

Reviewer 1

We would like to thank the anonymous reviewer for his comments. We believe they help us to improve the manuscript and give us some matters to improve the mission. Here below are our answers. A corrected version of the paper has been uploaded as a supplement.

Please note that we found an error in Table 1. The IF range is 10.975-18.975 GHz and not 10.075-18.075 GHz.

Reviewer comments are in blue, the citations from the original manuscript are in italic and the manuscript modifications are in red. The answer “Done” simply means that the manuscript has been modified following exactly the reviewer comment.

1) Although primarily focusing on wind retrievals the manuscript does not address the question of local oscillator stability. However, for a wind error below 1 m/s an oscillator stability of $df/f < 3.3e-9$ is needed. As the operation geometry does not allow observations in opposite viewing directions as done by other wind measurement techniques this stability needs to be long-term (i.e. for the entire mission lifetime) in order not to introduce trend artifacts. What are the expected frequency stability during heating/cooling of the satellite? What is the aging of the planned frequency source? Are there plans for a method to monitor the LO frequency? Please comment on this issue in the manuscript. Even if very high stability could be achieved and the induced bias was marginal, an upper limit should be indicated. I assume it is one of the questions a reader has when reading about Doppler shift measurements.

The LO stability is indeed a key parameter when measuring the winds. We should have discussed this issue in the paper and we have included a discussion in Pages 13-14 based on the instrument design described in the proposal.

Here are some additional information not included in the corrected manuscript:

In the instrument design report, it is stated that “a highly stable 10 MHz TCXO (Rakon RPT7050) is used as frequency reference to the PLL circuit. This TCXO has a long term stability (aging) of only ± 1 ppm/year (> 0.5 MHz). The VCO used is HMC529LP5 from Analog Devices. The output frequency of the LO unit is 13.293 GHz.”

A short term (24 hours) LO stability of 2 kHz ($df/f = 3 \cdot 10^{-9}$) has been required, it corresponds to a wind error of 1 m/s. The instrument team considers that such a performance is challenging and they guaranty a stability of 10 kHz. However discussions with the instrument team are still going on and we expect to improve the performances for both long and short timescales using different hardware or connecting SIW to the Innosat Spacecraft bus clock.

Table 2 (P13) has been modified to include short-term (24 hours) and long-term (1 month) local oscillator frequency variability: 2-10 kHz and > 0.5 MHz, respectively.

Page 14, Line 4. The paragraph has been rewritten in order to include a discussion on the LO frequency uncertainty:

Systematic retrieval errors emerge from uncertainties on the instrument, calibration and forward model parameters, and LOS angles (Tab. 2). ~~The most critical parameters are investigated using a perturbation method:-~~

It is difficult at this stage of the mission definition to provide proper values for these uncertainties. The given values are relatively close to those expected but rounded in the way that it will be straightforward to linearly scale the retrieval errors according to any future better knowledge of the parameter uncertainties. One may notice that the uncertainty on the line broadening parameter (G_i) is likely underestimated and the actual values should be between 1–4 % depending on the line. On the other hand, the calibration parameters ~~and sideband ratio~~ are likely overestimated. Anyway these errors induce a relatively constant retrieval bias that could be mitigated with ad-hoc corrections if their properties are well understood, e.g., time scale and latitudinal variabilities (see for example the JEM/SMILES data analysis in Baron et al. (2013b)).

Given the proposed design of the instrument (Murtagh, 2016), the 24-hours variability of the local oscillator frequency is between 2 and 10 kHz which straightly results to a LOS wind retrieval uncertainty of 1–5 m/s. The lower limit corresponds to the scientific requirement and the upper one is the worse acceptable case. Though it is a systematic error, it changes from one scan to another with a time correlation that has to be determined before launch. The impacts on other retrieved parameters are negligible. The 1-year frequency variability may be relatively large (>0.5 MHz or 250 m/s) and we should consider that an absolute frequency knowledge, good enough for retrieving winds, may not be available. The frequency calibration will be performed using short-term wind retrieval bias estimates within 40–60 km where other systematic errors are small.

Retrieval errors from other parameters are investigated in Sect. 5.2 using a perturbation method:

EQ17 ...

And in the conclusion (P22,L5):

~~The need for developing ad-hoc methods ...~~ Hence ad-hoc methods for reducing retrieval biases must be studied. These methods can be used to calibrate the LO frequency long-term trend that may arise with the proposed hardware. However, improvements of the instrument design for following the frequency trend with a precision better than 2 kHz, are still being investigated.

Methods for mitigating wind retrieval bias have to be defined. Looking at opposite directions such as it is done with a ground based instrument, is difficult in space (e.g., solar illumination issue) and not be efficient (the two opposite measurements will be 2000-3000 km away from each other). Other methods more likely based on daily zonal statistics have to be defined. For instance we may use the fact that systematic errors lead to zonal-wind retrieval errors with opposite sign on the ascending and descending orbit branches.

This issue has been added in Appendix A:

...

A systematic error e_{los} on the LOS wind retrievals propagates to the U and V components as follows:

1. The systematic error on the zonal-wind estimate is $e_u = e_{los} (\cos(\alpha_n) + \sin(\alpha_n))$
2. The systematic error on the meridional-wind estimate is $e_v = e_{los} (\cos(\alpha_n) - \sin(\alpha_n))$

We assume that e_{los} does not depend on the LOS orientation which is a valid assumption for the errors investigated in this paper (LO frequency, calibration, spectroscopy). We should note that $e_v = 0$ for $\phi_n = 45$ deg or 225 deg which occur at latitudes between 30N–50N on the ascending branch of the orbit and between 10N–30N on the descending branch. The cases $e_u = 0$ occur for the retrievals at the lowest and highest latitudes.

At the equator, the bias on the meridional wind is partly canceled out and the bias correction method used for JEM/SMILES analysis may not be satisfactory. For instance, an error $e_{los} = 1$ m/s induces an error $e_v = 0.2$ m/s. On the other hand, the error on the zonal component is 1.4 m/s with an opposite sign on the ascending and descending orbit branches. The sign difference may provide us with a way to characterize LOS wind retrieval systematic errors.

2) You suggest a sun-synchronous orbit crossing the equatorial ascending node at 18:00. I agree that this allows perfect conditions for wind observations by allowing to constantly observe the night side with the higher ozone concentrations. My concern about this choice is that the representativeness of the measurements of trace gases near the day-night terminator may be delicate as during this period the concentrations of photochemically active species undergo rapid changes. This may among others introduce an artificial annual cycle to your measurements simply by modifying the time before (after) the sunrise and after (before) the sunset the observations are made. Can you quantify this effect and what are your ideas to mitigate it?

Unfortunately the choice of the LT ascending node is fixed by the launcher and, in order to keep low Innosat mission budget, the choice is limited. This being said, as explained by the reviewer, wind and temperature retrieval performances are better in nighttime conditions but reactive species should be measured both in day and night times as for Aura MLS or MIPAS.

There is a compromise to be done. For this mission, we have chosen the most favorable conditions for wind measurements which are very challenging. Also, flying near the terminator provides favorable conditions in term thermal stability and solar-panel illumination.

The analysis of the species with diurnal variations (meso-O₃, ClO, HO₂, NO) will be performed with photo-chemical models. We will benefit from all the studies and methods implemented for previous missions like Odin or ACE/FTS. Most of the observations will be performed at SZA (+/- 10-20 deg from the terminator) when abundance changes will be slower than at sunrise or sunset.

Can you quantify this effect and what are your ideas to mitigate it? This is a very broad topic that cannot be addressed here. Each molecule, altitude, latitude and season should be treated as a special case.

Specific comments

Page 1, L1: Why is your instrument called "Stratospheric Inferred Winds" when effectively assessing the upper stratosphere and lower mesosphere?

Siw is a character of the Swedish mythology. The acronym put the focus on the stratosphere and wind. Though winds are only measured over about half of the stratosphere (30–50 km), the mission is primarily a stratospheric mission. Middle and upper stratospheric winds are a key product of the mission as explained in the paper. The mission is also able to provide a rather comprehensive description of the full stratosphere including high precision temperature and O₃ measurements as well as good measurements of important species for studying its chemistry, dynamics and radiative budget (H₂O, HCl, N₂O, HNO₃, ClO or HCN).

Good measurements of the mesosphere will also be performed but the instrument design is not optimized for such altitudes. A spectral resolution of 0.5 MHz would have been better as well as having

an additional spectral channel with a strong line for improving the temperature retrieval performances, temperature being a key parameter for inverting molecular lines.

p.2, l.5: “risk of an observation gap in the near future” Is there no citation for this statement?

We are not aware of a refereed paper discussing this issue. However the following presentation at a recent SPARC meeting is available on the Web. We have added its reference in the manuscript.

Livesey, N. J. and Santee, M. L.: Prospects for future spaceborne measurements of interest to the SPARC DA Community and how to improve those prospects, in: S-RIP 2017 and 13th SPARC-DA Workshop, <https://events.oma.be/indico/event/18/material/slides/16.pdf>, 2017.

p.2, l.20: You could maybe add a citation of a modeler stating that wind simulations in these regions are hard to obtain.

The references given in Line 20 (Baron et al., 2013, Pichon et al., 2015...), though they focus on the measurements, clearly shows difficulties of analysis and re-analyses to reproduce wind in the mesosphere. Because of the lack of measurements, most of the GCM wind evaluations have been performed for altitudes below 10~hPa. For instance, the difficulties for a GCM to reproduce Equatorial wind at 10 hPa has recently been discussed in Kawatani et al., (2016). A key dynamical feature of the upper part of the middle-atmosphere is the vertically propagating tides. Using temperature data, Sakazaki et al. (2018) found significant tide signature differences between the latest re-analyses and measurements of in the upper stratosphere and lower mesosphere. We have added these references as:

Modeling middle-atmospheric major dynamical phenomena such as vertically propagating tidal waves, high-latitude sudden stratospheric warming or equatorial quasi-biennial oscillation are still challenging (Limpasuvan et al., 2012; Newman et al., 2016; Orsolini et al., 2017; Sakazaki et al., 2018). Wind ... cannot be described by the geostrophic approximation such as in the equatorial region where the Coriolis force is weak and, in the upper stratosphere and mesosphere where waves and tides phenomena tend to dominate the wind fields (Baron, 2013, LePichon, 2015, Kawatani et al., 2016...

Kawatani, Y., Hamilton, K., Miyazaki, K., Fujiwara, M., and Anstey, J. A.: Representation of the tropical stratospheric zonal wind in global atmospheric reanalyses, *Atmospheric Chemistry and Physics*, 16, 6681–6699, doi:10.5194/acp-16-6681-2016, <https://www.atmos-chem-phys.net/16/6681/2016/>, 2016.

Sakazaki, T., Fujiwara, M., and Shiotani, M.: Representation of solar tides in the stratosphere and lower mesosphere in state-of-the-art reanalyses and in satellite observations, *Atmospheric Chemistry and Physics*, 18, 1437–1456, doi:10.5194/acp-18-1437-2018, <https://www.atmos-chem-phys.net/18/1437/2018/>, 2018.

p.2, l.24: does -> do

Done

p.2, l.25/27: The measurement approach presented in Baumgarten 2010 is also providing wind in the gap region. Please add citation at l.27.

Done

p.2, l.30: Rather 20 or 30 km?

Using the Rayleigh channel (signal backscattered by molecules), LOS wind can be retrieved up to about ~30 km with a precision better than 5 m/s and a resolution of 2 km.

Do you see Aeolus as a good complement to your mission if you get synchronous mission activity? Please comment on this.

In case of overlap between both missions, there is an obvious complementary since Aeolus targets wind below 30 km and SIW targets higher altitudes. However, in the altitude range between 20-35 km, the performances of both missions are weak. Also, Aeolus measures only the wind component along a single line-of-sight. These information are given in the paper and further discussions about the complementary of both missions are out of the scope of this paper.

Using Aeolus data together with SIW for scientific studies will be investigated though Aeolus lifetime is officially between 2018-2021. More generally, combining lidar and micro-wave or infra-red passive sensors should be the solution in the future for measuring winds from the surface to the lower thermosphere.

p.3, l.1: Please clarify that the wind profiles published in Wu et al. 2008 do not cover the gap region you defined as 30-70 km.

The sentence has been rephrased as follows:

The potential of MM/SMM limb sounders for measuring winds has been demonstrated with LOS wind retrievals between 70–90 km from MLS O2 line (Wu et al., 2008) and between 30–80 km from O3 and HCl lines measured with Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) (Baron et al., 2013b).

p.3, l.9: Please indicate the expected lifetime of SIW. Is there a chance to have it observing at the same time as SMILES-2? Would there be an added-value if both missions would be observing synchronously or would the expected higher performance of SMILES-2 make SIW obsolete?

Given the uncertainties on SMILES-2, having SIW is a very good thing. SIW lifetime is planned to be 2 years in order to allow the launch of a new Innosat mission every two years. If SMILES-2 is selected this year, the launch should be near 2025. In this case, SMILES-2 will follow SIW without overlapping time.

However, beside the budget consideration, SIW hardware lifetime could be longer than 10 years (e.g., as for MLS and SMR instruments) and a time expansion of the mission may then be possible. Having an overlap with SMILES-2 will benefit to both missions, and the quality of the scientific outcomes will be improved. For instance, the spatial and local time samplings are different and complementary. The fixed local times of SIW measurements will help to characterize non-diurnal changes in the SMILES-2 dataset such as non-migrating tide effects on temperature and wind. A long-term database can be produced with SIW that can not be done with SMILES2 whose the lifetime will be shorter than 5 years due to the limited lifetime of the cryo-cooler.

In term of data processing, we will share problems and information related to the 655 GHz band that has never been measured before (spectroscopic data, retrieval strategy, ...). Collaborations between both teams already exist and they will be strengthened if SMILES-2 is launched. This will lead to more efficiencies for defining, implementing and validating the processing chains.

The sentence p.3, l.9 has been rephrased as follows:

... and SIW has been selected for the 2nd launch near 2022. It will observe the middle-atmosphere (15–90 km) for a period expected to be at least 2 years, and will provide horizontal-wind vector within 30–90 km.

Sect. 2.1: Please extend the instrument description. It is clear that this is not an instrument paper, but some core characteristics of the receiver should be introduced here. This will moreover avoid that questions arise during the further read of the manuscript.

In this manuscript, we want to focus only on the main instrument characteristics that are relevant for the simulations. We do not want to go too deep in the description of hardware details. Moreover some of them may still be modified for optimizing the performances. We do not wish to add more details but, if the reviewer believes that an important information is missing, we will be happy to add it.

P.4, l.6: With your scanning scheme LOS winds at 45 and 135 deg will be recorded from a similar location only for 1 altitude of your scan. How large will the distance between this two components be at maximum? Is this sampling mismatch not critical for your calculations of one zonal and meridional wind profile with Eq. (A2)?

The maximum distance between 2 scans is less than 400 km. This is equivalent to the LOS horizontal resolution. No significant errors should be induced by the position mismatch.

The manuscript has been changed as follows (the modifications also includes reviewer 2 comment answer):

The forward antenna is used during the upward scans and the aftward one during the downward scans. With this choice, the horizontal displacement of the tangent point during a vertical scan is less than 300 km, the vertical motion of the line-of-sight partly counterbalancing the satellite motion. Using the line-of-sight (LOS) winds retrieved with the two antennas over close regions allows us to derive the meridional and zonal wind components (Appendix A). The separation between the LOS wind profiles is less than 400 km.

p.4, l.7: "continuously rotate" is misleading as it is in fact not an unaccelerated rotation but rather a succession of upward and downward scans.

I think this was an issue corrected after the quick review process. In the current version, the text is: "... the whole satellite will nod up and down in order to scan the limb alternatively upward and downward from about 15 to 90 km"

p.4, l.28: "at least a factor of 2... compared to other spectral regions." Please be more concrete. What are "other spectral regions".

The sentence has been rephrased as follows:

... a factor 2 the wind measurement sensitivity between 40–70 km compared to other spectral regions to retrievals performed from a band with similar characteristics but located at any other frequency under 800 GHz.

