Fig. 3a) samples the main solar beam from the tracker above. This is aimed at a distant wall as a useful visual reference for the operator to quickly assess tracker performance or look for the presence of cloud (Fig. 3b). A slightly larger non-vignetted portion of the main beam is directed into the feedback optics using a small mirror with dimensions of about 10 mm x 10 mm (Fig. 3c), with adjustment performed by the alignment mirror (Fig. 3d). This sample is focused with a small spotting telescope, half a set of binoculars (Fig. 3e) or by a custom objective lens and eyepiece combination. The image is focused onto the diodes and amp amplifier printed circuit board (PCB), see Fig. 3g.

Focus and positioning can be checked by placing white paper in front of the diodes. The image should be centred, circular and sharp. On the larger images, major sunspots may be seen. Electronic gain is adjusted to equal signal levels from the four channels, with emphasis on getting the levels in each pair equal (i.e. L = R, U = D). Physical protection and shielding from stray light are achieved using a sheet of inexpensive plastic IR filter (Optolite™ Industrial Plastics, UK) just in front of the diodes (Fig. 3g). The photodiode chosen needs a wavelength response in the near IR that matches any external filter used, e.g. PIN diode type BPW41N or BPW34F (Vishay). The signals are then routed to the tracker electronics box and sampled at 1 to 2Hz using four channels of the 10-bit analogue to digital convertor (ADC) within our motor control PCB. The algorithms that translates these values into motor movements are described below in Sections 3.2 and 3.3.

3.2 Feedback decision algorithm

Two parameters, set in a configuration file, are used to control decision making within the optical feedback system. The *Threshold* parameter is used to set the solar intensity level needed to initiate the use of optical feedback. During initial tracker installation, this threshold parameter is set to be somewhat below the minimum expected clear-sky diode signal level. This makes some allowance for taking measurements through haze or thin cloud (if required), and for the effect of mirrors becoming dirty over time. Each (averaged) diode signal level is compared to the threshold parameter value. If no diode signals exceed this value, then the sky is deemed too cloudy and optical feedback is not engaged. The tracker continues following the sun using passive mode. If one or more diodes exceed the threshold value, then optical feedback is activated.

When optical feedback is active, averaged L-R and U-D pairs are analysed individually using a *hysteresis* parameter. The signal difference within each pair must be greater than this value before a control action is taken. The hysteresis parameter helps prevent unnecessary control actions (or "hunting"). If the signal difference within a pair exceeds the hysteresis parameter value, the algorithms act to steer the mirrors in directions that minimises this difference by incrementing or decrementing a combination of azimuth and elevation error offset variables by 0.001° about every second. These error offsets are then used as a reference for the azimuth or elevation rotator positioning. The hysteresis parameter works well if set at about 10 – 30% of the threshold value and seems to have little effect on accuracy if the image perimeter and diode positions are well matched. Movement priority is given to correct the diode pair with the greatest difference in intensities. If all four signals satisfy hysteresis and threshold requirements the tracker can be called "locked" and no further corrective feedback is necessary. On a well-tuned system, with clear sky, the tracker can be locked for longer than a minute. Fast passing clouds have little effect on tracker pointing due to the long time-constant of the feedback loop. Any significant cloudiness is recorded in a logged file for post-processing of measurements and can also be used to halt automated observations until the sky is clear again. When the sky is too cloudy, the tracker reverts to passive mode, and continues tracking the calculated position of the sun.

At this stage it is important to note that there is no direct, simple relationship between a diode pair (e.g. U and D) and a single error offset variable (e.g. elevation). This is because the image at the diode reference plane rotates as the day progresses and is additionally modified by translation the image experiences through the feedback optics. This process is further explained below in Section 3.3.

