Overview of the Martian atmospheric submillimetre sounder FIRE

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Abstract
We propose a submillimetre-wave atmospheric emission sounding instrument, called Far-InfraRed Experiment (FIRE), for the Japanese Martian exploration programme “Mars Exploration with Lander-Orbiter Synergy” (MELOS). The scientific target of FIRE/MELOS is to understand the dust suspended meteorology of the Mars. FIRE will provide key meteorological parameters, such as atmospheric temperature profiles for outside and inside dust storms, the abundance profile of the atmospheric compositions and their isotopes, and wind velocity profiles. FIRE will also provide the local time dependency of these parameters. The observational sensitivity of FIRE/MELOS is discussed in this paper.
FIRE will explore the meteorological system of the Martian atmosphere including the interaction between its surface and atmosphere.

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1. General introduction

Continuous monitoring and high spatial resolution global mapping of atmospheric physical parameters, such as temperature, chemical compositions, and wind velocity, should be conducted in order to gain an understanding of the meteorology and climate systems of planetary atmospheres. Regarding the Martian atmosphere, it will be especially important to make observations inside and outside the dust distribution and the quantitative understanding on the interacting processes between atmospheric gases, surface, and aerosols.

The Trace Gas Orbiter (TGO) (Zurek et al., 2011) of the ESA-NASA ExoMars mission is scheduled to arrive at Mars in 2016. The orbiter will attempt a thorough exploration of the planet’s atmospheric composition by using instruments with unprecedented level of sensitivity. It will also characterise spatial and temporal variations in chemical distributions. Among the proposed scientific payloads, three spectrometers (MATMOS (Wennberg et al., 2011), SOIR/NOMAD (Vandaele et al., 2011), and EMCS (Schofield et al., 2011)) have been selected as the onboard instruments. These instruments will operate at visible (VIS), near-infrared (NIR), and thermal infrared (IR) wavelengths (SOIR/NOMAD has a UV channel as well), and their scientific target is to obtain clues about the possible origins of the gas sources in the Martian atmosphere, which requires very highly sensitive observations. Compared with other wavelengths, NIR and IR observations have advantages of detecting organic-related species such as methane or more complex hydrocarbons. The solar occultation technique with UV/VIS/NIR and IR realises high sensitivity for the molecular detection. That is why this method has advantages in exploring new species in the Martian atmosphere. However, since the solar/ stellar occultation observations require a background solar or stellar emission, they are impossible to track continuous change of the atmospheric composition as a function of the local time. Furthermore, UV, VIS, and NIR observations are affected by the opaqueness of the Martian dust and ice clouds. If the dust opacity becomes very high, observations of the atmosphere deep inside the dust storms are no longer feasible. This point may not be a critical issue for the TGO’s scientific objectives, that is, detection, mapping, and
characterising of the sources of new species, but it has a significant impact on Martian meteorological studies, which require observations under varying local times and dust-opacity conditions.

Currently, a new Mars exploration programme for the 2020s, named Mars Exploration with Lander-Orbiter Synergy (MELOS), is being discussed in Japan (Satoh and MELOS Working Group, 2009). One of the orbiters of MELOS is proposed to explore the Martian meteorology and climate system; more specifically, the dust meteorology, water cycle, atmospheric circulation, atmospheric chemistry, and mechanisms of dust storm development. To fulfill a successful post-TGO mission, we believe the key mission requirement is further understanding of the driving physical, chemical (including heterogeneous reactions), and radiative processes of the dust suspended in the Martian atmosphere by conducting observations independent of the local time and dust opacity. From this point of view, we propose a submillimetre-wave atmospheric emission sounding instrument with a passive heterodyne spectrometer called Far-InfraRed Experiment (FIRE) for MELOS.

Submillimetre-wave heterodyne spectroscopy is a powerful technique for observing spatial and temporal variations in the Martian atmosphere. It can be used to measure the atmospheric temperature, chemical compositions, and wind velocity from the surface to the upper atmosphere as well as sub-surface temperature. Millimetre/submillimetre observations are independent of the distributions of dusts, ice clouds, and aerosols because of their relatively smaller particle size (in the order of microns) than the observation wavelengths. Because this passive technique measures atmospheric thermal emission, millimetre/submillimetre observations allow contiguous observation at any local time. A number of rotational and vibrational transitions of atmospheric molecules in this wavelength domain enable us to simultaneously observe many species including isotopes. The pressure-broadened line shapes of those molecular transitions can be precisely measured with high frequency resolution of the microwave spectroscopy and related chemistry in the Solar System” (Hartogh et al., 2009).

The limited aperture sizes of these space-borne telescopes have a weak point in terms of spatial resolution, and they can observe only the disk-averaged spectra of Mars. The past and ongoing orbiter measurements remind us of the importance of high spatial resolution observations for distinguishing various spatial localities in the Martian atmosphere. From this point of view, we need to develop a submillimetre instrument onboard a satellite in a near-Mars orbit. An orbiter-onboard instrument has advantages not only in spatial resolution but also in the ability of pointing the full area of the instrument’s field-of-view toward the limb of the Martian disk. This limb-sounding geometry gives a much larger air mass (larger line-of-sight inside the Martian atmosphere) compared to nadir observation geometry, which observes vertically down along a rather thin (~100 km depth) Mars atmosphere. Hence, with limb sounding, we can drastically improve sensitivity to small-concentrated trace gases. This fact is clearly exhibited by comparing the upper and lower panels of Figs. 1 and 2, which show the spectral atlas of the Martian submillimetre emission. With limb sounding, the spectral signals coming from very small-concentration species (mixing ratios in the order of 10^{-7}) such as H_2O, HO_2, and O_3 are expected to be detected with a brightness temperature of ~ 10 K. Furthermore, by scanning several tangential heights on the limb, the vertical distribution of the atmospheric state can be retrieved with much better precision and resolution than nadir observations.

The idea of millimetre/submillimetre observations from near-Mars orbit has been investigated for almost every time there was a Martian orbiter mission since the late 1980s (Muhleman et al., 1985). For example, Muhleman and Clancy (1995) investigated the feasibility of millimetre (100–260 GHz in frequency) limb
emission observation to detect H\textsubscript{2}O and other key species. Later, a submillimetre limb sounder operating at the 500-GHz-band, named MIME, was proposed for the Mars Express mission (Hartogh, 1998). Successively, a 350-GHz-band instrument MAMBO has been proposed for the French CNES Mars Premier programme (Forget et al., 2002). Urban et al. (2005) further investigated the expected measurement capability of the MAMBO instrument. There was also another proposal called MARVEL for the NASA Mars Scout program and SWI for the ESA ExoMars mission. Recently, a 500-GHz-band instrument SOAR has been proposed to ExoMars TGO. The uniqueness of the SOAR was the capability to observe trace gases at the parts per trillion-volume mixing ratio level such as NH\textsubscript{3}, SO\textsubscript{2}, H\textsubscript{2}S, H\textsubscript{2}CO, and NO\textsubscript{2} by employing a tunable local oscillator. Although none of these proposals have become a reality due to various reasons, such as the weight and size of allowed payloads, the demand of a submillimetre instrument onboard an orbiter has never disappeared. In fact, the technical feasibility for space use has been demonstrated by MIRO, which was developed for the Rosetta mission (Gulkis et al., 2007).