Fig. 3: You display 9 GHz but the spectrometer bandwidth is 8 GHz. Please mark the (un)used frequency range in this figure.

The ranges outside the spectral bandwidth are now indicated with grey-shaded areas. The caption has been updated accordingly.

Fig. 3: What is the reason for the 2 GHz frequency shift compared to SMILES-2 (Ochiai et al 2017)?

There is no frequency difference with the band shown in Ochiai et al. (2017). In Ochiai et al., the band is displayed differently: each sideband is divided in two ranges of 4 GHz.

Fig. 3: Displaying the centre frequency of LSB and USB directly in the different panels would help to further clarify the figure.

The central frequency is now indicated in the plot x-labels.

p.5, l.7: I suggest to modify “so-called brightness temperature” to “so-called Rayleigh-Jeans brightness temperature” to make sure the user is not confused by the 1 mK of cosmic background (as I was at first).

Done

p.6, l.6: $i \rightarrow \nu_i$

Done

Fig. 4: It is not completely clear from the text what you intend to communicate to the reader with this figure. Please extend the description and reasoning in the text.

The text P6 l.7 is changed as follows:

and I is the specific intensity. The specific intensity is integrated along a LOS as that shown in Fig. 4. The LOS is characterized by the altitude of the tangent point ($i=0$), the angle with the meridional direction ϕ_n and narrow ranges i over which the atmosphere is considered homogeneous.

The index “ i ” (frequency) in Eq (3) is replaced with “ k ” to avoid confusion with the LOS range index used in the figure.

Eq. (2): Why do you use quadratic addition of the static antenna pattern and the broadening due to the scanning velocity? I would argue that, if you combine the static pattern with the scanning, your beam pattern becomes non-Gaussian. In any case, I think that by quadratic addition you drastically underestimate the width of your main lobe unless the scanning broadening is much smaller than the static beam width. If not the case, I would think that a linear addition would already be closer to reality while still underestimating the width of your beam (due to the non-Gaussianity introduced by the scanning). Please review the information about the beam width in the manuscript.

We agree with the reviewer that considering the effective antenna pattern as a Gaussian is an approximation. But it is a satisfactory approximation for a sensitivity study. The static antenna vertical width is about 5 km which is significantly larger than the altitude range scanned during the spectrum integration (1.1 km). Moreover the retrieval vertical resolution is 5 km, so such an approximation has no impacts on the results. Antenna side-lobes have also small impacts on the retrieval errors estimation and can be neglected.

The text is changed in order to clarify these points:

Given that the altitude range scanned during the spectrum integration is small compared to the static antenna vertical resolution (1.1 km and 5 km, respectively), the effective antenna pattern including the vertical scan, is approximated by a Gaussian function ...

The antenna sidelobes are also neglected. These approximations have negligible impacts on this study.

p.8, l.14: Why are you using JPL for some lines and Hitran for others?

The JPL lines used in this work are not in HITRAN. The text is changed as follows:

... that are not available in HITRAN and are, then, taken from the Jet Propulsion Laboratory catalog (Pickett et al., 2018).

p.8, l.16/17: You could indicate worst-case bias induced by these effects to show how marginal they are.

There is a lack of information for the pressure shift parameters. In HITRAN 2016, only values for HCl and H₂O lines are available. At 10 hPa (~30 km), the H₂O line shift is 230 kHz and an error of 2% corresponds to a wind error of ~2 m/s. This value should be smaller for O₃ lines.

The text is changed as follows:

The line frequency is also shifted by pressure but this effect is small above 25 km where winds are measured. For the H₂O line at 620 GHz, 2% error on the shift parameter corresponds to an error of 2 m/s at 10 hPa. The shift on O₃ lines should be smaller but the information is not available in HITRAN and further studies are needed to infer it.

p.10, l.1: You refer to T_{so} as antenna spillover. Looking at Eq (8) T_{so} rather refers to the average brightness temperature of the regions where the radiation which you receive because of the spillover in your optics actually comes from. Please adapt the wording.

The text has been rephrased as follows:

T_{so} is the mean brightness-temperature introduced by the optics spillover, ...

p.10, l.2/l.15: "spill-over" or "spillover". Please use consistent spelling

The term "spillover" is now used instead of "spill-over"

Eq. (10): You may state that you assume T_c = 0 here.

We changed the text as follows:

Assuming a linear response of the radiometer and using T_c << T_h, the radiometer gain is derived

Eq. (15): Does this linear approach suffice for all situation you expect to encounter? What happens if the truth is further away from the first guess than in Fig. 6? Is this linear retrieval also sensible for photochemically active species close to the day/night terminator?

The retrieval approach presented here is good enough for estimating the retrieval errors with respect to the atmospheric state. This is a very common approach used for other mission studies such as MLS, Odin and SMILES. The definition of a robust retrieval algorithm is not needed and it is not discussed in this paper. Let's note that methods to handle non-linear effects that can arise for cases with large differences between the first guess and the true atmosphere, exist. For instance, the linear scheme presented in the paper can be integrated into a standard Levenberg-Marquardt iterative scheme (e.g., see Urban et al. 2004 and Baron et al. 2011 given in the paper). For species such as ClO, N₂O, HOCl the problem is nearly linear even for large differences and a linear approach should provide good performances even near the terminator. The main issue in this case is possible large horizontal inhomogeneities near the tangent point. But such cases will be rare (see 2nd main comment answer).

Eq. (15): You use S_{dy} instead of S_y. What about error correlations? Can they be neglected and why? Please state it in text.

The correlations are not neglected. They are taken into account in Eq. 16 since the full matrix S_y is used. The diagonal matrix S_{dy} is only used in the inversion of K as a measurement weight.

The reason to not invert the full matrix is because it is too large (~8000 frequencies and 150 tangent heights) to be done with the computer used for this analysis. In the future, we will optimize the computations in order to reduce the matrix size and use sparse matrix algorithms for the inversion. In

theory (i.e, if the frequency correlations are properly characterized), the retrieval errors will slightly be decreased.

We changed the text as follow to make it clearer:

P13L10: "... the standard deviation of x , S_y is the full measurement error covariance matrix (Eq. 14) and ..."

p.13, l.15: Please add the reason for the increasing error at lower altitudes here.

lower altitude for wind retrieval. The error increase is due to the pressure broadening of the lines that is about 20–40 MHz at 10 hPa.

p.14, l.19: I suggest to refer to F_i as "centre frequency" instead of just "frequency".

Done (as well as in Table 2 and A1 captions)

p.13, l.20: How do you retrieve the elevation offset?

The elevation offset is one of the retrieval parameter in x . This is explained at the beginning of the section (P12,l10):

"The retrieved state $x_{\hat{}}$ is a vector including all the unknown parameters of the forward model, namely the atmospheric vertical profiles, a radiance offset on each spectrum and a mean pointing angle offset of the whole scan."

Since it is a standard approach, we do not think that we need to provide more details.

p.16, l.10: Please indicate the reason why the best performance is found over the northern polar regions.

The mesospheric wind measurement performances are the best over the night-time poles because of the O₃ enhancement. The text is changed as follows:

"The best performances are found over the northern polar region where the nighttime O_3 enhancement is the largest. There, the LOS-wind can be retrieved with a precision better than..."

Sect. 5.2: Why using a 10 times to large error for the sideband ratio? Indeed a 1% sideband uncertainty seems rather large. Please consider to modify it to the value of 0.1% that you found in your preliminary study. The choice of 1% uncertainty which you then qualify several times as too large unnecessarily complicates the reading of this section.

We changed the manuscript to consider an error of 0.1% on the DSB parameter. The x-scales of Fig. 11 and 12 have been changed accordingly as well as the DSB error discussions in sections 5.2.1 5.2.2 and conclusion (P22,L1).

p.18, l.15: have -> Has

Done

p.18, l.16: overlap over each other → overlap each other

Done

p.21, l.7: unusual -> Unusually

Done

p.22, l.28: Grammatically incorrect sentence

The sentence has been rephrased as follows:

“The retrieval of two line-of-sight winds over the same region allows us to compute ...”

p.23, l.1: $\alpha_n \rightarrow \phi_n$

Done

Eq. (B1): What is the significance of “max” here? $\text{eps}_x(x,M)$ seems to be a scalar (see Eq. (18)) so I don't see what you want to do by taking the maximum.

This term $\text{eps}_x(x,M)$ means the set of the errors induced by all the parameters of all the lines of a given species M. In the revised version, it is replaced by $\{\text{eps}_x(x,M,p_i)\}_{p_i}$ and the text is rephrased as:

“where M denotes the chemical species, $\text{eps}_x(x,M,p_i)$ is the error induced by the parameter p of the line i (Eq. 18), and $\{\text{eps}_x(x,M, p_i)\}_{p_i}$ is the set of errors induced by all the parameters of all the lines of the species M.”

Reviewer 2

We would like to thank the anonymous reviewer for his comments. We believe they help us to improve the manuscript and give us some matters to improve the mission. Here below are our answers. A corrected version of the paper has been uploaded as a supplement.

Please note that we found an error in Table 1. The IF range is 10.975-18.975 GHz and not 10.075-18.075 GHz.

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1) I think the authors have somewhat glossed over the trade inherent in such measurements between precision and resolution (vertical resolution mainly in this case). They can afford not to dwell on it in this study because they’ve chosen a rather coarse 5km spacing for their state vector resolution, but I do think it deserves some mention (but probably not any new calculations). At no point do they discuss averaging kernels, but I imagine they’ve computed them, or could do so very easily. I expect that such kernels indicate that the information content is a good match for their 5 km grid (i.e., that A is a good approximation to the identity matrix, except perhaps at the top and the bottom of the profiles). I would however like them to add a discussion to that effect somewhere in the text. Their mention of the potential of finer 3km resolution for temperature (page 17, line 7) implies that they have looked into this issue somewhat. I encourage them to talk about it just a bit more.

A weak regularization is used for inverting the forward model Jacobian matrix which gives unity averaging kernels. The vertical resolution is then given by the resolution of the retrieval altitude grid. We have chosen to use the same resolution of 5 km for every product over the whole altitude range in order to simplify the discussion. The resolution corresponds to the antenna field of view resolution (i.e., the vertical resolution of the measured radiance). However proper retrieval algorithms will consider the best resolution for each product considering the trade-off between vertical resolution and precision. The manuscript has been modified to clarify these points as follows:

Page 12, Line 12:

“The retrieval altitudes range ... The *retrieval* grid vertical resolution is $5\text{~}\text{unit}\{\text{km}\}$ that corresponds to the effective *vertical* field-of-view of the instrument”

Page 13, Line 4:

“... U_x is a diagonal matrix for stabilizing the matrix inversion. Its element square-roots correspond to very large standard deviations (STD) of x , typically $> 10000\%$, 1000 K, 1000 m/s for VMR, temperature and LOS wind, respectively. The regularization effects are negligible where *the measurement is relevant* the retrieval errors (null space and measurement errors) are much smaller than the U_x related STD. In other words, the averaging kernels are unity at altitudes where the measurement is relevant and the retrieval vertical resolution is that of the retrieval altitude grid.”

Page 15, Line 4:

The precision ($1-\sigma$) is given for *a retrieval vertical resolution of $5\text{~}\text{unit}\{\text{km}\}$ and for a single-scan and a vertical resolution of 5 km and for a single-scan*. It is possible to use the altitude information inscribed in the pressure broadened lineshape, for retrieving atmospheric profile with a

better resolution but at the cost of the precision. Precision degradation can be afforded for products retrieved from strong signals (e.g., O_3 or temperature) or for those whose the vertical resolution is more scientifically relevant than the temporal or horizontal one (precision can be improved by averaging data). On the other hand, degrading the vertical resolution may be necessary for providing useful information on products derived from weak signals (e.g., HOCl). Later, using the results of this study and based on scientific requirements, the retrieval algorithm will be optimized for providing the best compromise between precision and resolution for each of the main products.
~~...Also the retrieval vertical resolution can be increased for improving the precision of species with weak lines.~~

2) The authors make no mention of frequency stability requirements for the instrument Local Oscillator (presumably tied to some lower frequency clock source). I presume the instrument (or spacecraft) design includes some suitable source, possibly tied to GPS signals. If it is better than 1 part in 10^9 , then I think it's OK to ignore it, otherwise it should probably be investigated for its impact on wind accuracy. Either way, it should probably be discussed. Measuring lines on either side of the LO can significantly reduce sensitivity to that term (at the expense of wind precision), but if the measurement approach relies on that it should certainly be discussed.

The LO stability is indeed a key parameter when measuring the winds. We should have discussed this issue in the paper and we have included a discussion in Pages 13-14 based on the instrument design described in the proposal.

Here are some additional information not included in the corrected manuscript:

In the instrument design report, it is stated that “a highly stable 10 MHz TCXO (Rakon RPT7050) is used as frequency reference to the PLL circuit. This TCXO has a long term stability (aging) of only ± 1 ppm/year (>0.5 MHz). The VCO used is HMC529LP5 from Analog Devices. The output frequency of the LO unit is 13.293 GHz.”

A short term (24 hours) LO stability of 2 kHz ($df/f = 3 \times 10^{-9}$) has been required, it corresponds to a wind error of 1 m/s. The instrument team considers that such a performance is challenging and they guarantee a stability of 10 kHz. However discussions with the instrument team are still going on and we expect to improve the performances for both long and short timescales using different hardware or connecting SIW to the Innosat Spacecraft bus clock.

Table 2 (P13) has been modified to include short-term (24 hours) and long-term (1 year) local oscillator frequency variability: 2-10 kHz and >0.5 MHz, respectively.

Page 14, Line 4. The paragraph has been rewritten in order to include a discussion on the LO frequency uncertainty:

Systematic retrieval errors emerge from uncertainties on the instrument, calibration and forward model parameters, and LOS angles (Tab. 2). ~~The most critical parameters are investigated using a perturbation method.~~

It is difficult at this stage of the mission definition to provide proper values for these uncertainties. The given values are relatively close to those expected but rounded in the way that it will be straightforward to linearly scale the retrieval errors according to any future better knowledge of the parameter uncertainties. One may notice that the uncertainty on the line broadening parameter (G_i) is likely underestimated and the actual values should be between 1–4 % depending on the line. On the other hand, the calibration parameters ~~and sideband ratio~~ are likely overestimated. Anyway these errors induce a relatively constant retrieval bias that could be mitigated with ad-hoc corrections if their properties are well understood, e.g., time scale and latitudinal variabilities (see for example the JEM/SMILES data analysis in Baron et al. (2013b)).

The 24-hours variability of the local oscillator frequency is between 2 and 10 kHz which straightly results to a LOS wind retrieval uncertainty of 1–5 m/s. The lower limit corresponds to the scientific requirement and the upper one is the worse acceptable case. Though it is a systematic error, it changes from one scan to another with a time correlation that has to be determined before launch. The impacts on other retrieved parameters are negligible. The 1-year frequency variability may be relatively large (>0.5 MHz or 250 m/s) and we should consider that an absolute frequency knowledge, good enough for retrieving winds, may not be available. The frequency calibration will be performed using short-term wind retrieval bias estimates within 40–60 km where other systematic errors are small.

Retrieval errors from other parameters are investigated in Sect. 5.2 using a perturbation method:

EQ17 ...

And in the conclusion (P22,L5):

Hence ad-hoc methods for reducing retrieval biases must be studied. These methods can be used to calibrate the LO frequency long-term trend that may arise with the proposed hardware. However, improvements of the instrument design for following the frequency trend with a precision better than 2 kHz, are still being investigated.

Specific comments

Page 1

Line 2: "... platform, with a launch planned for near 2022. It is ..."

Done

Line 6: "... perpendicular directions in order to reconstruct ..."

Done

Line 7: Consider putting commas before and after "near 655 GHz"? Also add "amount" of" between "small" and "wind"

Done

Line 10: First word "the" -> "a"

Done

Line 17: "... parameters and for study of methods ..."

