amt-2017-194

The CHRONOS mission: Capability for sub-hourly synoptic observations of carbon monoxide and methane to quantify emissions and transport of air pollution

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Response to Reviewer 2:

We thank the reviewer for their careful evaluation of our manuscript. We address each comment (in blue) with an embedded response (in black) below. We detail new text that has been added to the revised manuscript (in green).

General comments:

The manuscript 'The CHRONOS mission: Capability for sub-hourly synoptic observations of carbon monoxide and methane to quantify emissions and transport of air pollution' by D. P Edwards at al. describes a new mission concept of satellite remote sensing of both trace gases using a geostationary orbit. The proposed instrument is based on MOPITT instrument heritage. Although having such a mission would provide exciting new measurements, the paper itself provides only little scientific news. The MOPITT heritage is discussed extensively in the literature and the possibility to observe CO and CH4 using a geostationary orbit is already discussed e.g. by Butz et al., 2015 and O'Brein et al., 2016.

We respectfully disagree with the comment "the paper itself provides only little scientific news… and the possibility to observe CO and CH4 using a geostationary orbit is already discussed e.g. by Butz et al., 2015 and O'Brein et al., 2016."

The CHRONOS mission concept addresses tropospheric (air pollution) chemistry, specifically, carbon monoxide and methane, the two principal sinks for the hydroxyl radical. Hydroxyl provides the ability of Earth's troposphere to cleanse itself of trace constituents that are harmful and even toxic to plants, animals, and people. When combined with NASA's planned TEMPO observations, CHRONOS observations meet the tropospheric chemistry science objectives of the GEO-CAPE mission (Fishman et al., 2012).

The CHRONOS focus on tropospheric chemistry then results in requirements for frequent time sampling (sub-hourly), and for simultaneous sampling over extended domains ("snapshot") that would be significantly impaired by instrument solutions that take hours to scan a continental domain and sampling patterns that are limited to few times daily, as described in O'Brien et al. (2016) or Butz et al. (2015). An instrument capable of instantaneous observations everywhere over a continental domain with the ability to provide full precision observations everywhere in that domain within 10 minutes is scientific news for meeting the tropospheric chemistry objectives.

Compared to the CHRONOS requirement for CO measurement in two spectral regions, the GeoCARB limitation to CO in one spectral region means that GeoCARB would not able to evaluate vertical pollution transport, or to provide the test of these atmospheric motions as calculated by advanced atmospheric models (NAS, 2017). The Committee on Earth Observing Satellites (CEOS) has identified the absence of multispectral CO observations after MOPITT as a critical data gap when they met in June 2017.

We agree that MOPITT capabilities are well documented in the literature. An important point of the paper is to report the rationale and specifics of the CHRONOS instrument evolution of MOPITT (CHRONOS provides simultaneous, sub-hourly sampling everywhere in the domain instead of temporally discontinuous orbital tracks with, at best, daily revisit; and CHRONOS improves spatial resolution to 4 km x 4 km from MOPITT's 22 km x 22 km).

the downstream from mission objectives to instrument and product requirements is not always traceable for me… Sec 2.2 …. already concludes that CHRONOS meets all the objectives although the instrument …. is discussed much later in the paper

This paper was written with the intent of laying out the science case first and then describing the measurement requirements and instrument. This may be different to some instrument papers, but it is also becoming a frequent style for papers, reports, and surveys following the "Traceability Matrix" approach (e.g., NRC, 2007, and the currently in-process NASA/NOAA/USGS 2017 Decadal Survey).

science objectives for CH4 geo observations are not always convincing to me

Section 6.2 discusses OSSEs by Wecht et al. (2014) that evaluated the potential of hourly methane observations (such as we describe in this paper) for constraining emissions. Wecht et al. report that hourly observations constrain methane emissions more than a factor of two better than daily observations (TROPOMI), and significantly better than GOSAT.

it is not clear to me if air quality forecast can really be improved with these uncertainties

At the end of Section 2.2, we describe previously published OSSE studies that show the benefit, compared to the ground-based monitoring network, of high spatial and temporal resolution sampling from GEO in constraining transport patterns and in constraining the distribution of near-surface CO concentrations. Specifically, Edwards et al (2009) cites improved skill scores for near surface CO, and Zoogman et al (2014) demonstrates improvements to near surface ozone from joint CO-ozone assimilations.

Specific comments:

1. Figure 1: What is the spatial coverage of the MOPITT panels? For a better comparison, both MOPITT and WRF-Chem images should use the same color code, which should be indicated in a corresponding figure legend.

Details of the MOPITT instrument are included in the references in the Introduction. MOPITT uses a cross-track scan of 640 km that allows for almost complete coverage of the Earth's surface in about 3 days, with pixels of 22 km x 22 km horizontal resolution. The intent of Figure 1 is to graphically depict spatial coverage as a function of hourly sampling for MOPITT compared to what might be seen from CHRONOS. It is not intended as a comparison of MOPITT CO values with the WRF-Chem model. Validation of MOPITT against both models and observations, taking into account averaging kernel sensitivity and a priori assumptions not considered in this figure, are covered by the MOPITT references in the manuscript (and references therein).

2. Figure 3: The figure shows CH4 in situ measurements with significant enhancements whereas changes in the total column is much less (4.9 %). I think this enhancement is given on the spatial sampling of the in situ measurements but do not necessarily represent the CH4 enhancement for a 4x4 km2 sampling of CHRONOS. I can imagine this makes a different.