3. Scientific targets of the submillimetre sounder, FIRE

There have been many orbiter and lander explorations of the Martian atmosphere with IR and UV/VIS instruments. Our instrument, FIRE, primarily focuses on enabling us to understand meteorological processes on Mars based on the rich knowledge of the temporal and spatial variations in the atmospheric state including those acquired from previous explorations rather than searching for any new atmospheric constituents. In this section we describe some topical scientific targets of FIRE.

3.1. Three-dimensional mapping of water vapour

We already have plenty of data for daytime column density of water vapour, including horizontal distributions and seasonal changes through several Martian years, observed using the Thermal Emission Spectrometer onboard the Mars Global Surveyor (MGS-TES) (Smith, 2004), Planetary Fourier Spectrometer onboard Mars Express (MEx-PFS) (Fouchet et al., 2007), Spectroscopy for Investigation of Characteristics of the Atmosphere onboard Mars Express (MEx-SPICAM) (Trokhimovsky et al., 2008), and Compact Reconnaissance Imaging Spectrometer for Mars onboard the Mars Reconnaissance Orbiter (MRO-CRISM) (Smith et al., 2009). Most of these data sets are vertically integrated column abundances of water vapour derived from nadir-geometry IR observations. Moreover, information on variances with local time has been less investigated because of the limitation of the orbit of past satellites.

The vertical distributions of water vapour have been observed from ground-based radio telescopes (Encrenaz et al., 1991, 1995; Clancy et al., 1996) and space-borne telescopes such as the Submillimeter Wave Astronomy Satellite (SWAS) (Gurvew et al., 2000), Odin satellite (Biver et al., 2005), and Photodetector Array Camera and Spectrometer (PACS) onboard the Herschel Space Observatory (Portyankina et al., 2010). These ground-based and space-borne telescopes can detect only disk-averaged distributions. By means of solar occultation, MEx-SPICAM has measured vertical profiles of water vapour but with limitations in regards to
the local time coverage (Fedorova et al., 2009). In fact, nighttime distributions and diurnal variations of water vapour have never been observed.

The change in vertical distributions of water vapour is a major key for investigating water transport on Mars. If the hygropause (cut-off height of water vapour) is high enough, water can be transported from summer to winter hemispheres with meridional circulation. Clancy et al. (1996) showed the seasonal change in hygropause on low- and mid-lattitudes. They showed that the hygropause can seasonally vary in the altitude range below 10 km (around aphelion, northern summer) to higher than 25 km (around perihelion, northern winter). Moreover, the limb-haze observations of water ice by the Viking Orbiter showed that the hygropause reaches above \( \sim 50 \) km during a global dust storm (Jaquin et al., 1986). A study using a Mars General Circulation Model (MGCM) with a simple water cycle scheme reproduced such a change in hygropause with season and dust loading (Kuroda et al., 2008a).

With FIRE, we plan to observe a detailed three-dimensional distribution of water vapour on Mars, including time variation through day and night, from a Mars orbiter. By combining simultaneous observations of atmospheric temperature, wind velocity, and the abundance of other minor species, the dynamical and chemical processes of the water vapour transport will be revealed.

3.2. Measurement of the [HDO]/[H\(_2\)O] ratio

Mars is currently a dry planet, but cameras onboard the Mars orbiters and landers have revealed topographic evidence of past liquid water flow (Seibert and Kargel, 2001; Okubo and McEwen, 2007; McEwen et al., 2007; Squire et al., 2009). Where has the surface liquid water gone?—some of the water is thought to have escaped into space. Even at present, there are thin water-ice clouds and water vapour in the Martian atmosphere, and they can yield important clues to the nature of this water escape by measuring the abundance of isotopes such as water vapour deuterium isotope (HDO). Since the vapour pressure of HDO is lower than that of H\(_2\)O, HDO becomes fractionated at condensation—therefore, it concentrates in the water-ice clouds. The water in the ancient ice sheets should have a lower ratio of HDO against H\(_2\)O abundances (hereafter [HDO]/[H\(_2\)O] ratio) than in the water-ice clouds (Fishier et al., 2008). By investigating the spatial and temporal changes in the [HDO]/[H\(_2\)O] ratio of water vapour and ice, we will be able to understand the nature of the present water cycle, which can also be related to the escape of water.

Up to now, observations of the [HDO]/[H\(_2\)O] ratio have been done with ground-based telescopes. The averaged [HDO]/[H\(_2\)O] ratio is 5–6 times larger than in the terrestrial Standard Mean Ocean Water (SMOW, corresponding to \( 3.1152 \times 10^{-4} \) (Owen et al., 1988; Krasnopolsky et al., 1997). It has also been reported that there are large spatial variances in the [HDO]/[H\(_2\)O] ratio, from 2 to 8 times of SMOW (Villanueva et al., 2008). However, this observational data shows only daytime column density, and the vertical and nighttime distributions of the [HDO]/[H\(_2\)O] ratio have been never observed. Observations of the vertical distributions are planned using the Heterodyne Instrument for the Far Infrared (HIFI) onboard the Herschel Space Observatory (Hartogh et al., 2009), but the horizontal resolution will be low.

Montmessin et al. (2005) first simulated the HDO cycle on Mars using an MGC model developed at Laboratoire de Meteorologie Dynamique (LMD) in France. They found that the seasonal change in the [HDO]/[H\(_2\)O] ratio was very small (on the order of 2%) in low latitudes and the value became lower in polar regions during autumn and winter when the water vapour pressure becomes very low. The simulated latitudinal distributions of the ratio in northern spring was in good agreement with a recent ground-based observation by Novak et al. (2011). However, these numerical experiments are opposite to the observations of Mumma et al. (2003), which show clear tendencies with a higher [HDO]/[H\(_2\)O] ratio when the air is dry (Fisher et al., 2008). The simulated [HDO]/[H\(_2\)O] ratio can increase if the atmosphere becomes drier, but only when the water vapour column is less than 0.2 in precipitable microns.

With FIRE, we plan to observe detailed three-dimensional distributions of the D/H ratio for both daytime and nighttime. This is expected to reveal the mechanism of climate change and atmospheric escape, as well as the mysteries of large spatial variances of the humidity in the atmosphere from current observations and simulations.

3.3. Detection of hydrogen radicals and H\(_2\)O\(_2\): stability of CO\(_2\) atmosphere and important oxidants of a biomaker

Carbon dioxide in the Martian atmosphere splits into CO and O by UV photodissociation, but the recombination reaction is spin forbidden. Thus, it is estimated that all CO\(_2\) will be converted into CO and O in about 6000 years. However, the present Martian atmosphere consists of about 95% CO\(_2\) and only about 500 to 1000 ppmv of CO (Smith et al., 2009; Swinyard et al., 2010; Hartogh et al., 2010b). How is this CO\(_2\)-rich atmosphere maintained? It is hypothesised that the hydrogen radicals (H, OH, and HO\(_2\)) work as catalysts to recover CO\(_2\) (McElroy and Donahue, 1972; Parkinson and Hunten, 1973).