Done

Page 2

Line 7: First word "of" -> "in"

Done

Sentence spanning lines 7, 8, and 9: I'd turn this sentence around: "Some important species, such as HO₂ and ClO, have their clearest signals in this region of the spectrum (refs.)" or something similar.

Done

Line 11: "... and measurements are not perturbed by ..."

Done

Line 16: "... have difficulties in reproducing it where ..."

Done

Sentence spanning lines 20-22: Again, I'd turn this around: "As climate and weather models increase their vertical range to encompass more of the stratosphere and mesosphere, the need for measurements to improve the accuracy of models in this region, and hence at lower altitudes, can be expected to rise", or something like that.

Done

Page 3

Discussion in first paragraph: Would be good to mention the WINDII and HRDI instruments and UARS. Was the information they provided not useful for your purpose, or at least some aspects of your purpose? Even though it was a while ago, were there not some questions that those instruments answered?

Both HDRI and WINDII are described in Shepherd et al. (2015). However it is true that HRDI should be explicitly cited since it is the only spaceborne instrument designed measuring wind in the stratosphere and mesosphere (WINDII measured winds above 90 km). The manuscript has been changed has follow:

Page 2, line 21-22:

~~Though there is a strong need for middle-atmospheric wind measurements to validate and constrain the models, only high altitude (>90 km) wind measurements with optical sensors currently exist on a global scale (Shepherd, 2015).~~ Only High Resolution Doppler Imager (HRDI) on Upper Atmospheric Research Satellite (1993-2005) has been able to measure horizontal winds over the stratosphere and mesosphere (Ortland et al., 1996), and current spaceborne sensors are not able to measure wind accurately below 90 km (Shepherd, 2015).

Page 4

Lines 5-10: If you're nodding the spacecraft, presumably the rotation axis of that nod is along the flight direction. Does that not give the two tangent points a non-vertical locus?

Is the choice to alternate the two views between the up and down scans intended to make them more vertical? If so it would be good to mention that explicitly.

The tangent height foot-print is not vertical. It moves along the orbit track with the satellite (7 km/s) and toward the satellite along the LOS in the ascending scan and away from the satellite during the descending scan. The nodding movement is performed over a small angle range, the deviation of the tangent points wrt to the vertical is small.

The text (P4,L6) has been modified as follow:

... upward and downward from about 15 to 90 km. The forward antenna is used during the upward scans and the aftward one during the downward scans. With this choice, the horizontal displacement of the tangent point during a vertical scan is less than 300 km, the vertical motion of the line-of-sight

partly counterbalancing the satellite motion. Using the line-of-sight (LOS) winds retrieved with the two antennas over close regions ~~will~~ allows us to derive the meridional and zonal wind components (Appendix A). The separation between the LOS wind profiles is less than 400 km.

P4,L10:

The following sentence is removed:

“The forward antenna is used during the upward scans and the aftward one during the downward scans.”

Page 5

Table 1: 1 MHz for the spectrometer resolution seems a bit on the coarse side to me, given the upper stratosphere / mesosphere target. Have studies been performed to see if finer resolution (e.g., some "zoomed in" lower bandwidth spectrometers on selected lines) might not improve the wind measurements?

The paper shows simulations based on the proposal status but the instrument design optimizations are still investigated such as the possibility to have different frequency resolution. A spectral resolution of 0.5 MHz for key mesospheric lines would improve the wind retrieval precision by more than 20% above 70 km (e.g., Fig. 6 in Baron (2013a)). Temperature retrieval should also be improved but further simulations have to be conducted to quantitatively assess the improvements.

The 200 MHz frequency range between IF = 17.2 and 17.4 GHz (LO=638.075 GHz) is the range that should be selected in priority. It contains the strong H₂O line (620.701 GHz) and the two strongest O₃ lines (620.825 and 655.289 GHz).

The second priority would be to increase of the resolution for the NO lines (651.1 GHz).

In order to compensate the telemetry data increase, the resolution could be decreased in other frequency range such as in the spectral window near the N₂O stratospheric line (652.8 GHz).

and we will not discuss this point in the main text. However this potential improvement is added in the conclusion:

P22L18: *“...could improve the measurement sensitivity by more than 20 %. Retrievals could also be improved in the mesosphere by increasing the frequency resolution to 0.5 MHz between the intermediate frequencies 17.2 and 17.4 GHz, a range that contains the strong H₂O line (620.701 GHz) and the two strongest O₃ lines (620.825 and 655.289 GHz). Implementing such a setting is under investigation.”*

Page 9

Line 24: If it's not too difficult, it would be nice to quantify "small" (e.g., of order 10 cm/s?)

The vertical width of the intensity weighting function is about 1 km. (WF are defined for a single ray before antenna convolution). At the equator, a horizontal wind of 100 m/s induces an error is 7 cm/s for a LOS point at 1km above the tangent point.

The error is given as $(V_e + V_{los}) \cdot (1 - \sin(\phi_i))$ with V_e the Earth rotation speed along the LOS (<370 m/s) and V_{los} is the horizontal LOS wind and ϕ_i the angle between the nadir direction and the LOS.

The manuscript is changed has follows:

P9, L24: *These errors are ~~small~~ smaller than 10 cm/s and have negligible impacts on the retrievals.*

Page 11

Line 21: "AURA/MLS" -> "Aura MLS"

Done as well as replacing AURA with Aura in other places.

Line 27: You cite Figure 2, but that figure shows the coverage for the SIW orbit, not the Aura orbit. I don't see the need for a second figure, so perhaps it's simpler just to remove the citation of Figure 2 here?

The black dashed lines show the Aura SZA vs Latitude for January.

Page 12

Line 13: "that corresponds to" -> ", corresponding to"

Done

Page 13

Line 4: I completely understand your dropping the non-diagonal terms in S_y , but it seems a shame after you went to such lengths to compute them long hand. Given the power of computers these days, is it still too much work to compute the full matrix inverse, at least once, and see what difference it makes? I guess it is rather large, so probably not. In which case, why to go such lengths to take up space in the earlier sections defining it? It might simply be easier to tell us up front that you plan to ignore those terms and explain why that's OK, rather than exposing the reader to the full algebra only to discard it.

The correlations are not neglected. They are taken into account in Eq. 16 since the full matrix S_y is used. The diagonal matrix S_{dy} is only used in the inversion of K as a measurement weight. The manuscript is changed to make this point clearer:

P13L10: "... the standard deviation of x , S_y is the full measurement error covariance matrix (Eq. 14) and ..."

The reason to not invert the full matrix is because it is too large (~8000 frequencies and 150 tangent heights) to be done with the computer used for this analysis. In the future, we will optimize the computations in order to reduce the matrix size and use sparse matrix algorithms for the inversion. In theory (i.e, if the frequency correlations are properly characterized), the retrieval errors will slightly be decreased.

Page 17

Line 18: "First, we note that, except for O3 and H2O, all ..."

Done

Line 30: Actually, ClO can be non-zero at night in some cases.

We agree and the statement has been softened: "... but vanish in general during nighttime."

Page 18

Line 24: Comma needed after "On the other hand"

Done

Simulation study for the Stratospheric Inferred Winds (SIW) sub-millimeter limb sounder

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Abstract. Stratospheric Inferred Winds (SIW) is a Swedish mini sub-millimeter limb sounder selected for the 2nd InnoSat platform, with a launch planned near 2022. It is intended to fill the altitude gap between 30–70 km in atmospheric wind measurements and also aims at pursuing the limb observations of temperature and key atmospheric constituents between 10–90 km when current satellite missions are probably stopped. Line-of-sight winds are retrieved from the Doppler shift of molecular emission lines introduced by the wind field. Observations will be performed with two antennas pointing toward the limb with perpendicular directions **in order** to reconstruct the 2-D horizontal wind vector. Each antenna has a vertical field of view of 5 km. The chosen spectral band near 655 GHz, contains a dense group of strong O₃ lines suitable for exploiting the small **amount** of wind information in stratospheric spectra. Using both sidebands of the heterodyne receiver, a large number of chemical species will be measured including O₃-isotopologues, H₂O, HDO, HCl, ClO, N₂O, HNO₃, NO, NO₂, HCN, CH₃CN and HO₂. This paper presents a simulation study for assessing the measurement performances. The line-of-sight winds are retrieved between 30–90 km with the best sensitivity between 35–70 km where the precision (1- σ) is 5–10 m s⁻¹ for a single scan. Similar performances can be obtained during day and night conditions except in the lower mesosphere where the photo-dissociation of O₃ in day-time reduces the sensitivity by 50 % near 70 km. Profiles of O₃, H₂O and temperature are retrieved with a high precision up to 50 km (< 1 %, < 2 %, 1 K, respectively). Systematic errors due to uncertainties on spectroscopic parameters, on the radiometer sideband ratio and in the radiance calibration process are investigated. A large wind retrieval bias of 10–30 m s⁻¹ between 30–40 km can be induced by the air-broadening parameters uncertainties of O₃ lines. This highlights the need for a good knowledge of these parameters and **for study** of methods to mitigate the retrieval bias.

1 Introduction

Millimeter and sub-millimeter (MM and SMM) limb sounders have been successfully used for more than two decades to probe the atmospheric composition and the temperature from the upper-troposphere to the lower thermosphere (Waters et al., 1993; Murtagh et al., 2002; Waters et al., 2006; Kikuchi et al., 2010). The first generation of Millimeter Limb Sounder (MLS)

provided unique observations of ClO, O₃, H₂O and HNO₃ allowing, for instance, a better understanding of the physical and chemical processes leading to the northern high-latitude O₃ depletion (Waters et al., 1993). Subsequent SMM missions have allowed the monitoring of the middle-atmosphere (15–110 km) **almost** without interruption since the first MLS and have significantly contributed to the current middle-atmospheric measurement database (Hegglin and Tegtmeier, 2017). However, 5 no successors of these missions are planned yet, and there is a risk of an observation gap in the near future (Livesey and Santee, 2017).

The advantages of such observations are manifold. The thermal emission spectrum at MM and SMM wavelengths is rich in isolated spectral lines from asymmetric molecules and molecular oxygen. **Some important chemical species, such as HO₂ and ClO, have their clearest signals in this region of the spectrum** (Urban et al., 2005; Khosravi et al., 2013; Sagawa et al., 2013; 10 Millán et al., 2015). The O₂ lines give temperature and pressure, and the limb geometry provides a suitable vertical resolution for describing the middle-atmosphere. Molecules are sensed in the thermal equilibrium state with no diurnal difference in the measurement performance, **and measurements are not perturbed by** stratospheric polar-clouds and aerosols. Furthermore, the technology is mature allowing missions to operate over a period longer than a decade. Methods have already been used for improving the horizontal resolution with tomographic observations (Livesey et al., 2006; Christensen et al., 2015) or for 15 obtaining very high signal-to-noise ratio using 4-K cryogenic cooling (Kikuchi et al., 2010).

Modeling middle-atmospheric major dynamical phenomena such as **vertically propagating tidal waves**, high-latitude sudden-stratospheric warming or equatorial quasi-biennial oscillation are still challenging (Limpasuvan et al., 2012; Newman et al., 2016; Orsolini et al., 2017; Sakazaki et al., 2018). Wind is one of the primary parameters for describing the physical state of the atmosphere but models have **difficulties in reproducing it** where the atmospheric flow cannot be described by the geostrophic 20 approximation, such as in the equatorial region where the Coriolis force is weak and, in the upper stratosphere and mesosphere where waves and tides tend to dominate the wind fields (Baron et al., 2013b; Le Pichon et al., 2015; Kawatani et al., 2016; Duruisseau et al., 2017; Rüfenacht et al., 2017). **As climate and weather models increase their vertical range to encompass more of the stratosphere and mesosphere, the need for measurements to improve the accuracy of models in this region, and hence at lower altitudes, can be expected to rise** (Baldwin et al., 2003; Hoppel et al., 2008; Baldwin et al., 2010; Gerber et al., 25 2012). **Only High Resolution Doppler Imager (HRDI) on Upper Atmospheric Research Satellite (1991–2005) has been able to measure horizontal winds over the stratosphere and mesosphere (Ortland et al., 1996), and current spaceborne sensors are not able to measure wind accurately below 90 km (Shepherd, 2015).** Ground-based stations do not cover the globe uniformly and most of the data are limited to heights below 30 km (Ishii et al., 2017) or above 70 km (Baumgarten, 2010). However recent efforts have been made to close this altitude gap (Baumgarten, 2010; Rüfenacht et al., 2014; Le Pichon et al., 2015; Blanc et al., 30 2018).

Providing wind data in the middle atmosphere from space is one of the challenges for future missions. The European Space Agency is going to launch this year the Atmospheric Dynamics Mission equipped with a wind lidar to demonstrate the feasibility of such measurements (Stoffelen et al., 2005). However a lidar is well suited for measuring wind in the troposphere but has poor precision above 20–30 km (Ishii et al., 2017). The Stratospheric Wind Interferometer For Transport studies

35 (SWIFT) has been studied by the Canadian Space Agency for deriving winds between 15–45 km from O₃ infra-red emission lines (Rahnema et al., 2013). The mission was originally planned for 2010 but it is now very uncertain.

The potential of MM/SMM limb sounders for measuring winds has been demonstrated with line-of-sight wind retrievals between 70–90 km from the MLS O₂ line (Wu et al., 2008) and between 30–80 km from O₃ and HCl lines measured with Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) (Baron et al., 2013b). Wind is one of the main
5 outcomes of SMILES-2 that is proposed to the Japan Aerospace Exploration Agency (JAXA) (Ochiai et al., 2017). It is a large instrument (>500 kg) using cryogenic SMM and THz receivers designed for very high sensitive observations between 15–150 km. **If it is selected this year** the launch will be near 2025. Two smaller missions are studied with the possibility to be launched as soon as 2020–22. Wu et al. (2016) propose a small instrument for measuring the atomic oxygen line at 2.06 THz in order to retrieve its abundance as well as temperature and wind in the lower thermosphere. However this mission cannot
10 provide stratospheric and lower mesospheric information. The second proposal is Stratospheric Inferred Winds (SIW). It is a small and low-cost satellite mission studied within the Swedish Innosat program (Lindberg, 2016; Murtagh, 2016). Through this program, it is planned to launch a scientific mission every two years, and SIW has been selected **for the 2nd launch near 2022**. It will observe the middle-atmosphere (15–90 km) **for a period expected to be at least 2 years, and will provide** horizontal-wind vector within 30–90 km. The other primary products are the profiles of temperature, O₃, H₂O and more than a dozen
15 of other chemical species. With this mission it will be possible to ensure the continuous monitoring of the middle-atmosphere avoiding a SMM measurement gap.

In this paper we present a simulation study to assess the potential of SIW. A special focus is put on the main parameters: wind, temperature, O₃ and H₂O that are derived from the strongest lines in the selected spectral bands. Section 2 describes the mission and the observation technique. The measurement simulation and the retrieval method are explained in Sect. 3 and 4,
20 respectively. The measurement performances are discussed in Sect. 5 and concluding remarks are given in the final section.

