

We would like to sincerely thank the reviewer for his comments. We believe they help us to improve the manuscript significantly and give us many useful suggestions to improve the mission. We have corrected the manuscript according reviewer's comments and answer the reviewer's question point by point below.

- 5 Reviewer comments are in italic blue, the manuscript modifications are in red. The answer "Done" means that the manuscript has been modified following exactly the reviewer comment.

Reply to general comments

- 10 *1) I understand that the realization of such mission is uncertain, and a lot of details are not decided yet. However, it would be nice to know how the authors plan to realize it: When and to who this mission could be proposed? Launch date? Which technology will be used and is it tested with ground based systems? Where the value of Tsys come from? ...*

Reply: We appreciate your understanding, and a lot of details are not finally decided at the time this manuscript was written. More details about our plan have been added to the manuscript now.

15

The information about TALIS mission has been added in section 1:

"THz Atmospheric Limb Sounder (TALIS) is the pre-research project of civil aerospace technology proposed by China National Space Administration (CNSA) ... The pre-research will be completed in 2020 and a prototype will be tested. The satellite mission equipped with TALIS will be proposed around 2021".

20

Section 2.1 has been rephrased, more details about the instrument have been added:

- 25 "The TALIS payload (Fig. 1) and its proposed scan characteristics are summarized in Table 1. The instrument will be set at a sun-synchronous orbit at a normal altitude of 600 km. The offset parabolic antenna is made of a single reflector with 1.6 m projective aperture and four independent feeds. The layout of four discrete feeds is shown in Fig. 2. Compared with the quasi-optical separation layout (such as MLS), this strategy is easier and has higher observation precision. But it will lead to an observed difference of about 20 km between the four radiometers. The widths of the field of view (FOV) at the tangent point are about 5.5, 3.8, 3.3, and 0.96 km respectively. The two-point calibration method is adopted by TALIS, and an extra calibration target is set at the bottom of the antenna. The extra target can be used to improve the calibration precision and evaluate the antenna effect and nonlinearity. At the beginning of the scan, TALIS will view the hot target (ambient temperature) and the extra target (lower temperature) in 3 s, and then it will scan the limb from 0 to 100 km vertically and obtain the spectra every 1 km with an integration time of 0.1 s, finally, it views the cold space at 200 km in 5 s. The process of retrace is the same (also record data) and giving a total period of about 36 s".
- 30

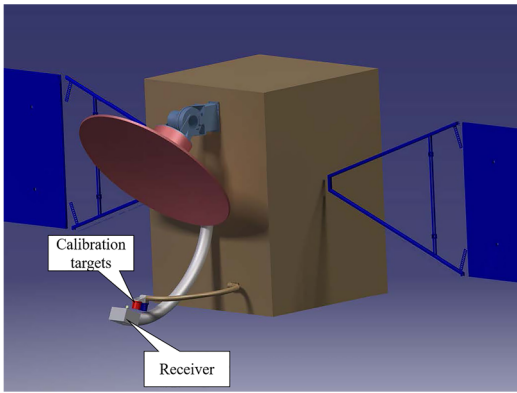


Figure 1. The schematic diagram of TALIS payload

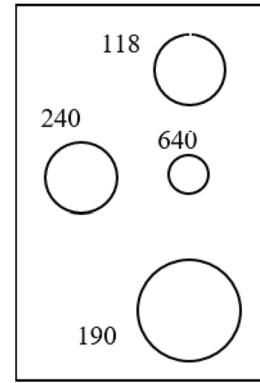


Figure 2. The layout of the four antenna feeds

Table 1. Characteristics of the TALIS payload

Satellite altitude	600 km
Scan altitude	0–100 km
LOS nadir angle	66.07–68.17° (2.1°)
Scan velocity	0.21° s ⁻¹ (36 s scan ⁻¹)
Spectrum integration time	0.1 s (1 km)
Antenna size	1.6 m
Antenna vertical FOV	5.5, 3.8, 3.3, 0.96 km
Spectrometer Bandwidth	2 GHz
Spectrometer resolution	2 MHz
LO frequency	120, 190.1, 239.66, 642.87 GHz

5 2) *What is the size of the antenna? The retrieval vertical resolution should be included in the description of the retrieval performance. The measurement performance of the main products (temperature, H₂O, O₃) should be compared with those of Aura/MLS.*

Reply: The size of the antenna is 1.6 m. The retrieval vertical resolution has been added to each product discussion.

10

Section 4.2 is added to show the performance comparison between TALIS FFT spectrometer and MLS ‘Standard’ 25-channel spectrometer (Fig.9 to 11):

“As discussed in section 2.2, TALIS has similar bands to EOS MLS. The major difference between these two instruments is the spectrometers used in limb sounding. A simulation is performed to compare the performance of the main products between TALIS FFT spectrometer and EOS MLS ‘Standard’ 25-channel spectrometer. Figure 9 to 11 show the retrieval products of TALIS and MLS, all the factors are identical except the spectrometer.

15

According to the simulation results, TALIS can do a better job than EOS MLS because of the wider bandwidth and finer resolution. Temperature precision of TALIS is improved 1–2 K compared with EOS MLS and the vertical resolution is improved about 2 km. H₂O precision is improved about 2–10 %. O₃ precision is improved about 2–20 % and retrieved well in the mesosphere”.

5

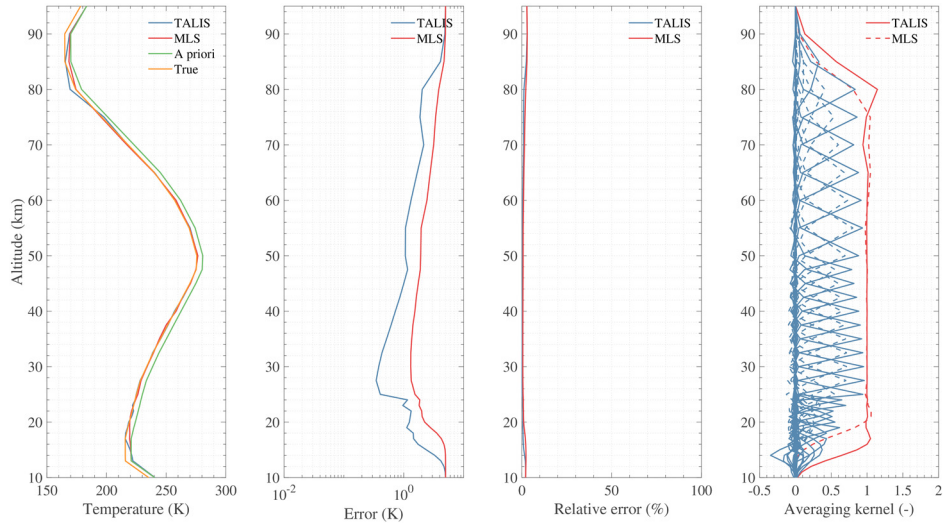


Figure 9. Temperature product comparison between TALIS FFT spectrometer and MLS ‘Standard’ spectrometer using 118.75 GHz line. All other factors are identical.

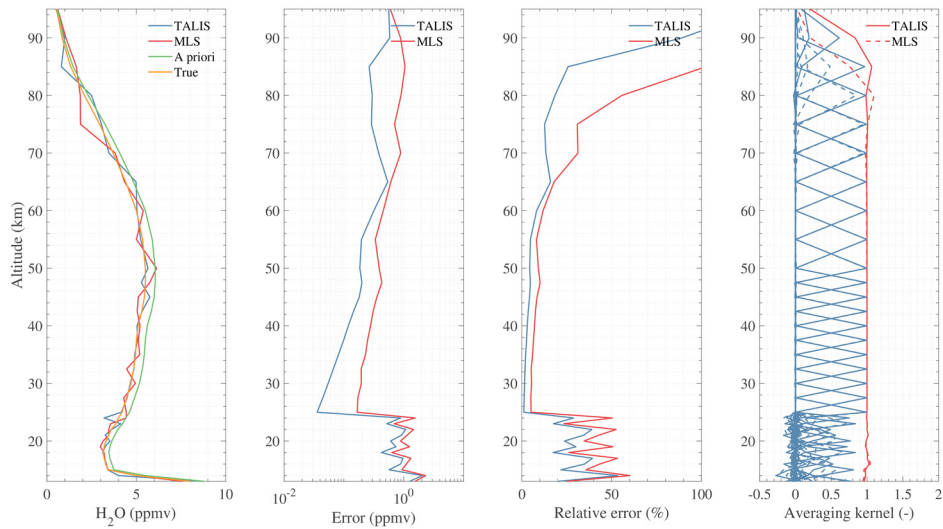


Figure 10. H₂O product comparison between TALIS FFT spectrometer and MLS ‘Standard’ spectrometer using 183.31 GHz line. All other factors are identical.

10

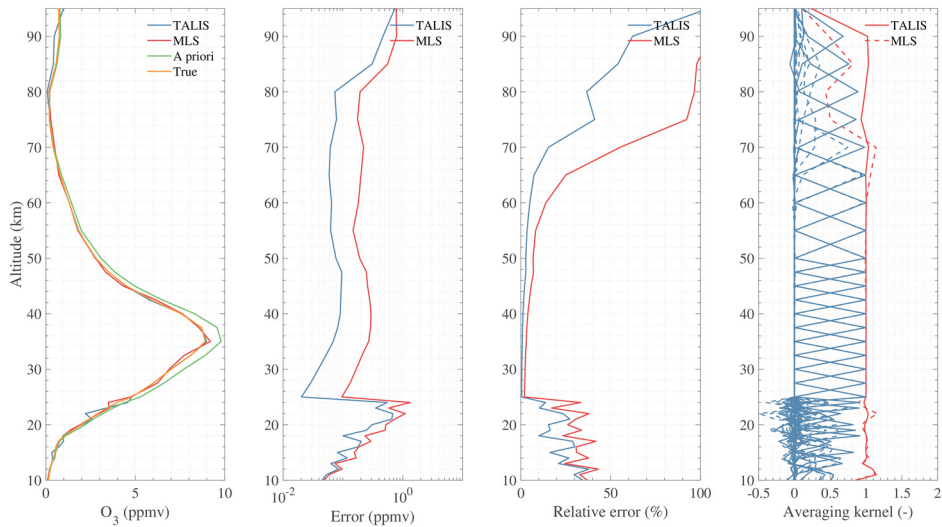


Figure 11. O₃ product comparison between TALIS FFT spectrometer and MLS ‘Standard’ spectrometer using 235.71 GHz line. All other factors are identical.

- 5 *3) The spectral resolution is lower than MLS at the center of key lines such as O₂ @119 GHz and H₂O@183 GHz (0.2 MHz vs 2 MHz). This choice has a significant impact on the retrievals in the mesosphere. It should be discussed.*

Reply: ‘Standard’ 25-channel spectrometers of MLS have the poor spectral resolution. So Digital autocorrelator (DAC) spectrometers are needed to provide the finer spectral resolution for measurements in the mesosphere. However, according to the sensitivity formula, 0.2 MHz resolution will lead to a large noise of about 6-7 K, it needs a trade-off between resolution and noise. Our simulation results show that TALIS can measure O₂ and H₂O from upper-troposphere to mesosphere well.

- 15 *4) More details on the observation strategy could be provided (latitude coverage, local time, ...). They are important when discussing the measurement of radical such as ClO, NO₂, NO, HOCl, HO₂ which have strong diurnal variations (see for instance Khosravi et al.: Diurnal variation of stratospheric and lower mesospheric HOCl, ClO and HO₂ at the equator: comparison of 1-D model calculations with measurements by satellite instruments, Atmos. Chem. Phys., <https://doi.org/10.5194/acp-13-7587-2013> 2013.)*

Reply: We agree that the observation strategy is very important. TALIS is designed to be global coverage, and the local time is not determined yet since it is the pre-research. Thank you for your comments. We will consider the observation strategy with the satellite mission.

Reply to specific comments

Page 1, L25: “Terahertz limb ...”, Most of the statements in this sentence are specific of limb sounding in general. I would rather write “Limb sounders ... in a wide altitude range. In the terahertz domain, the measurement performances are independent of the day-night cycle.”

5 Reply: Done.

Page 1, L29: The reference “Ochiai et al., 2017” may not be the best one here since it describes a proposed mission (as indicated further in the paper). The potential for wind measurement has been demonstrated in the mesosphere with Aura/MLS (Wu et al., 2008) and in the stratosphere with JEM/SMILES (Baron et al., 2013).

10 TALIS should be able to provide wind information between 40 and 60 km (low T_{sys} and more than 10 strong lines). Are the authors plan to investigate the line-of-sight wind retrievals? If yes, this point could be added in the conclusion as future studies.

Reply: Done. The reference has been changed.

15

Indeed, wind measurement has been considered in our mission and whether the 655 GHz spectrometer should be included is also being discussed. This will be discussed in the future works.

This point has been added in the conclusion as follows:

20 “Apart from these products, some potential products will be discussed in the future works. Line-of-sight wind is important information which could be measured by TALIS. Cloud IceWater Content (IWC) is also an essential product provided by passive microwave radiometer. Future studies will also investigate the Zeeman effect as it polarizes and changes the shape of the O_2 lines”.

25 Page 2, L15 and 20: To my knowledge TLS is not a selected mission yet.

Reply: Done. The sentence has been removed.

Page 3, Sect 2.1: What is the antenna size? What is the scan velocity?

30

Reply: The antenna size is 1.6 m, and the scan velocity is 0.21°s^{-1} .

Page 3, L18. The O_2 line will be measured with less bandwidth than Aura/MLS which is equipped filter bank at ± 4 GHz from the O_2 line center. This difference should be discussed as well as the consequences for temperature and pressure

measurement in the upper-troposphere. Is the O₂ line at 239 GHz can compensate the loss of information compared to Aura/MLS?

5 Reply: The ‘Wide’ filters of MLS make measurements extending down into the troposphere. Compared with MLS, the 118 GHz temperature product of TALIS will lack some information in the upper-troposphere. However, our simulation shows that the 240 GHz temperature product can provide the information in the upper-troposphere.

A statement has been added to temperature retrieval as follows (P11, L18):

10 *“‘Wide’ filters of MLS make measurements extending down into the troposphere, and TALIS is lack of the information. However, the retrieval precision of 240 GHz band is better in the upper troposphere and the 240 GHz product can compensate for the loss of information. Result of 643 GHz band looks similar to that of 240 GHz band”.*

Page 4, L21 “Using ... in the 643 GHz bands can measure ... ” should be “Using ... in the 643 GHz band, one can measure”

15

Reply: Done.

Page 4, L24 “Sato et al., 2013” should be “Sato et al., 2012”.

20 Reply: Done.

Page 5, L5: “... because of the negative bias in ClO ... ” I find this statement unclear.

Reply: We are sorry that this is a wrong statement and has been removed.

25

Page 5, Fig. 1-4: Stronger colors should be used. The linewidth could also be increased.

Reply: Done. All figures have been plotted again.

30 *Page 7, Eq 1: This equation is not used in the study. I would remove it and discuss Eq 4 instead. Same for the sentence “The so-call phase function ...” in P8L7.*

Reply: Done. The paragraph has been rephrased as follows:

“Radiative transfer describes the emission, propagation, scattering, and absorption of electromagnetic radiation (Mätzler., 2006). Scattering usually can be neglected above the upper troposphere because of the cloud free. In this way and assuming Local Thermodynamic Equilibrium (LTE), the formal solution of the radiative transfer equation is defined by

$$I_\nu(S_2) = I_\nu(S_1)e^{-\tau_\nu(S_1,S_2)} + \int_{S_1}^{S_2} \alpha_\nu(s)B_\nu(T)e^{-\tau_\nu(s,S_2)} ds, \quad (1)$$

5 where I_ν is the radiance at frequency ν reaching the sensor, α is the absorption coefficient and τ is the opacity or optical thickness. B_ν stands for the atmospheric emission which is given by Planck function describing the radiation of a black-body at temperature T and frequency ν per unit solid angle, unit frequency interval and unit emitting surface (Urban et al., 2004):

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1}, \quad (2)$$

where h is the Planck constant, c is the speed of light, k_B denotes Boltzmann constant”.

10

Page 8, L6: The sentence “Thus the radiance can be converted ...” is unclear. The so-call Brightness-temperature unit is obtained from the linear transformation of the intensity in SI using the Rayleigh-Jeans factor: see Eq 3 in Urban et al., 2004 (reference given in P8, L4).