The hydrogen peroxide ([H\(_2\)O\(_2\)]) on Mars is thought to be an important oxidant of methane, a possible biomarker, able to shorten the lifetime of CH\(_4\) created by photochemical reactions from two HO\(_2\) radicals (Atreya et al., 2006), and the electrical effects in dust devils (Delory et al., 2006). Hydrogen peroxide has been observed using ground-based and space-borne telescopes with a global-mean mixing ratio of up to \( \sim 40 \) ppbv (Encernaz et al., 2002, 2004, 2008; Clancy et al., 2004; Hartogh et al., 2010b). Spatial distributions of H\(_2\)O\(_2\) have never been observed, though detection from the MEx-PFS spectrum data is ongoing (Aoki et al., 2009).

We also plan to directly observe the spatial and time distributions of H\(_2\)O\(_2\) and HO\(_2\) using FIRE. These observations are essential to confirm the quantitative contributions of related chemical reactions, in combination with the methane observations with IR instruments, and we hope to gain insights into the CO\(_2\) recovery processes and the oxidation processes of methane.

3.4. Direct measurements of wind velocity

Submillimetre observations can directly measure the wind velocity of the Martian middle atmosphere from Doppler shifts detected on the absorption/emission spectra of atmospheric molecules. There are several examples of observations of Doppler wind velocities from ground-based submillimetre telescopes (Lellouch et al., 1991b; Clancy et al., 2006; Cavalié et al., 2008; Moreno et al., 2009) for altitudes of 40–70 km. However, the resolution of those observations is sparse, with horizontal resolution of \( > 300 \) km and vertical resolution of \( \sim 20 \) km. Moreover, large differences can be seen between the observations of Doppler wind velocity and the numerical results from current MGC models. Observations done by Moreno et al. (2009) indicate the existence of day-to-night circulation in the summer southern hemisphere, which is not reproduced using the LMD MGC. In addition, the observed easterly (retrograde) wind velocity tends to be much faster than the MGC simulations, especially in northern summer (Kuroda and Hartogh, 2007, 2010; Moreno et al., 2009).

A planet-encircling dust storm changes the wind field to a large extent. A simulative study conducted by Kuroda et al. (2009) showed that the meridional wind toward the winter pole at a height of \( 40–60 \) km strongly accelerated from \( \sim 10 \) m s\(^{-1}\) to a maximum of \( \sim 60 \) m s\(^{-1}\) due to a solstitial global dust storm. Observations done by Moreno et al. (2009) showed a large zonal...
anomaly of zonal wind and strong southward wind in the southern hemisphere during a global dust storm in 2001, which are consistent with the corresponding MGCM simulations (Moreno et al., 2009; Kuroda and Hartogh, 2010).

We plan to make the first mapping of wind velocity by limb scanning from Mars orbit, and will investigate the mechanisms of wind accelerations for various seasons and dust loadings. The direct measurements of wind velocity are also expected to allow the first detection of equatorial atmosphere oscillations, such as semiannual oscillations indicated by Kuroda et al. (2008b), to compare the dynamical characteristics of the Martian atmosphere with those of other planets.

3.5. Dynamics and chemistry of the middle atmosphere

At present, there are much less observational data of the middle atmosphere (60–140 km altitude) compared to the lower (0–60 km altitude) and upper (100–180 km altitude) atmospheres. Recently, the Mars Climate Sounder onboard the Mars Reconnaissance Orbiter (MRO-MCS) first observed three-dimensional temperature fields between 60 and 80 km in altitude, and found that the middle atmospheric temperatures above the winter pole were at maximum ~60 K higher than those of the lower part of the polar atmosphere (McCleese et al., 2008).

Observational data of the dynamics in the middle atmosphere above 80 km in altitude is still very limited, but the importance of this altitude region that connects the measurements of the lower and upper atmospheres has been indicated in several studies. Heavens et al. (2010) and Medvedev et al. (2011a,b) indicated the effects of gravity waves on temperature and wind fields at altitudes higher than ~60 km. In addition, Seth and Brahmananda Rao (2008) pointed out the effects of planetary waves associated with the Martian topography and baroclinic instability on the ionisation rate distributions of the upper atmosphere.

Moreover, current MGCM simulations that connect the lower and upper atmospheres (González-Galindo et al., 2009; McDunn et al., 2010) overestimate the temperature of the nighttime mesopause (80–100 km altitude) by 10–30 K compared to the observational data from MEx-SPICAM (Forget et al., 2009). Forget et al. (2009) discussed that this was probably because of an underestimation of the atomic oxygen concentration that controls the CO2 IR cooling, but more observational data of atmospheric compositions around mesopause are needed to prove this hypothesis.

With FIRE, we also plan to perform the first mappings of temperature fields, wind fields, and composition in the middle atmosphere allowing investigations of dynamics and chemistry in this yet unexplored altitude region. This attempt will provide us with the initial understanding of atmospheric processes connected from the surface to the ionosphere.

4. Instrumental overview

Although the detailed mission design of the MELOS orbiter has not been decided yet, the instrumental requirement for FIRE has been discussed. In this section we describe the current concept of our proposed instrument/FIRE.

4.1. Frequency selection

We have chosen the frequency region of 500–650 GHz for the observation frequency of FIRE after comparing the advantages and disadvantages of each frequency region over 300–800 GHz.

- 500–650 GHz is the optimum frequency region to simultaneously observe water vapour, winds, trace gases, and radical species with the altitude coverage from the surface to >120 km. Potential target species, such as HCl, have their transitions at only this domain. We also have experience heritage with Odin/SMR and SMILES.
- The 800-GHz region has an advantage of a better spatial resolution than other lower frequencies, but the receiver noise temperature is expected to be about 6000 K. This is 3–6 times higher than other frequency regions.
- The 350-GHz region has a better receiver noise temperature. However, observations are limited in quality with respect to the following points: the line intensities of H2O and CO in this domain are relatively weak compared to the other regions, which results in limited measurement sensitivity for water vapour, temperature, and winds. Furthermore, the spatial resolution will degrade.

Below, we describe the line selection for water vapour, which achieves sensitivity at a wide altitude range from the surface to the upper atmosphere. The essential point is to simultaneously measure two H2O transitions with different line intensities: a very strong line and a moderate one. The strong line provides good sensitivity to the low H2O number density at higher altitudes and in the winter polar region where the atmosphere becomes very dry, while the moderate line allows us to measure H2O in the lower atmosphere with no spectrum line saturation.