2 Mission description

2.1 Observation and instrument characteristics

The scientific payload (Fig. 1) and observations characteristics are summarized in Table 1. This is the proposed setting which can still be slightly modified. The platform will be set on a sun-synchronous polar orbit at an altitude of 550 km. It will fly near
25 the terminator crossing the equatorial ascending node at 18:00 local-time (LT). Atmospheric observations will be performed toward the night side using two antennas looking perpendicularly to each other with angles from the satellite velocity of 45° and 135°, respectively. The antennas will point toward close air-masses with few minutes delay (Fig. 2). They are fixed on the platform and the whole satellite will nod up and down in order to scan the limb alternatively upward and downward from about 15 to 90 km. The forward antenna is used during the upward scans and the aftward one during the downward scans. **With this**
30 **choice, the horizontal displacement of the tangent point during a vertical scan is less than 300 km, the vertical motion of the line-of-sight partly counterbalancing the satellite motion.** Using the line-of-sight (LOS) winds retrieved with the two antennas

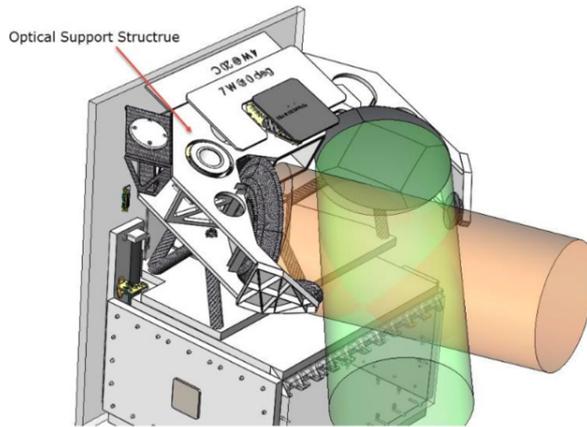


Figure 1. View of the Innosat satellite. The box in the lower-part is the platform service module. Above it is the scientific payload including the two antennas. The field of views are represented with green and beige colors (from Omnisys instruments co).

over close regions allows us to derive the meridional and zonal wind components (Appendix A). **The separation between the LOS wind profiles is less than 400 km.**

The signals from the antennas are alternatively sent to a single radiometer passively cooled to 70 K below the ambient temperature, and analysed with an auto-correlator spectrometer. The heterodyne radiometer operates in double-sideband (DSB) mode yielding to the superposition in the measured spectrum of the two image bands with respect to the local oscillator. The bandwidth and resolution are 8 GHz and 1 MHz, respectively.

The strategy for acquiring the calibration data is not definitively decided yet and will probably be optimized in the future. Currently the plan is as follows. A calibration load onboard the platform (black body at ambient temperature) is viewed at the bottom and top of each scan during the turnaround. While limb scanning, the atmosphere and cold-sky are observed alternatively with an integration time of 0.5 s each. Hence, atmospheric spectra are obtained every 2.3 km with an effective vertical resolution of about 5 km.

2.2 Spectral bands

The measured spectrum is composed of molecular lines spectrally resolved (Fig. 3). Using a radiative transfer model, they are inverted to retrieve geophysical information. Volume mixing ratio (VMR) and temperature are retrieved from their amplitude, whereas tangent-height pressure and line-of-sight wind are retrieved from the width and the frequency position of the lines, respectively.

The Doppler shift induced by the LOS wind (2 kHz for 1 m s^{-1}) is small compared to the line broadening (1 – 100 MHz). This gives a very weak signal to exploit, especially in the lower stratosphere. Baron et al. (2013a) have shown that the spectral region near 655 GHz is the most suitable one for measuring wind with the current hardware. It contains a dense group of

Table 1. Characteristics of the SIW payload and observations. The relationship between tangent-height and LOS angle is derived for an Earth radius of 6370 km and a satellite altitude of 550 km above the geoid.

Payload volume	40×70×40 cm ³
Payload mass/power	17 kg/47 W
Antenna diameter	30 cm
Satellite altitude	500–600 km
Orbit inclination	98 ° (sun synchronous)
Latitude range	65 °S–82 °N
Local time of ascending node	18:00
Scan altitude	10–90 km
LOS nadir angle	67.25–69.03 ° (1.78 °)
Scan velocity	0.05 ° s ⁻¹ (35 s/scan)
Spectrum integration time	0.5 s (1.14 km*)
Antenna vertical FOV	5 km
DSB system temperature	1000–1200 K
ACS Bandwidth	8 GHz
ACS resolution	1 MHz
LO frequency	638.075 GHz ($\lambda = 0.47$ mm)
IF frequency	10.975–18.975 GHz
Frequency \Leftrightarrow velocity	1 m s ⁻¹ \Leftrightarrow 2 kHz

* Tangent point vertical displacement

strong O₃ lines (second row of Fig. 3), that increases by at least a factor 2 the wind measurement sensitivity between 40–70 km compared to retrievals performed from a band with similar characteristics but located at any other frequency under 800 GHz. This band also allows us to retrieve temperature with a good precision in the stratosphere without measuring an O₂ line.

The local-oscillator frequency has been carefully selected in order to include as many as possible spectral lines and to reduce the line superposition from both sidebands. Hence lines of chemical species such as HCN (620.3 GHz), H³⁷Cl (625.0 GHz) H³⁵Cl (625.9 GHz), ³⁵ClO (649.5 GHz), NO (651.1 GHz) and N₂O (652.8 GHz) are clearly visible. A strong H₂O line is located at 620.7 GHz but very close to an O₃ line with similar strength. Lines from around twenty molecules are available though some are very weak such as H₂CO, CH₃Cl or BrO. Finally let's note that most of the lines where IF > 14 GHz have already been measured with **Aura MLS** and JEM/SMILES.

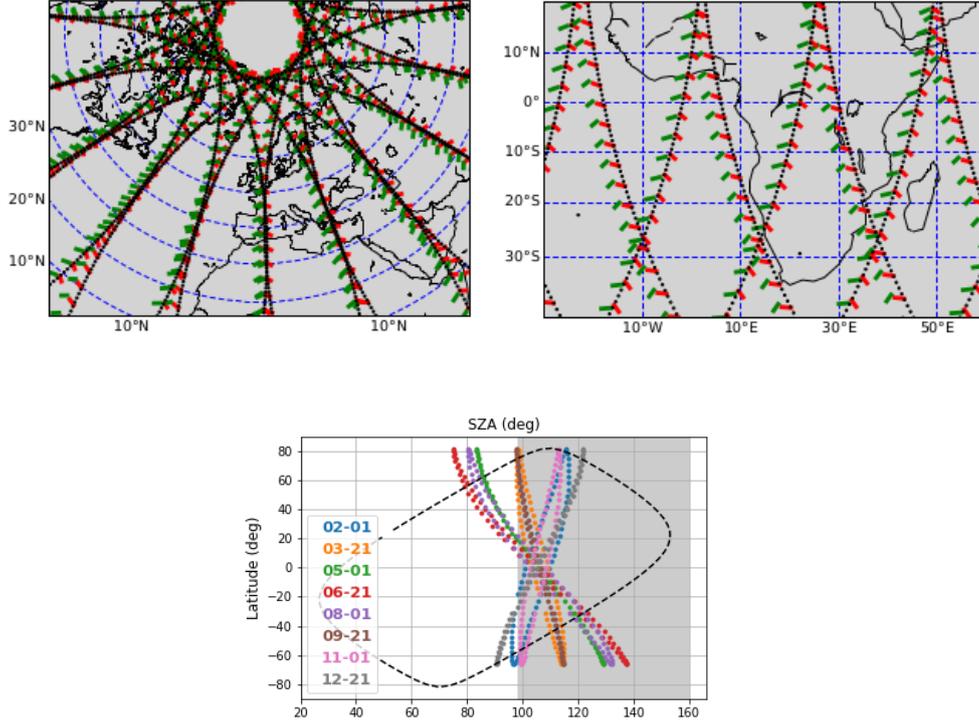


Figure 2. The upper panels show the footprints of the forward (45°) and aftward (135°) views over a 24-hour period. the forward antenna is used during the upward scans (red lines) and the aftward one during the downward scans (green lines). The first tangent point of the upward-scans are located on the black-dotted lines. The lower panel shows the solar zenith angles with respect to latitudes for various days representative of the seasonal variation (colored dots) together with those of the **Aura MLS** data (DJF, 2011) used in the simulations (dashed line). The shaded area shows the nighttime measurements in the mesosphere where the O_3 diurnal variation is the strongest.

3 Measurement modeling

3.1 Radiative transfer and instrument

The signal is a spectral and spatial average of specific intensities ($\text{W m}^{-2} \text{sr}^{-1} \text{Hz}^{-1}$) over narrow instrumental functions. It is expressed in the so-called **Rayleigh-Jeans** brightness temperature T_b equal to (Urban et al., 2004)

$$T_b(\theta_j, \vartheta_k) = \kappa_b \int_{\Delta\vartheta} d\vartheta \quad g^{\text{SP}}(\vartheta - \vartheta_k) \left\{ w_{\text{lsb}}(\vartheta) \int_{\Delta\theta} G_e^{\text{ant}}(\theta - \theta_j, \nu_{\text{lo}} - \vartheta) I(\theta, \nu_{\text{lo}} - \vartheta) d\theta \right. \\ \left. + (1 - w_{\text{lsb}}(\vartheta)) \int_{\Delta\theta} G_e^{\text{ant}}(\theta - \theta_j, \nu_{\text{lo}} + \vartheta) I(\theta, \nu_{\text{lo}} + \vartheta) d\theta \right\}, \quad (1)$$

where ϑ_k is the frequency of the k th spectral component of the measurement, θ_j is the mean nadir angle during the measurement integration time of the j th spectra of the scan, and I is the specific intensity. **The specific intensity is integrated along a LOS as**

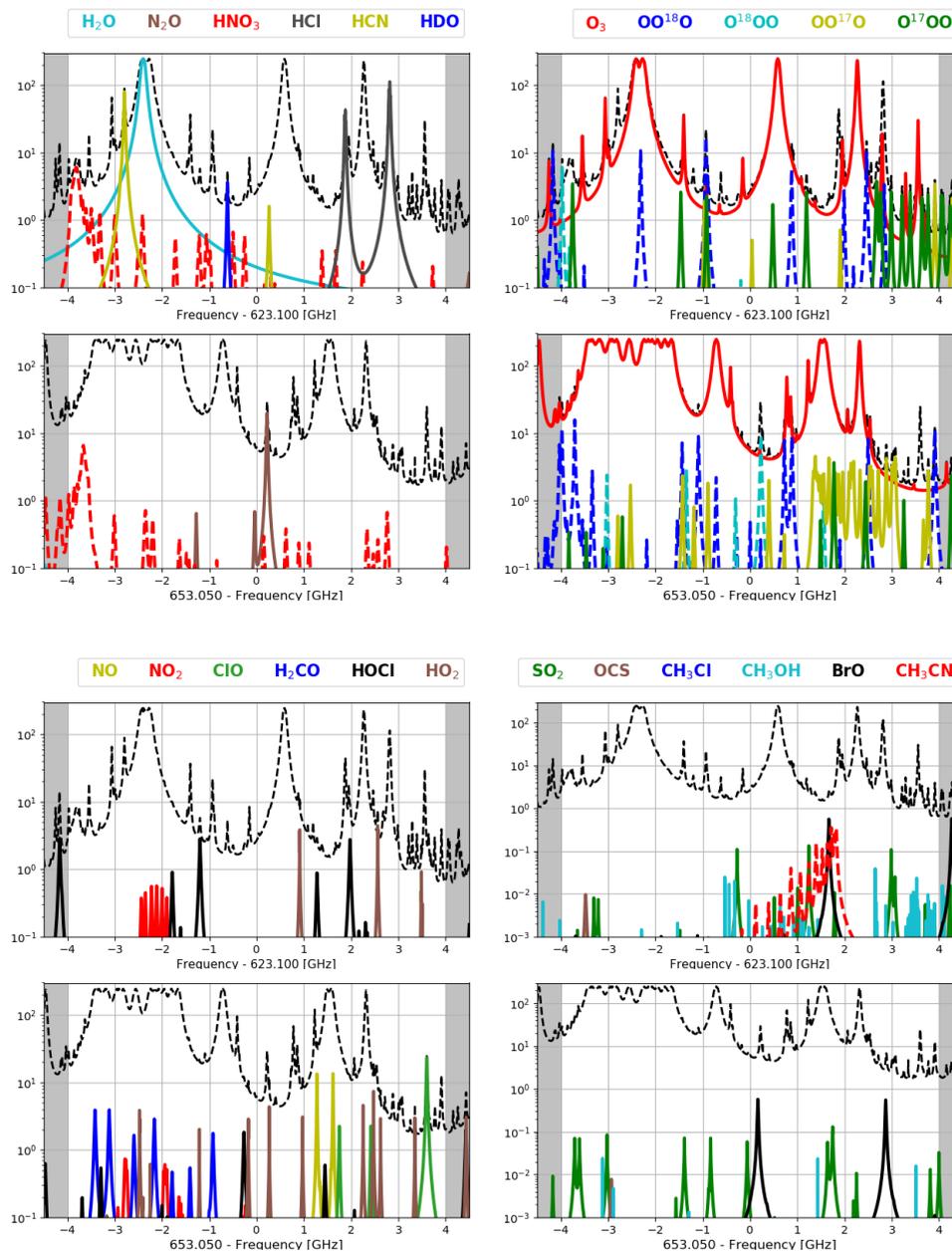


Figure 3. Contribution of the most relevant chemical species to the SIW spectrum. More than 20 molecules are shown in 4 groups of two panels. In each group, the upper panel shows the lower sideband spectrum (dashed black lines) with a central frequency of 623.1 GHz and the lower panel shows the upper sideband one with a central frequency of 653.05 GHz. The colored lines are single-molecule spectra. Grey-shaded areas are outside the bandwidth. The tangent height is 35 km and frequencies are ordered according to the intermediate frequencies. The intensity is given in brightness temperature (y-axis).

that shown in Fig. 4. The LOS is characterized by the altitude of the tangent point, the angle with the meridional direction ϕ_n and narrow ranges over which the atmosphere is considered homogeneous. The heterodyne receiver is sensitive to atmospheric radiation at frequencies $\nu_{lo} \pm \vartheta$ where ν_{lo} and ϑ are the local-oscillator and intermediate frequencies (Tab. 1). The instrumental functions are the spectrometer channel response g_{sp} (Hz^{-1}), the relative weight of the radiometer sidebands w_{lsb} , and the effective antenna pattern G_e^{ant} . The parameter κ_b is the Rayleigh-Jeans factor, used to convert the intensity into brightness temperature:

$$\kappa_b = \frac{c^2}{2k_b\nu_{lo}^2},$$

5 where $c = 2.997924 \times 10^8 \text{ m s}^{-1}$ is the speed of light in vacuum and $k_b = 1.380662 \times 10^{-23} \text{ J K}^{-1}$ the Boltzmann constant. The spectrometer channel response is assumed to be Gaussian with a Full-Width-Half-Maximum (FWHM) of 1 MHz. **Given that the altitude range scanned during the spectrum integration is small compared to the static-antenna vertical resolution (1.1 km and 5 km, respectively), the effective antenna pattern including the vertical scan,** is approximated by a Gaussian function with the FWHM:

$$5 \sigma_e^{\text{ant}} = \sqrt{\left(\frac{1.22}{D} \frac{c}{\nu_{lo}}\right)^2 + \left(\dot{\theta} \Delta_T\right)^2}, \quad (2)$$

where D (m) is the antenna diameter, $\dot{\theta}$ (rad s^{-1}) is the vertical scan velocity and Δ_T is the spectrum integration time. **The antenna sidelobes are also neglected. These approximations have negligible impacts on this study.** A constant spectral sideband weight is used, $w_{lsb}(\vartheta) = 0.5$. The integrals in Eq. (1) are computed over ranges $\Delta\theta$ and $\Delta\vartheta$ set to 3 times the FWHM of their corresponding response functions.

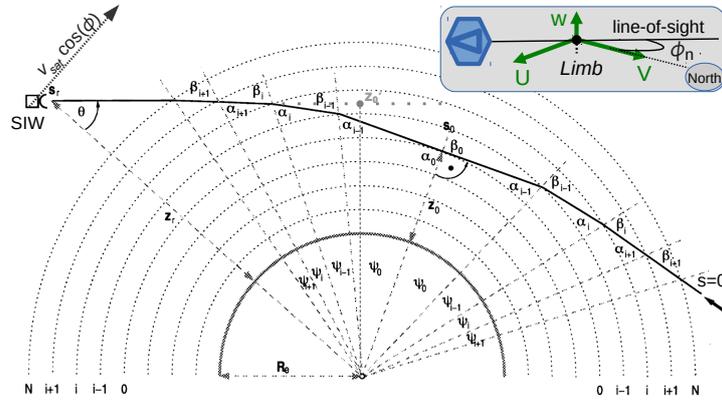


Figure 4. Limb sounding geometry for a refracted line-of-sight (full line) and a none refracted one (dashed line). The panel on the right-upper corner shows the orientation of the LOS with respect to the wind components at the tangent point. Figure is adapted from Urban et al. (2004).