15 Reply: As discussed in reference, the so-call Brightness-temperature can be obtained by Planck’s law or Rayleigh-Jeans law. Actually, Planck’s radiation law is the standard formula transform radiance to blackbody’s absolute temperature. Rayleigh-Jeans law is the approximation to Planck’s law and its linear transformation will make the calculation simpler. However, Rayleigh-Jeans law will lead to a brightness temperature error which varies with frequency and temperature. Although Rayleigh-Jeans law is commonly used in limb sounding, we want to use Planck function since it is widely used in the
20 meteorological satellites all over the world such as Advanced Microwave Technology Sounder (ATMS) and FY-3D Microwave Humidity and Temperature Sounder (MWHTS). We will study the impact of these two different formulas in further works.

Reference:

25 Weng, Fuzhong and Zou, Xiaolei.: Errors from Rayleigh–Jeans approximation in satellite microwave radiometer calibration systems, Applied Optics, 52, 505–508, <https://doi.org/10.1364/AO.52.000505>, 2013

The sentence has been removed and we added a statement at the last of section 3.1 as follows:

“The measured radiance is transformed to brightness temperatures using the Planck’s function”.

30

Page 9, L7: “The predicted radiance \hat{y} are compared ...”. I disagree with this statement. The measurement is compared with a noiseless prediction as written in Eq9: χ^2 depends on “ $y-F(x,b)$ ” and not on “ $y-\hat{y}$ ”. This part should be rephrased.

Reply: We are very sorry for our carelessness. The sentence has been rephrased as follows:

“The noiseless predicted radiance $F(x, b)$ are compared with the observed radiance y so that the unknown state which minimize the cost function χ^2 could be found”.

5

Page 9, L15: The notation for the system temperature should be consistent with that used in Tab. 1 (Trec vs Tsys). More information/references on how the Tsys values are defined should be provided.

Reply: Done. All the Trec have been replaced by Tsys. System noise temperature (Tsys) means the sum of receiver noise temperature (Trec) and the atmosphere temperature received by the antenna (T_A). It is an equivalent temperature determined by receivers.

Page 9, L25: What the authors mean by “strict approach”?

15 Reply: “strict approach” means OEM can describe the error completely, the sentence has been rephrased as follows:

“The OEM method provides an approach to describe the retrieval error completely”.

Page 10, L22. Is “vertical separation” the spacing between retrieval altitudes? What is the instrument field-of-view? What is the altitude range between 2 spectra? Are they the same as in the Livesey and Snyder study?

20

Reply: “vertical separation” means the altitude space between two spectra assumed in our simulation. The simulation antenna patterns of the four radiometers are shown in Fig. 8. The proposed FOV of TALIS are 5.5, 3.8, 3.3, 0.96 km, and TALIS record the spectra every 1 km. According to the study of Livesey and Snyder, there is a trade-off between the vertical resolution and information gained, and little information is lost by going from twelve to six surfaces per decade. Thus, we use 2.5 km in our simulation for simplicity since the FOV of TALIS are similar to MLS. We will discuss the best vertical resolution of TALIS in the future works.

The sentence has been rephrased as follows:

30 “In this simulation, the scan altitude range is from 10 to 95 km and the spectra are obtained every 2.5 km. As the effective FOV of TALIS are similar to MLS, we use 2.5 km as the vertical resolution. It is the trade-off between the step of efficient limb observation and the optimum information can be obtained (Livesey and Snyder, 2004)”.

Page 10, L30: The sentence “The true profiles are perturbed to be the a priori profiles” is not clear. Are the true profiles derived by perturbing a priori profiles?

Reply: The a priori profiles are derived by perturbing true profiles. The sentence has been rephrased as follows:

“The true species profiles are multiplied by a factor of 1.1 to be the a priori profiles, and the true temperature profile is added a 5 K offset to be the a priori profile”.

5

*Page 11, L1: I don't understand the factor $\sqrt{2}$. Should it be a factor of 2? T_{sys} for SSB = 2 * T_{sys} for DSB with Eq6 definition (the sideband signals are divided by 2). In Table 1, it should be clearly indicated that T_{sys} is for SSB. In Eq 10, it should be clearly indicated that there is a factor to be included for DSB case.*

10 Reply: The factor of $\sqrt{2}$ comes from the noise equivalent bandwidth. As described in the reference: “It should be stated at this stage that the radiometer bandwidth B in the sensitivity formula is the predetection bandwidth, that is, the IF bandwidth, and not the total RF bandwidth, which is $2B$ in DSB receivers”.

Reference:

15 Skou N, Vine D L.: Microwave Radiometer Systems: Design and Analysis, Norwood Ma Artech House P, 2006, 26-27

T_{sys} is the system noise temperature for the band. In Table 1, this is a single-sideband value for 118 GHz radiometer, and double-sideband value for other radiometers. A statement is added to Table 1.

20 The sentence has been rephrased as follows:

“where T_{sys} is the system noise temperature which is the sum of receiver noise temperature and the atmosphere temperature received by the antenna, β is the noise equivalent bandwidth and $\Delta\tau$ is the integration time for measuring a single spectrum. When it comes to DSB radiometer, the ϵ need to be divided by $\sqrt{2}$ ”.

25 *Page 11, L7: “... plotted in the figures.” The figure numbers should be indicated “... plotted in Figs 5 to 21”. The plots will be clearer if a grid would be added. Also a log scale should be used for the errors (difficult to see details if the errors are small).*

Reply: Done. All figures have been plotted again.

30

Page 11, L15-19: The vertical resolution derived from the width of the averaging kernel should be described and discussed. This is a general comment that should be applied to all products. Also the results should be compared with those from Aura/MLS, at least for the most important ones (temperature, H_2O and O_3).

Reply: The vertical resolution has been added to all products.

The comparison of TALIS and MLS retrievals are shown in section 4.2. (see general comments)

5 *Page 11, L19: The sentence “Results of 643 GHz seems not very good” should be rephrased. For me the results look fine in the upper troposphere compared to the two other bands. The error is 2 K, like that for the 240 GHz band and the vertical resolution looks similar.*

10 *I think the 2 following information should be given: - Is the tangent height pressure retrieved? - The Zeeman effect polarizes and changes the shape of the O₂ lines (Schwartz et al., 2006). Future studies will investigate the impacts in the measurement performance above 60 km. [Schwartz et al., EOS MLS forward model polarized radiative transfer for Zeeman-split oxygen lines, IEEE Transactions on Geoscience and Remote Sensing, doi:10.1109/TGRS.2005.862267]*

Reply: The sentence has been rephrased as follows:

“Result of 643 GHz looks similar in the upper troposphere compared to the 240 GHz band”.

15 Tangent height pressure can be derived from the hydrostatic equilibrium equation, it is not retrieved in this simulation. A statement has been added as follows:

“Once the temperature profile is retrieved, the pressure profile can be calculated from the hydrostatic equilibrium equation using a known pressure and temperature at a reference tangent point. The pressure profile is not a direct product and is not shown here”.

20

Zeeman effect is not considered because of the large computational complexity. These impacts will be concerned in the future works. It has been added in the conclusion.

Page 13, L3: I would rephrase the first sentence as “The H₂O profile, another key parameter, can be measured ...”

25

Reply: Done.

Page 15, L2: “covering” should be “covers”

30 Reply: Done.

Page 15, L4: “The other two retrievals ... poor precision”, I think this sentence is too negative since a good performance is achieved between 20 and 60 km with the 190 and 650 GHz bands.

Reply: This sentence has been rephrased as follows:

“The other two bands also show good performance from 25 to 60 km with a single scan precision < 5%”.

Page 17, L1: “widely exist” could be removed (-> HNO₃ is a common species in the stratosphere ...)

5

Reply: Done.

Page 17, L1: It is unclear what “stable lines” mean.

10 Reply: It has been rephrased as follows:

“relatively strong lines”.

Page 17, L17: The statement “seems bad” is negative and not quantitative. I think it should be stated that the 643 GHz signal is stronger than that in the 240 GHz band, but it is strongly absorbed by O₃ below about 30 km. However after averaging the measurements, information can be retrieved between 25 and 70 km with a precision better than 50%.

15

Reply: This sentence has been rephrased as follows:

“The 643 GHz signal is stronger than that in the 240 GHz band, but it is strongly absorbed by O₃ below about 30 km. However, after averaging the measurements, information can be retrieved between 25 and 70 km with a precision better than 50%”.

20

Page 19, L3: “can be retrieved by 190 GHz ...” should be “can be retrieved from the band at 190 GHz while the band at 643 GHz ...”

25 Reply: Done.

Page 21, L1-2: The statement “is not desirable” is not appropriate. This line will be “desirable” if the radiometer at 640 GHz is not working. Instead, I would state that the best retrievals are performed from the band at 640 GHz but information can also be retrieved from the radiometer at 190 GHz with less precision.”

30

Reply: This sentence has been rephrased as follows:

“However, the result shows that the best retrievals are performed from the band at 643 GHz but information can also be retrieved from the 190 GHz radiometer with less precision”.

Page 23, Plot b: What happens at 32 and 65 km? There are strong increases of sensitivity.

Reply: It is not clear what happened yet, maybe it is related to the grid resolution. We will study this problem in the future works.

5

Page 25, L4: “exist” should be removed (-> “There are several weak lines in the spectral...”)

Reply: Done.

10 *Page 28-29, The discussion for NO₂ and NO should include the effects of their diurnal variation (this is also true for HO₂, ClO). Around 40 km, NO₂ vanishes in daytime and NO in nighttime. Since the a priori error is assumed proportional to the VMR, no good measurement sensitivity near 40 km can be found for NO₂ in daytime and for NO nighttime. Therefore, I think it is important to clearly define which conditions are considered in the calculation and to discuss the consequences in term of retrieval sensitivity.*

15

Reply: In simulation, NO₂ is the nighttime profile and NO is the daytime profile. The conditions have been added.

Page 33: The expression such as “... temperature < 2 K” should be Done. (e.g., ... temperature with a precision < 2 K). Several similar cases occur in the conclusion.

20

Reply: Done.

Page 33, L4: Any plan to derive IWC? If yes, this could be indicated as future works.

25 Reply: Yes. It has been added in the conclusion as future works.

Page 33, L17 The sentence “Although the single scan precision seems not very”, as I already mentioned before, such statement is not appropriate. I think a statement such as “The best sensitivity is found between 70~90 km where the precision is better than ...” would be better.

30

Reply: The sentence has been rephrased as follows:

“The best sensitivity is found between 70~90 km where the VMR of CO is large, and the precision is better than 50%”.

Performance Evaluation of THz Atmospheric Limb Sounder (TALIS) of China

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Abstract. THz Atmospheric Limb Sounder (TALIS) is a microwave limb sounder being developed for atmospheric high precision observation by the National Space Science Center, Chinese Academy of Sciences (NSSC, CAS). It is designed to measure the temperature and chemical species such as O₃, HCl, ClO, N₂O, NO, NO₂, HOCl, H₂O, HNO₃, HCN, CO, SO₂, BrO, HO₂, H₂CO, CH₃Cl, CH₃OH, and CH₃CN with high vertical resolution from surface to about 100 km to improve our comprehension of atmospheric chemistry and dynamics, and to monitor the man-made pollution in the atmosphere. Four heterodyne radiometers including several FFT spectrometers of 2 GHz bandwidth with 2 MHz resolution are employed to obtain the atmospheric thermal emission in broad spectral regions centred near 118, 190, 240, and 643 GHz. A theoretical simulation is performed to estimate the retrieval precision of the main targets. Single scan measurement and averaged measurement are considered in simulation, respectively. Temperature profile can be obtained with the precision of < 2K for a single scan from 15 to 85 km by using 118 GHz radiometer, and the 240 and 643 GHz radiometer can provide temperature information in the upper troposphere. **Chemical species such as H₂O, O₃, HCl show relatively high single scan retrieval precision of 1–20% over most of the useful range and ClO, N₂O, HNO₃ can be retrieved with a precision < 50%.** The other species should be retrieved by using averaged measurements because of the weak intensity or low abundance.

1 Introduction

High precision observation of the Earth's atmosphere is essential to the numerical weather prediction and climate change studies. The satellite can provide global coverage atmospheric monitoring in a short time. Instruments such as nadir microwave sounder and infrared sounder have been applied to measure the atmospheric temperature and humidity but with the poor vertical resolution and altitude range (Swadley et al., 2008). **Limb sounders** can not only provide the temperature profile with better vertical resolution but gather information on chemical composition in a wide altitude range. **In the terahertz domain, the measurement performances are independent of the day-night cycle.** Microwave limb sounding is a particularly useful technique in detecting stratospheric and mesospheric temperature and chemistry, and also has large potential for global wind measurement in the middle and upper atmosphere (Wu et al., 2008; Baron et al., 2013).

A few instruments have been launched in recent twenty years, their observation data have offered a better understanding of the physical and chemical processes in the Earth's atmosphere. The first instrument applying the microwave limb sounding technique from space was the Microwave Limb Sounder (MLS) onboard the Upper Atmosphere Research Satellite (UARS) launched in 1991. The sounder offered unique information of temperature/pressure, O₃, H₂O, ClO, and additional data products including SO₂, HNO₃, and CH₃CN (Waters et al., 1993). The Sub-Millimetre Radiometer (SMR) onboard the Odin satellite launched in February 2001 was the first radiometer to employ sub-millimetre in limb sounding. Various target species such as O₃, ClO, N₂O, HNO₃, H₂O, CO, NO, as well as isotopes of H₂O, O₃, and ice cloud have been detected (Murtagh et al., 2002; Urban et al., 2005; Eriksson et al., 2007). EOS MLS, the follow-on of UARS MLS onboard the Aura satellite launched in July 2004 gave successful observations of OH, HO₂, H₂O, O₃, HCl, ClO, HOCl, BrO, HNO₃, N₂O, CO, HCN, CH₃CN, SO₂, ice cloud, and wind (Waters et al., 2004; Waters et al., 2006; Wu et al., 2008; Livesey et al., 2013). The Superconducting Submillimeter-wave Limb-Emission Sounder (SMILES) onboard the Japanese Experiment Module (JEM) of the International Space Station (ISS) launched in September 2009 (Kikuchi et al., 2010). SMILES was equipped with 4K cooled Superconductor–Insulator–Superconductor (SIS) mixers to reduce the system noise temperature so that the sensitivity of the SMILES was higher than that of other similar sensors such as MLS and SMR (Takahashi et al., 2010; Baron et al., 2011). Currently, several new instruments are being developed. Stratospheric Inferred Winds (SIW) is a Swedish mini sub-millimetre limb sounder for measuring wind, temperature, and molecules in the stratosphere. It can provide horizontal wind vectors within 30–90 km, as well as the profiles of temperature, O₃, H₂O and other abundant chemical species (Baron et al., 2018). SIW is designed for small satellites and will be launched as early as 2020–2022. In addition, the follow-on of SMILES, SMILES-2, is being studied for measuring the whole vertical range of 15–180 km with low noise (Ochiai et al., 2017).

THz Atmospheric Limb Sounder (TALIS) is the pre-research project of civil aerospace technology proposed by China National Space Administration (CNSA). TALIS is being designed at National Space Science Center, the Chinese Academy of Sciences (NSSC, CAS) for high precision measurement of atmospheric temperature and key chemical species. It has four microwave radiometers in the frequency bands of 118, 190, 240, and 643 GHz which are similar to EOS MLS. TALIS mission objectives are to provide the information for research on the dynamics and the chemistry of the middle and upper atmosphere by measuring the volume mixing ratio (VMR) profile of the chemical species and other atmospheric condition such as cirrus with much finer spectral resolution. The pre-research will be completed in 2020 and a prototype will be tested. The satellite mission equipped with TALIS will be proposed around 2021.

In this paper, we present a simulation study on precision estimates for the geophysical parameters measured by TALIS. The outline of the present study is as follows: Section 2 describes the instrument characteristics and spectral bands. The retrieval method and the simulation result are discussed in Sects. 3 and 4, respectively. The final section gives a conclusion about the performance and future works.

2 Instrument overview

2.1 Instrument characteristics

The TALIS payload (Fig. 1) and its proposed scan characteristics are summarized in Table 1. The instrument will be set at a sun-synchronous orbit at a normal altitude of 600 km. The offset parabolic antenna is made of a single reflector with 1.6 m projective aperture and four independent feeds. The layout of four discrete feeds is shown in Fig. 2. Compared with the quasi-optical separation layout (such as MLS), this strategy is easier and has higher observation precision. But it will lead to an observed difference of about 20 km between the four radiometers. The widths of the field of view (FOV) at the tangent point are about 5.5, 3.8, 3.3, and 0.96 km respectively. The two-point calibration method is adopted by TALIS, and an extra calibration target is set at the bottom of the antenna. The extra target can be used to improve the calibration precision and evaluate the antenna effect and nonlinearity. At the beginning of the scan, TALIS will view the hot target (ambient temperature) and the extra target (lower temperature) in 3 s, and then it will scan the limb from 0 to 100 km vertically and obtain the spectra every 1 km with an integration time of 0.1 s, finally, it views the cold space at 200 km in 5 s. The process of retrace is the same (also record data) and giving a total period of about 36 s.