As shown in Fig. 1, the H2O (10–101) transition at 556.9 GHz is the strongest line in the frequency region below 1 THz; therefore, it can be most effectively used to observe the upper atmosphere where the atmospheric density and H2O concentration are small. With decreasing altitude, the atmospheric pressure increases exponentially, and we have to consider a large dynamic range in the H2O specific density if we want to obtain the full view of its vertical distribution. It is well known that the water vapour amount in the Martian lower atmosphere has a significant seasonal and spatial variation from very dry (in the order of 1 ppmv) to wet (more than 100 ppmv) conditions. Indeed, the H2O 556.9-GHz line is saturated in the latter case and will no longer be usable to probe the water vapour amount. To solve this problem, we plan to observe an additional H2O line at 620.7 GHz (the 527–441 transition) with line intensity two orders of magnitude smaller than that of the 556.9-GHz line. Table 1 shows a list of the planned target frequencies of FIRE, and their intermediate frequencies (IFs) for down conversion. There is also the possibility to observe HCl and H2O if we adopt a tunable local oscillator (LO).

4.2. Instrumental requirement

The FIRE instrument is composed of an offset cassegrain antenna for the submillimetre-wave region, Schottky receivers, IF amplifiers, and backend spectrometers. The exact orbit of the MELOS orbiter is still under discussion, but one of the possible

<table>
<thead>
<tr>
<th>Band</th>
<th>Species</th>
<th>Centre freq. (GHz)</th>
<th>1st IF (GHz)</th>
<th>2nd IF (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO freq. (GHz)</td>
<td>First 563.2</td>
<td>Second 6.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>H2O</td>
<td>556.936</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>13CO</td>
<td>550.927</td>
<td>12.3</td>
<td>5.6</td>
</tr>
<tr>
<td>c</td>
<td>12CO</td>
<td>576.268</td>
<td>13.0</td>
<td>6.3</td>
</tr>
<tr>
<td>d</td>
<td>O3</td>
<td>570.999</td>
<td>7.8</td>
<td>1.1</td>
</tr>
<tr>
<td>LO freq. (GHz)</td>
<td>First 606.0</td>
<td>Second 8.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>H2O</td>
<td>620.701</td>
<td>14.7</td>
<td>6.1</td>
</tr>
<tr>
<td>f</td>
<td>HD &amp;</td>
<td>599.926</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>H2O2</td>
<td>591.434</td>
<td>14.6</td>
<td>6.0</td>
</tr>
</tbody>
</table>
orbits being discussed is a highly elliptical one with a periapsis of ~ 450 km (or even much closer to Mars) and an apoapsis of several Martian radii. Fig. 3 shows an schematic image of limb and nadir observations of FIRE on such a highly elliptical orbit. The FIRE instrument will observe the submillimetre-wave emission from the limb of the Martian atmosphere when the MELOS orbiter is around the periapsis of its orbit. The limb scanning observation will be used so that the emission from several tangential altitudes can be measured. For the rest of the orbit, FIRE is planned to observe in the down looking geometry to perform a horizontal mapping over the Martian disk.

The diameter size of the FIRE antenna is determined according to the vertical resolution requirement in the limb observations. We set the vertical resolution requirement, for the middle atmospheric observations, better than 3 km, which corresponds to about one-fourth of the Martian atmospheric scale height. Assuming a periapsis height of 450 km, an antenna diameter larger than 40 cm is required to achieve such a vertical resolution with the 500–600-GHz observation frequency. The mass requirement of the antenna, i.e., as light as possible, is also a critical point in instrumental development. The antenna, manufactured from a material of carbon fiber reinforced plastics (CFRP), will be about 0.7 kg for the adopted antenna diameter of 40 cm.

Quasi-optics components including an ortho-mode transducer (OMT) system combines the submillimetre signals from the antenna, local oscillator, and calibration system, which uses the 2.7-K cosmic microwave background. The submillimetre LO signal will be generated using a frequency multiplier. A Schottky barrier mixer diode operating at ambient temperature will be adopted as the basic concept of our instrument/FIRE, instead of selecting actively cooled higher sensitivity mixers, because of the stringent resource restriction on the mass and power of an orbiter. The receiver noise will be about 2000 K at 500–650 GHz as a conservative estimate. High-electron-mobility transistor (HEMT) receivers are also a candidate for a part of the receiver system.

There are several types of spectrometers, such as Chip transform spectrometers (CTSs) (e.g., Hartogh and Hartmann, 1990; Villanueva and Hartogh, 2004), acousto-optical spectrometers (AOSs) (e.g., Mazuray et al., 2001; Siebertz et al., 2007), and digital autocorrelator spectrometers (ACSs) (e.g., Belgacem et al., 2004). The performance of these spectrometers have been successfully demonstrated onboard recent space-borne submillimetre instruments. A CTS has been used on the Rosetta/MIRO instrument, AOS on Odin/SMR, JEM/SMILES and Herschel/HIFI, and ACS on Herschel/HIFI. In addition, for a 2020s mission there is also a potential for further development of a new technology such as digital polyphase filter bank spectrometers (Jarnot et al., 2010). Each type of spectrometer has its own strengths and weaknesses. The basic requirements for our Martian submillimetre sounder are (1) a high frequency resolution (~100 kHz) for measuring winds from Doppler shifts, (2) clean and stable baseline characteristics by suppressing the ripples and standing waves for measuring the accurate line shape, (3) a wide bandwidth, and (4) low mass, volume, and power consumption. From this point of view, current candidates for FIRE will be a combination of a wide bandwidth ACS and a very high frequency resolution CTS- or PFB-like spectrometer.

<table>
<thead>
<tr>
<th>Measurement requirement</th>
<th>Limb scan and nadir mapping observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Global, including high latitude regions</td>
</tr>
<tr>
<td>Altitude coverage</td>
<td>(−140 km), depending on the observation species</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>~ 30 km (Nadir)</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>~ 3 km (Limb), ~ 8 km (Nadir)</td>
</tr>
<tr>
<td>Time resolution</td>
<td>One disk map per every 4 h</td>
</tr>
<tr>
<td>Mission lifetime</td>
<td>More than 1 Martian year</td>
</tr>
<tr>
<td>Orbit</td>
<td>(1) Non-sun synchronised, (2) inclined, and (3) including both high and low altitudes orbit</td>
</tr>
<tr>
<td>Mass and Power (target)</td>
<td>Limited science: 5 kg, 10 W</td>
</tr>
<tr>
<td></td>
<td>Full science: 16 kg, 40 W</td>
</tr>
</tbody>
</table>

Table 2: A summary of the mission requirement of the submillimetre sounder FIRE.