10 3.2 Specific intensity and wind

The specific intensity is computed using the radiative transfer equation:

$$I(\theta, \nu) = \int_{s=0}^{s_r} B_\nu(s) K_\nu(s, \{\nu_a(s)\}_{\text{lines}}) \exp\left(-\int_{s'=s}^{s_r} K_\nu(s', \{\nu_a(s')\}_{\text{lines}}) ds'\right) ds, \quad (3)$$

where s indicates the position on the LOS, B is the Planck function ($\text{W m}^{-2} \text{sr}^{-1} \text{Hz}^{-1}$) and K (m^{-1}) is the absorption coefficient. The background cosmic radiation ($T_b \approx 1 \text{ mK}$) is neglected. The absorption coefficient is computed with a line-by-
 5 line and continua models (Urban et al., 2004). The spectroscopic parameters describing the molecular lines are taken from the HITRAN catalog (Rothman et al., 2009) except those for BrO, CH₃Cl and CH₃CN **which are not available in HITRAN and are, then, taken from the Jet Propulsion Laboratory catalog** (Pickett et al., 1998). The frequency of the spectral lines viewed from the receiver ($\{\nu_a(s)\}_{\text{lines}}$) depends on the mean relative motion of the molecules with respect to the receiver, i.e., satellite velocity and wind. The Doppler-shift effect on the Planck function is neglected. The line frequency is also shifted by the
 10 atmospheric pressure but this effect is small above 25 km where winds are measured. **For the H₂O line at 620 GHz, 2% error on the shift parameter corresponds to an error of 2 m s⁻¹ at 10 hPa. The shift on O₃ lines should be smaller but the information is not available in HITRAN and further studies are needed to infer it.**

A spherical Earth is assumed for assessing the impacts of all the parameters contributing to the line Doppler shift. At a height z_i and for a LOS nadir angle θ , the line apparent frequency is (Kursinski et al., 1997)

$$15 \nu_a(\theta, z_i) = \nu_0 \left(1 - \frac{[V(z_i) \cos(\phi_n) + (U(z_i) + \omega_e R_e \cos(\Lambda)) \sin(\phi_n)] \sin(\alpha_i)}{c} + \frac{W \cos(\alpha_i)}{c} + \frac{V_{\text{sat}} \cos(\phi) \sin \theta}{c} \right) \quad (4)$$

where ν_0 (Hz) is the rest frequency of the transition, V_{sat} is the satellite velocity with respect to a fixed frame attached to the Earth center, (U, V, W) is the 3-D wind velocity defined with respect to the Earth surface, and ω_e , Λ and R_e are the Earth rotation angular velocity (rad s^{-1}), the latitude and the geoid radius at the position i . The LOS nadir angle at z_i is α_i , and ϕ_n is the angle between the LOS and the north direction (Fig. 4). At the tangent height point ($i = 0$), $\alpha_0 = 90^\circ$ and the Doppler
 20 shift $\delta\nu(\theta, z_0)$ is

$$\delta\nu(\theta, z_0) = -\frac{\nu_0}{c} \left(V_{\text{los}}(z_0) + \omega_e R_e \cos(\Lambda) \sin(\phi_n) - V_{\text{sat}} \cos(\phi) n_0 \frac{z_0 + R_e}{z_r + R_e} \right), \quad (5)$$

where z_r is the receiver height, n_0 is the refractive index at the tangent point, $\sin(\theta) = n_0 \frac{z_0 + R_e}{z_r + R_e}$ and V_{los} is the LOS component of the horizontal wind:

$$V_{\text{los}}(z_0) = V(z_0) \cos(\phi_n) + U(z_0) \sin(\phi_n). \quad (6)$$

25 At the equator and for the forward LOS, the Doppler shifts due to the satellite velocity and to the Earth rotation are $\approx -8 \text{ MHz}$ ($+4000 \text{ m s}^{-1}$) and $\mp 0.74 \text{ MHz}$ ($\pm 370 \text{ m s}^{-1}$), respectively. In order to simplify the calculations, we consider the case of a pseudo LOS-wind profile which, unlike a real one, induces a Doppler-shift $\delta\nu(z) = -\nu_0/c V_{\text{plos}}(z)$ that is independent of the angles α_i and Earth rotation, and includes the vertical changes due to the satellite velocity:

$$V_{\text{plos}}(z) = V_{\text{los}}(z) - V_{\text{sat}} \cos(\phi) n_z \left(\frac{z - 50 \text{ km}}{z_r + R_e} \right). \quad (7)$$

30 At the tangent point, the pseudo wind induced the same Doppler-shift as that given in Eq. (5) to within the same constant over the full vertical scan. The constant includes the Earth rotation effects and most of the satellite velocity ones. The terms embedded in this constant are known with a precision better than 1 m s^{-1} using the star-trackers and GPS data onboard the satellite. Such a setting is chosen to yield the satellite-velocity induced Doppler-shift to zero at $z = 50 \text{ km}$, center of the vertical scan.

5 The pseudo-wind approximation induces errors on the line apparent frequency at positions on the LOS other than the tangent point. These errors are smaller than 10 cm s^{-1} and have negligible impacts on the retrievals. Indeed, VMR and temperature retrievals are not sensitive to small frequency errors, and regarding wind retrieval, the information is extracted from optically thin measurements which are characterized by narrow specific-intensity weighting functions peaking at the tangent point.

3.3 Calibration and measurement noise

10 The raw intensity delivered by the spectrometer is expressed as (Olberg et al., 2003):

$$C_{i,j} = G_{i,j} [T_{sys}(i,j) + \eta_x T_b(i,j) + (1 - \eta_x) T_{so}(i)] \quad (8)$$

with i and j are the tangent height and frequency indices, T_{sys} is the double sideband system temperature, T_{so} is the mean brightness-temperature introduced by the optics spillover, η_x is the efficiency of the integrated antenna ($x=a$) or hot-load horn ($x=c$), and G is the radiometric gain. The last is

$$15 \quad G_{i,j} = g_{i,j} (1 - \alpha \langle C_{i,j} \rangle) \quad (9)$$

where $\langle \bullet \rangle$ denotes the average over the frequencies j and α is a positive coefficient to account for a non-linear response of the radiometer (Ochiai et al., 2013). The double-sideband system temperature of SIW is expected to be about 1100 K (OMNISYS, private communication). The signal intensity is calibrated using the emissions from the cold sky with a Rayleigh-Jeans temperature $T_c \approx 10^{-3} \text{ K}$, and from an ambient temperature hot-load (Rayleigh-Jeans temperature $T_h \approx 250 \text{ K}$) measured between

20 two scans. Assuming a linear response of the radiometer and using $T_c \ll T_h$, the radiometer gain is derived as (Olberg et al., 2003)

$$\hat{G}_j = \frac{\bar{C}_h(j) - \bar{C}_c(j)}{\epsilon T_h}, \quad (10)$$

where ϵ is the hot-load emissivity, and C_h and C_c are the receiver raw outputs for the hot load and cold-sky. The upper-bars $\bar{\bullet}$ indicate that an average value over the whole scan is used. The brightness temperature of the atmospheric signal is then

$$25 \quad \hat{T}_b(i,j) = \frac{C_{atm}(i,j) - \bar{C}'_c(i,j)}{\eta_a \hat{G}_{i,j}} + \text{offset}_i, \quad (11)$$

where C_{atm} is the receiver output when the atmosphere is viewed and $\bar{C}'_c(i,j)$ is the cold sky output interpolated at the C_{atm} time. We consider that during the scan, the atmosphere and cold-sky are viewed alternatively during 0.5 sec each. The second term of the equation is a tangent-height dependent offset induced by the antenna spillover. Such radiance offset is retrieved

together with the geophysical information and it is not considered as a retrieval error source. The brightness temperature error from the radiometer noise and the calibration model is

$$\begin{aligned}\delta\widehat{T}_b(i,j) &= \frac{\delta C_{atm}(i,j)}{\widehat{G}_j} + \frac{\delta\overline{C}'_c(i,j)}{\widehat{G}_j} + \widehat{T}_b(i,j)\frac{\delta\widehat{G}_j}{\widehat{G}_j} + \widehat{T}_b(i,j)\frac{\delta\eta_a}{\eta_a} + e_{NL}(i,j) \\ &= \epsilon_{atm}(i,j) + \epsilon'_c(i,j) + (\epsilon_{\overline{h}}(j) + \epsilon_{\overline{e}}(j))\beta_h(i,j) + (e_{\overline{h}} + e_{\eta_a})\widehat{T}_b(i,j) + e_{NL}(i,j)\end{aligned}\quad (12)$$

where ϵ_{atm} and ϵ'_c are white noises on the atmospheric and cold-sky brightness temperatures (Eq. 11), $\epsilon_{\overline{e}}$ and $\epsilon_{\overline{h}}$ are those on the hot-load and cold-sky spectra in Eq. (10), and $\beta_h = \frac{T_b(i,j)}{\epsilon T_h}$. The two last elements of the equation are systematic errors induced by relative errors $e_{\overline{h}}$ and e_{η_a} on the hot-load emission (ϵT_H) and the antenna efficiency (η_a), and the error due to the receiver non-linearity (e_{NL}).

The noise standard-deviation is given by the radiometric equation (Jarnot et al., 2006; Ochiai et al., 2013):

$$\sigma_t(i,j) = [T_{sys}^{dsb}(i,j) + T_b(i,j)] \sqrt{\frac{1}{wt} + \left(\frac{\Delta G}{G}\right)^2}, \quad (13)$$

where w (=1 MHz) is the noise equivalent bandwidth of spectrometer channel and t is the observation time. The term $1/wt$ describes a spectrally uncorrelated noise while $(\Delta G/G)$ describes a fully spectrally correlated noise (Jarnot et al., 2006; Ochiai et al., 2013), that is, at first approximation, a radiance offset that is mitigated by the subtraction of the cold sky in Eq. 11. Considering the average and interpolation on the cold-sky and hot loads outputs, the covariance matrix describing the measurement noise is then:

$$\mathbf{S}_y(u,u') = \begin{cases} \sigma_a^2 + \sigma_c'^2/2 + (\sigma_c^2 + \sigma_h^2)\beta_h^2(u) & \text{if } i = i' \text{ and } j = j' \\ \sigma_c'^2/2 + (\sigma_c^2 + \sigma_h^2)\beta_h(u)\beta_h(u') & \text{if } |i - i'| = 1 \text{ and } j = j' \\ (\sigma_c^2 + \sigma_h^2)\beta_h(u)\beta_h(u') & \text{if } |i - i'| > 1 \text{ and } j = j' \\ 0 & \text{if } j \neq j' \end{cases} \quad (14)$$

where $u = i \cdot N_f + j$ and $u' = i' \cdot N_f + j'$ and N_f the number of frequencies per spectrum. Here we consider an integration time of 2 sec for the hot load and cold sky spectra in Eq. 10 (used for assessing σ_c and σ_h). The time needed for acquiring the hot-load spectra is available between the termination of a scan and the beginning of the next one. Cold-sky spectra can be obtained in very various ways. A simple one is to construct them using the first 4 and last 4 cold-sky spectra measured during a scan.

The error e_{NL} due to the radiometer non-linear response, i.e., non-zero α in Eq. 9, is the difference between the true brightness temperature T_b and the calibrated one \widehat{T}_b , computed as follows (Baron et al., 2011):

1. $G_{cold,i,j}$ is computed applying Eq. (8) to the cold-sky view assuming $C_c = 1800$ ADU that is consistent with Odin/SMR (Olborg et al., 2003), $T_{sys} = 1100$ K, $T_b(\text{cold-sky}) = 0$ K and $\eta_x = 1$. The value $g_{i,j}$ is then computed (Eq. 9).
2. C_{hot} and C_{atm} are computed given $T_{hot} = 250$ K and T_b using an iterative process initialized with G_{cold} (Eqs. 8 and 9).
3. Finally we compute \widehat{G} (Eq. 10), \widehat{T}_b (Eq. 11) and $e_{NL} = \widehat{T}_b - T_b$.

4 Retrieval errors

4.1 Reference atmosphere

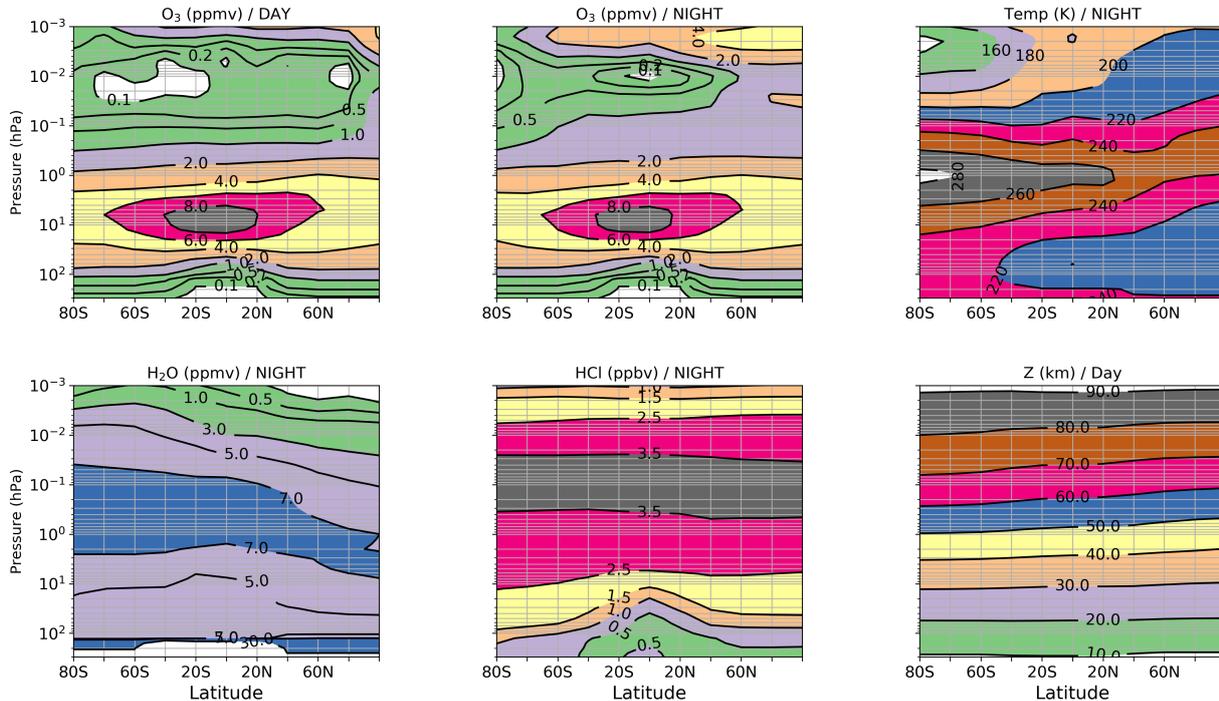


Figure 5. Zonal mean distribution of the most relevant atmospheric parameters for the retrieval error assessment. The upper panels show the O₃ distributions on pressure levels for day and night labeled climatologies as well as the night temperature one. The lower panels show the night distributions for H₂O, HCl, and geopotential altitude. The white regions indicate values smaller than the color scales.