TALIS has four radiometers which cover the significant thermal emission spectra in the 118, 190, 240, and 643 GHz regions (see Table 2). Single-sideband (SSB) can keep the complete spectral lines while double-sideband (DSB) can cover more spectral lines because of the image band. Thus, all the radiometers of TALIS will operate in the double-sideband mode except the 118 GHz radiometer. Eleven FFT spectrometers of 2 GHz bandwidth with 2 MHz resolution will be used in TALIS. The bands and system noise temperature for each radiometer are shown in Table 2.

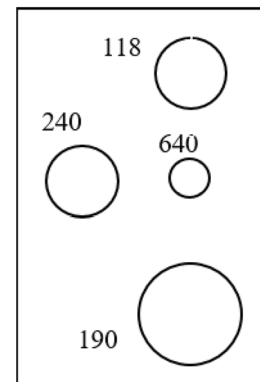
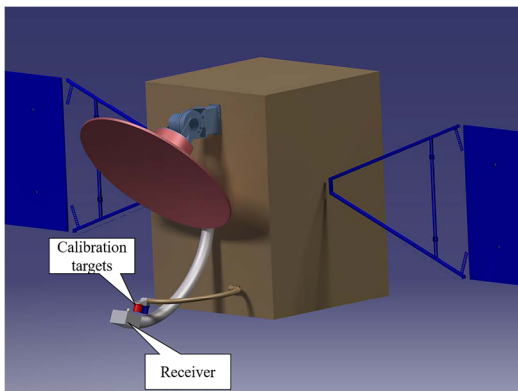


Figure 1. The schematic diagram of TALIS payload

Figure 2. The layout of the four antenna feeds

Table 1. Characteristics of the TALIS payload

Satellite altitude	600 km
Scan altitude	0–100 km
LOS nadir angle	66.07–68.17° (2.1°)
Scan velocity	0.21° s ⁻¹ (36 s scan ⁻¹)
Spectrum integration time	0.1 s (1 km)
Antenna size	1.6 m

Antenna vertical FOV	5.5, 3.8, 3.3, 0.96 km
Spectrometer Bandwidth	2 GHz
Spectrometer resolution	2 MHz
LO frequency	120, 190.1, 239.66, 642.87 GHz

Table 2. Spectral bands and Tsys of TALIS

Radiometer	TALIS (GHz)	Tsys* for TALIS	Tsys for MLS	Radiometer	TALIS (GHz)	Tsys for TALIS	Tsys for MLS
118 GHz	117.75–119.75	800 K	1200 K	240 GHz	229.66–231.66 247.66–249.66	1000 K	1200–1600 K
190 GHz	175.5–177.5 202.7–204.7	1000 K	900–1100 K		232.16–234.16 245.16–247.16		
	178.9–180.9 199.3–201.3				234.66–236.66 242.66–244.66		
	183.0–185.0 195.2–197.2				643 GHz		
627.37–629.37 656.37–658.37							
632.37–634.37 651.37–653.37							
634.87–636.87 648.87–650.87							
648.87–650.87							

* This is a single-sideband value for 118 GHz radiometer, and double-sideband value for other radiometers.

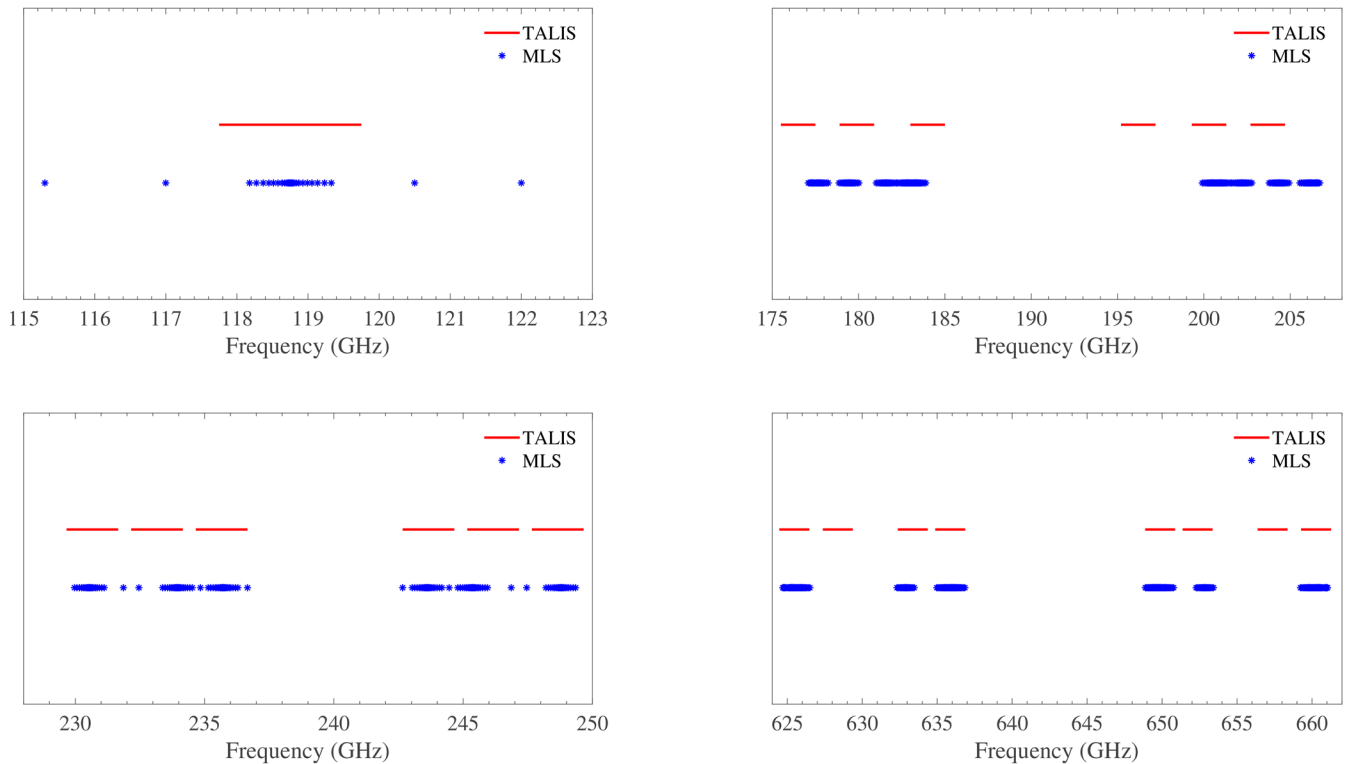


Figure 3. Spectral bands of EOS MLS and TALIS radiometers.

2.2 Spectral bands

The spectral bands of TALIS are selected with the following criteria: (1) maximizing the number of species which will exert a strong influence on atmospheric chemistry and dynamics, (2) necessary space between the passband, (3) trade-off between realizable bandwidth and resolution. TALIS covers most spectral bands of EOS MLS and extends them (see Fig 3), but lack the 2.4 THz band. The broader bandwidth and the finer resolution of TALIS can provide higher retrieval precision and effective altitude range compared with EOS MLS. More chemical species can be measured by TALIS, such as NO₂, NO, and SO₂ (normal concentration).

The 118 GHz radiometer, covering the strong O₂ line at 118.75 GHz, is used to measure the atmospheric temperature and tangent pressure. Since there are few meteorological data set about the temperature above the middle atmosphere with good vertical resolution, it is necessary to measure the temperature profile with wide altitude range, good vertical resolution, and high precision. Other information such as ice cloud can be treated as additional measurement. Figure 4 gives an overview of the 118 GHz spectral band.

The 190 GHz radiometer is mainly designed to cover the 183.31 GHz H₂O line. Monitoring water vapour is important for understanding the mechanisms that humidity feedback on climate, and is essential for improving the accuracy of the weather forecast. Other chemical species such as N₂O, ClO, O₃, and HCN are also included in 190 GHz bands (see Fig. 5).

The main objective of the 240 GHz radiometer is to measure the CO at 230.54 GHz and the strong O₃ lines in a wide spectral band where upper tropospheric O₃ can be obtained with high precision because of the weak water vapour continuum absorption. In addition, the 233.95 GHz O₂ line will be used to measure temperature and tangent pressure together with 118.75 GHz line. SO₂ is an important pollutant in the Earth' atmosphere and will give rise to acid rain. There is no obvious SO₂ emission with the standard profile present in the passband of 240 GHz radiometer. The only SO₂ which is observable by MLS comes from volcanic eruptions. MLS demonstrated that SO₂ can be measured by 190 GHz, 240GHz, and 640 GHz radiometer, but only 240 GHz SO₂ product is recommended for general use. (Pumphrey et al., 2015). The wide and strong lines of HNO₃ can be used to retrieve profile well. NO₂ is a unique species not covered by EOS MLS, and TALIS's wider bandwidth and finer resolution have the potential ability to measure it. The spectra of 240 GHz radiometer are depicted in Fig. 6.

The 643 GHz radiometer is designed to cover as many spectral lines as possible, thus about 17 species are included. The spectral lines covering O₃, HCl, ClO, N₂O, O₂, and H₂O are clearly visible (Fig. 7), and other lines which are relatively weak such as NO, HNO₃, CO, SO₂, BrO, HO₂, H₂CO, HOCl, and CH₃Cl, can also be used. The O₂ line at 627.75 GHz and the H₂O line at 657.9 GHz have the potential to be used as supplements to 118 and 190 GHz radiometers. O₃ is the major species in the stratosphere and mesosphere, which is quite important in atmospheric radiation transfer. Using the high sensitivity lines in the 643 GHz bands, one can measure O₃ with high precision (Takahashi et al., 2011; Kasai et al., 2013). The only lines of HCl below 1 THz are in the 625 GHz frequency band, thus HCl can be measured by 643 GHz radiometer. ClO is a key catalyst for ozone loss and the 649.45 GHz line is suitable for ClO observation with good precision (Santee et al., 2008;

Sato et al., 2012). The HOCl, which will affect stratospheric chlorine budget, has distinct lines above 600 GHz, and the 635.87 GHz line has been pointed out to be the best line for observation (Urban, 2003). Both 649.701 and 660.486 GHz lines can be used to measure the hydroperoxyl radical HO₂, which will contribute to the catalytic ozone chemistry in the upper stratosphere and mesosphere (Millán et al., 2015). Since ClO, HO₂, and HOCl all can be measured, the reaction rate of ClO and HO₂ to form HOCl in the atmosphere can be determined (Johnson et al., 1995). N₂O can be measured at 652.834 GHz, which has been validated by MLS (Lambert et al., 2008). NO has two weak signals at 651.45 and 651.75 GHz which can be used to measure the abundance. HNO₃ can be measured using 650 GHz bands. Measuring these nitrogen species will help researchers to understand the chemistry and dynamics of the atmosphere better. The BrO, which plays an important role in the depletion of ozone, can be measured using 624.768 and 650.179 GHz lines. Because of the low abundance of BrO, measurements must be significantly averaged in order to get reliable results (Millán et al., 2012). CO and H₂CO are the major species in the CH₄ oxidation to CO₂ and H₂O in the stratosphere and mesosphere (Suzuki et al., 2015). The major spectral line of CO used by MLS is at 230.538 GHz, however, the 661.07 GHz line can also provide information (Livesey et al., 2008). H₂CO has a line at 656.45 GHz, but the signal is very weak. The SO₂ lines in the 660 GHz band have the potential to detect the background levels of SO₂. CH₃Cl can be measured in the 649 GHz band near the line of ClO. **MLS measured CH₃OH and CH₃CN in the troposphere and lower stratosphere by 625 GHz spectrometer** (Pumphrey et al., 2011).

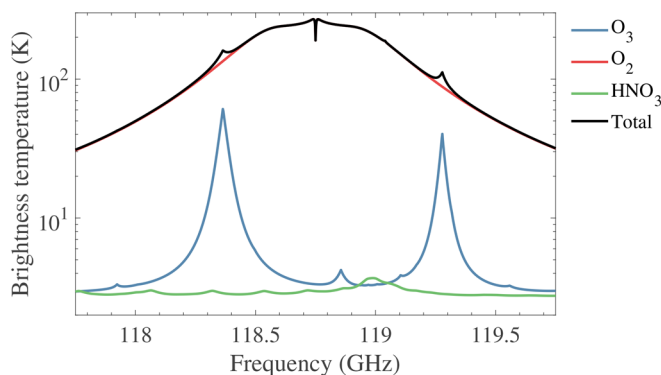


Figure 4. Contributions of the main target chemical species to the 118 GHz spectrum. The brightness temperature is measured from single sideband radiometer. The tangent height is 30 km.

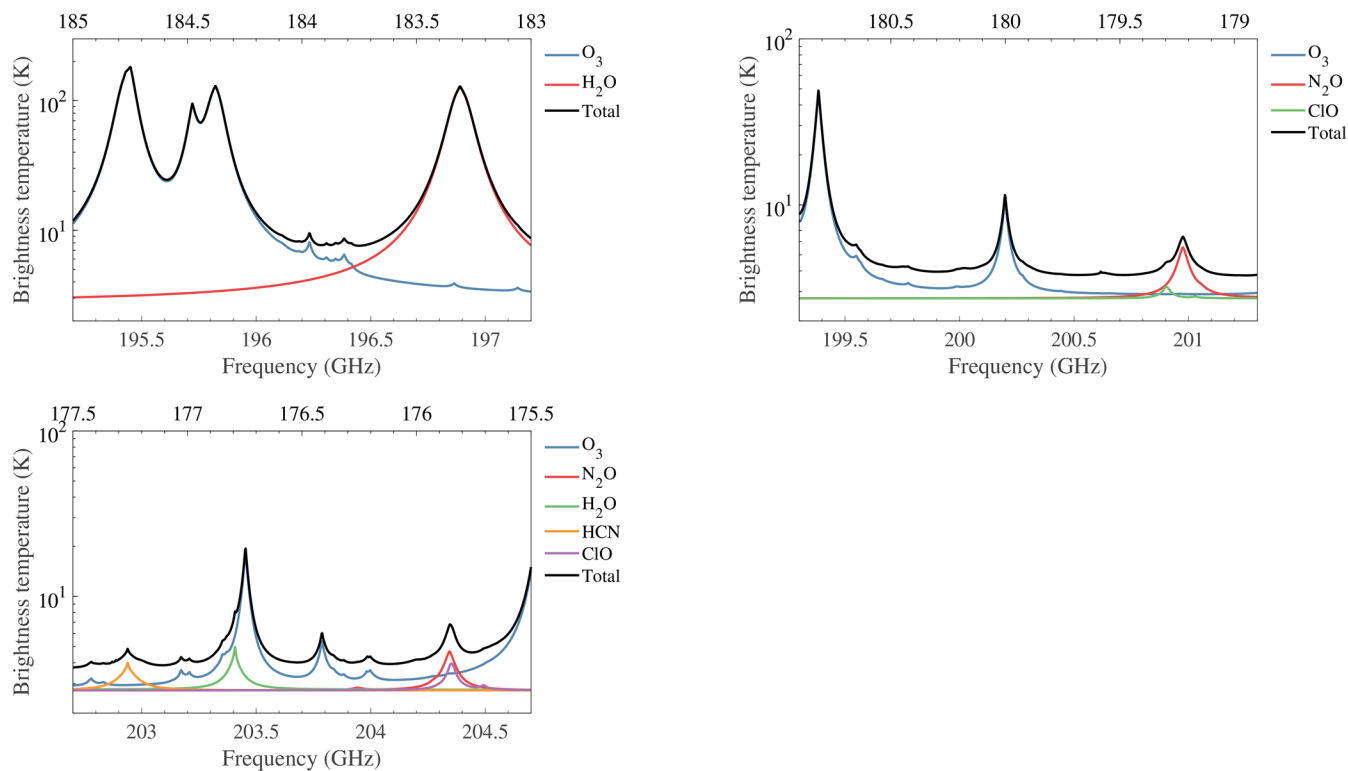


Figure 5. Contributions of the main target chemical species to the 190 GHz spectra. The brightness temperature is measured from double sideband radiometer. The tangent height is 30 km. The top axis represents the lower sideband frequencies and the bottom axis represents the upper sideband frequencies. Each panel represents a single spectrometer.