5. Setup for the sensitivity study

5.1. Forward and inversion modelling

The measurement sensitivity of FIRE is investigated by simulating the retrieval of interested physical parameters, such as a vertical profile of water vapour, from synthetised measurement spectra. The measurement spectra are synthesized using the a priori atmospheric state, and the inversion of the measurement is performed based on the optimal estimation method (OEM, Rodgers, 1976, 1990). This inversion methodology has been widely applied to the remote sensing of planetary atmosphere (e.g., Kikuchi et al., 2010). We use the AMATERASU (Advanced Model for Atmospheric Terahertz Radiation Analysis and Simulation, Baron et al., 2008) for both forward and inversion model. Line-by-line radiative transfer calculations are adopted in the AMATERASU forward model. Temperature, pressure, H$_2$O, and CO profiles are based on the European Mars Climate Database.
(EMCD) v4.1 (Forget et al., 1999; Lewis et al., 1999). We use three atmospheric scenarios: warm, cold, and extremely dry cases, as shown in Fig. 4. The former two cases are used for all the calculations in this study, and the extremely dry case is additionally tested when the feasibility of H₂O observation is examined. Carbon dioxide molecular concentration is set to 0.9532 at all altitudes. Other minor molecules are assumed to have vertically uniform profiles with mixing ratios set considering the recent observational results (Table 3). The 5 ppb of O₃ corresponds to the column ozone abundances of 14 and 23 μm-atm under the adopted cold and warm atmospheric scenarios, respectively, which fits with the range of the MEZ-SPICAM measurements (Perrier et al., 2006). The isotropic ratios are assumed to be the same as the terrestrial values except for HDO. Based on ground-based measurements conducted by Owen et al. (1988) and Krasnopolsky et al. (1997), we use [HDO]/[H₂O] of 1.558 × 10⁻³, which corresponds to a value five times the terrestrial standard mean ocean water, SMOW.

Two line shape functions are used depending on the pressure: the Voigt line shape is used where the pressure broadening line width is less than 40 times the Doppler line width. At higher pressures, the Van Vleck–Weisskopf line shape is adopted. For simplicity, we do not consider atmospheric refraction. Spectroscopic parameters in our forward model are based on the HITRAN 2008 compilation (Rothman et al., 2009) but with modification on the air-pressure-broadening coefficient to account for the Martian CO₂ atmosphere. The pressure broadening coefficients for specific H₂O lines are derived from laboratory measurements (Sagawa et al., 2009). For other lines, we scale the HITRAN air-pressure-broadening coefficients (i.e., those appropriate to the terrestrial N₂ and O₂ atmospheres) by a factor of 1.7. This scaling factor is derived by averaging the ratios of the broadening coefficients in air and CO₂ of the transitions measured by Sagawa et al. (2009). The temperature dependencies of the broadening coefficients are kept as they are in the HITRAN database, since there is almost no literature on this for CO₂ broadening. It should be noted that the knowledge on the spectroscopic parameters, in particular the broadening coefficients, for the CO₂ atmosphere is important in the radiative transfer of the Martian and Venusian atmosphere, as discussed in relevant studies (Sagawa et al., 2009; Fedorova et al., 2010). Further laboratory measurements and theoretical predictions of the spectroscopic parameters are required to perform more dedicated sensitivity studies or to analyze real data obtained from the Martian atmosphere.

We investigate the sensitivity of the submillimetre observations in both the limb and nadir observation geometries. Limb observation is assumed to be carried out with an orbit altitude of 450 km above the surface, which may correspond to the centrec

![Fig. 4. Atmospheric scenarios adopted in this study. (Left) Temperature profiles for warm, cold and extremely dry cases. The dot symbols are marked every 10 km in altitude. (Centre, Right) Volume mixing ratio profiles of H₂O and CO, respectively. For other minor species, see Table 3.](image)

### Table 3

Minor molecules considered in the radiative transfer calculations. The volume mixing ratios of H₂O and CO are those for the lower atmosphere (see Fig. 4 for their vertical distributions). For other species, vertically constant profiles are assumed.

<table>
<thead>
<tr>
<th>Species</th>
<th>Mixing ratio</th>
<th>A priori error (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>~ 300 ppmv (warm)</td>
<td>100</td>
<td>EMCD v4.1 Forget et al. (1999), Lewis et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>~ 4 ppmv (cold)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>~ 0.2 ppmv (ext. dry)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HDO</td>
<td>1.558 × 10⁻³ × [H₂O]</td>
<td>200</td>
<td>Ground-based Owen et al. (1988), Krasnopolsky et al. (1997)</td>
</tr>
<tr>
<td>CO</td>
<td>~ 700 ppmv (warm)</td>
<td>20</td>
<td>EMCD v4.1 Forget et al. (1999), Lewis et al. (1999)</td>
</tr>
<tr>
<td></td>
<td>~ 1000 ppmv (cold)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>~ 1000 ppmv (ext. dry)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>1400 ppmv</td>
<td></td>
<td>Herschel/HIFI observation Hartogh et al. (2010b)</td>
</tr>
<tr>
<td>O₃</td>
<td>5 ppbv</td>
<td></td>
<td>MEZ-SPICAM Perrier et al. (2006)</td>
</tr>
<tr>
<td>H₂O₂</td>
<td>2 ppbv</td>
<td></td>
<td>Herschel/HIFI observation Hartogh et al. (2010b)</td>
</tr>
<tr>
<td>HO₂</td>
<td>1 ppbv</td>
<td></td>
<td>MAOAM-chemical transport model Sonnemann et al. (2010)</td>
</tr>
</tbody>
</table>
of an elliptic orbit. The full width at half maximum of a 40-cm diameter antenna beam becomes roughly 3 km at 556 GHz at the tangent point. In the limb measurements, we assume a vertical scan at tangential heights ranging from 0 to 130 km by acquiring a spectrum every 3 km. Nominal data integration time for each tangential height of limb observations is set as 0.5 s. For the nadir observation geometry, we assume the orbit at a rather far distance from Mars, 6 Martian radii (approximately 2 × 10^6 km). Under such a nadir observation condition, a 40-cm diameter antenna yields a footprint of 30 km at 556 GHz. In practise, the effective horizontal spatial resolution is defined by the antenna scanning speed to map the Martian disk and the data integration (averaging) time on one spatial point. As a nominal configuration, we assume a data averaging time of 2 s for the nadir mapping geometry. For the bandwidth and resolution of the spectrometer, we assume a hybrid of the ACS and either CTS or PFB types as discussed in the previous section. It has a total bandwidth of 4 GHz and a non-uniform spectral resolution: resolution of 100 kHz at the central ± 100-MHz region, and then increases up to 50-MHz resolution at the end of the bandwidth (Table 4).

The precision on the retrieved parameters is theoretically provided as an advantage of optimal estimation method (OEM). We discuss measurement sensitivity through evaluating the following factors: (1) the response of the measurement to the true atmospheric state, (2) the vertical resolution of the measurement, and (3) the expected precision of the retrieved state. These factors are examined by calculating averaging kernels and retrieval errors propagated from the a priori error and the measurement error. An averaging kernel matrix describes the response of the retrieved profile to a perturbation in the true atmospheric state. The sum of the averaging kernel for a certain retrieved state, i.e., a retrieved parameter at a certain altitude, provides the measurement response regarding to that retrieved state. We define the validity of measurement sensitivity for the altitudes where the measurement responses are in the range of 0.8–1.2. Moreover, the vertical spread of the averaging kernel gives an estimate of the vertical resolution of the measurements.

In the OEM analysis, the 1-σ errors on the retrieved profile are theoretically derived from the statistical noises on the measurements, the error on the a priori state, and the covariances of those noises and a priori values. We adopt the following a priori errors: 100% of the a priori state for H_2O, 20% for CO, 200% for HDO, 20 K for the temperature, and 100 m s^{-1} for the line-of-sight (LOS) wind velocity.