While the individual in-situ measurements shown in Fig. 3 are indeed not at the CHRONOS spatial resolution, the methane enhancements observed near oil/gas and feedlot operations during the 2014 FRAPPE DISCOVER-AQ campaign were persistent over the spiral flight tracks shown, each spiral with an approximate radius of 10 km (see e.g, Flynn et al., 2016). The total column calculation that yields the quoted 4.9 % difference therefore corresponds to the CHRONOS pixel scale. As the reviewer points out, high methane values at very small scale, as might be expected from an individual pipe leak, would not probably not produce the necessary column enhancement to be detected at the CHRONOS pixel scale. We are careful to suggest emissions estimates for CH_4 at the county-level spatial scales (~40 km x 40 km) as demonstrated in the referenced OSSE by Wecht et al. (2014a) as part of the studies for GEO-CAPE.

We clarify this in the revised Figure 3 caption: Vertical profiles were measured over cities, identified by spiral flight tracks (each spiral has ~10 km radius).

3. Figure 4 and 12: These figures do not present new material and can be discussed in the text with appropriate references.

While this material may be understood by some readers, these figures have never before been published and we think they help elucidate the CHRONOS measurement concepts much more clearly than we could describe with text. We have found frequently that audiences are not familiar with the principles of GFCR, as compared to more usual grating spectrometer or FTIR measurement approaches. CHRONOS also employs alternating gas/vacuum cells, which is different to the MOPITT pressure-modulated and length-modulated GFCR technique. For these reasons, we believe that Figure 4 provides valuable context.

Clarified: Specified 'the CHRONOS GFCR measurement' in the text of the Figure 4 caption.

A similar comment applies to Figure 12. Of all the current and planned CO measuring instruments, MOPITT is the only one making multispectral CO retrievals. The other instruments either make SWIR column measurements or TIR mid-troposphere measurements. As a result, readers who are not familiar with the MOPITT literature will not appreciate the advantage of the multispectral approach in providing independent near-surface CO concentrations to understand emissions and pollution transport. This is a primary motivation for the CHRONOS concept.

4. Page 23, line 509: To my knowledge, it is not demonstrated that CH4 can be retrieved from real MOPITT data with a cloud coverage of 5 %. I doubt that this is possible considering the strict

cloud filtering of GOSAT observations for CH4 retrieval.

As outlined in Section 3.3 and references therein, MOPITT does not retrieve CH4 with or without clouds, due to well-documented instrumental issues.

It is an advantage of GFCR that ‘contaminating’ signals that are spectrally flat across the radiometer filter passband are effectively cancelled out by the D/A signal. We have added a description to Section 4 as follows:

While the approach of using D/A for retrievals discussed in Section 3 will cancel some of the errors due to undetected aerosols or clouds (e.g., thin cirrus), remaining retrievals errors (e.g., O’Dell et al., 2011), particularly for CH_4, will require further study using both CHRONOS radiances and GOES-16 ABI observations.

5. Page 19 line 414: The aerosol optical depth should be provided at a reference wave- length within the SWIR fit window. Depending on the size of the aerosol parameter, this can be very small.

The value of AOD used in the 2.25 micron SWIR window aerosol simulation was 0.089. This is now added to the text. This aerosol case was chosen to represent high pollution loading with the most significant AOD values in our SWIR window.

We have added to Figure 7 caption: (...AOD is 0.089, which is obtained by scaling the OPAC urban aerosol case by 1.5)

6. Table 2: I think, a discussion for elevated aerosol layers and cirrus is needed for a better error estimate. From other missions, we know that these are relevant error sources.

We agree that this is a tricky problem and we expect to use the CHRONOS radiances as well as GOES-16 ABI cloud measurements to diagnose and potentially flag observations that might not be properly filtered by our cloud detection approach. We will also follow the approaches identified for OCO-2 observations to detect and quantify retrieval errors due to undetected aerosol and thin cirrus clouds (e.g., O’Dell et al., 2011). We have added discussions to Section 3.2 in response to Reviewer 1 and to the cloud detection paragraph in Section 4 as noted in Specific comment 4 above.

7. Table 2: Here a precision requirement of <10 % is given, whereas Fig 2 indicates that urban air quality daily evolution is in the order of 1-2 ppm. I doubt that with this large precision, urban daily evolution can be measured. See also page 17, line 383-385.

We recognize the opportunity for confusion between ppm and ppb and have corrected Figure 2 to show 1000-2000 ppb rather than 1-2 ppm for CO. Precision requirement of 10% is approximately 10 ppb based on global average abundance of CO.

8. Page 15 line 335-340. The SCIAMACHY CH4 product is inferred from 1.6 micron measurements, GOSAT also uses the methane sensitivity at 1.6 micron, which in both cases differ from the CHRONOS SWIR window at 2.2 micron.

The measurement of CH_4 at 2.2 microns was considered by SCIAMACHY prior to the detector icing problem, is used by S5-P/TROPOMI, and will be used by GeoCARB. The spectral band used for methane is summarized in the new Table 3.

9. Section 6: I am not sure if I overlooked it, but when discussing synergies with other mission an indication of a launch window is required. I think, also the Sentinel-5 mission and IASI-NG should be mentioned here.

We have revised Table 3 to reflect a CHRONOS launch no earlier than (NET) 2024 and have included Sentinel-5. We chose not to include IASI-NG as it makes observations only in the MWIR (similar to other sounders such as the current IASI instrument and CrIS). As described in Sections 5.1 and 6.1, these instruments do not generally have measurement sensitivity to the full column.

I also miss a discussion of GEOCarb, which would measure CO, CO_2 and CH_4. Because the mission concept is already published, it should not be ignored in this manuscript.

We have added a discussion of GeoCARB in Section 6 and in the revised Table 3.

10. Table 3: This table does not provide new information, which is not already discussed in the text. It also does not fit the format of a science publication to my opinion.

We have revised Table 3 to include only details of CO and CH_4 measurements.