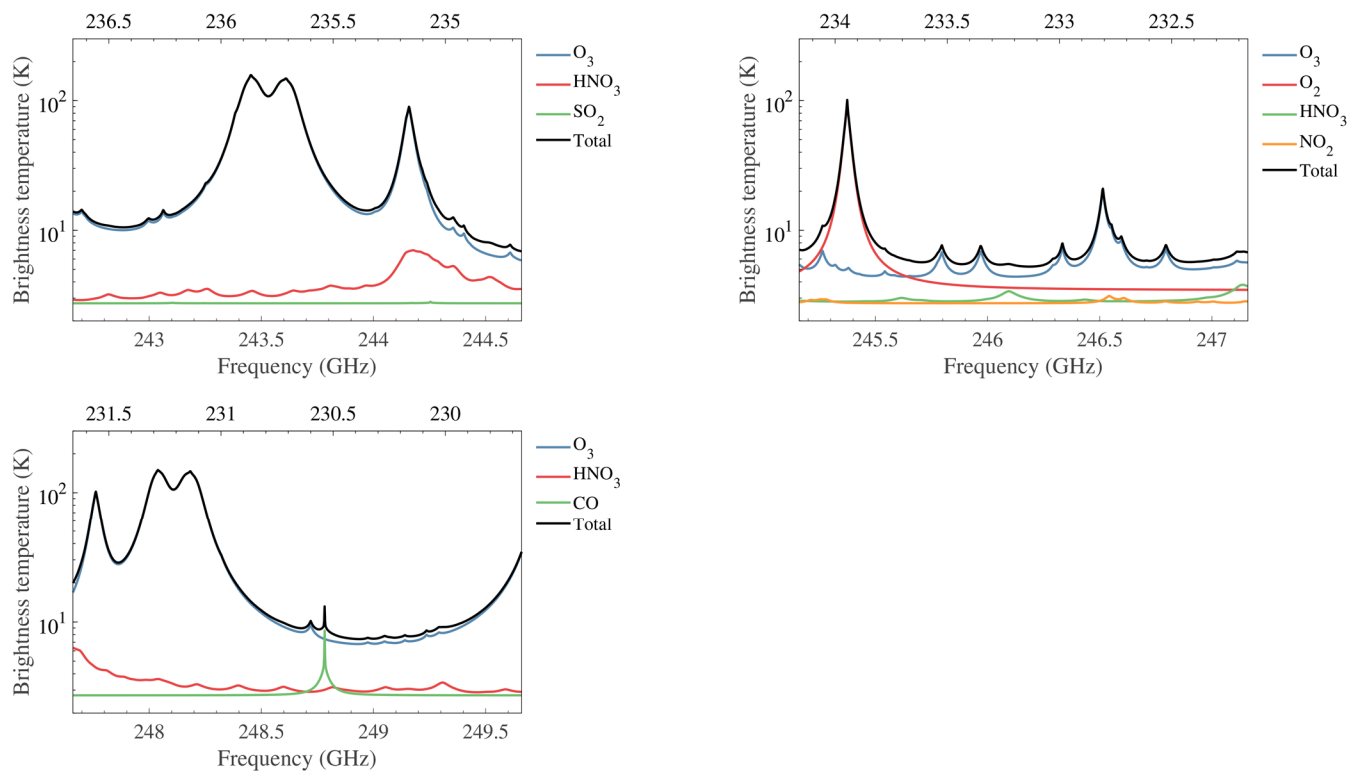


Figure 6. Contributions of the main target chemical species to the 240 GHz spectra. The brightness temperature is measured from double sideband radiometer. The tangent height is 30 km. The top axis represents the lower sideband frequencies and the bottom axis represents the upper sideband frequencies. Each panel represents a single spectrometer.

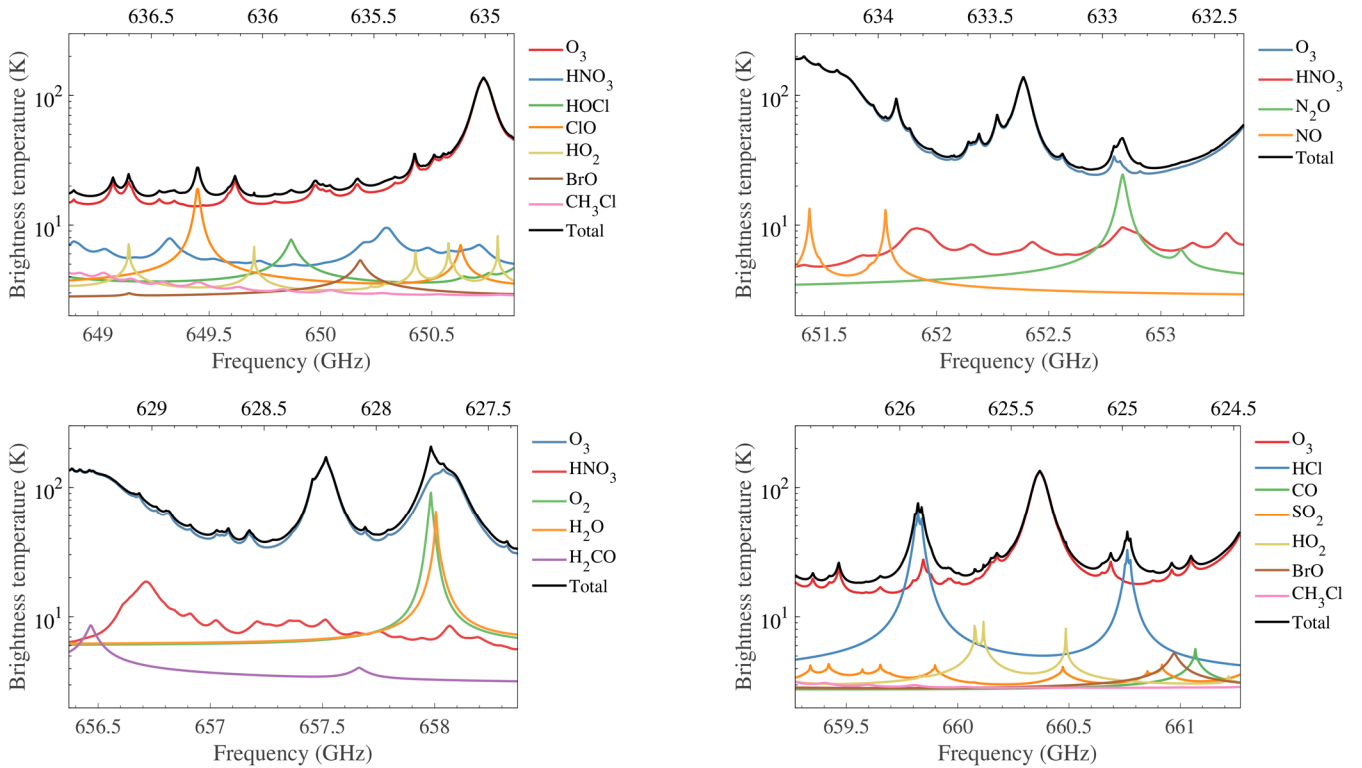


Figure 7. Contributions of the main target chemical species to the 643 GHz spectra. The brightness temperature is measured from double sideband radiometer. The tangent height is 30 km. The top axis represents the lower sideband frequencies and the bottom axis represents the upper sideband frequencies. Each panel represents a single spectrometer.

3 Retrieval methodology

3.1 Forward model

The retrieval of data measured by microwave limb sounder requires the accurate simulation of the observed thermal emission spectra. The forward model is a mathematical tool used to describe the radiative transfer, spectroscopy, and instrumental characteristics. The output of the forward model is the convolution of atmospheric radiation and instrument response.

Radiative transfer describes the emission, propagation, scattering, and absorption of electromagnetic radiation (Mätzler., 2006). Scattering usually can be neglected above the upper troposphere because of the cloud free. In this way and assuming Local Thermodynamic Equilibrium (LTE), the formal solution of the radiative transfer equation is defined by

$$I_v(S_2) = I_v(S_1)e^{-\tau_v(S_1,S_2)} + \int_{S_1}^{S_2} \alpha_v(s)B_v(T)e^{-\tau_v(s,S_2)} ds, \quad (1)$$

where I_ν is the radiance at frequency ν reaching the sensor, α is the absorption coefficient and τ is the opacity or optical thickness. B_ν stands for the atmospheric emission which is given by Planck function describing the radiation of a black-body at temperature T and frequency ν per unit solid angle, unit frequency interval and unit emitting surface (Urban et al., 2004):

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/k_B T} - 1}, \quad (2)$$

5 where h is the Planck constant, c is the speed of light, k_B denotes Boltzmann constant.

Spectroscopy is the method to calculate the absorption coefficient which requires pressure, temperature, and the species concentrations along the line of sight. The basic expression can be written as:

$$\alpha(\nu) = nS(T)F(\nu), \quad (3)$$

where S is called the line strength, F means the line shape function, and n is the number density of the absorber.

10 Sensor characteristics also have to be taken into account by the forward model, including the antenna field-of-view, the sideband folding, and the spectrometer channel response (Eriksson et al., 2006).

Firstly, the radiance which encounters the antenna response could be expressed by the integration:

$$I_\nu^a = \int_\Omega I_\nu(\Omega) W_\nu^a(\Omega) d\Omega, \quad (4)$$

where W_ν^a is the normalized antenna response function. Normally, the variation of I_ν in azimuth angle dimension can be neglected or calculated before-hand. Secondly, a heterodyne mixer needs to convert the signals to intermediate frequency, which will lead to a consequence that the lower and upper sideband are folded. The apparent intensity after the mixer can be modelled as:

$$I_\nu^{if} = \frac{W_\nu^s(\nu) I_\nu^a + W_\nu^s(\nu) I_\nu^a}{W_\nu^s(\nu) + W_\nu^s(\nu)}, \quad (5)$$

where W_ν^s means the sideband response. At last, the final signal will be recorded by spectrometers, which can be described in a similar way as the antenna response:

$$I^c = \int_\nu I_\nu^{if} W_\nu^c(\nu) d\nu. \quad (6)$$

Here W_ν^c means the normalized channel response, and the radiance is denoted I^c .

The measured radiance is transformed to brightness temperatures using the Planck's function.

3.2 Retrieval algorithm

25 Optimal estimation method (OEM) is the most common method used in atmospheric sounding for retrieving vertical profiles of chemistry species (Rodgers, 2000).

In OEM theory, a predicted noisy measurement $\hat{\mathbf{y}}$ can be expressed by a forward model \mathbf{F} with an unknown atmospheric state \mathbf{x} and the system noise ϵ_y according to:

$$\hat{\mathbf{y}} = \mathbf{F}(\mathbf{x}, \mathbf{b}) + \epsilon_y. \quad (7)$$

30 The noiseless predicted radiance $F(x, b)$ are compared with the observed radiance y so that the unknown state which minimize the cost function χ^2 could be found. The cost function is given by:

$$\chi^2 = [\mathbf{y} - \mathbf{F}(\mathbf{x}, \mathbf{b})]^T \mathbf{S}_y^{-1} [\mathbf{y} - \mathbf{F}(\mathbf{x}, \mathbf{b})] + [\mathbf{x} - \mathbf{x}_a]^T \mathbf{S}_a^{-1} [\mathbf{x} - \mathbf{x}_a], \quad (8)$$

where \mathbf{x}_a is a priori state vector, \mathbf{S}_a and \mathbf{S}_y stand for the covariance matrices representing the natural variability of the state vector and the measurement error vector, respectively. Assuming there is no correlation between channels, the off-diagonal elements of \mathbf{S}_y are zero and the diagonal elements are set to the square of the system noise. Usually, a simple formula can be

5 used to determine the SSB radiometric noise standard deviation:

$$\epsilon = \frac{T_{sys}}{\sqrt{\beta} d\tau} \quad (9)$$

where T_{sys} is the system noise temperature which is the sum of receiver noise temperature and the atmosphere temperature received by the antenna, β is the noise equivalent bandwidth and $d\tau$ is the integration time for measuring a single spectrum.

10 When it comes to DSB radiometer, the ϵ need to be divided by $\sqrt{2}$. The diagonal elements of the \mathbf{S}_a specify a priori variance and the off-diagonal terms are used to describe correlations between adjacent elements in order to make the retrieved profile smoother.

Finally, the Levenberg–Marquardt method which is the modification of the Gauss-Newton iterative is used to solve the nonlinear problem. The solution is given by

$$\mathbf{x}_{i+1} = \mathbf{x}_i + [(\mathbf{I} + \gamma)\mathbf{S}_a^{-1} + \mathbf{K}_{xi}^T \mathbf{S}_y^{-1} \mathbf{K}_i]^{-1} \{ \mathbf{K}_{xi}^T \mathbf{S}_y^{-1} [\mathbf{y} - \mathbf{F}(\mathbf{x}_i)] - \mathbf{S}_a^{-1} (\mathbf{x}_i - \mathbf{x}_a) \}, \quad (10)$$

15 where γ denotes the Levenberg–Marquardt parameter, and \mathbf{K}_{xi} represents the weighting function matrix (Jacobian).

The OEM method provides **an approach to describe the retrieval error completely**. The averaging kernel matrix \mathbf{A} , which represent the sensitivity of the retrieved state to the true state, is written as:

$$\mathbf{A} = \mathbf{G}_y \mathbf{K}_x = \frac{\partial \hat{\mathbf{x}}}{\partial \mathbf{x}}, \quad (11)$$

where the \mathbf{G}_y is the contribution matrix, which express the sensitivity of the retrieved state to the measurement:

$$20 \quad \mathbf{G}_y = \frac{\partial \hat{\mathbf{x}}}{\partial \mathbf{y}} = (\mathbf{K}_x^T \mathbf{S}_y \mathbf{K}_x + \mathbf{S}_a^{-1})^{-1} \mathbf{K}_x^T \mathbf{S}_y^{-1}. \quad (12)$$

The retrieval resolution can be estimated from the full width at half-maximum (FWHM) of the averaging kernel (Marks and Rodgers, 1993).

There is another useful variable defined as measurement response, which represents the true state contribution in the retrieval (Baron et al., 2002):

$$25 \quad W(i) = \sum_j |A(i, j)|. \quad (13)$$

The ideal measurement response should be near 1. In practice, reliable range of a retrieval is usually characterised by $|W - 1| < 0.2$.

The total retrieval error can be described by three covariance matrices, the smoothing error covariance matrix which is from the need of a priori information:

$$30 \quad \mathbf{S}_n = (\mathbf{A} - \mathbf{I}) \mathbf{S}_a (\mathbf{A} - \mathbf{I})^T, \quad (14)$$

the measurement error covariance matrix due to the measurement noise:

$$\mathbf{S}_m = \mathbf{G}_y \mathbf{S}_y \mathbf{G}_y^T, \quad (15)$$

and the model parameter error covariance matrix introduced by the uncertainties in the forward model:

$$\mathbf{S}_s = \mathbf{G}_y \mathbf{K}_b \mathbf{S}_b \mathbf{G}_y \mathbf{K}_b^T. \quad (16)$$

4 Measurement performance

5 4.1 Simulation setup

The objective of the simulation is to evaluate the observation performance of TALIS. In this simulation, the forward model Atmospheric Radiative Transfer Simulator (ARTS 2.3) and its corresponding retrieval tool Qpack2 are used (Eriksson et al., 2005; Eriksson et al., 2011). The instrumental setup follows the characteristics of TALIS described in Table 1 and Table 2. The ideal rectangle channel response function is used. **The simulation antenna patterns of the four radiometers are shown in Fig. 8. As the antenna calibration can be done by a linear function, it has no impact on the following simulation, so antenna pattern is not added in simulation below.**

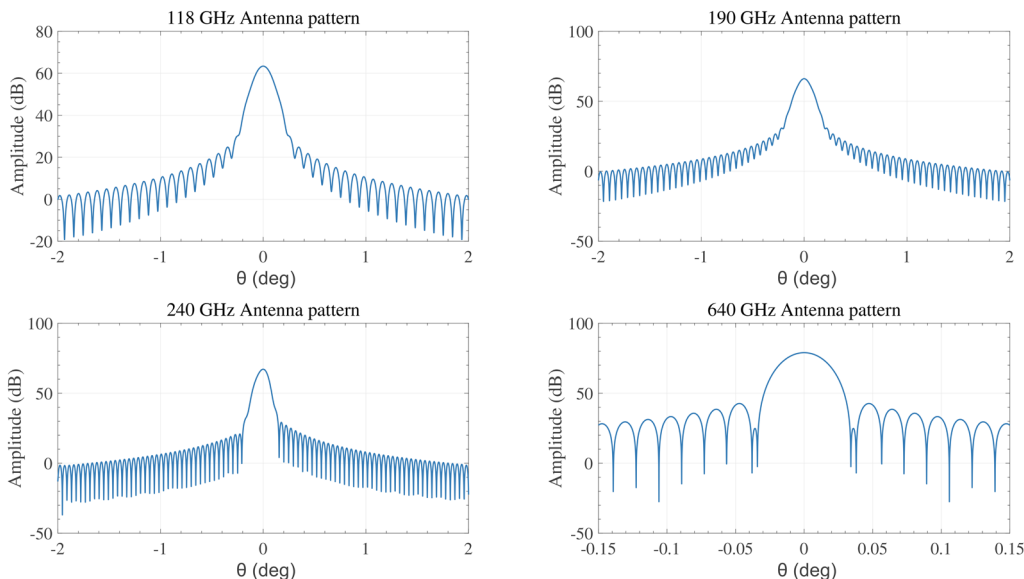


Figure 8. The antenna patterns of TALIS.

