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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 1:

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:

CO2 and CH4 monitoring with gas filter correlation technology from GEO is very important mission from both global warming and air quality monitoring points of view. Observation needs are well described. Recently many GEO and LEO GHG monitoring programs have been proposed. The authors should describe difference from the Geo-CARB program using grating spectrometer technology.

We agree that more description of the differences between CHRONOS and GeoCARB, which was recently selected for the NASA EVM-2 program, is needed. We have added the following text to Section 6.1:

NASA selected the GeoCARB mission in November 2016, with capability to measure CO in one spectral region (Polonsky et al. 2014; Kumer et al., 2013) and primary carbon cycle science objectives unrelated to air pollution transport. Compared to the CHRONOS requirement for CO measurement in two spectral regions, this GeoCARB limitation to CO in one spectral region precludes GeoCARB from evaluating vertical pollution transport, or providing the test of these atmospheric motions as calculated by models (NAS, 2017). Both Polonsky et al. (2104) and Kumer et al. (2013) describe mission descopes that eliminate GeoCARB measurements of CO entirely if needed to ensure success for GeoCARB CO_2 and solar induced fluorescence science objectives.

And to Section 6.2:

GeoCARB describes CH_4 measurements in the SWIR (2.3 µm) region with 1% precision three times per day at 5 km x 5 km spatial resolution (O’Brien et al., 2016), although earlier studies (Kumer et al., 2013) explored methane measurements at 1.65 µm. GeoCARB’s more frequent methane observations than TROPOMI may provide for similar precision in a smaller spatial footprint than TROPOMI. CHRONOS could observe CH_4 as often as every 10 minutes in daylight with 0.7% precision and 4 km x 4 km resolution. These frequent CHRONOS CH_4 measurements could be co-added to improve hourly precision, or used to examine anthropogenic source evolution over time.

GeoCARB parameters are also included in Table 3, now revised in response to Reviewer 2.

CHRONOS has advantage to measure both solar reflected light from surface and thermal radiation from middle of the troposphere. However, it is not clear gas filter correlation technique is more accurate and/or precise than other technique such as grating spectrometer and FTS in CH4 retrieval.

The gas filter correlation technique achieves accuracy and precision in trace gas retrieval similar to grating spectrometers and FTS by virtue of very high effective spectral resolution and high throughput (low noise). We have clarified the choice of spectral technique by adding to the discussion in Section 3.1:

The effective spectral resolution of the GFCR response function (Edwards et al., 1999, figure 3) matches the pressure-broadened Lorentz full-width-half-maximum (FWHM) for weak-absorption lines (Beer, 1992), and ranges from 0.08 cm^{-1} to 0.16 cm^{-1} for 200 hPa to 800 hPa GFCR gas cells (Pan et al., 1995). This optimal spectral resolution for measuring tropospheric trace gas absorption and for probing the spectral line profile to obtain information on the trace gas atmospheric vertical distribution is difficult to achieve for most spectrometers without sacrificing signal amplitude (grating spectrometers) or increasing noise (Fourier transform spectrometers). The limitation for the GFCR technique is that atmospheric retrievals are made only for those gases contained within the cells of the instrument. However, for observations of CO and CH_4 from GEO (50 times farther from Earth than LEO), the advantages of both fine spectral resolution and high throughput provided by CRONOS's gas filter correlation radiometry make for a particularly robust measurement approach.

New references:

Polonsky, I. N., O'Brien, D. M., Kumer, J. B. and O'Dell, C. W.: Performance of a geostationary mission, geoCARB, to measure CO2, CH4 and CO column-averaged concentrations. Atmospheric Measurement Techniques, 7(4), pp.959-981, 2014.

Kumer, J.J.B., Rairden, R.L., Roche, A.E., Chevallier, F., Rayner, P.J. and Moore, B.: September. Progress in development of Tropospheric Infrared Mapping Spectrometers (TIMS): GeoCARB Greenhouse Gas (GHG) application. In Infrared Remote Sensing and Instrumentation XXI (Vol. 8867, p. 88670K). International Society for Optics and Photonics, 2013.

National Academies of Sciences, Engineering, and Medicine: Powering Science: NASA's Large Strategic Science Missions. Washington, DC: The National Academies Press. https://doi.org/10.17226/24857, p33, p81, 2017.