The measurement performances depend on the atmospheric state which depends on the latitude, season and local time. (For our calculations, we assume that the zonal variations of the mean atmospheric state are negligible.) The most relevant parameters to take into account are the profiles of O₃, H₂O, HCl, temperature and pressure (or geopotential height). A zonal-mean climatology of these parameters has been built, covering all latitudes divided into 11 bins (Fig. 5). These climatologies are based on Aura MLS observations (v3.3) performed between November 15 2009 and February 15 2010. This period has been chosen because of the strong contrast between the winter-pole and summer-pole conditions that provides large meridional variations of atmospheric states. Moreover, it was characterized by a stable northern polar vortex, which was not affected by any strong perturbation (Kuttippurath and Nikulin, 2012). MLS observes in the moving direction from a sun-synchronous platform. The orbit inclination is 98° from the Equatorial plane. Each latitude is observed at two different local-times, e.g. 1:45 and 13:45 LT at the Equator. These two LT are used to characterize the day- and night-time conditions though it is daytime (nighttime) for both LT over the southern (northern) boreal latitudes (Fig. 2). Bad data have been removed following the MLS

user’s guide documentation (Livesey et al., 2011), except for the data flagged with negative errors that are biased toward the MLS retrieval a-priori. Using such data allows us to span the altitude coverage of the profiles up to 110 km with information suitable for this study. Other molecules are taken from the Whole Atmosphere Community Climate Model (WACCM) (Marsh et al., 2013) and extracted at the climatology latitudes and LT. For HOCl, HCN and CH₃CN only tropical profiles are used. Because of their relatively weak signal, their variabilities do not impact the overall measurement performances and only typical abundances are needed to discuss the relevance of the measurement.

4.2 Retrieval Method

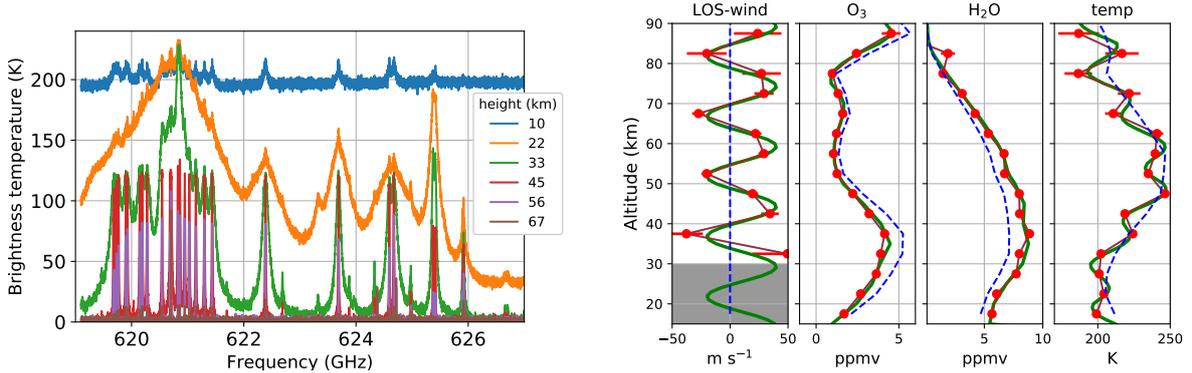


Figure 6. Left panel: Double sideband spectra with respect to the lower sideband frequency. Only a few spectra of the full vertical scan are shown (see legend). Right panel: Retrieved profiles with a vertical resolution of 5 km for nighttime arctic conditions. The blue-dashed lines are the a priori profiles (first guess), the green lines are the truth and the red line-circles are the retrieved values. The horizontal bars indicate the 1- σ errors due to instrument thermal noise.

The simulations are performed with the radiative transfer and retrieval codes used in the SMILES research processing chain (Baron et al., 2011) which has been validated with real observations (Kasai et al., 2013). The retrieved state \hat{x} is a vector including all the unknown parameters of the forward model, namely the atmospheric vertical profiles, a radiance offset on each spectrum and a mean pointing angle offset of the whole scan. The atmospheric profiles are the volume mixing ratio (VMR) profiles of the chemical species, as well as those of temperature and LOS wind.

The retrieval altitudes range from 10 to 90 km, a range fully encompassed within the scan range (10–90 km). The grid resolution is 5 km corresponding to the effective vertical field-of-view of the instrument. Such a setting allows us to perform retrievals using a simple linear least-squares method with weak regularization. The retrieved vector is given by the equation:

$$\hat{x} = x_0 + (K^T S_{d,y}^{-1} K + U_x^{-1})^{-1} K^T S_{d,y}^{-1} (y - y_0), \quad (15)$$

where y is the measurement, x_0 is a first guess of the unknown parameters and y_0 is the associated simulated spectra, $K = \frac{\partial T b}{\partial x}$ is the Jacobian matrix of the forward model (Eq. 1), $S_{d,y}$ is a diagonal matrix equal to the diagonal of S_y (Eq. 14), and U_x

is a diagonal matrix for stabilizing the matrix inversion. Its element square-roots correspond to very large standard deviations of \mathbf{x} , typically $> 10000\%$, 1000 K , 1000 m s^{-1} for VMR, temperature and LOS wind, respectively. The regularization effects are negligible where the retrieval errors (null space and measurement errors) are much smaller than the U_x related STD. In other words, the averaging kernels are unity at altitudes where the measurement is relevant and the retrieval vertical resolution is that of the retrieval altitude grid.

5 The retrieval precision is derived from the linear mapping of the measurement noise covariance onto the retrieved parameters space:

$$\epsilon_{x,n}^2 = \text{diag}(\mathbf{G} \mathbf{S}_y \mathbf{G}^T), \quad (16)$$

where $\epsilon_{x,n}$ is the standard deviation of $\hat{\mathbf{x}}$, \mathbf{S}_y is the full measurement covariance matrix (Eq. 14) and $\mathbf{G} = (\mathbf{K}^T \mathbf{S}_{d,y}^{-1} \mathbf{K} + \mathbf{U}_x^{-1})^{-1} \mathbf{K}^T \mathbf{S}_{d,y}^{-1}$.

10 Figure 6 (right panel) shows retrieved profiles of LOS-wind, O_3 , H_2O and temperature using a simulated noisy measurement (Fig. 6, left panel). The measurement is computed using perturbed profiles from the climatology at $80^\circ\text{N}/\text{nighttime}$, hereafter named true profiles. The true profiles are defined with a vertical resolution of 0.5 km . The H_2O and HCl climatological profiles are multiplied by 1.2 and the O_3 one is multiplied by 0.8 . An offset of -5 K (10 m s^{-1}) and a 9 km -period oscillation with an amplitude of 8 K (15 km , 30 m s^{-1}) are added on the temperature (wind) profile. A good agreement is found between the
 15 retrieved and true profiles. Below 40 km , the wind retrieval error strongly increases and we should consider that 30 km is the lower altitude for wind retrieval. The error increase is due to the pressure broadening of the lines that is about $30\text{--}40\text{ MHz}$ at 10 hPa . Other profiles are retrieved with low errors over most of the vertical range. A small oscillation is however seen on the H_2O profile that likely arises from the simple retrieval calculation (linearity and weak regularization). These results are obtained with relatively large differences between the true and reference profiles and show that this retrieval setting can safely
 20 be used for the error analysis.

Systematic retrieval errors emerge from uncertainties on the instrument, calibration and forward model parameters, and LOS angles (Tab. 2). It is difficult at this stage of the mission definition to provide proper values for these uncertainties. The given values are relatively close to those expected but rounded in the way that it will be straight-forward to linearly scale the retrieval errors according to any future better knowledge of the parameter uncertainties. One may notice that the uncertainty on the line
 25 broadening parameter (G_i) is likely underestimated and the actual values should be between $1\text{--}4\%$ depending on the line. On the other hand, the calibration parameters are likely overestimated. Anyway these errors induce relatively constant retrieval biases that could be mitigated with ad-hoc corrections if their properties are well understood, e.g., time scale and latitudinal variabilities (see for example the JEM/SMILES data analysis in Baron et al. (2013b)).

The 24-hours variability of the local oscillator frequency is between 2 and 10 kHz which straightly results to a LOS wind
 30 retrieval uncertainty of $1\text{--}5\text{ m s}^{-1}$. The lower limit corresponds to the scientific requirement and the upper one is the worse acceptable case. Though it is a systematic error, it changes from one scan to another one with a time correlation that has to be determined before launch. The impacts on other retrieved parameters are negligible. Given the proposed design of the instrument (Murtagh, 2016), the 1-year frequency variability may be relatively large ($>0.5\text{ MHz}$ or 250 m s^{-1}) and we should

Table 2. Systematic errors on observational and forward model parameters: calibration hot-load temperature (T_h , Eq. 12) and radiance linearity assumption (α , Eq. 11), sideband ratio (w_{lsb} , Eq. 1), local oscillator frequency (ν_{lo} , Eq. 1) over 24-hours and 1-year, antenna efficiency (η_a , Eq. 8), spectroscopic-line center frequency (F), pressure broadening (G) and strength (S), and LOS azimuth and elevation angles (θ, ϕ , Fig.4).

Calibration		Sideband ratio	Local oscillator		Ant. efficiency	Spectroscopy			LOS angles
ϵT_H	α	w_{lsb}	24 hours	1 year	η_a	F	G	S	θ, ϕ
1 %	0.5×10^{-5}	0.1%	2 – 10 kHz	> 0.5 MHz	$\sim \epsilon T_H$	10 kHz	1 %	1 %	0.5 mrad

consider that an absolute frequency knowledge, good enough for retrieving winds, may not be available. Frequency calibration will be performed using short-term wind retrieval bias estimates within 40–60 km where other systematic errors are small.

Retrieval errors from other parameters are investigated in Sect. 5.2 using a perturbation method:

$$\epsilon_{x,p} = \mathbf{G}(\mathbf{y}_p - \mathbf{y}_0), \quad (17)$$

where $\epsilon_{x,p}$ is the error induced by the parameter p and \mathbf{y}_p is the measurement assessed after changing the value of p according to its uncertainty. The spectroscopic errors are expressed for each molecule considering that the errors on the line parameters are mutually independent:

$$\epsilon_{x,M} = \sqrt{\sum_i \left(\epsilon_{x,M,F_i}^2 + \epsilon_{x,M,G_i}^2 + \epsilon_{x,M,S_i}^2 \right)}, \quad (18)$$

where $\epsilon_{x,M}$ denotes the total spectroscopic error due the molecule M , and F_i , G_i and S_i denote the center frequency, air-broadening parameter and line-strength of the line i .

The following errors will not be discussed. The errors on the LOS azimuth and elevation angles induces error smaller than 1 m s^{-1} on the LOS wind retrievals. The mean elevation offset of the scan is retrieved with a precision better than 0.2 mrad. The retrieval error induced by the antenna efficiency is not discussed given that it has similar properties than that induced by the hot load emission error (Eq. 12).

5 Measurement performances

5.1 Retrieval precision

Results are discussed on pressure levels and the corresponding altitudes are shown in Figure 5. The precision (1- σ) is given for a single-scan and a vertical resolution of 5 km. It is possible to use the altitude information inscribes in the pressure broadened lineshape, for retrieving atmospheric profile with a better resolution but at the cost of the precision. Precision degradation can be afford for products retrieved from strong signals (e.g., O_3 or temperature) or for those whose the vertical resolution is more

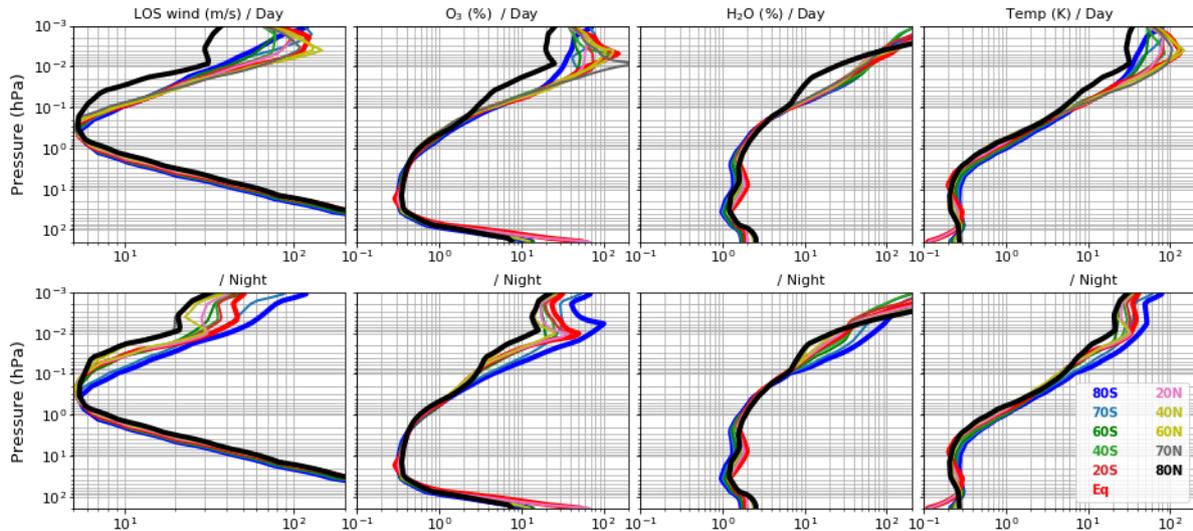


Figure 7. Single-scan retrieval precision ($1-\sigma$) for line-of-sight wind (left-most panels), O_3 (2nd column panels), H_2O (3rd column panels), and temperature (right-most panels). The line colors correspond to latitude bins (see legend) and thick lines are used for those corresponding to polar and equatorial regions. Errors are given for day- and nighttime labeled profiles. Note that southern (northern) polar profiles are actually both daytime (nighttime) ones.

20 scientifically relevant than the temporal or horizontal one (precision can be improved by averaging data). On the other hand, degrading the vertical resolution may be necessary for providing useful information on products derived from weak signals (e.g. HOCl). Later, using the results of this study and based on scientific requirements, the retrieval algorithm will be optimized for providing the best compromise between precision and resolution for each of the main products. Let's note that for all products
 5 LOS (Fig. 2). They can be averaged for improving the precision by a factor $\sqrt{2}$.

5.1.1 O_3 retrieval

Figure 7 shows the retrieval precisions for temperature, LOS-wind and, O_3 and H_2O that have the strongest lines. A good precision is found for O_3 retrieval over the whole altitude range (200–0.001 hPa) because of the **unusually** large number of lines compared to other MM/SMM missions. Between 100 and 0.2 hPa, the relative error is better than 2 % and does not vary
 10 significantly with latitudes and local times. A high precision <0.4 % is found between 50–2 hPa. There, the retrieval vertical resolution could be improved to 3–4 km with a precision of ≈ 1 % (not shown). In the upper part of the retrieval range, the relative precision strongly varies with latitudes and local-times. The errors are 30–50 % in nighttime and 40–100 % in daytime. The poorest relative precision is found near 0.01 hPa during daytime where most of O_3 is photo-dissociated (Fig. 5). Above, the relative precision slightly improves due to the O_3 mesospheric secondary peak (Fig. 5).

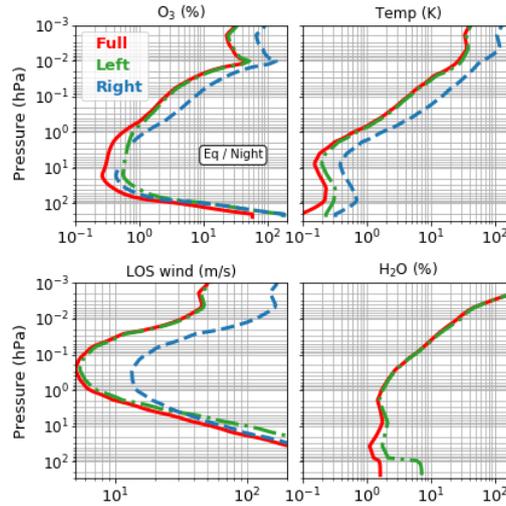


Figure 8. Single-scan retrieval precision ($1-\sigma$) for O_3 and temperature (upper panels), and line-of-sight wind and H_2O (lower panels). Errors are calculated for a full band retrieval (red lines), the left half IF-band (10.075–14.075 GHz, blue lines) and the right half IF band (14.075–18.075 GHz, green lines). Results are shown for Equatorial nighttime conditions.

- 15 Figure 8 shows that above 1 hPa most of O_3 information is provided from the first half of the spectrum that contains the cluster of O_3 lines near 655 GHz (Fig. 3 and Fig. 6). Below this altitude, both sides of the spectrum contribute equally to the O_3 retrieval. The O_3 -line cluster is the main source of information for the LOS wind and temperature retrievals above 4 hPa and 200 hPa, respectively (Fig. 8).