In this simulation, the scan altitude range is from 10 to 95 km and the spectra are obtained every 2.5 km. As the effective FOV of TALIS are similar to MLS, we use 2.5 km as the vertical resolution. It is the trade-off between the step of efficient limb observation and the optimum information can be obtained (Livesey and Snyder, 2004).

A mid-latitude summer atmospheric condition (profiles of BrO and HO₂ are from MLS L3 data) is chosen to perform the simulation. The scattering from tropospheric clouds, refraction, and Zeeman effect are not considered because of the large computational complexity. A spectroscopic line parameters catalogue created with the data taken from JPL catalogue (Pickett et al., 1998), HITRAN database (Rothman et al., 2013), and Perrin catalogue (Perrin et al., 2005) is used for line-by-

line absorption calculation. The measurement covariance matrix is set diagonal as described in Sect.3 in order to reduce the computing time. 100% of a typical profile is used to build the a priori covariance matrix with 3 km vertical correlation between the adjacent pressure levels by a parametric Gaussian function. **The true profiles are defined with a vertical resolution of 0.5 km. The true species profiles are multiplied by a factor of 1.1 to be the a priori profiles, and the true temperature profile is added a 5 K offset to be the a priori profile.**

5 **The retrieval grid resolution is 1 km below 25 km, 2.5 km below 50 km, and 5 km above 50 km.**

The expected 1σ noise is calculated by Eq. (10), and thus the noise is assumed to be 2 K, 1.7 K, 1.7 K, and 5 K, respectively. The species such as BrO and HO₂ which emission radiances are small compared with the system noise must be averaged to increase the precision. Here the lower noise (1σ noise multiply a factor of 0.1) is used to represent the averaged production.

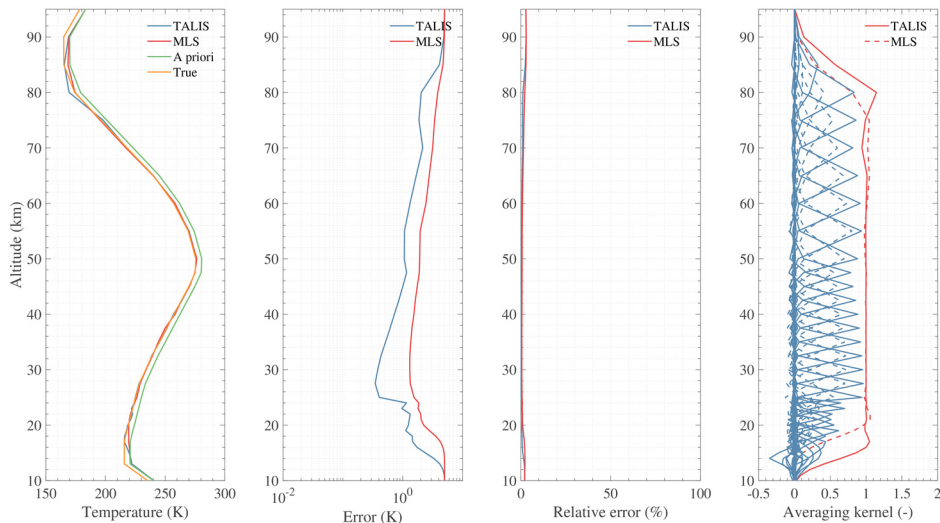
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4.2 Comparison of TALIS and EOS MLS

As discussed in section 2.2, TALIS has similar bands to EOS MLS. The major difference between these two instruments is the spectrometers used in limb sounding. A simulation is performed to compare the performance of the main products between TALIS FFT spectrometer and EOS MLS ‘Standard’ 25-channel spectrometer. Figure 9 to 11 show the retrieval products of TALIS and MLS, all the factors are identical except the spectrometer.

15

According to the simulation results, TALIS can do a better job than EOS MLS because of the wider bandwidth and finer resolution. Temperature precision of TALIS is improved 1–2 K compared with EOS MLS and the vertical resolution is improved about 2 km. H₂O precision is improved about 2–10 %. O₃ precision is improved about 2–20 % and retrieved well in the mesosphere.



20

Figure 9. Temperature product comparison between TALIS FFT spectrometer and MLS ‘Standard’ spectrometer using 118.75 GHz line. All other factors are identical.

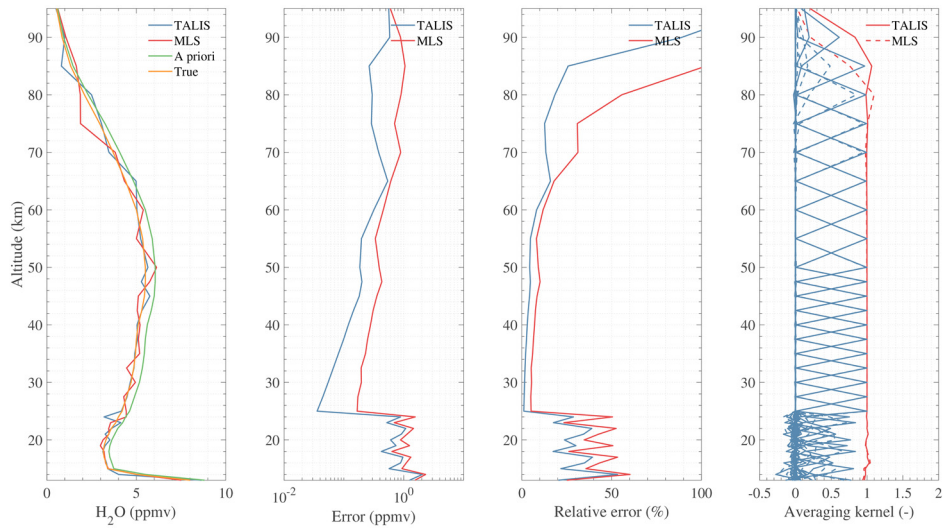
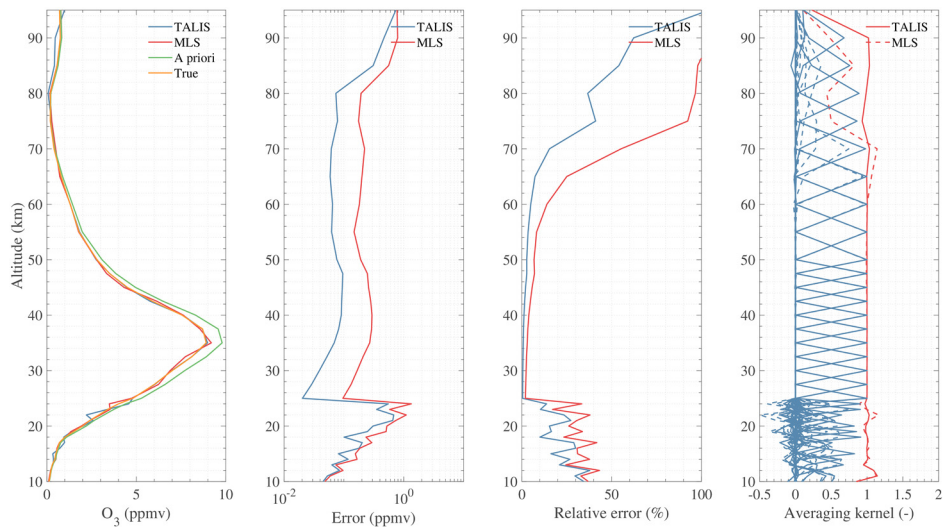


Figure 10. H₂O product comparison between TALIS FFT spectrometer and MLS ‘Standard’ spectrometer using 183.31 GHz line. All other factors are identical.



5 Figure 11. O₃ product comparison between TALIS FFT spectrometer and MLS ‘Standard’ spectrometer using 235.71 GHz line. All other factors are identical.

4.3 Retrieval precision

Since the simulation has been performed, an evaluation of the retrieval precision on the target species of TALIS is made. Retrieval profile, a priori profile, and true profile are all plotted in Figs. 12 to 28. The precision (square root of diagonal elements of the error covariance matrix) is given for a single scan and averaged measurement respectively, and the relative error is also provided. Auxiliary information about averaging kernel function and measurement response are also included. Results are discussed in details in the followings.

4.3.1 High precision products

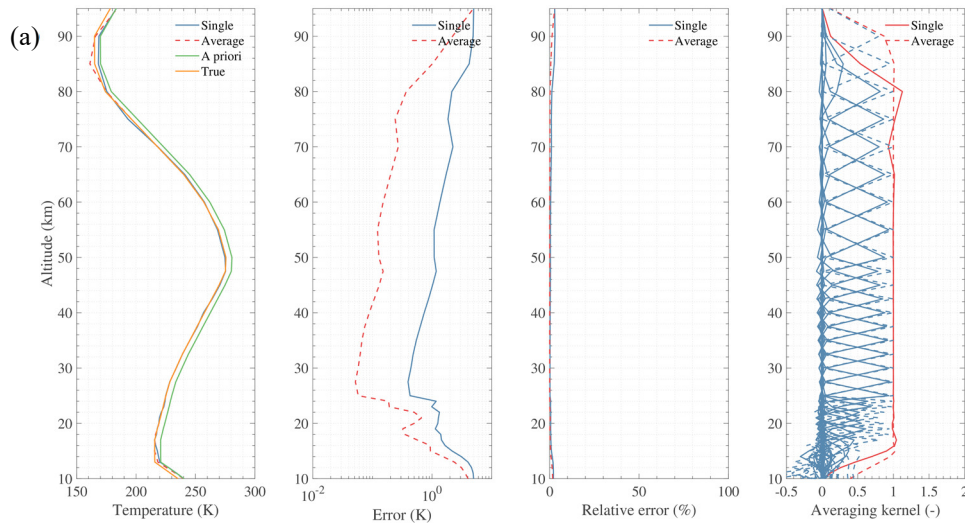
Temperature, H₂O, O₃, HNO₃, HCl, N₂O, and ClO are treated as high precision products because of the good precision for a single scan measurement. These products can be used in scientific research directly.

Atmospheric temperature is the most important parameter that can be retrieved with high signal-noise ratio in lower frequency or good vertical resolution in high frequency by using O₂ lines. TALIS will use 118 GHz radiometer to detect atmospheric temperature profile, with 240 and 643 GHz radiometers worked as supplement products. Results are shown in Fig. 12, the sensitivity is significantly high at the 118 GHz band. Single scan precision is < 1K from 25 to 45 km and < 2K at other useful range. The retrieval vertical resolution is 2.5 km below 50 km and 5–6 km from 50 to 80 km. The precision of averaged measurement will be < 1K from 15 to 85 km.

10 ‘Wide’ filters of MLS make measurements extending down into the troposphere, and TALIS is lack of the information. However, the retrieval precision of 240 GHz band is better in the upper troposphere and the 240 GHz product can compensate for the loss of information. Result of 643 GHz band looks similar to that of 240 GHz band.

Once the temperature profile is retrieved, the pressure profile can be calculated from the hydrostatic equilibrium equation using a known pressure and temperature at a reference tangent point. The pressure profile is not a direct product and is not shown here.

15



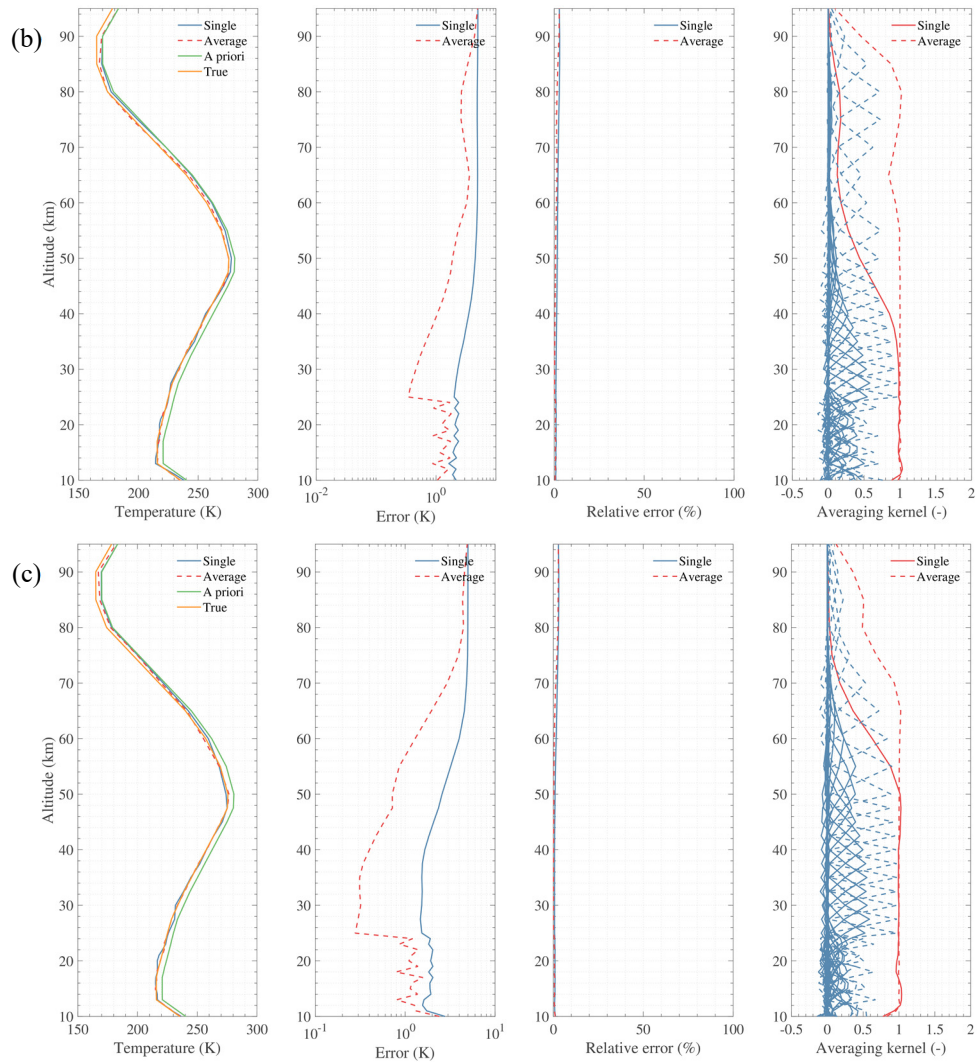


Figure 12. Simulation results of temperature retrieval using 118.75 (a), 233.95 (b), and 627.75 GHz (c) lines.

The H_2O profile, another key parameter, can be measured by 190 and 643 GHz radiometers. The 183.31 GHz line is generally used by humidity sounder to detect water vapour with high precision. Figure 13 shows the retrieval precision will be $< 10\%$ from 25 to 75 km by 190 GHz single scan measurement with the vertical resolution of 2.5–5 km. Averaged measurement has the retrieval precision $< 1\%$ at 25–80 km, $< 20\%$ at other effective altitudes. The profile can also be retrieved by 643 GHz radiometer with less precision.

