<u>Authors' response to Anonymous Referee #2</u>

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.

… I share the concerns of Reviewer #1 that certain sections could be significantly improved by re-writing with a better focus on the narrative progression.
Response: We have attempted to improve the narrative progress with re-writing and re-ordering sections of the manuscript. Specifically, section 3 (optical feedback) has been rewritten in light of comments from both referees. We have appended the revised draft for this section at the end of this document.

Also, while the authors dive in with significant details on some portions of the design, other sections read as if their inclusion was simply an afterthought (e.g., two brief sentences regarding the cover for the tracker – a critical component of any remotely operated system.)
Response: We discuss this matter in more detail below.

Lines 64-77: Section 2 Intro – I suggest improving the clarity of this section intro with a more direct connection between the question posed on line 65 (accuracy required) and the answer of 0.05 deg given on line 74.
Response: We decided to change the intro to this section, turning the question into the statement: "However, the tracker should be fit for purpose, with an accuracy that suits the intended application.".

Line 70: comma after MIR
Response: Thanks, comma added

Line 98: "...needs used within..."
Response: As noted by Ref #1. Replaced with "required"

Line 99: please include version of PyEphem
Response: We used version 3.7.6.0 in at least one instance. We decided not to add this detail to the text because it is not especially important.

Line 163: "...are also simple, AND easy to implement and comprehend"
Response: This sentence was removed during the rewrite of section 3.

Line 201: How does the system respond to a partially obstructed solar disk (sliding along the edge of a cloud over many seconds). And how does it recover after such an episode? Could you increase the 0.001deg/sec offset adjustment based on the degree of signal difference within a sensor pair to more quickly recover?
Response: This is a good question to ask as it raises the issue of the inherent weakness of edge detection and the potential to improve the simple feedback algorithm. How the tracker responds to such a cloud episode depends on such factors as the value chosen for the "cloudiness" detection when deciding threshold parameter value, and how the diodes are placed in relation to the image edge (and their relative sizes). Without doubt, cloud obscuring any diode will affect pointing, but less so than would occur with a true quadrant diode sensor. This is because we see a sharp transition as the image edge slides off small active area the opposing diode in the pair (as compared to a larger segment area of a quadrant detector). A camera-based system should be able to perform better in this respect (compared to either edge detection or quadrant solutions).

In an FTS measurement, we really don't want any significant signal intensity change through the measurement period (which may be several minutes). Our preference is to have the threshold parameter set so that the measurements get flagged as "cloudy" in the daily log file (and the measurements are later removed). In post processing we further filter on detecting an intensity change. In either case we remove the measurement, which to a large degree, removes measurements with cloud induced mispointing.

There is much potential to improve the algorithm. We have trialled changing the step-size based on sensor-pair error difference, but it meant some customising was necessary for each of our installations (they are all very different – something we aim to change). A better approach may be to use a form of PID control loop, or switch to PID once initial lock has been established. This is something we are very keen to try. In the meantime, the simple system we use works well enough.

We have broadened the discussion on these potential improvements within section 7.1, by specifically mentioning PID control and dynamic step size:
"This could also be sped-up by saving and reusing offsets from a recent clear day, or dynamically changing step size depending on the magnitude of the diode pair difference."

We also added a discussion about cloud:
"An inherent weakness with the edge detection method is the response to a partial obscured solar disk. Under this situation the pointing is affected to some degree, but less so than would occur with a quadrant detector. A camera should be able to behave better in this situation.".

Line 230: Reference to webserver before the webserver is introduced.
Response: Thanks. This is corrected in the rewrite for section 3:
"This can be done using the application's buttons on-screen (see Sect. 5.1 which discusses the webserver, and also Fig 6.).".

Line 250: The threshold level setting procedure / choice of hysteresis parameter is not particularly clear. How do you define "works well" when set at 10%?
Response: We clarify the setting of this parameter in the rewrite of section 3, for expample:
" 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.".

Line 260: drop s from mains?
Response: We have replaced the word "mains" with the more universal "AC".

Line 288: Does simply passing the reference point in normal operating mode sufficiently maintain the rotator stage's knowledge of its position? While such knowledge may not be necessary in active tracking, is it not still needed in the passive ephemeris tracking mode?
Response: We think you are asking "is the ephemeris used during passive mode (and thus at night?)" If so, the answer is yes. The software also remembers the rotator position at all times. At sunrise, active tracking will then again start fine-tuning the pointing based on adding an offset to the rotator position.

Section 3 (optical feedback) has been rewritten in light of comments from both referees. Specifically, we have clarified the operation of passive and optical feedback modes in the revised text. We have appended the revised draft for this section at the end of this document.

Line 333: Space after Fig.
Response: Added thanks.

Line 367: Why is the tracking accuracy not regularly analysed for the other two trackers you have built?
Response: The other three trackers are used with Mid-IR spectrometers which don't normally measure in the wavelengths we use to retrieve TCCON S-G shift. Two of the spectrometers can have beam splitters and detectors exchanged so the required Near-IR measurements can be made but this is invasive, and only done occasionally (e.g. for the spectrometer intercomparison in 2019). We have changed the sentence to correctly read:
"Tracker accuracy has been analysed on our trackers capable of TCCON measurements and can routinely produce a pointing accuracy of 0.02° from solar centre.".