5.1.2 Wind and temperature retrievals

- 5 The performance of the LOS wind retrieval strongly depends on the O_3 abundance. With the current definition of the orbit (equator ascending node at 18:00 LT), most of the measurements are performed in nighttime (Fig. 2), which is a favorable case for measuring wind. The best performances are found over the northern polar region where **the nighttime O_3 enhancement is the largest. There, the** LOS-wind can be retrieved with a precision better than 10 m s^{-1} between 2 and 0.02 hPa (Fig. 7). Comparable performances are found for nighttime equatorial and mid-latitude retrievals over a similar vertical range but with
- 10 a slightly lower upper limit (0.03–0.04 hPa). In daytime, the uppermost altitude for obtaining similar precision dropped to 0.1 hPa over most of the latitudes. At 10 hPa, the error is $50\text{--}60 \text{ m s}^{-1}$ and averaging 2 weeks of equatorial data in 10° latitude bin gives a precision of about 2 m s^{-1} . Since the precision is much poorer below this altitude, the 10 hPa level should be considered as the lowest altitude for obtaining useful wind information.

- At 0.01 hPa, the nighttime LOS wind precision changes with latitudes from 20 m s^{-1} to 50 m s^{-1} (the southern polar profile is excluded) and from $40\text{--}60 \text{ m s}^{-1}$ in daytime. At this altitude, the H_2O line at 620.7 GHz contributes significantly to the wind retrieval, especially during daytime. Over the polar regions, strong NO enhancements frequently occur in the middle

atmosphere due to energetic particle precipitation (EPP) (Randall et al., 2007; Pérot et al., 2014; Orsolini et al., 2017). During such events, the NO lines can be increased by more than a factor 10 that would improve the wind and temperature retrievals.

Temperature can be retrieved with a precision better than 1 K below 1 hPa. The retrieval vertical resolution can be improved to 3 km with a precision better than 1 K between 200 and 5 hPa (not shown). Above 0.2 hPa, the precision decreases to 10–30 K near 0.01 hPa in nighttime and to 30–80 K in daytime. During daytime most of the mesospheric information is provided
5 by the strong H₂O line at 620.7 GHz.

5.1.3 H₂O and other molecules retrievals

The H₂O profile is retrieved from the line at 620.7 GHz and, below 100 hPa, from the continuum induced by far lines. The precision is better than 3 % (20 %) below 0.3 hPa (0.05 hPa). For altitudes above 0.1 hPa, the relative error increases and exhibits large latitudinal variations, e.g., 10–50 % at 0.2 hPa. The largest errors are found during daytime when the signal
10 from O₃ is weak. Under such conditions, temperature is retrieved from the single H₂O line. The forward model inversion becomes ill-conditioned and both H₂O and temperature errors strongly increase. This issue is clearly illustrated with the much smaller H₂O daytime errors estimated without retrieving temperature compared to those with temperature retrieval (Fig. 9). Constraining the mesospheric temperature would significantly improve the mesospheric H₂O retrievals.

The retrieval precision for other molecules are shown in Fig. 9. First, we note that, except for O₃ and H₂O, all chemical
15 species are retrieved from optically thin lines and the VMR error profiles have similar characteristics and are independent of the VMR values. The minimum VMR error is found near 10 hPa. Below, the errors increase due spectral line overlapping. The atmosphere becomes opaque near the tropopause. From the middle stratosphere to the mesosphere, the errors increase due to the decrease of atmospheric density (the error decreases only as $\approx \text{pressure}^{-0.6}$ because the density decrease is partly compensated by the narrowing of the lines).

20 The best measurement performances with respect to the VMR are found for HCl, N₂O, HCN, CH₃CN and HNO₃. Good information can also be inferred for the four most abundant O₃ isotopologues and from HDO. Important chemically active species such as ClO, NO, NO₂ or HO₂ can also be retrieved. If necessary the relative precision can be improved by averaging profiles or decreasing the retrieval vertical resolution. Deriving useful information for species such as BrO or HOCl will be challenging.

25 Chemically active species exhibit large variabilities. The photo-chemistry driven diurnal variation is the most common one. For instance, stratospheric ClO, NO and mesospheric HO₂ are more abundant in daytime but vanish **in general** during nighttime. Special events that occur more or less frequently can strongly increase the signal-to-noise ratio. For instance, ClO VMR frequently reaches 1.5 ppbv near 20 km during polar springtime due to the chlorine activation during the polar winter. The enhancement of SO₂ after strong volcanic eruption can also be measured (Pumphrey et al., 2015). EPP induced enhancement of
30 NO_x and HO_x are an other example. During such events nighttime NO can reach levels of 10-100 ppbv between 10–0.1 hPa, levels much larger than the measurement single-scan precision (2–20 ppbv). EPP induced enhancements are not well represented in the models (Randall et al., 2007; Pérot et al., 2014; Orsolini et al., 2017) and SIW has a strong potential for providing key insights on their dynamical and chemical sources.

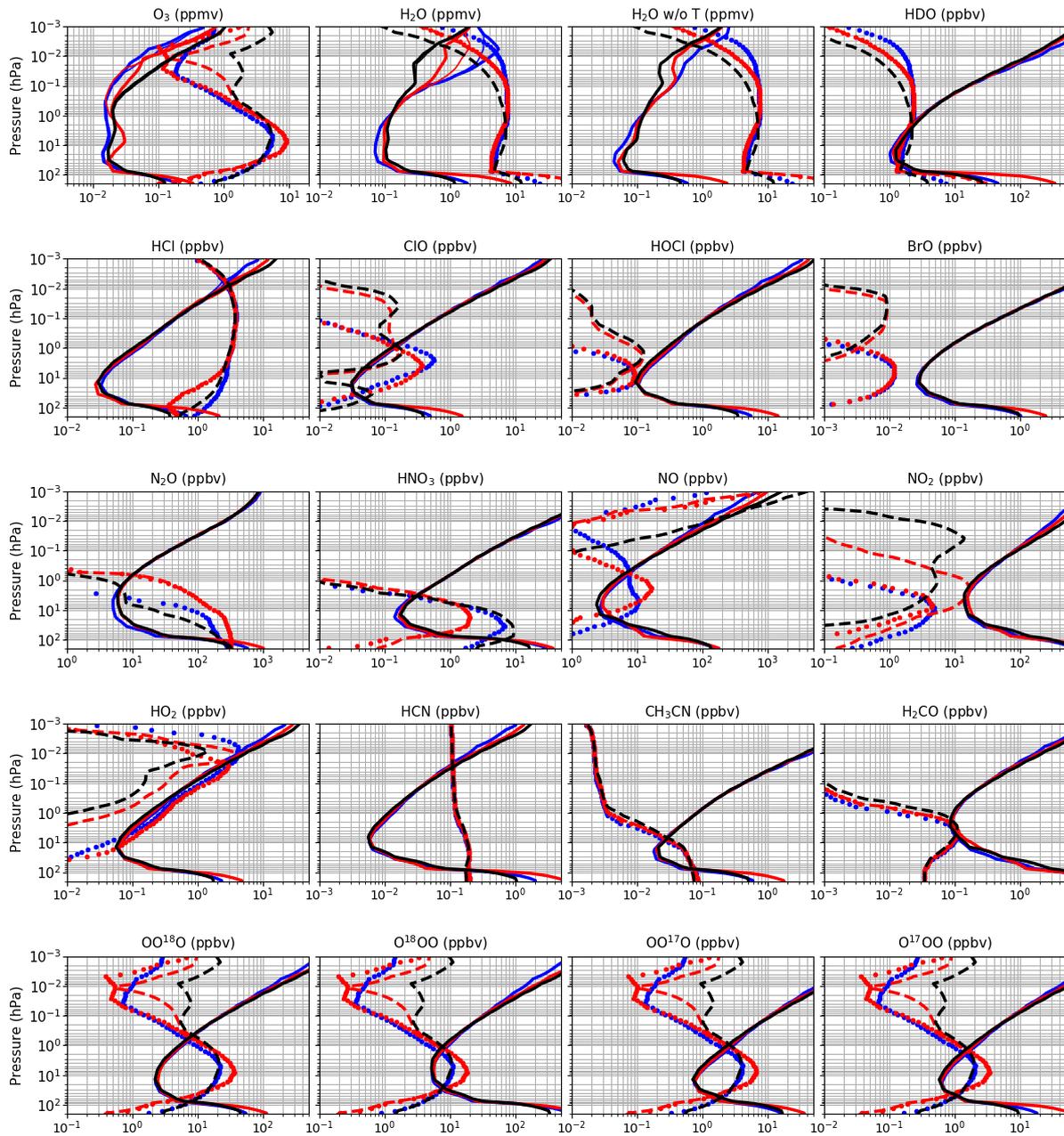


Figure 9. Retrieval single-scan precision (full lines), nighttime VMR (dashed lines) and daytime VMR (dotted lines) profiles. Profiles are shown at 80°S (blue line), Equator (red line) and 80°N (black line). The thick (thin) red full-lines are nighttime (daytime) conditions. The H₂O results without temperature retrieval are indicated with "w/o T".

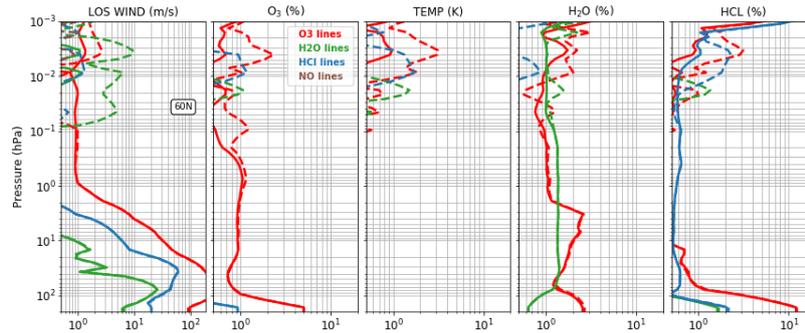


Figure 10. Spectroscopic induced errors on LOS wind, temperature, O₃, H₂O and HCl retrievals (see panel titles). The full-lines (dashed-lines) show the nighttime (daytime) condition at 60N.

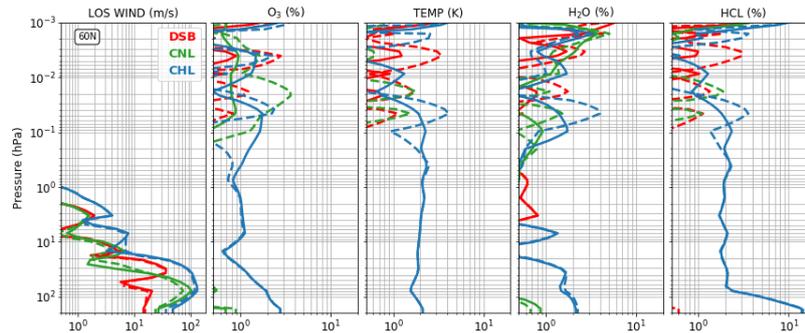


Figure 11. Same as Fig. 10 but for double-sideband ratio (DSB), radiometer nonlinearity (CNL) and calibration hot-load emission (CHL). The error assumptions are summarized in Tab. 2.

5.2 Systematic errors

The errors induced by the spectroscopic uncertainties on the most important lines have been estimated for the LOS-wind, temperature, O₃, H₂O and HCl retrievals. We consider the 50 most intense O₃ lines over the whole bandwidth, two HCl triplets (624.9 and 625.9 GHz), two NO triplets (651.4 and 651.7 GHz) and the 620.7 GHz H₂O line. Systematic errors induced by the double-sideband ratio (DSB), the calibration hot-load temperature and the radiometer non-linearity are also discussed for the same products.

5.2.1 Wind retrieval

Figure 10 clearly shows three altitude ranges for the wind retrieval errors induced by the spectroscopic parameters. Results are given for the latitude 60°N. Above 0.1 hPa, a daytime error of 3–5 m s⁻¹ is induced by the frequency uncertainty on the H₂O line (Tab. A3). During nighttime, the signal is dominated by about 15 O₃-lines and a retrieval error of only 1 m s⁻¹ is induced by their frequency uncertainty (Tab. A1 and A2). The same error of 1 m s⁻¹ is found between 1 and 0.1 hPa both during day

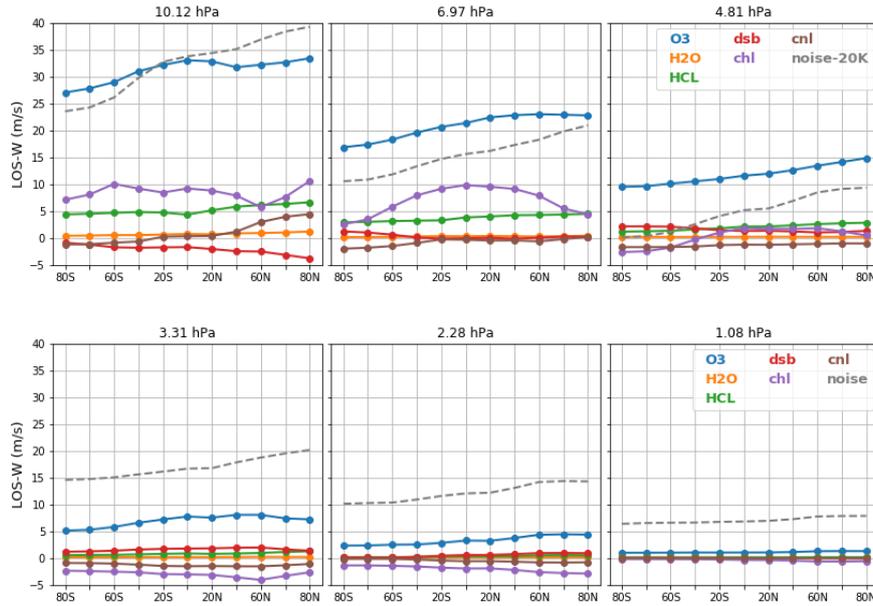


Figure 12. Line-of-sight wind retrieval biases with respect to latitudes near 10, 7 and 5 hPa (upper panels), and near 3, 2 and 1 hPa (lower panels). Biases are shown for the uncertainties on the spectroscopic parameters of O₃, HCl, and H₂O, the double-sideband ratio, the calibration hot load and the calibration non-linearity.

and night times. No impact of the NO lines has been found, even at higher latitudes, but this would not be the case for EPP enhanced profiles. Below 1 hPa, the lines broadened by the pressure overlap each other. Consequently the uncertainties on the air-broadening parameters and to a lesser extent, the line strength of the O₃ lines contribute to the retrieval error. The bias increases up to 20–30 m s⁻¹ at 10 hPa.

Figure 11 shows the retrieval errors induced by the double-sideband ratio (DSB), the calibration hot-load temperature and the radiometer non-linearity. These parameters introduce errors on the wind retrieval only below 1 hPa. **The uncertainty on the calibration hot-load temperature is the dominant retrieval error, reaching 5–8 m s⁻¹ between 2–10 hPa. The O₃ lines parameters is the main source of errors between 10–1 hPa for all latitudes (Fig. 12).**

Methods for mitigating wind retrieval bias have to be developed taking into account SIW observation characteristics (see Appendix A). For JEM/SMILES analysis, a retrieval bias of 20–40 m s⁻¹ between 8–5 hPa was reduced to less than 4 m s⁻¹ between 30S–50N by considering that the mean tropical flow is zonal (Baron et al., 2013b). Meteorological analyses and reanalysis at mid-latitudes can also be used for characterizing the retrieval biases below 5 hPa.

5.2.2 Temperature and VMR retrievals

The biases on O₃, HCl and temperature retrievals due to the spectroscopic parameters are small. They are lower than 1 % and 0.5 K between 100 and 0.02 hPa. Above 0.02 hPa, the biases increase but remain smaller than 5 % and 4 K. The errors are induced by the air-broadening and strength parameters of O₃ and H₂O lines. The strong impact of the H₂O line parameters onto the HCl retrieval reveals error amplifications due to the temperature retrieval. Using constraints on the temperature retrieval should allow us to reduce such effects.