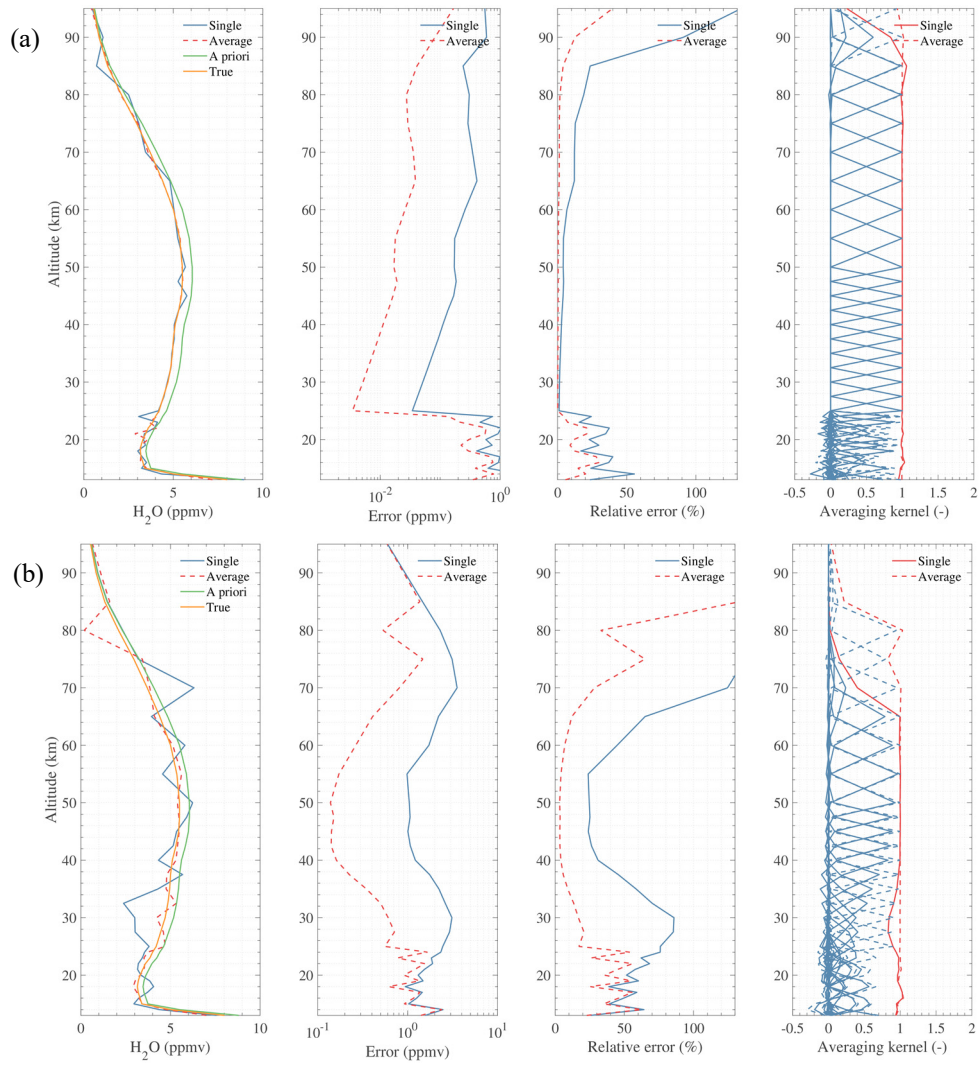
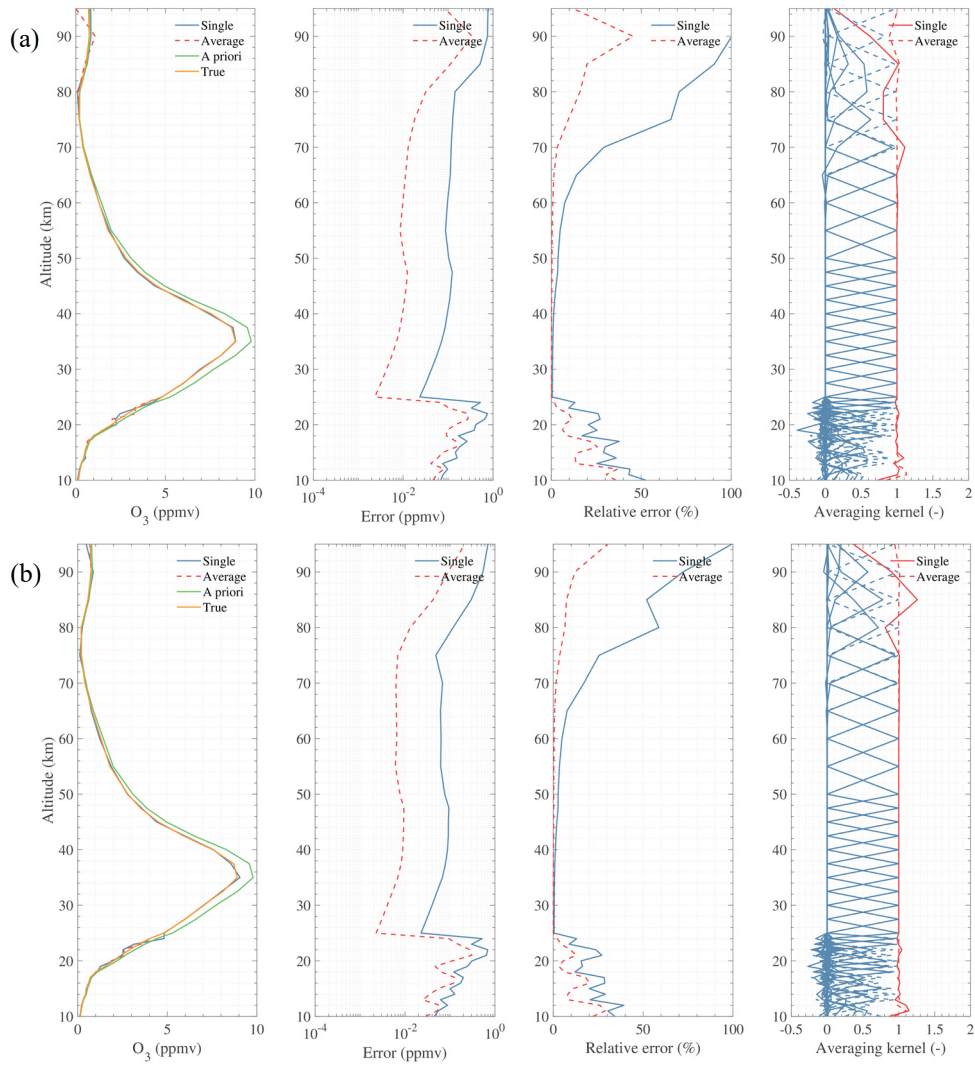


Figure 13. Simulation results of H₂O retrieval using 183.31 (a) and 657.9 GHz (b) lines.

O₃ has quite strong intensity in most spectral regions of TALIS. All the radiometers except 118 GHz can be used to observe this gas which is important for energy balance (Fig. 14). The 240 GHz radiometer which covers the 235.7 GHz line has the highest O₃ sensitivity. The profile can be retrieved with a single scan precision < 5% from 25 to 60 km and the vertical resolution is 2.5 km. The vertical resolution will degrade to 5–8 km for altitudes higher than 60 km. By averaging the measurements, the precision will be < 1% at 25–65 km. The other two bands show good performance from 25 to 60 km with a single scan precision < 5%.



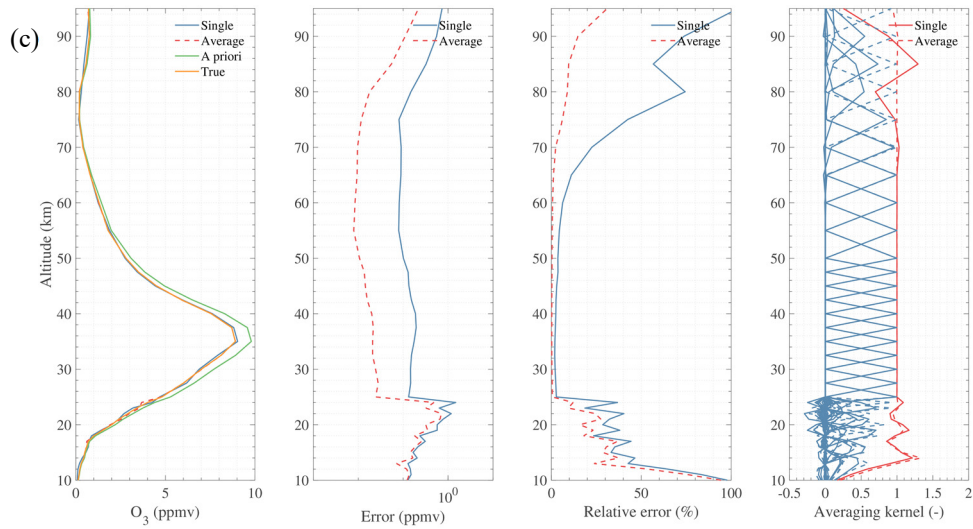
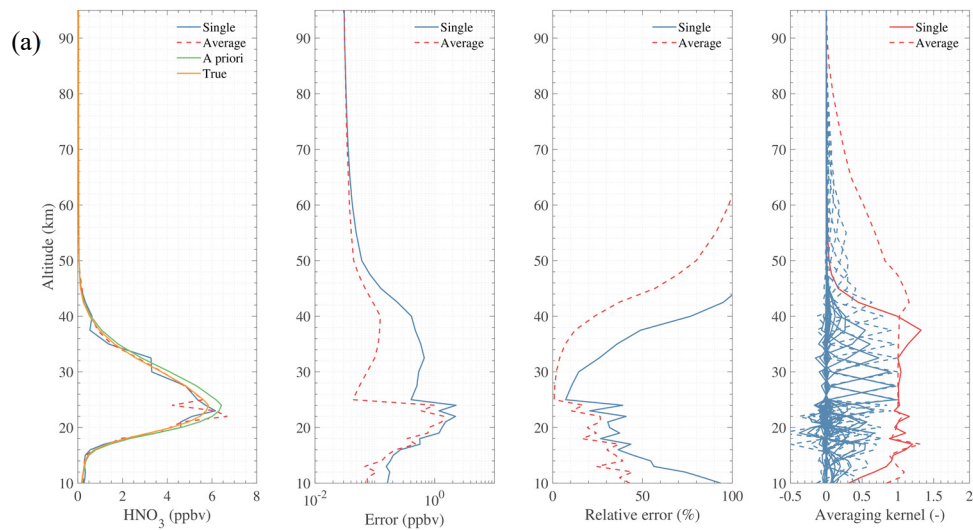


Figure 14. Simulation results of O₃ retrieval using 190 (a), 235.7 (b), and 657.5 GHz (c) lines.

HNO₃ is a common species in the stratosphere and has **relatively strong lines** at 240 and 643 GHz bands. Figure 15 shows the results of HNO₃ retrieval. The 240 GHz radiometer can measure HNO₃ at 25–35 km altitude range with a single scan precision < 30% and the **vertical resolution is 2.5–5 km through most of the useful range**. Averaging the measurements can improve the retrieval with a precision < 10% from 25 to 35 km. **The 643 GHz signal is stronger than that in the 240 GHz band, but it is strongly absorbed by O₃ below about 30 km. However, after averaging the measurements, information can be retrieved between 25 and 70 km with a precision better than 50%.**



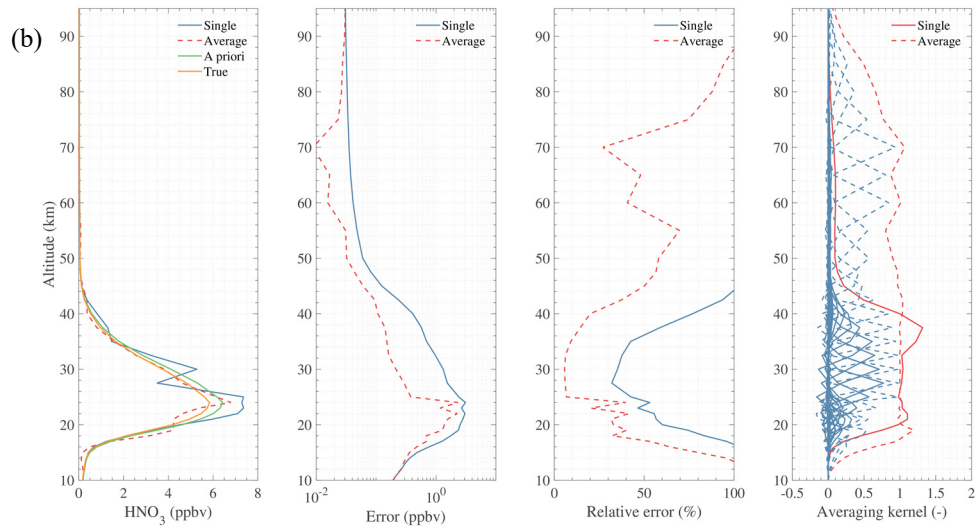


Figure 15. Simulation results of HNO₃ retrieval using 244 (a), and 656 GHz (b) lines.

Figure 16 shows the expected precision of HCl observation. HCl can be measured at 25–50 km with < 20% single scan relative error. **The vertical resolution is 2.5–5 km through most of the useful range.** By averaging the measurements, the precision will be < 5% at 25–65 km.

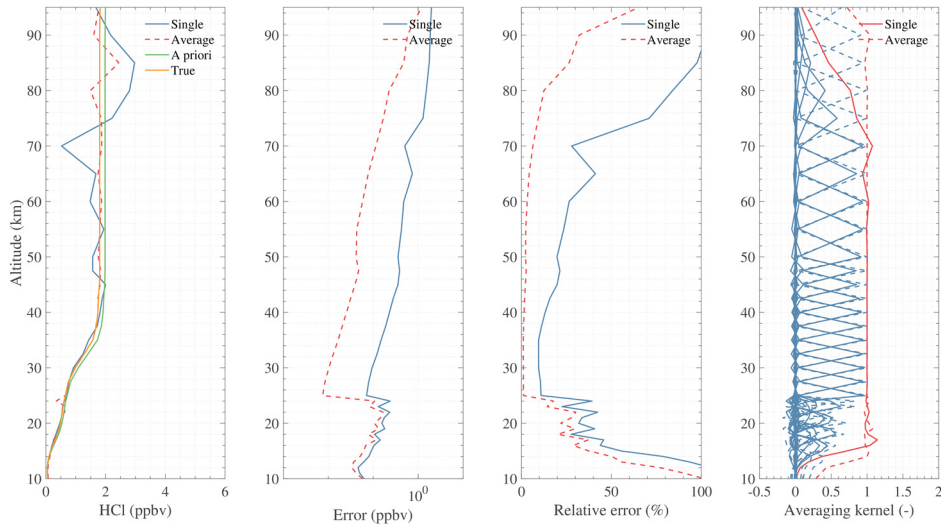


Figure 16. Simulation result of HCl retrieval using 624.9 GHz lines.

N₂O can be retrieved from the band at 190 GHz in the upper troposphere while the band at 643 GHz can provide more information in the stratosphere. Figure 17 shows that single scan precision of 190 GHz is < 40% at 10–35 km with the **vertical resolution of 2.5–5 km.** By averaging the measurements, the precision will be < 30% from 10 to 45 km. The 643 GHz can give the similar precision at 15–50 km.