The other two trackers haven't had analysis using S-G shift and are not discussed individually in terms of accuracy, although we expect they perform well judging by image monitoring.

Line 370: While I applaud the addition of the wall image in the design – certainly a very useful visual for a lab operator in the room – I would hardly refer to it as a valid means of monitoring the tracking accuracy, especially for a design which you emphasize can be efficiently operated remotely. I recommend de-emphasizing the quick visual method, and perhaps more clearly highlighting the consistency of the offset errors as a function of alt/az.
Response: The are a few points raised in this comment. Firstly, we cannot take credit for the wall image idea and it's not part of the tracker design at all. However, it is quick and easy method of checking that the tracker is functioning (and accurate) and that the sun is clear. We use it daily. The eye and brain can tell, in a glance, that all is well with the tracker. The next best method to quickly assess accuracy is to view the spectrometer input aperture (if you can see it, which would need a transparent cover added). But this assumes that the 45-edgree mirror (which not strictly part of the tracker) is adjusted correctly to centre the image on the aperture. Indeed, this operator error is responsible for many of the large jumps in S-G shift plotted in Figure 13. This is discussed in line 505 of the draft. The tracker itself probably performs with a higher consistent accuracy than is indicated by Figure 13 – but until we physically attach the feedback to the spectrometer, we can't see this by using the S-G shift method.
After producing the Figure 13, and seeing these jumps, we decided to advance our work schedule and have now achieved a working prototype feedback optic attached to the instrument. We have trialled this by intentionally moving the instrument and watching as the feedback steers the image back to the centre of the aperture. This will undoubtably improve long-term retrieved pointing accuracy and spectrometer data quality, although in itself may not improve the accuracy of the tracker (when considered as a unit on its own).

In the draft, we refer to "remote" twice when discussing reliability and once when discussing access control over the network using the webserver interface. To assess accuracy in a truly remote site, with no staff present, the best method remains S-G shift (if these measurements are possible), or via a camera constantly viewing of the input aperture. However, with no humans in the remote lab to cause problems, we are quite confident that edge detection method will remain accurate no matter whether the feedback optics are on the tower or the spectrometer. Tracker performance can then be monitored periodically by looking at offsets, the diode solar intensities (logged each second) or the webserver.

The alt/az offset errors remain a useful diagnostic as you say and are readily available at any time. With some extra effort, it might be possible to extract the nature of the error (alignment or levelling). If so, this would be even better.

We have considered this comment carefully but decided to leave the text unchanged.

Line 410: Given that the offset errors are a function of alt/az, how useful is a single alt/az setup offset parameter pair? I imagine these much be updated throughout the year?

Response: It's true these errors offsets are some function of alt/az. But they also have an underlying fixed offset component which comes from the "random" uncertainty when the tracker was initially parked during the last powered-up (the parking error resulting from a single coarse flag). It makes sense to zero this at some stage, but inevitably it will be done at different alt/az than last time (possibly months ago). Hence the offset of the plots clearly seen in Figure 12. Comparing plots of errors offsets with radically different day lengths would also appear a bit awkward, but (by pure good fortune) the months plotted in figure 12 have similar solar characteristics. We added: "...similar day length…" to the sentence discussing figure 12.

In terms of using error offset values to "pre-correct" (line 240 in draft) then yes, the offsets would lose their value after a few weeks. The pre-correction would need to either be a dynamic process (using values from recent clear days) or use a historical (annual) dataset or fitted function. Both are valid options worth trying, especially if we needed more precise passive tracking (e.g. lunar observations).

Line 516: This manuscript regularly emphasizes the remote operation of this tracker. Thus, a reliable automated cover is a critical component of the design. I believe it would be very appropriate and desirable to include more information on the cover design in this manuscript.

Response: We agree that the cover is a critical component of the complete observation system and another potential weakness that needs careful design and construction. Typically, a cover is designed to "match" the tracker, which in this case now rotates 360 degrees, continuously! While we would love to include a full description of this design (successfully in use with two of our four trackers), we feel it is beyond scope for this manuscript. However, we do feel encouraged to consider it a candidate for future publication, perhaps as a technical note, in the near future. In terms of a cover for a remote site, then the reliability of the design takes on even more importance. We have added the line:
"The authors would like to present the design of this cover in a future publication."

Fig 13: Despite being well within the required accuracy requirements, I would like the authors to speak to the changes in S-G parameter seen in November 2018 and in early Jan 2019 ahead of the optics cleaning

Response: We agree these are major steps in retrieved S-G shift. Unfortunately, the exact cause cannot be determined because not every disturbance in the laboratory is logged. For example, we often have tour groups of visitors through the lab, or other staff. The lab space is very tight. Often someone will lean on or bump the large spectrometer instruments (or worse, bump the tower 45-degree mirror). We expect these disturbances to be less of a problem now that the feedback optics are physically attached to the spectrometer. We have added the following sentence to the section discussing figure 13:

“Other large steps in S-G shift, for example November 2018 and in early January 2019 have no logged cause but are likely the result of human presence in the laboratory resulting in the instruments being bumped.”.

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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.