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Interactive Comment

Interactive comment on "Rugged optical mirrors for Fourier-Transform Spectrometers operated in harsh environments" *by* D. G. Feist et al.

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Dear referee,

thank you for your helpful comments. In the following, your comments are in bold face and my replies are in standard type face.

Review: Mirrors degradation inevitably occurs in harsh environment, so the authors express the possibility of using rugged mirrors to measure atmospheric trace gases from solar spectra in such environment. After reviewing the commonly used mirrors, and listing the effects that they may be encountered, the capacity of rugged mirrors is assessing at MPI-BGC's TCCON site on Ascension Island. The paper is well written, well-structured and the subject is valuable for

the measurements community in order to know the limitation of certain kind of mirrors. However, the paper lacks of analysis about the effect of the mirror reflectivity on atmospheric spectra and/or atmospheric retrievals.

The last point is well taken. We have investigated the issue further and looked for practical ways to address the effect of mirror reflectance on the data quality. Unfortunately, there are limitations to what we can do, mainly due to the remote location of our site:

- our site is about 7000 km away from our home institution. We can only visit it once or twice per year for maintenance trips of about two weeks each.
- we cannot provide direct comparisons between different mirror types under comparable conditions. Every time the mirrors were replaced on site, the previous set of mirrors was already completely destroyed. Besides, while the steel mirrors can be exchanged without realignment, switching between gold and steel mirrors requires dismounting and fully realigning the solar tracker – a procedure that takes 1–2 days and may severly affect the solar tracker's pointing quality.
- the lower reflectance of the steel mirrors has to be accounted for by changing the gain and threshold settings of the quadrant diode that is used for tracking the sun. Some of these settings also have to be adjusted from time to time to account for pointing problems when the sun is close to zenith (several weeks per year). Therefore, the solar tracker parameters and the tracking quality often change for reasons that have nothing to do with the mirrors themselves.
- we have no direct measure of mirror reflectance. In the manuscript, we use the quadrant diode's signal amplitude as a qualitative proxy for reflectance. However, this is not a robust quantity because it is also affected by haze, thin clouds, tracking quality, and solar zenith angle.

For this reason, we can only try to estimate some of the effects you requested from our time series. Dedicated tests and measurements are not realistic.

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Major revision: In general, the paper need more deepen details. The main effects of the signal loss due to mirror degradations on atmospheric spectra and retrievals is not addressed at all. Could you comment on the effect of the signal degradation on atmospheric spectra?

We investigated several ways to quantify this. Looking directly at spectra sounds easier than it actually is: the main problem would be to find sets of spectra where only the mirror reflectance has changed while other key parameters remained the same. This is very difficult because a number of factors (see above) affect the luminosity of the solar radiation entering the FTS. To see the effect of degradation in a quantitative way, one would have to find spectra that were taken several weeks apart but still during the same time of the day, at nearly the same solar azimuth and elevatation angle, under the same weather conditions, and the same amount of total water vapour, haze and cirrus clouds in the atmosphere. Therefore parameters like signal-to-noise – which depend directly on the luminosity – are not really suitable.

A more practical way is to look at the output of the retrieval itself. The TCCON retrieval retrieves the total column of the target species simultaneously with the O_2 column as a proxy for airmass. This approach minimizes a lot of the effects that are caused by differences in luminosity. The effect on the retrieved quantities is also much more relevant to the data user. Details are given below.

Are the degradation seen with wavelength dependency?

We cannot tell with certainty because we did not look into the effect on individual spectra (see above). However, nothing in the Ascension Island data series suggests that there is anything unusual with any on the retrieved species (which are retrieved in many different spectral regions) or the airmass retrieved from the O_2 column (usually a good indicator for spectral issues).

What is the impact on measurements errors, signal to noise ratios, precision of the solar pointing, other spectral parameters?

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measurement errors: there is a weak but visible correlation between noise in the retrieved XCO_2 values and the time since the last mirror cleaning. To be more precise, we looked at XCO_2 retrieved during the same day and within a small range of solar zenith angles. One would assume that these values should be constant. However, their standard deviation increases with the number of days since the last mirror cleaning. Up to 2 weeks after mirror cleaning, the effect is small but becomes clearly pronounced afterwards. We will add a new figure that illustrates this effect to the final version of the manuscript.

signal-to-noise ratio: as said above, we could not find a good way to quantify this.

solar pointing: there are basically two regimes. The quadrant diode needs a minimum threshold amplitude to track reliably. This is typically set to 30-50% of the maximum amplitude (clear sky, clean mirror). When the actual amplitude drops below that threshold, the tracker looses the sun more often or is not able to find it at all. This would result in an increased number of spectra where tracking was lost during the measurement. However, the quadrant diode signal is also influenced by effects like haze or cirrus clouds which are hard to distinguish from mirror reflectance loss. So it would be very hard to show that an increased number of tracking losses was due to the mirrors rather than due to a period of enhanced cirrus.

other spectral parameters: not sure what would be suitable besides signal-to-noise ratio.