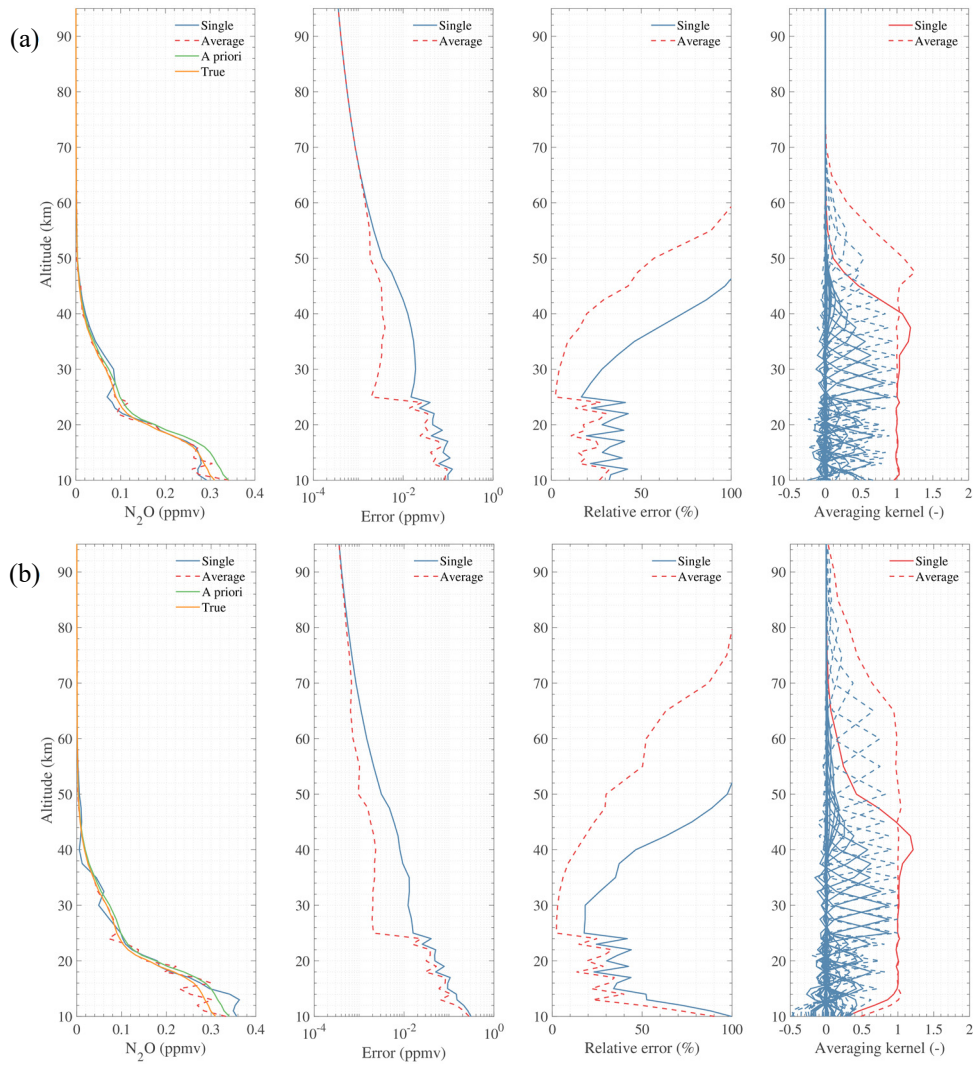


Figure 17. Simulation results of N₂O retrieval using 200.98 (a), and 652.834 GHz (b) lines.

CIO can be retrieved from radiances measured by 190 and 643 GHz bands (Fig. 18). However, the result shows that the best retrievals are performed from the band at 643 GHz but information can also be retrieved from the 190 GHz radiometer with less precision. Single scan measurement from 643 GHz radiometer can be used to obtain CIO with 30–50% precision from 30 to 45 km, and the vertical resolution is about 3–4 km throughout the useful range. By averaging the measurements, precision will be 5–30% from 25 to 60 km.

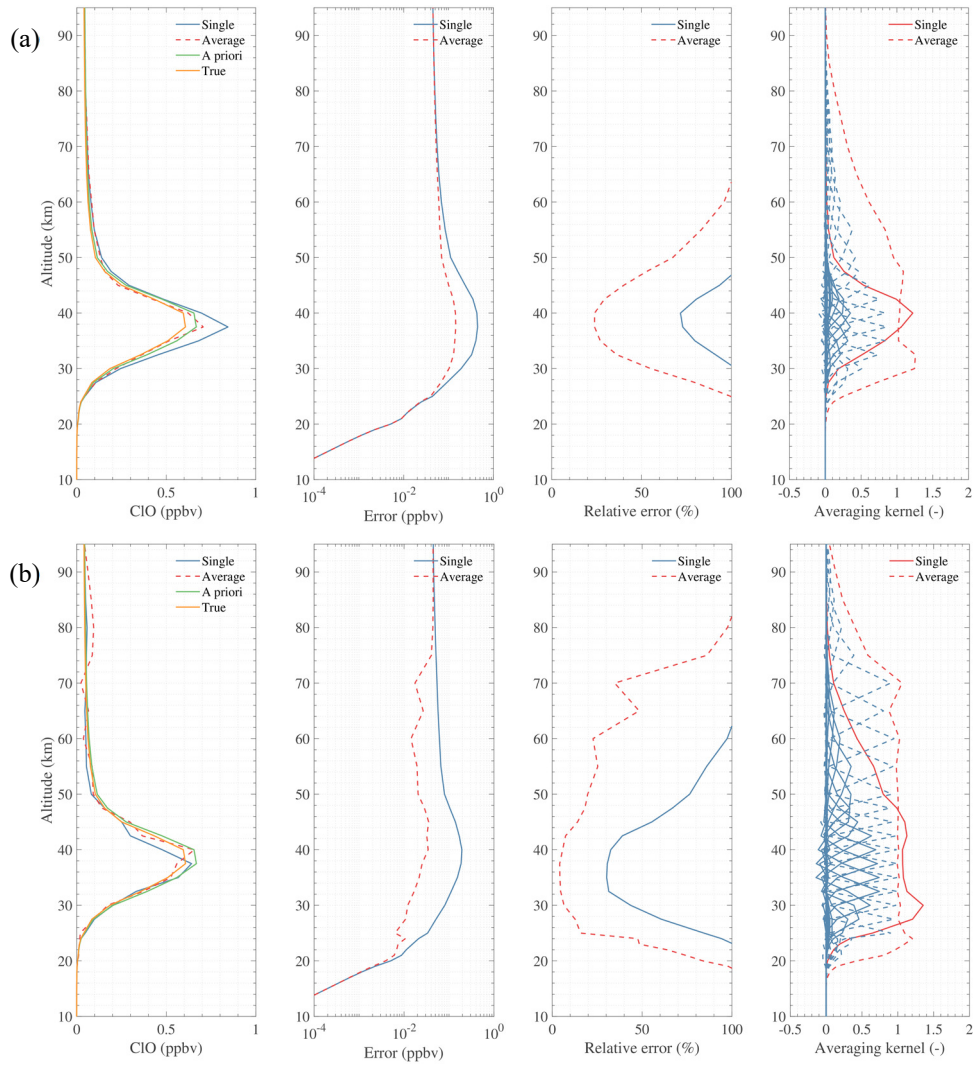


Figure 18. Simulation results of ClO retrieval using 203.4 (a) and 649.45 GHz (b) lines.

4.3.2 Medium precision products

5 Medium precision products including CO, HCN, CH₃Cl mean that their single scan retrieval precisions are not satisfying, but can be used to some degree. There is a choice for the user to select the single scan or averaged products.

CO can be measured using 230.538 and 661.07 GHz lines. Figure 19 shows that the 240 GHz radiometer can provide CO information with 40–90% single scan precision from 10 to 70 km. **The vertical resolution is in the range 3.5–5.5 km from the upper troposphere to the lower mesosphere, degrading to 6–10 km in the upper mesosphere.** By using averaged measurements, CO can be retrieved with < 40% relative error from 10 to 25 km, < 20% relative error at the range of 25–95 km. However, the retrieval of 643 GHz measurement shows poor precision.

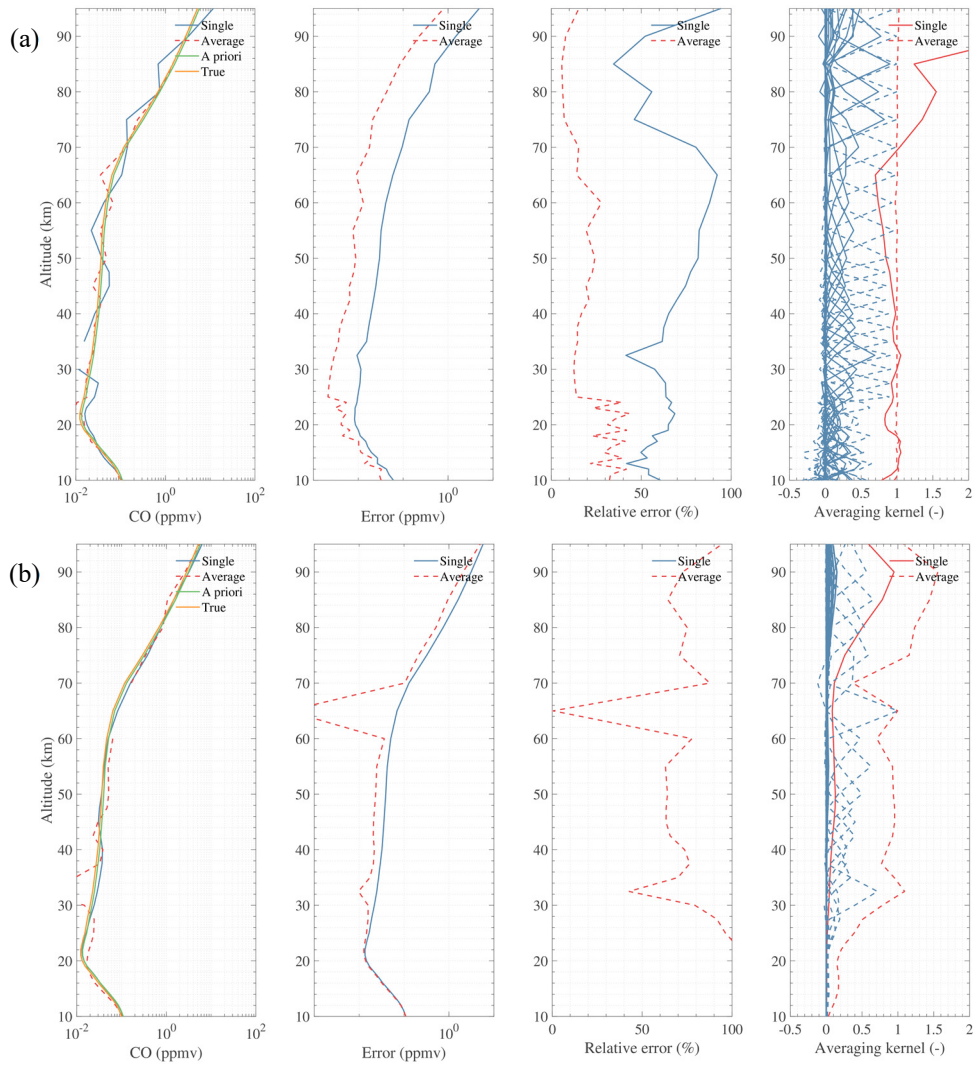


Figure 19. Simulation results of CO retrieval using 230.538 (a) and 661.07 GHz (b) lines.

HCN is measured by 190 GHz radiometer at 177.26 GHz line. The single scan precision is around 50% from 18 to 32 km and the vertical resolution is about 5 km at the height of 30 km, degrading to 8 km at about 40 km (Fig. 20). By averaging the measurements, the relative error will be < 50% at 15–60 km.

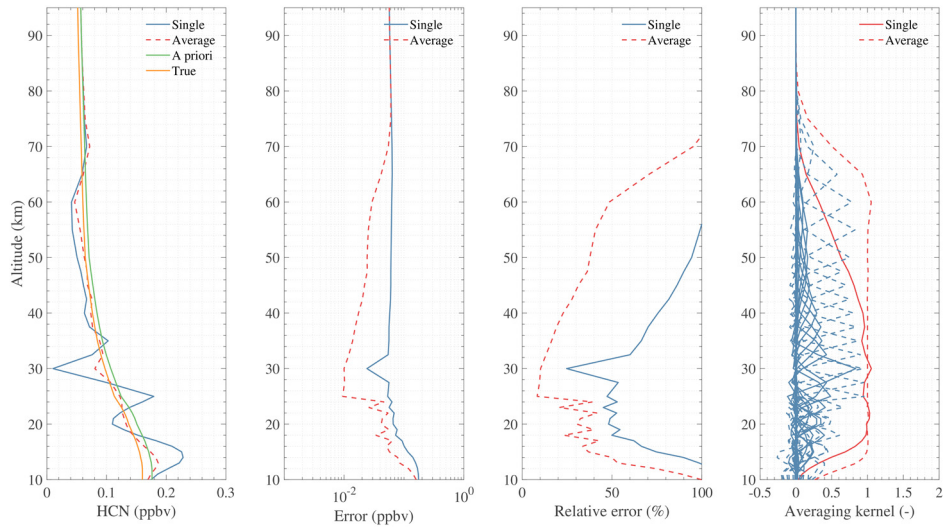


Figure 20. Simulation result of HCN retrieval using 177.26 GHz line.

CH₃Cl can be measured by the 643 GHz radiometer. As the result shows (Fig. 21), the 649.5 GHz band are suitable for CH₃Cl observation in the upper troposphere and lower stratosphere. It can be measured with 40–50% single scan precision from 15 to 23 km, with 20–50% averaged precision from 12 to 30 km. **The vertical resolution is about 3 km over most of the useful range.**

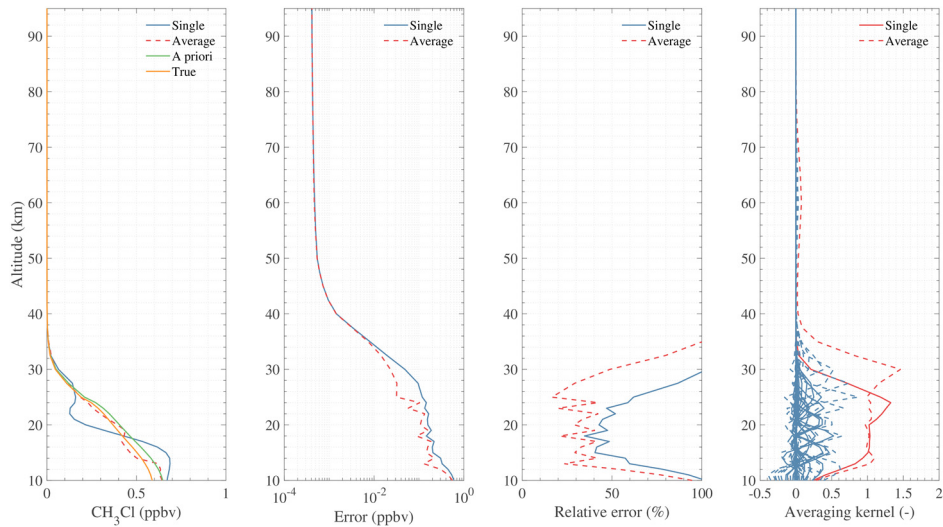
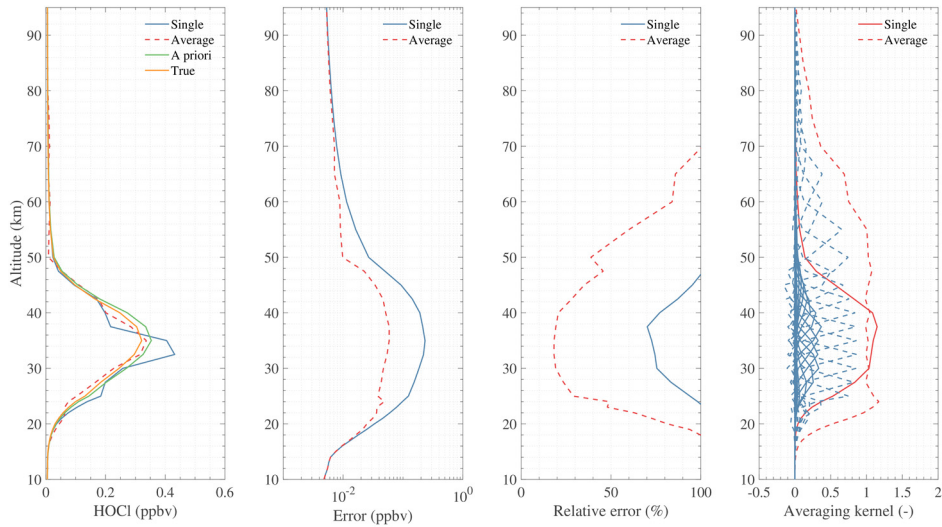


Figure 21. Simulation results of CH₃Cl retrieval using 649.5 GHz lines.

4.3.3 Low precision products

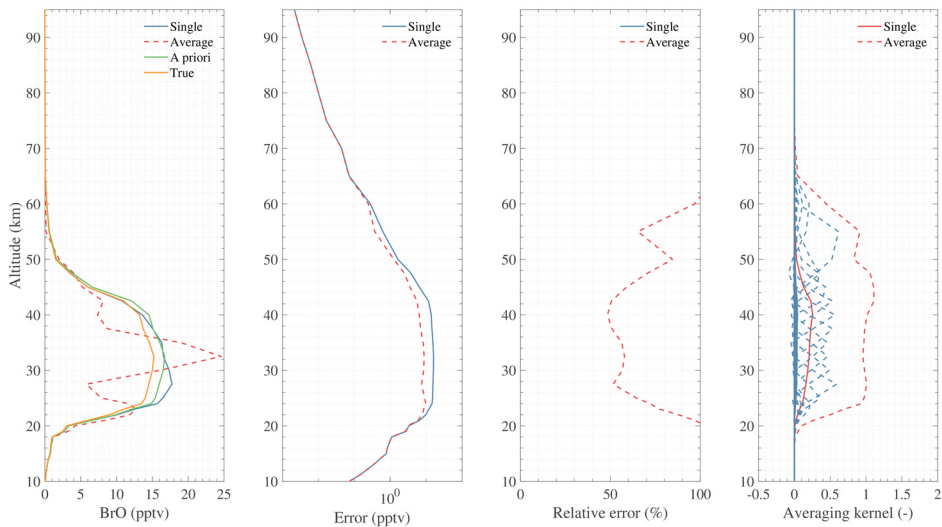
10 There are several weak lines in the spectral regions of TALIS such as HOCl, BrO, and HO₂. Significantly average must be done to these measurements in order to obtain reliable and satisfying precision.