O'Brien, D. M., Polonsky, I. N., Utembe, S. R., and Rayner, P. J.: Potential of a geostationary geoCARB mission to estimate surface emissions of CO_2, CH_4 and CO in a polluted urban environment: case study Shanghai, Atmospheric Measurement Techniques, 9, 4633–4654, https://doi.org/10.5194/amt-9-4633-2016, 2016.

Pan, L., Edwards, D. P., Gille, J. C., Smith, M. W., and Drummond, J. R.: Satellite remote sensing of tropospheric CO and CH4: forward model studies of the MOPITT instrument, *Appl. Opt.*, *34*(30), 6976–6988, doi:10.1364/AO.34.006976, 1995.

Beer, R.: Remote Sensing by Fourier Transform Spectrometry, *Wiley, New York*, 1992.

How to achieve 1% accuracy in CH4 retrieval under aerosol and high thin cloud condition without light path modification information should be described in more detail.

For the retrieval of CH_4 in the presence of clouds and aerosols, we added to Section 3.2:

SCIAMACHY and GOSAT CH_4 SWIR retrievals are sensitive to scattering by dust, aerosols and thin cirrus (Gloudemans et al., 2008; Schepers et al., 2012) and address these errors by using CO_2 (with known abundance) as a proxy for the scattering effects or by performing a physical retrieval of effective parameters for the scattering layer. For GOSAT CH_4 data, these two approaches yield similar precision (~17 ppb) and biases less than 1% compared to TCCON (Wunch et al., 2010), but with lower bias for the proxy method (Schepers et al., 2012). In the proxy retrieval using CO_2, the dry mole fraction of CH_4 (x_{CH4}) is computed by $x_{CH4} = \frac{[CH4]}{[CO2]} x_{CO2}$ where $[CH4]$ and $[CO2]$ are the retrieved columns from spectral radiances that are close in wavenumber and x_{CO2} is the dry mole fraction computed from a global model of atmospheric CO_2 (Frankenberg et al., 2005; Schepers et al., 2012). This method assumes that aerosol scattering modifies the light path for CO_2 and CH_4 spectral absorption in the same way, and that model values for x_{CO2} are accurate.

Retrievals with GFCR measurements are similar to the "proxy retrieval" but they correct the input radiance instead of the retrieved column, and do not make assumptions about aerosol scattering in different spectral bands or rely on knowing CO_2 abundance. CHRONOS uses the D/A signal ratio where D and A are both modified in the same way by aerosol scattering, which has a smooth spectral behavior over the CHRONOS bandpass. This ratio gives an accurate total column amount, but to compute a dry mole fraction (xCH4), we require additional information about the surface pressure (for example, from GOES-16 meteorological data) in order to estimate the dry air column. In general, GFCR retrievals are more resilient than spectral radiance measurements to errors in surface and contaminant species assumptions due to the use of radiance differences and ratios (Pan et al., 1995).

Authors mention single case of aerosol but thin cloud such as high-altitude cirrus is not discussed. Authors proposed use of GOES satellite data for cloud detection but aerosol and thin clouds are difficult to filter out.

As described in Section 4, CHRONOS's primary cloud detection comes through its own GFCR measurements based on many years of experience with MOPITT cloud detection. The fact that CHRONOS is in GEO and making observations of the same scene sub-hourly, also affords some advantages for cloud detection by means of being able to look at very frequent signal differences in combination with GEO imagery from GOES-16 ABI. We have added the following text to Sec. 4:

While the approach of using D/A for retrievals discussed in Section 3.3 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.

Specific Comments

(1) Plumes Page 5, Fig 1 Description of diurnal variation of CO emission and typical wind speed in WRF-Chem will help readers' understanding Page 10, Fig. 3 Description of CH4 emission source in Greeley, CO will help readers' understanding.

Clarified: The text of the Figure 1 caption has been updated to state that the WRF-Chem run is driven by analyzed meteorology, and that changes in the distribution of CO are expected as a result of changes in both emissions and meteorology.