As Rodgers (1990) discussed, the overall retrieval error derived in the OEM analysis is conventionally divided into three parts: (1) the error due to the statistical measurement noises, (2) the error coming from the finite spatial resolution of the remote sensing system and also from the adopted a priori information, and (3) the error due to the uncertainties in the forward model such as the correctness of the physics implemented in the model and parameters used within. We focus on the first two error sources (hereafter called (1) measurement error and (2) null space error) because they are strongly related to the instrumentation and observation strategy. Where the measurements have no sensitivity to the retrieval parameters, the retrieval error becomes identical to the a priori errors. The uncertainty in the spectroscopic parameters mentioned in the previous paragraph is involved in the third error component, the model parameter error, and the evaluation of its impact on the measurement sensitivity is for future work.

For the limb scan simulations, the averaging kernels and retrieval errors were calculated in the vertical grid from 0 to 48 km with 3 km intervals, 48 to 68 km with 4 km intervals, and 74 to 130 km with 6 km intervals. This increase in interval at the higher altitude is set to reduce the computational time spent for the altitudes where the measurement sensitivity becomes less. In nadir observation, the vertical grid from 0 to 90 km with 6, 8 or 10 km intervals was used: 6 km was selected for the H_2O retrieval, 10 km for HDO, and 8 km for the rest. These choices were determined on the basis of the typical vertical resolution of FIRE for each species. Any other specific configurations for each case of the presented retrieval simulations, if they exist, were described in their relevant subsections afterwards.

5.2. Effect of dust

We investigated the effect of dust in the submillimetre domain by applying the AMATERASU radiative transfer model with scattering modules inherited from the SARTre model (Mendrok et al., 2008; Mendrok, 2006). The actual physical properties of Martian dust may vary widely and are not fully constrained by the current observational knowledge. We prepared dust data on the basis of information gathered from relevant previous work described below. Optical properties of the dust have been calculated using the Mie theory assuming spherical particles. Beside particle size, the refractive index of the material determines the particle optical properties. However, no refractive index data of Martian dust had been available for the submillimetre-wave region. Hence, we roughly estimated the complex refractive index from data obtained by Wolff and Clancy (2003) by carrying the furthest IR values of their paper (at 135 μm) as constants to the submillimetre region resulting in values of n = 2.7 – 0.6i. Particles with an effective mean radius of r_eff = 1.6 μm and variance of σ_{r_eff} = 0.2 μm have been considered (Tomasko et al., 1999). With the particles being very small in relation to the wavelength (size parameter in the order of 10^{-3}), Martian dust exhibits low scattering in the submillimetre region; hence, it practically acts as a purely absorbing/emitting substance. Dust density is described by an exponential function decreasing with a scale height of 8 km between the surface and 25 km in altitude and the dust-free conditions mentioned above. The dust specific density at the surface has been assumed as 1 × 10^{-4} cm^{-3}, corresponding to about 2.5 particles cm^{-3}. The chosen profile agrees fairly well with the dust model by Conrath (1975) and Wolff et al. (2006) for a parameterisation value of ν ~ 0.3. Furthermore, this results in a mid-IR (wavenumber of 1075 cm^{-1}) total column dust opacity of about 0.5. Both the profile parameterisation value and IR opacity are comparable to the cases classified as high dust activity in the study by Wolff et al. (2006).

Fig. 5 shows the dust induced brightness temperature (BT) change in the submillimetre region for nadir and limb observations (tangential height of 20 km). No instrumental modelling is considered here. The plotted values are calculated by subtracting the synthetic brightness temperature spectrum of a dust-free case from one simulated assuming the previously described dust conditions (i.e., ΔBT = BT_{dust} − BT_{clear}). For the nadir observation geometry, the effect of the dust is negligible (in the order of nK in brightness temperature). For the limb observation geometry,

<table>
<thead>
<tr>
<th>Frequency range (MHz)</th>
<th>Resolution (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>50 &lt;</td>
<td>ν−ν_0</td>
</tr>
<tr>
<td>200 &lt;</td>
<td>ν−ν_0</td>
</tr>
<tr>
<td>600 &lt;</td>
<td>ν−ν_0</td>
</tr>
<tr>
<td>1000 &lt;</td>
<td>ν−ν_0</td>
</tr>
</tbody>
</table>
a cold space background is observed through an optically thin atmosphere. In the window regions of the spectrum, where gas absorption is extremely low, dust becomes a significant contributor to total atmospheric opacity. This results in a recognizable increase in the BT baseline in the spectral windows as about the order of the dust-free signal itself. However, the stronger gas absorption lines are not affected and the observation remains in an optically thin regime in the window regions, i.e., the measurement is still sensitive to in-dust-layer atmospheric conditions. Furthermore, since the dust practically acts as a broadband absorber/emitter in the submillimetre region, dust opacity can be handled as an additional continuum contribution to the molecular absorption and likewise be estimated in the retrieval process. These results confirm the fact that submillimetre observations of the gas composition of the Martian atmosphere are feasibly independent of the dust opacity even if a dust storm occurs. That is, submillimetre observations enable all-time and in-dust monitoring of the atmospheric state, which is a very unique and indeed a strong point of the submillimetre instrument for Martian atmospheric observations.

6. Results: expected sensitivity of the submillimetre sounder

6.1. Temperature retrieval from CO lines

The temperature profile is retrieved from atmospheric spectra of optically thick lines. Carbon monoxide is often used to probe the thermal structure of the Mars atmosphere (e.g., Cavalié et al., 2008; Hartogh et al., 2010a) since CO is vertically well mixed with relatively constant and mixing ratios. In practise, temperature retrieval should be bundled with the retrieval of CO mixing ratios. From this point of view, it is helpful to simultaneously observe $^{12}$CO and $^{13}$CO, which contain different sensitivities regarding temperature and CO abundance. We simulated the temperature retrieval from a single limb scan observation of $^{13}$CO 550.9 GHz and $^{12}$CO 576.2 GHz lines. The warm atmospheric scenario was assumed. A fixed $[^{12}$CO]/$[^{13}$CO] ratio equal to the terrestrial value, i.e., 89.01, was used in this analysis. An a priori error of 20 K and 20% of the a priori state were adopted for the temperature and CO profiles, respectively. The measurement sensitivity to the temperature profile, with assuming the warm atmospheric scenario, is shown in Fig. 6. The averaging kernels and the corresponding measurement response are plotted on the left panel, indicating good temperature sounding from the surface to 120 km. The vertical resolution and 1-σ retrieval error are shown in the centre and right panels, respectively. The total retrieval error

![Figure 5](image1.png)  
**Fig. 5.** Dust induced brightness temperature differences in nadir and limb (tangential height of 20 km) observation geometries. The cases shown here apply refractive index of $n=2.7-0.6i$. The results for the nadir geometry is scaled by a factor of 1000 for visibility reasons.