Could you show and comment spectra measured by the different mirrors, and at different states of the reflectivity reduction?

As said before, I cannot provide spectra that were taken under identical conditions except for the mirror type or the reflectance loss. This would be possible under laboratory

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conditions but not in the field on Ascension Island. The strongly varying atmospheric water wapour alone would already render this comparison useless.

Also you mentioned TCCON and NDACC networks and their ability to measure gases in the atmosphere. However effect of mirror degradation and/or mirror types on atmospheric retrievals is not shown. Could you address this issue?

The issue will be adressed by a new subsection and an additional figure that shows the noise increase in the retrieved XCO_2 values.

From a station/network point of view, the effect of the different mirror types is clearly visible in our measurement statistics. Please have a look at the attached plot (Fig. 1) which shows the number of observations made with the different mirrors:

May–Sep 2012: unprotected gold mirror (destroyed at end of period)

Mar–Jun 2013: protected gold mirror (destroyed at end of period)

since Sep 2013: steel mirrors

Note that the data gaps after 2013 were not related to mirror problems.

Fig 9, you show reflectivity for one mirror but measuring solar absorption spectra require two mirrors. What is the total reflectivity for two mirrors?

These measurements were actually taken with two mirrors at the same incident angle (45°) that is used in the solar tracker. The total reflectance is the product of the mirrors' reflectances: $R_{tot} = R_1 \times R_2$. What is plotted in Fig. 9 is the estimated single-mirror reflectance $R = \sqrt{R_1 \times R_2}$. This was done to make the numbers comparable to typical reflectances for standard mirror materials. Since this seems to be unclear, I will explain this more clearly in the final manuscript. The updated version of Fig. 9 also contains reflectance curves for Gold, Aluminium and other materials for comparison.

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What is a spectrum look like with steel mirrors? How is this spectrum compared to a spectrum measured with other type of mirrors?

As explained above, we cannot provide this.

What is the effect on retrieved concentrations?

This has already been addressed above.

Minor revision: Abstract, line 10: MPI-BGC is an acronym not defined.

Will be fixed in the final manuscript.

Section 3.1, p 10718, line 4: miss the ":" at the end of the sentence.

Will be fixed in the final manuscript.

Section 3.1, p 10718, line 15: the type number is not defined before here. Clarify it by mentioning figure 6?

Thanks for spotting. I will make a reference to Fig. 6.

Section 3.1, p 10718, line 1: "PREN>32 are considered to be seawater resistant." Is there any reference for this?

There are many references on the internet that claim this number. However, I could not find a reference in the scientific literature. Please note that in this industrial community, many publications are not easily available or only at high cost.

Section 3.1, p 10718, line 11: labeled as 1.xxxx. Are you sure this is not a problem?

We already discussed this point with the editor and the AMT chief editors. It is acceptable if we can provide an alternative way for others to check our results. Providing the steel type would actually not help much since others could still not produce the mirror surface. So the main issue with others reproducing our results is that our mirrors are prototypes and only two pairs exist. However, we would provide our spare set of steel

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mirrors to interested parties for testing at no cost. I will add a note explaining these conditions to the final manuscript.

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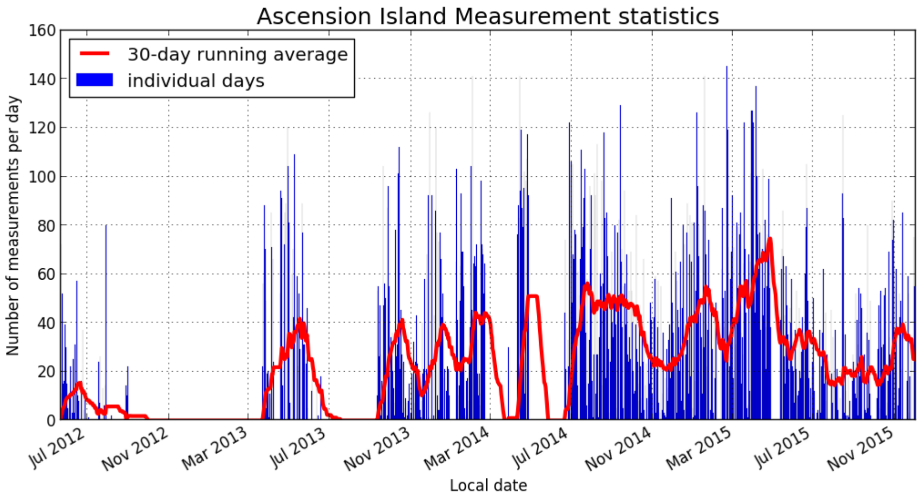

Fig. 1. Measurement statistics for Ascension Island. Unprotected gold mirrors: May-Sep 2012, protected gold mirrors: Mar-Jun 2013, steel mirrors: since Sep 2013.