Figure 1: Comparison of MOPITT and CHRONOS spatial and temporal coverage over a 5-hour period. The top panels show MOPITT retrievals of near-surface CO for Tuesday Aug. 1, 2006, with pink colors indicating low CO (~ 60 ppbV) and green to red indicating higher values (200 – 300 ppbV). The middle and bottom panels show a simulation of CHRONOS observations using WRF-Chem (Grell et al., 2005) at 4 km horizontal resolution driven by analyzed meteorology (Barth et al., 2012) for the same date. Here blue colors indicate low CO (~60 ppbV), red colors indicate high CO (~300 ppbV) and light greys indicate clouds. Circled areas in the zoomed bottom panels provide detailed examples of changes in CO concentrations over the 5-hour period with pollution from Chicago moving to the west and clouds moving east over the Washington DC area. Urban traffic patterns and weather fronts change the distribution of air pollution throughout the day. Sub-hourly CHRONOS data could assist with attributing the sources of pollution and determining areas affected downwind.

New reference added:

Barth, M. C.**,** Lee, J., Hodzic, A., Pfister, G., Skamarock, W. C., Worden, J., Wong, J., and Noone, D.: Thunderstorms and upper troposphere chemistry during the early stages of the 2006 North American Monsoon, *Atmos. Chem. Phys.*, **12**, 11,003-11,026, doi:10.5194/acp-12-11003-2012, 2012.

Similarly, the text of the Figure 3 caption now includes source description:

Figure 3: Aircraft in situ measurements of CH_4 from the FRAPPE-DISCOVER-AQ in the Colorado Front Range on Aug. 2, 2014. Vertical profiles were measured over cities, identified by spiral flight tracks (each spiral has ~10 km radius). Note that the highest values of CH_4 are plotted last. Total column CH_4 computed from the vertical profiles is different by 4.9% between Ft. Collins (urban) and Greeley (oil/gas and feedlot operations). CHRONOS spatial resolution is indicated by the overlaid grid, illustrating that CHRONOS column measurements would have the spatial resolution and precision to distinguish sub-hourly differences in county-scale CH_4 abundances from space. Data courtesy of Glenn Diskin, NASA.

(2) Page 7, Line 162, It is not clear. Does it mean between 6 and 12%?

Text changed to read "…. between 6 and 12%.".

(3) Page 10, Line 242, "Air quality criteria to protect public health" Reference or explanation is needed.

Clarified: The text referred to has been rewritten as: Nine months before the U.S. Environmental Protection Agency was founded, air quality criteria were established for carbon monoxide (U.S.,

1970) to protect public health in compliance with the 1967 amendments (Public Law 90-148) to the Clean Air Act of 1963 (Public Law 88-206).

(4) Page 12, Line 298 The brief description of the reason why 5μrad is needed.

The text "The displacement between a single paired gas/vacuum measurement is limited to ≤5 μrad/60 msec to ensure acceptable changes in ground pixel reflectance based on MOPITT experience (Deeter et al., 2011), and on simulated radiance errors using representative GEO spacecraft pointing data", has been rewritten to read:

Observation simulation studies using representative GEO spacecraft pointing data have been performed to determine the effect of 'jitter' in spacecraft pointing during the acquisition of a signal pair. The displacement between a single paired gas/vacuum measurement is limited to ≤5 μrad to ensure acceptable changes in ground pixel reflectance based on MOPITT experience (Deeter et al., 2011). This requirement corresponds with a gas cell-to-vacuum cell frame time limited to 60 msec, readily achievable with a physically realistic cell size and rotation frequency, frame acquisition and readout rate. The large (>3000 kg) size of a commercial communications spacecraft therefore serves to naturally attenuate jitter sources over very short time frames, avoiding the need for a costly image stabilization subsystem.

(5) Page 13, Line 313, "the effect of variations in the underling surface" Does it mean fine spectral structure of surface albedo?

Clarified: The text "the effect of variations in the underling surface" has been changed to read "the effects of variations in the underlying surface temperature, emission, and reflectivity".

(6) Page 15, Figure 6, "solid red lines at filter half-power point" Is it 50% transmittance point? The transmittance at red line looks about 40%.

These are the 50% transmittance points, now noted in figure caption.

(7) Page 16, Line 366 (<10%) Accuracy requirement for CO and CH4 must be different but instrument is similar. CO accuracy of 10% is reasonable and was demonstrated with MOPIT. How is the accuracy of 1% achieved in the CH4 retrieval? Aerosol and thin cloud cause bias error and averaging cannot reduce the bias. Recent CH4 satellite retrieval such as GOSAT use O2A band in 0.76 micron to estimate light path modification by aerosol and CH4.