![Figure 6](image2.png)  
**Fig. 6.** Temperature retrieval from a single limb scan observation of $^{12}$CO and $^{13}$CO. (Left) Averaging kernels of the retrieved temperature profile with indicating the measurement response as an envelope. (Centre) Vertical resolution estimated from the averaging kernels. (Right) Expected retrieval errors (measurement error, null space error, and the sum of these two as total retrieval error). For comparison, the vertical resolution and 1-σ retrieval error derived from the individual $^{12}$CO- or $^{13}$CO-line observations are shown in dashed and dotted lines, respectively.
was calculated as the summation of the measurement error and the null space error. At altitudes from the surface to 30 km, the 1-σ precision of temperature retrieval was estimated to be better than 2 K. A vertical resolution of 3 km was achieved there. From 30 to 60 km, the precision became 2–6 K and the resolution was 3–8 km. Above 60 km, the retrieval precision still maintained a better level than 10 K up to 110 km. Such a good sensitivity at high altitudes is due to the $^{12}$CO line, whose line opacity remains thick at those altitudes. On the other hand, the $^{12}$CO line is less sensitive to temperature at the lower atmosphere (below 25 km) compared to the $^{13}$CO line. This is because of the strong opacity of the $^{12}$CO line. The weak isotope $^{13}$CO line brings the improvement on the measurement sensitivity to temperature in those low altitudes, as shown in Fig. 6.

Temperature and abundances of CO were simultaneously retrieved in these simulations. The correlation between the two retrieval parameters, i.e., the response of the retrieved temperature profile to the CO abundance, is displayed in Fig. 7. The plotted values are the temperature retrieval error introduced by 1%-error on CO mixing ratio. Such correlations for simultaneous $^{12}$CO and $^{13}$CO observations and separate observations of individual CO lines are shown in the figure. The temperature-CO correlation factor is within the range of ± 0.1 (below 120 km) for simultaneous measurements of $^{12}$CO and $^{13}$CO, whereas it becomes larger when attempting to retrieve temperature and CO from a single line observation of either $^{12}$CO or $^{13}$CO. This fact indicates the effectiveness of observing two CO lines simultaneously for constraining temperature and CO abundance.

The capability of measuring CO is shown in Fig. 8. Carbon monoxide can be measured from the surface up to 120 km or even much higher. Retrieval precision was better than 10 ppmv below 30 km, and remained better than 50 ppmv up to 80 km. The $^{13}$CO line looses sensitivity at the lowermost altitudes below 10 km. This is because that the signal of the $^{13}$CO line at optically thin frequency channels, where sensitivity to CO comes from, is contaminated by the far wing spectral signal of the $^{12}$CO 556.9 GHz transition (as can be seen in Fig. 2) at those low altitudes.

For nadir observation geometry, the measurement sensitivities to temperature and CO abundance were severely limited to between the surface and ~50 km with poorer vertical resolution (Figs. 9 and 10). It is sensitive to temperature from the surface to 40 km with a precision better than 3 K and a vertical resolution of ~8 km. The correlation between temperature and CO retrievals were larger than that of the limb observations for the same altitudes, but still less than 0.03 K (for 1%-error on CO mixing ratio). With respect to CO abundance, the broad and low amplitude averaging kernels indicate that the considered nadir looking measurements have almost no sensitivity to its vertical distribution. The available information for CO is the mean mixing ratio at altitudes of ~10–40 km.

6.2. $\text{H}_2\text{O}$ retrieval from the limb scan observation

As shown in Fig. 1, $\text{H}_2\text{O}$ has a number of transitions in the submillimetre region. Among them, the pure rotational transition (11$_{11}$–10$_{10}$) at 556.9 GHz has the strongest line intensity, followed by the transition (21$_{11}$–20$_{02}$) at 752.0 GHz and (20$_{22}$–11$_{11}$) at 987.9 GHz. Assuming that the typical noise level of the submillimetre receivers increases along with the observation frequency, we selected the 556.9 GHz $\text{H}_2\text{O}$ transition as the primary observation line for optimizing sensitivity to the low $\text{H}_2\text{O}$ number density at the middle atmosphere.

Fig. 11 shows the expected measurement sensitivity, vertical resolution, and 1-s retrieval precision derived by simulating a single limb scan measurement of the 556.9 GHz $\text{H}_2\text{O}$ line, assuming the extremely dry atmospheric scenario. It is noted that we assumed that the temperature profile is constrained independently from the $\text{H}_2\text{O}$ retrieval. On the retrieval error plot, 1%, 5%, 10%, and 50% levels of the a priori profile are overplotted for comparison. Even under the very dry condition, the averaging kernels indicate a promising sensitivity to $\text{H}_2\text{O}$ abundances at the altitude range from the surface to above 80 km. In the range between 0 and 40 km, $\text{H}_2\text{O}$ can be measured with 1-s precision better than 5% of the a priori profile and with a vertical resolution
of ~3 km. Above 40 km, the sensitivity was better than 10% of the a priori profile up to 70 km.

As described in the previous section, it is expected that the abundance of H$_2$O varies in a very wide range. The H$_2$O mixing ratio at the lowest atmospheric layer can be as large as ~300 ppmv. We investigated the H$_2$O sensitivity under such a condition by using the warm atmospheric scenario. Fig. 12 shows that a clear difference from the sensitivity calculated under the extremely dry condition: the measurement sensitivity drops off at lower altitudes below 20 km. This problem cannot be solved even if we average several scans, whereas the sensitivity to high altitudes (~100–120 km) can be improved with increasing the number of averaging scans. This is because, within the assumed observation bandwidth (4 GHz), the 556.9-GHz H$_2$O line becomes so optically thick that the saturation of the line signal makes the measurement no longer sensitive to the water vapour in the lower atmosphere. To solve this problem, we plan to observe another H$_2$O line at a frequency of 620.7 GHz (5 32–4 21), whose line intensity is approximately two orders of magnitude smaller than the 556.9-GHz line. The measurement sensitivity of the 620.7-GHz H$_2$O line is shown in Fig. 13. By observing this line, H$_2$O can be measured within a precision of 2 ppmv at an altitude.
range from the surface to \( \sim 20 \) km under the high \( \text{H}_2\text{O} \) opacity scenario. This precision corresponds to the level less than 1% of the assumed \textit{a priori} \( \text{H}_2\text{O} \) abundance. Above 40 km, the 620.7-GHz measurement starts to lose sensitivity to \( \text{H}_2\text{O} \). By combining the two \( \text{H}_2\text{O} \) lines of 556.9 and 620.7 GHz, we can obtain the vertical distribution of \( \text{H}_2\text{O} \) with a precision of \(<1\%\) from the surface to 40 km and \(<10\%\) at 40–60 km in a single limb scan observation.