The 635.87 GHz line is the most appropriate line for HOCl observation. However, the single scan retrieval has poor precision of 70–100% with the **vertical resolution of about 6 km**. Figure 22 reveals that HOCl can be retrieved from 22 to 52 km with averaged measurement precision of 15–50%.



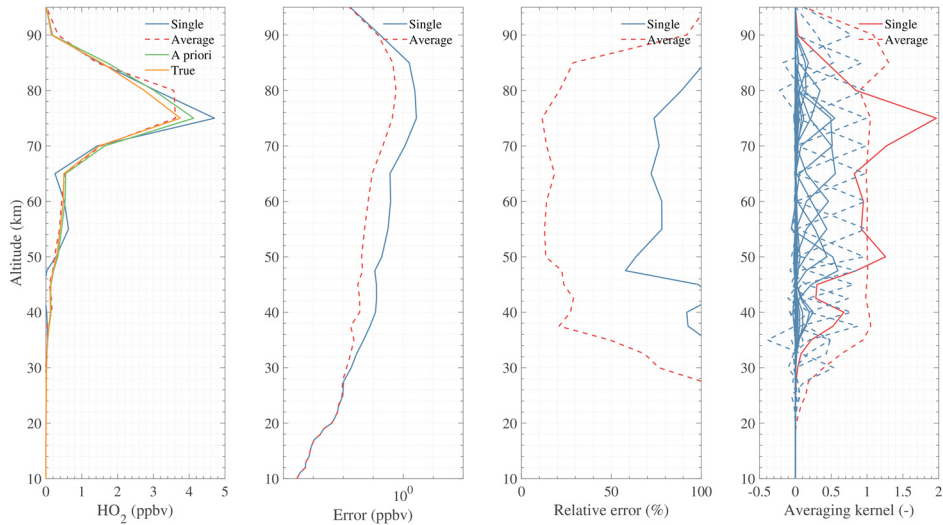
5 **Figure 22. Simulation result of HOCl retrieval using 635.87 GHz line.**

BrO can be measured by using 624.768 GHz spectral line. Figure 23 shows the simulation result of BrO retrieval. As the averaging kernel reveals, there is almost no useful information in single scan measurement because of the quite poor signal-to-noise ratio. Therefore, averaging is needed to obtain reliable and scientific results. The error is 50–80% from 23 to 56 km with the **vertical resolution of about 4 km**.



10 **Figure 23. Simulation results of BrO retrieval using 624.768 GHz line.**

HO₂ can be measured by the 643 GHz radiometer with 10–50% precision at the vertical range of 35–85 km by using averaged data (Fig. 24). The precision of single scan retrieval is not desirable because of the weak signal. **The vertical resolution is about 6 km.**



5 **Figure 24. Simulation results of HO₂ retrieval using 649.701 GHz line.**

4.3.4 Promising products

The unique products are the target species which are not covered by EOS MLS but covered by TALIS. There are four gases: NO, NO₂, H₂CO, and SO₂ (normal VMR). However, their signals all have weak intensity and must be averaged to improve the retrieval precision.

- 10 NO (daytime) can be retrieved from averaged data with 10–40% precision at 30–95 km (Fig. 25) **while it vanishes in the nighttime. The vertical resolution is about 6 km.** While its single scan measurement has no information in the area where NO largely exists.

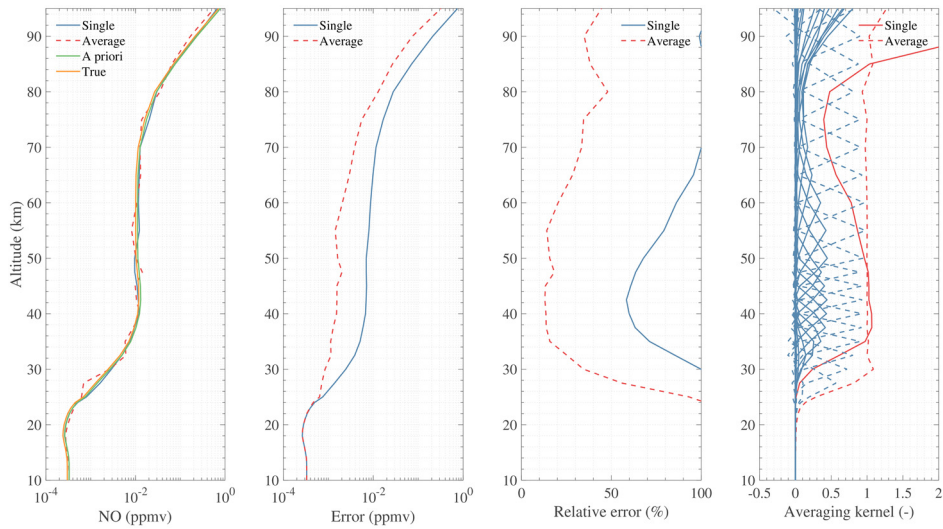


Figure 25. Simulation result of NO retrieval using 651.75 GHz line.

NO₂ (nighttime) has a weak line in the spectrum of 240 GHz band and it vanishes in the daytime. Figure 26 shows that only averaged measurement can provide some information at 25–40 km with the precision of about 50% in the nighttime.

5 The vertical resolution is about 5 km.

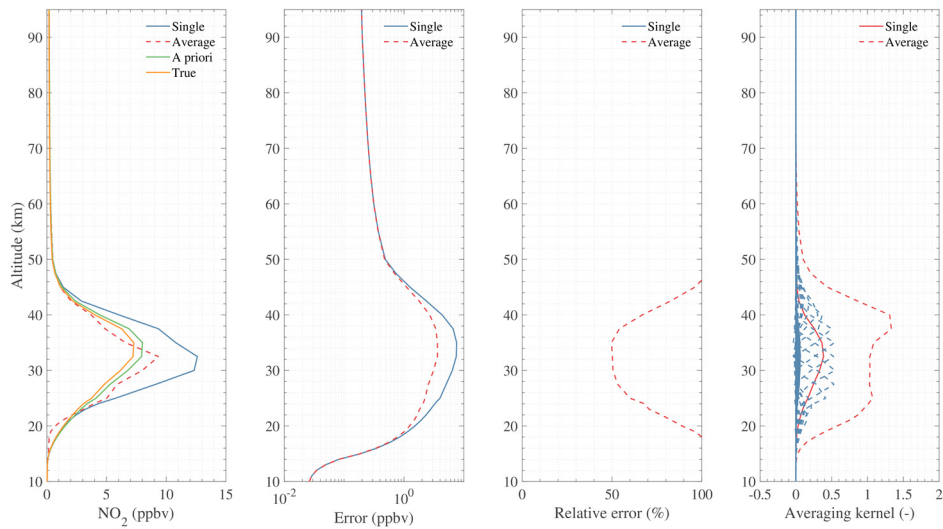


Figure 26. Simulation result of NO₂ retrieval using 232.7 GHz lines.

Although H₂CO has a line at 656.45 GHz, its emission radiance is too weak. Almost no useful information can be obtained (Fig. 27). However, this line has the potential to measure H₂CO. More average or other effective methods should be

10 applied to get acceptable precision.

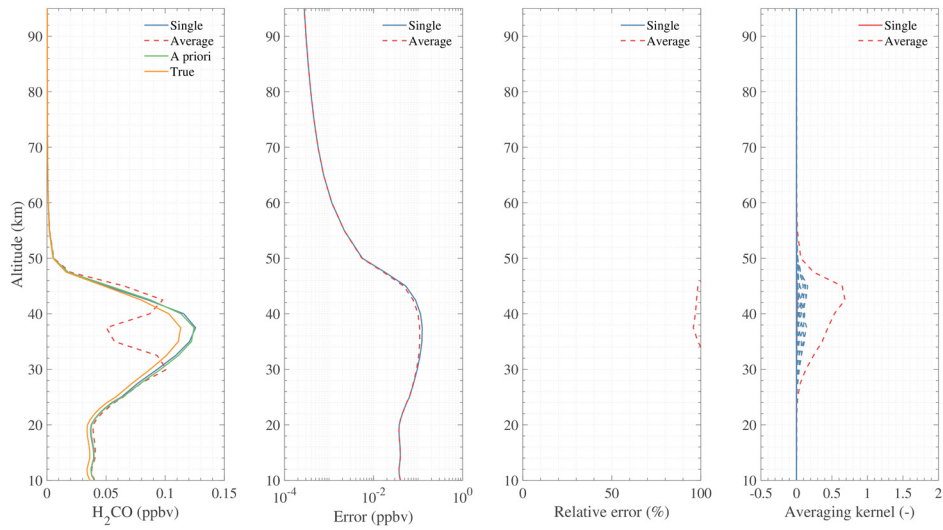


Figure 27. Simulation result of H₂CO retrieval using 656.45 GHz line.

MLS standard SO₂ product is taken from the 240 GHz retrieval, but only effective when its concentration significantly enhanced. TALIS has both 240 and 643 GHz radiometer which covering the lines of SO₂. The 240 GHz radiometer can be used to measure SO₂ like the way of MLS. The 643 GHz radiometer can give the concentration of nominal background. The averaged result shows that SO₂ can be retrieved at 40–75 km with the relative error about 20–60% (Fig. 28). **The vertical resolution is about 6 km.**

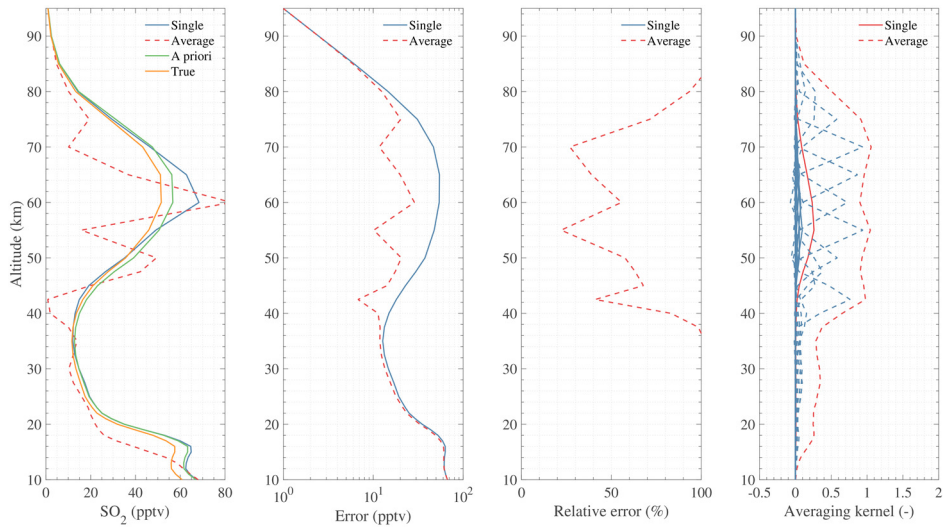


Figure 28. Simulation result of SO₂ retrieval using 659 GHz lines.

5 Conclusions

Simulation analysis for temperature and chemical species retrieval have been performed to assess the measurement performance of TALIS and to support the mission. This study mainly focuses on a large number of important chemical species in middle and upper atmosphere which can be observed by limb sounder. The results are summarized in Table 3.

- 5 The results of seven high sensitivity products are reliable. 118, 240, and 643 GHz observations of O₂ are used to estimate temperature profile which is quite important in meteorology. The 118 GHz radiometer can obtain temperature **with a precision** < 2 K at 15–80 km and the 240 and 643 GHz radiometers can provide information in the upper troposphere. The 190 GHz radiometer can be used to measure H₂O **with a precision** < 10% in a wide vertical range and give information of upper tropospheric humidity. O₃ can be measured by three radiometers, and the 240 GHz radiometer has the best precision.
- 10 **The precision is** < 5% from 25 to 60 km by single scan measurement. HNO₃ can be derived from 240 GHz retrieval with a precision < 40%. The result of HCl single scan retrieval is < 40% over most of the useful range. The 190 GHz radiometer can give a good estimate to N₂O profile **with a precision about** 20–40%, while 643 GHz measurement can provide more information at higher altitudes. Single scan precision of ClO measured by 643 GHz radiometer is about 30% in the area where ClO mainly exists. CH₃Cl can be measured in the upper troposphere and low stratosphere **with a precision about** 50%.
- 15 The profile of CO retrieved from 240 GHz measurement is better than that from 643 GHz measurement. **The best sensitivity is found between 70–90 km where the VMR of CO is large, and the precision is better than 50%**. HCN have 50% single scan precision at 18–32 km which may need to be averaged. Other measurements such as HO₂, HOCl, NO, NO₂, BrO, SO₂, and H₂CO must be significantly averaged before scientific use because of the weak signals. **As the results show that the precision of some products become much poorer suddenly at a height of 25 km, it seems that the retrieval grid resolution does not**
- 20 **match the achievable resolution.**

Apart from these products, some potential products will be discussed in the future works. Line-of-sight wind is important information which could be measured by TALIS. Cloud IceWater Content (IWC) is also an essential product provided by passive microwave radiometer. Future studies will also investigate the Zeeman effect as it polarizes and changes the shape of the O₂ lines.

- 25 TALIS has strong potential to monitor chemical composition in the whole Earth's atmosphere which is important for numerical weather prediction models and to characterize the long-time change of climate. Measurement data can be used for atmospheric chemistry and dynamics study which is quite important for the geoscience. A better understanding of the key chemical and dynamical processes in the middle and upper atmosphere will help us solve the climate problem more efficient.

- 30 This paper is the preliminary analysis of the instrument. More studies such as structure optimization, calibration research, and error analysis will be performed to support the mission.

Table 3. Simulation results of TALIS retrieval precision

Product	Radiometer	Single precision	Average precision
Temperature	118 GHz, 240 GHz	< 2K (10–75 km)	< 1K (10–85 km)

H ₂ O	190 GHz	< 10% (25–75 km)	~ 1% (25–80 km)
O ₃	240 GHz	< 5% (25–55 km)	~ 1% (25–70 km)
HCl	643 GHz	10–50% (15–70 km)	< 10% (25–75 km)
N ₂ O	190 GHz, 643 GHz	20–40% (10–40 km)	< 40% (10–50 km)
HNO ₃	240 GHz	10–50% (15–35 km)	< 50% (10–45 km)
ClO	643 GHz	30–50% (30–45 km)	< 30% (25–60 km)
CO	240 GHz	40–90% (10–70 km)	< 40% (10–95 km)
HCN	190 GHz	20–50% (18–32 km)	10–50% (15–60 km)
CH ₃ Cl	643 GHz	40–50% (15–23 km)	20–50% (12–30 km)
HOCl	643 GHz	70–90% (27–43 km)	15–50% (22–52 km)
BrO	643 GHz	/	50–80% (23–56 km)
HO ₂	643 GHz	60–80% (47–67 km)	10–50% (35–85 km)
NO	643 GHz	60–80% (33–55 km)	10–40% (30–95 km)
NO ₂	240 GHz	/	50–60% (25–40 km)
H ₂ CO	643 GHz	/	/
SO ₂	643 GHz	/	20–60% (40–75 km)

Code and data availability. ARTS can be downloaded at <http://www.radiativetransfer.org/getarts/>. Qpack is included in the Atmlab which can be downloaded from <http://www.radiativetransfer.org/tools/>. Profiles and spectroscopy data of Perrin and HITRAN are included in ARTS XML Data. JPL molecular spectroscopy catalogue is available at <https://spec.jpl.nasa.gov/>.

5 MLS version 4.2 data can be obtained at <https://doi.org/10.5067/Aura/MLS/DATA3020>.

Author contribution. Zhenzhan Wang designed the mission concept. Wenyu Wang performed the simulate and wrote the manuscript. Wenyu Wang and Yongqiang Duan analysed the results. Zhenzhan Wang edited the article.

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

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