The measurement accuracy requirements of the observations are set by the product accuracy required to answer the science questions (multispectral CO accuracy 10%, and CH_4 accuracy 1% as stated by the Reviewer). Measurement accuracy requirements are discussed in Section 3.2. While the instrument is the same, the measurements of CO and CH4 and the underlying spectral signatures and radiative transfer are different. The CHRONOS instrument acquires fewer or additional observations in each spectral channel to achieve the required signal-to-noise. In Section 3.3, Table1 provides the measurement passbands for optimized spectral sensitivity. We have added to Table 1 the minimum signal-to-noise ratio for each measurement, and the number of observations needed to achieve that minimum SNR, and supplemented the text preceding the Table as follows:

Table 1 lists the modeled signal-to-noise (SNR) and the total number of individual data acquisitions in each pixel in the 2D detector array (“frames”) obtained in a single 9.7-minute data acquisition period, for the minimum radiance case defined from MOPITT on-orbit radiance records. This minimum SNR provides at least 30% margin for meeting the radiance precision requirements.

(8) Page 17, Lines 375-333, “there 3 minute retrieval” “These 3 minute retrieval” and relation between âLij3 min intervals and retrievals are not clear. What is the definition of “single (âLij10 min) data”?

The original text appears to be corrupted. We have rewritten the text to clarify as follows:

Profile or column retrieval precision requirements are achieved in ground processing by averaging geo-located, cloud screened radiances for three minutes (375 separate gas-vacuum measurements for each product: CO [4.6 µm, 800 hPa], CO [4.6 µm, 200 hPa], CO [2.3 µm, 100 hPa]; and 750 measurements of CH_4 [2.2 µm, 800 hPa]). A single retrieval for each product is performed on these averaged radiances. The process of averaging radiances and then retrieving products is repeated for all data acquired in the 9.7-minute data acquisition period.

(9) Page 21, Line 455, “all digital” What do the authors mean by “all digital”? Usually detectors and readout electronics have analogue portion such as amplifier and analogue to digital converter.

The “all-digital” focal plane arrays became available for science use in the early 2000s. For all of the cited arrays, signal amplification and analog-to-digital conversion occur in the readout integrated circuit (ROIC) at each pixel, leading to the term “in-pixel digitization” or “all digital”. This type of array is what enables CHRONOS to quantify very small differences in radiance. We have added a reference to:

Brown, M.G., Baker, J., Colonero, C., Costa, J., Gardner, T., Kelly. M., Schultz, K., Tyrrell, B., and Wey, J.: Digital-pixel focal plane array development, Proc. SPIE 7608, Quantum Sensing and Nanophotonic Devices VII, 76082H (January 22, 2010); doi:10.1117/12.838314, 2010.

Although the title above says “digital pixel”, text in this and other papers refer to “all digital” or just “digital” focal plane arrays, which is now a common usage we adopt in the manuscript.

(10) Page 22, Line 487, “radiance calibration” Brief description of radiance calibration is needed.

We have added a brief description of radiance calibration to Section 4 as follows:

For on-orbit radiance calibration, CHRONOS views high-precision hot and cold black bodies and deep space for the MWIR channels, and a tungsten lamp (LandSat Operational Land Imager heritage) and a closed aperture for the SWIR calibration within each 10-minute data acquisition.

(11) Page 23, Figure 11, vertical axis “#obs in domain/# pixels Explanation is needed.

Clarified: Added text to the figure caption: “#obs in domain/# pixels (the number of cloud-free pixels observed as a fraction of the total number of pixels in the region)”.

(12) Page 30, Line 639, “launch in 2017”

We have changed the GOSAT-2 launch to 2018 at this location and in Table 3.

Page 32 table 3 OCO-3 (2017-) I think GOSAT-2 launch is scheduled to be in 2018 as the authors indicated in Table 3. I think OCO-3 has less possibility to be launched this year.

Table 3 has been revised in response to Reviewer 2.

Technical Corrections

(1) Page 24, Line 522, “total hydrometeors > 10-8/kg/kg” Is it 10ˆ-8?

Corrected: Changed to 10^{-8}/kg/kg.

(2) Page 34, Line 723, “et al.” and many others. AMT authors guideline says “Please supply the full author list with last name followed by initials.” Other formats also do not meet the guideline.

Corrected: Formats have been changed to match guidelines throughout.