The retrieval of H₂O above 0.2 hPa has a small bias <2 % that is induced by the uncertainties on the air-broadening and strength parameters of the 620.7 GHz H₂O line. Below this altitude, the retrieval error reaches 5 % mainly due to the air-broadening parameters of the overlapping O₃ lines at 620.69 and 623.669 GHz (Tab. A1). Below 100 hPa, the H₂O lines outside the band are the main signal for the retrieval (not shown), and the 620.7 GHz H₂O line weight in the retrieval is small.

The DSB and calibration parameters induced errors on O₃, HCl and temperature retrievals are small below 0.1 hPa, i.e., lower than 3 % and 2 K (Fig. 11). The calibration hot-load temperature and the radiometer non-linearity dominate the temperature retrieval error. **The VMR and temperature retrievals are also sensitive to the DSB uncertainties and radiometer non-linearity above 0.1 hPa, especially in daytime. These errors are likely increased by the temperature retrieval.**

6 Conclusions

A simulation study has been conducted to support the mission definition of SIW and to assess the measurement performances. This small mission will be launched near 2022 for monitoring the middle-atmosphere (10–90 km) using the thermal emission lines near 640 GHz of a large number of chemical species. This analysis focuses on the main outcomes, namely LOS wind, temperature, O₃ and more than a dozen of other chemical species. The error assessment is performed taking into account the day-night and latitudinal atmospheric variabilities.

The **unusually** large number of strong O₃ lines at 653–657 GHz allows us to measure the 2-d horizontal wind between 10 and 0.001 hPa and temperature between 100 and 0.1 hPa as well as providing a high-sensitivity to O₃ between 100–0.001 hPa. LOS wind is an original outcome for such a mission. It demands a special observation setting involving 2 antennas in order to retrieve two perpendicular components of the wind vector. Each component can be measured between 2 and 0.03 hPa with a precision better than 10 m s⁻¹ and vertical resolution of 5 km. Other spaceborne instruments have poor sensitivity in this altitude range. A sunsynchronous polar orbit allowing us to perform night-time measurements is currently considered. Such conditions are the most favorable for mesospheric wind, temperature and ozone measurements but not for active chemical species such as stratospheric ClO or strato-mesospheric HO₂ that generally vanish during nighttime.

The impact of systematic errors induced by the spectroscopic parameters and, by the instrument and calibration parameters are discussed. This work highlights **the need for a good characterization of the spectroscopic parameters** (air-broadening, strength, and center frequency **and pressure shift**) of key O₃, H₂O and NO lines. Even so, a large wind measurement bias may occur between 10 and 2 hPa mainly due to errors on O₃ line air-broadening parameters. **Hence ad-hoc methods for reducing retrieval biases must be studied. These methods can be used to calibrate the LO frequency long-term trend that may arise with**

the proposed hardware. However, improvements of the instrument design for following the frequency trend with a precision better than 2 kHz, are still being investigated.

SIW shows a strong potential for the study of various scientific issues. It can provide for the first time global information on the horizontal wind between 30–90 km that can be used to validate chemical and climate models. It has the potential for contributing to the characterization of long trend series of temperature, O₃, H₂O and HCl, that are important for climate studies and for monitoring the chemical composition of the mid-atmosphere. The mission can provide data to study the dynamics of the middle atmosphere. Based on SIW observations, specific studies on key dynamical processes, such as the quasi-biennial oscillation, the semi-annual oscillation or sudden stratospheric events for example, could be carried out. A better understanding of these phenomena, in addition to global mid-atmospheric wind measurements, would significantly improve our knowledge of the climate system. Not discussed in this paper is also the capability of SIW for measuring ice water content in the tropical upper-troposphere (Eriksson et al., 2014). Observing the same air-mass from two perpendicular directions could provide interesting information considering the high spatial inhomogeneities of cloudy scenes.

Optimization of the calibration procedure will be studied in order to improve the measurement precision. Here we have assumed an equal observation time for the cold-sky and atmosphere measurements. Changing the time sharing in favor of atmospheric observations could improve the measurement sensitivity by more than 20 %. The retrievals could also be improved in the mesosphere by increasing the frequency resolution to 0.5 MHz at the intermediate frequency range between 17.2 and 17.4 GHz that contains the strong H₂O line (620.701 GHz) and the two strongest O₃ lines (620.825 and 655.289 GHz). Implementing such a setting is under investigation.

The InnoSat platform offers a quick opportunity to fly SIW. This is important since the current SMM limb missions have already exceeded by far their lifetime expectations and they risk to stop soon. However such a platform strongly limits the design of a SMM instrument and its performances. A larger antenna would improve the vertical resolution and an additional receiver with a narrow bandwidth measuring an oxygen or a strong water vapor line would significantly improve the wind and temperature retrievals in the mesosphere. Such improvements are studied for the much larger SMILES-2 mission (Ochiai et al., 2017) presented in the introduction section and which also includes the same spectral window as SIW. However this mission can not be launched before 2025 if selected.

25 Appendix A: LOS and horizontal winds

The retrieval of two line-of-sight winds over the same region allows us to compute the meridional (V) and zonal (U) components. Applying Eq. (6) to the forward and aftward viewing antenna, the two retrieved LOS wind are:

$$\begin{aligned} V_{\text{los,fwd}} &= U \sin(\phi_n) + V \cos(\phi_n) \\ 30 \quad V_{\text{los,aft}} &= U \sin(\phi_n + \delta) + V \cos(\phi_n + \delta) \end{aligned} \tag{A1}$$

where ϕ_n is the angle of the forward-looking line-of-sight with respect to the north direction and δ is the angle between the two lines of sight. It is straight forward to show that

$$\begin{aligned} U &= \frac{1}{\sin(\delta)} (V_{\text{los,aft}} \cos(\phi_n) - V_{\text{los,fwd}} \cos(\phi_n + \delta)) \\ V &= \frac{1}{\sin(\delta)} (V_{\text{los,fwd}} \sin(\phi_n + \delta) - V_{\text{los,aft}} \sin(\phi_n)) \end{aligned} \quad (\text{A2})$$

and the random errors on U and V are:

$$\begin{aligned} \epsilon_U &= \frac{\epsilon_{\text{los}}}{\sin(\delta)} \sqrt{\cos(\phi_n + \delta)^2 + \cos(\phi_n)^2} \\ \epsilon_V &= \frac{\epsilon_{\text{los}}}{\sin(\delta)} \sqrt{\sin(\phi_n + \delta)^2 + \sin(\phi_n)^2} \end{aligned} \quad (\text{A3})$$

where ϵ_{los} is line-of-sight wind retrieval error. For $\delta = 90^\circ$, we have:

$$\begin{aligned} U &= (V_{\text{los,aft}} \cos(\phi_n) + V_{\text{los,fwd}} \sin(\phi_n)) \\ V &= (V_{\text{los,fwd}} \cos(\phi_n) - V_{\text{losaft}} \sin(\phi_n)). \end{aligned}$$

- 10 The random error on each wind component becomes $\epsilon_U = \epsilon_V = \epsilon_{\text{los}}$. The transformation $(V_{\text{los,fwd}}, V_{\text{los,aft}})$ to (U, V) corresponds to a vector rotation of $\frac{\pi}{2} - \phi_n$. This configuration is that for which $\epsilon_U^2 + \epsilon_V^2 = 2 (\epsilon_{\text{los}}/\sin(\delta))^2$ is minimum.

A systematic error e_{los} on the LOS wind retrievals propagates to the U and V components as follows:

1. The systematic error on the zonal wind estimate is $e_u = e_{\text{los}} (\cos(\phi_n) + \sin(\phi_n))$
2. The systematic error on the meridional wind estimate is $e_v = e_{\text{los}} (\cos(\phi_n) - \sin(\phi_n))$.

- 15 We assume that e_{los} does not depends on the LOS orientation which is a valid assumption for the errors investigated in this paper (LO frequency, calibration, spectroscopy). We should note that $e_v = 0$ for $\phi_n = 45^\circ$ or 225° which occurs at latitudes between 30°N – 50°N on the ascending branch of the orbit and between 10°N – 30°N on the descending branch. The cases $e_u = 0$ occur for the lowest and highest latitudes retrievals.

- At the equator, the bias on the meridional wind is partly canceled out and the bias correction method used for JEM/SMILES analysis may not be satisfactory. For instance, an error $e_{\text{los}} = 1.0 \text{ m s}^{-1}$ induces an error $e_v = 0.2 \text{ m s}^{-1}$. On the other hand, the error on the zonal component is 1.4 m s^{-1} with an opposite sign on the ascending and descending orbit branches. The sign difference may provide us with a way to characterize LOS wind retrieval systematic errors.

Appendix B: Spectroscopic lines

- 25 The following tables show the most relevant spectroscopic lines for the retrievals of the LOS wind, O_3 , Temperature, H_2O and HCl . The relative retrieval impact of each parameter is defined as:

$$\rho_{x,\text{M},p_i} = \frac{\epsilon_{x,\text{M},p_i}}{\max(\{\epsilon_{x,\text{M},p_i}\}_{p_i})} \quad \text{with } p_i = F_i, G_i \text{ or } S_i, \quad (\text{B1})$$

where M denotes the chemical species, ϵ_{x,M,p_i} is the error induced by the parameter p of the line i (Eq. 18), and $\{\epsilon_{x,M,p_i}\}_{p,i}$ is the set of errors induced by all the parameters of all the lines of the species M .

Table A1. Relative impact of O₃ line parameters on temperature, O₃, H₂O and LOS wind retrievals. For a retrieved product, the impact is defined as error to the maximum error ratio (see text). Results are given for 10, 1 and 0.1 hPa levels (Equatorial night-time conditions). Only parameters having an impact larger than 0.5 at any of the considered altitudes are shown. The parameters are the center frequency (S), the air-broadening parameter (G) and the line strength (S). The line is characterized by its frequency (MHz).

Parameter	LOS wind			O3			Temperature			H2O			HCl		
Lower sideband															
620687-F	-	-	0.6	-	-	-	-	-	-	-	-	-	-	-	-
-G	-	-0.5	-	-	-	-	-	-	-	0.8	0.5	-	-	-	-
-S	-	-1.0	-	-	-	-	-	-	-0.5	1.0	0.7	-	-	-	-
620825-F	-	0.6	1.0	-	-	-	-	-	-	-	-	-	-	-	-
-G	0.8	-	-	-	-	-	-	0.9	-	0.7	-	-	-	-	-
-S	0.7	-	-	-	-	-	-	1.0	0.8	0.6	-	-	-	-	-
623688-F	-	0.8	0.7	-	-	-	-	-	-	-	-	-	-	-	-
-G	-	-	-	-	-	-	0.8	-	-	-0.7	-0.5	-	-	-	-
-S	-	-	-	-	-	-	1.0	-	-	-0.8	-0.5	-	-	-	-
625370-F	-	0.7	-	-	-	-	-	-	-	-	-	-	-	-	-
-G	-1.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-S	-	-	-	1.0	1.0	1.0	-1.0	-	0.5	-	1.0	1.0	-	1.0	1.0
Upper sideband															
650732-F	-	0.7	-	-	-	-	-	-	-	-	-	-	-	-	-
-G	-1.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
-S	-0.5	-	-	0.9	0.9	0.9	-0.9	-	-	-	0.9	0.9	-	1.0	0.9
651475-F	-	0.7	1.0	-	-	-	-	-	-	-	-	-	-	-	-
-G	-0.5	-	-	-	-	-	-	-	-	-	-	-	1.0	-	-
-S	-0.6	-	-	-	-	-	-	-	-	-0.5	-	-	1.0	-	-
651556-F	-	0.9	0.5	-	-	-	-	-	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-	-	-0.9	-	-	-	-	-	-
653763-F	-	0.7	0.9	-	-	-	-	-	-	-	-	-	-	-	-
-G	-	-	-	-	-	-	-	-	-	-	-	-	-0.6	-	-
-S	-	-	-	-	-	-	-	-	-	-	-	-	-0.6	-	-

Competing interests. The authors declare that they have no conflict of interest

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Table A2. Continuation of Tab. A1.

Parameter	LOS wind			O3			Temperature			H2O			HCl		
654713-F	-	0.7	0.9	-	-	-	-	-	-	-	-	-	-	-	-
-S	-0.5	-	-	-	-	-	-	-	-	-	-	-	-	-	-
654851-F	-	0.7	0.9	-	-	-	-	-	-	-	-	-	-	-	-
655004-F	-	0.7	0.8	-	-	-	-	-	-	-	-	-	-	-	-
655121-F	-	0.7	0.8	-	-	-	-	-	-	-	-	-	-	-	-
655202-F	-	0.7	0.9	-	-	-	-	-	-	-	-	-	-	-	-
655289-F	-	0.6	1.0	-	-	-	-	-	-	-	-	-	-	-	-
-G	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-	0.6	0.8	-	-	-	-	-	-
655607-F	-	0.7	0.9	-	-	-	-	-	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-	-	-	-	0.5	-	-	-	-
655873-F	-	0.7	0.9	-	-	-	-	-	-	-	-	-	-	-	-
655960-F	-	0.7	0.9	-	-	-	-	-	-	-	-	-	-	-	-
656005-F	-	0.8	0.8	-	-	-	-	-	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-	-	0.5	-	-	-	-	-	-
656224-F	-	0.7	0.8	-	-	-	-	-	-	-	-	-	-	-	-
656251-F	-	0.7	0.7	-	-	-	-	-	-	-	-	-	-	-	-
656383-F	-	0.8	0.6	-	-	-	-	-	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-	-	-0.6	-	-	-	-	-	-
656419-F	-	0.8	0.5	-	-	-	-	-	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-	-	-0.9	-	-	-	-	-	-
656461-F	-	0.7	-	-	-	-	-	-	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-	-	-1.0	-	-	-	-	-	-
656476-F	-	0.6	-	-	-	-	-	-	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-	-	-0.7	-	-	-	-	-	-

Table A3. Same as Tab. A1 but for the H₂O line parameters

Parameter	LOS wind			O3			Temperature			H2O			HCl		
620701-F	-	1.0	1.0	-	-1.0	-	-	-	-	-	-	-	-	0.5	-
-G	1.0	-1.0	-	0.9	0.8	1.0	0.6	-	1.0	0.9	0.9	0.7	0.7	-	1.0
-S	-	-	-	1.0	0.7	-	1.0	1.0	-	1.0	1.0	1.0	1.0	1.0	-
622482-G	-	-	-	-	-0.5	-	-	-	-	-	-	-	-	-	-
-S	-0.8	-	-	-	0.7	-	-	-	-	-	-	-	-	-	-

Table A4. Same as Tab. A1 but for the HCl line parameters.

Parameter	LOS wind			O3			Temperature			H2O			HCl		
624964-S	-0.6	-	-	-	-	-	-0.6	0.5	-	-	-	-	-	-	-
624977-G	-	-	-	-	-	-	0.6	-	-	-	-	-	-	-	-
-S	-	-	-	-	-	-	-1.0	0.5	-	-	-	-	-	-	-
625901-F	-	0.6	0.6	-	-	-	-	-	-	-	-	-	-	-	-
-G	0.9	-	-	-0.7	-0.7	-0.6	-0.6	-0.9	-	-	-0.6	-0.6	-	-	-
-S	-1.0	-	-	-	-	-	1.0	-	0.5	-	-	-	0.7	0.5	0.6
625918-F	-	1.0	1.0	-	-	-	-	-	0.5	-	-	-	-	-	-
-G	-	-	-	-1.0	-1.0	-1.0	-	-1.0	1.0	-1.0	-1.0	-1.0	-	-0.5	-
-S	1.0	-	-	-	-	-	0.6	-1.0	0.6	0.7	-	-	1.0	1.0	1.0
625931-G	-0.6	-	-	-	-	-	-	-0.5	-	-	-	-	-	-	-
-S	1.0	-	-	-	-	-	-	-	-0.7	-	-	-	-	-	-

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