3.3 Image translation and rotation algorithm

An algorithm is needed to map the required image movement directions, relative to the feedback plane (i.e. up, down, left, right), into the correct combination of movement directions for the elevation and azimuth rotators. There are two traditional approaches to finding this solution. One method involves absolute calculation using the knowledge of the illumination source coordinates, tracker baseplate Euler angles, and the tracker and feedback system optical components to calculate the required tracker movement, e.g. (Merlaud et al., 2012; Reichert et al., 2015). The second method deduces the required tracker movement empirically, by taking a small subset of deliberate mispointing measurements to calculate the required tracker angular movements e.g. (Gisi et al., 2011). We used the first approach to generate the basic algorithm, and then once-only, when the tracker is first installed, manually perform deliberate mispointing to characterise the optical geometry of the installation in terms of two parameters.

The ***translation*** parameter accounts for the overall effect of the many reflection and projection translations that occur through the tracker and the optical feedback optics. For example, a single lens might invert an image and a mirror may perform another translation. The translation parameter is easily determined by intentionally commanding the tracker to shift the image in a certain direction. This can be done using the application's buttons on-screen (see Sect. 5.1 which discusses the webserver, and also Fig 6.). The Parameter string is chosen to encode the required translation so that movements commanded to left, right, up and down work in the correct relationship to each other. The options for this parameter are "LR", "UD", "LRUD" or simply "N" for none. Once this parameter is set, the ***rotation*** parameter is chosen to map the resulting image movements to the correct direction on the feedback plane at the diodes. To do this, the observed angular offset is estimated in degrees (e.g. "60") and forms the rotation parameter. The rotation parameter need not be very accurate, within 10 degrees is adequate. This is because any small trigonometric errors that accumulate are eventually corrected as if they were from a mechanical source. To reduce a mispointing signal imbalance at the diodes, the algorithm may move a combination of the azimuth and elevation rotators. This is achieved by incrementing or decrementing the error offset variable relating to each rotator. These error offsets effectively become the long-term integrator function, and mainly correspond to the systematic error in levelling and alignment. Error plots of consecutive clear days show similar behaviour, as do plots of similar day length even six months apart (Fig 12), opening-up the possibility of using recorded error offset values to identify alignment errors or indeed pre-correct errors during passive mode operation.

Figure 4 identifies the optical components and their pointing vectors. The algorithm was developed to reduce the pointing error by using the mispointing vector from the edge detection diodes. Coordinate matrix transformations T, due to tracker mirror reflections and rotations of the incoming radiation, are required to translate the mispointing vector ([Ex,Ey]), in the optical feedback plane, to the tracker azimuth and elevation axis angular movement reference frame ([Eaz,Eel]). [Eaz,Eel] = T([Ex,Ey]).

Unlike Merlaud et al. (2012), the tracker offset Euler angles are not considered in the pointing vector coordinate transformations. With adequate tracker levelling and optical alignment, the tracker baseplate Euler angles are minor and can be compensated for by active tracking. The devised algorithm is mathematically equivalent to that described in detail by Reichert et al. (2015). The readers are directed to this reference for a detailed explanation of the coordinate transformations.

3.4 Initial adjustment of the optical feedback system during installation

A new solar tracker must be correctly aligned and levelled prior to initial adjustment of the feedback optics. The optical feedback system should be disabled during this process. The solar beam from the tracker must be made vertical (checking by back-reflecting off an oil bath) and the 45°-degree mirror (M4 in Fig. 4) under the tracker adjusted to direct the beam horizontally to centre the solar image on the spectrometer input aperture. The tracker and spectrometer optical axes are now co-aligned. The next step is to centre the solar image on the feedback diodes using the adjustment mirror (Fig. 3d). The sky should be clear and cloud-free so that amplifier gains can now be adjusted make the four diode values equal. The threshold and hysteresis parameters can now be set as described above (Sect. 3.2). The optical axes of the tracker, spectrometer and optical feedback are now coaligned. When the feedback system is enabled it will maintain the solar image centred on the spectrometer entrance aperture regardless of small errors in the solar tracker alignment or levelling.