The alternative selection for the optically thinner \( \text{H}_2\text{O} \) line is either 380.2-GHz (414–321) or 448.0-GHz (423–330) lines. These lines have similar line intensities as the 620.7-GHz line (strictly speaking, 448.0 GHz is the strongest of the three and 620.7 GHz is the weakest). The upper panels of Fig. 14 show the measurement responses and error profiles for several \( \text{H}_2\text{O} \) transitions in the 300–800-GHz region under the warm atmospheric scenario. The observation frequency dependencies of the antenna beam size and the system temperature have been taken into account in these calculations as follows: we assumed a system temperature of 1000, 1500, and 3000 K for 300-, 400-, and 700-GHz bands, respectively.
The errors on this figure are represented as relative values with respect to the assumed a priori profile, in order to give an easy comparison to the different atmospheric scenario simulations. As expected from the closeness of their line intensity, these three H\textsubscript{2}O lines (380.2, 448.0, 620.7 GHz) show similar sensitivity to the water vapour profile. The upper boundary of the measurement response profile of the 380.2-GHz H\textsubscript{2}O line is highest among the three despite the fact that the largest-intensity line is 448.0 GHz. This is mostly because the lower measurement noise level is at 380.2 GHz compared to 448.0 GHz. The advantage of using different opacity H\textsubscript{2}O lines, instead of using different opacity lines from different isotopes such as H\textsuperscript{18}O, is that we can retrieve H\textsubscript{2}O profiles in a wide vertical range without introducing uncertainty due to the isotopic ratio assumption. The lower panels in Fig. 14 show sensitivity estimations for the extremely dry atmospheric scenario in which a very low H\textsubscript{2}O concentration is assumed. Under such a condition, the
556.9-GHz observations will sufficiently provide sensitivity at altitudes from surface to 50 km (precision better than 10%) and 50–80 km (precision better than 20%).

6.3. H₂O retrieval from the nadir observations

Fig. 15 shows the nadir observation sensitivity to the H₂O profile for the warm and extremely dry atmospheric scenarios. For comparison, we also show the sensitivity of a nadir observation with 25 s data integration. With a nominal 2 s integration, H₂O will be measured from surface to ~30 km with a precision better than 20% of the a priori state and a vertical resolution of ~8 km under the warm scenario. From an altitude above 30 km, the retrieval error increases to 50% at 40 km, which constitutes the upper-altitude limit of measurement sensitivity. Sensitivity can be improved by increasing the integration time of the measurements. The results from 25 s observation indicate that the retrieval precision at the lowermost altitude (4 km) can be improved as better than 5% (warm case).

For the extremely dry atmospheric scenario, sensitivity worsens at most of the altitude compared to the warm scenario due to smaller H₂O concentration. The nadir observation of 556.9 GHz with 2 s integration time results in sensitivity to altitudes only below ~15 km with a vertical resolution of ~10 km. Increasing the integration time to 25 s will expand the upper boundary of the good-sensitivity region to ~20 km. The near-surface H₂O abundance can be measured with a 1% precision (extremely dry case) by integrating over 25 s.

As the near centre frequencies of the 556.9 GHz line become saturated under the warm atmospheric scenario, the ACS’ wide bandwidth of 4 GHz is essential in retrieving the H₂O abundance at a lower altitude from the nadir observation. Fig. 16 shows the impact of the observation bandwidth on the altitude range of the sensitivity measurement. The total retrieval error from a 2 s observation is plotted. By increasing the observation bandwidth from 0.5 to 4 GHz, the vertical ranges of a constant retrieval precision become remarkably wider. Further extension of the bandwidth beyond 4 GHz does not significantly improve the retrieval precision.

6.4. HDO retrieval from the 599.9 GHz line

Measuring HDO is another important objective in Mars science. In this study, the (211–202) transition at 599.9 GHz was selected as the observation line because of its significant line intensity, not being contaminated by other strong molecular lines.
and feasibility of sharing a common LO frequency with other targets.

At 753.4 GHz, there is another HDO line whose line intensity is stronger than that of 599.9 GHz and, in fact, is one of the largest intensity lines in the submillimetre domain. However, this (312–303) transition is located too close to the opaque H2O line at 752.0 GHz and is inadequate for HDO measurements.

The capability of measuring HDO with a single limb scan measurement was estimated by assuming a priori error as 200% of the HDO a priori mixing ratios to take into account its large variability. In Fig. 17, the calculated sensitivity for a single limb scan observation under the warm and extremely dry conditions is shown. Under the warm scenario, a 1-s retrieval precision better than 1% of the a priori profile was expected at an altitude range between 0 and 20 km. By combining with the sensitivity estimation result of the H2O 556.9 GHz transition (a 1% error at 0–20 km, Fig. 13), this 1% error on HDO abundance yields an [HDO]/[H2O] error of 0.1 SMOW (5 SMOW is assumed for a bulk value) with a single limb scan measurement. Above 20 km, the 599.9 GHz HDO measurement maintained its sensitivity up to 40 km by decreasing the precision in the range of 1–20% of the a priori profile. For these altitudes, the 556.9 GHz H2O measurement achieves the precision of ~1% (Fig. 12), and the [HDO]/[H2O] errors

**Fig. 15.** Measurement sensitivity of a nadir looking observation of 556.9 GHz and 620.7 GHz H2O lines. The measurement response and the total retrieval error for the 25-s data integration case are shown with dotted lines.

**Fig. 16.** Change of the H2O retrieval precision associated with change of observation bandwidth of 556.9 GHz nadir observation.
are expected to be 0.2 and 1.0 SMOWs at altitudes of 30 and 40 km, respectively. Such a sensitive determination of the vertical profile of $\frac{[\text{HDO}]}{[\text{H}_2\text{O}]}$ will enable dedicated discussion on the isotropic fractionation effect in the Martian atmosphere. For the extremely dry case, the HDO retrieval precision was limited to worse than 10%. This error determines the precision of $\frac{[\text{HDO}]}{[\text{H}_2\text{O}]}$ derivation as 0.5–2.5 SMOW at altitudes of 0–10 km.

6.5. Wind

The wind velocity projected along the LOS of an observation can be measured from the Doppler shift of the observed spectrum. For this measurement, a high frequency resolution and little disturbance from ripples on the spectral bandpass are indispensable. Since the AMATERASU forward model uses horizontally homogeneous multi-layered atmospheric shells, all the physical parameters of the atmospheric state are set as a function of the tangential height (or the vertical altitude for the nadir observation geometry). In this study, we treat the LOS wind profile in the same manner as other atmospheric physical parameters, i.e., for any observing geometries the same tangential height dependency is applied for the LOS wind profiles for each observing geometry. This assumption gives physically inappropriate results if an LOS wind at a certain tangential height is retrieved from a combination of several LOS-geometry observations. Therefore, in the presented sensitivity study, we retrieve the LOS wind at the tangential altitudes of each limb scan spectrum. This is done by excluding the frequency channels whose total opacity is larger than 2 from the inversion analysis.

The LOS wind sensitivity derived from limb scan observations of the $^{13}$CO 550.9 GHz and $^{12}$CO 576.2 GHz lines is shown in Fig. 18. The upper panels show the simulation for a single scan, and the lower ones are for that averaged over 25 scans. This demonstrated that the $^{13}$CO line has an advantage of measuring the LOS wind at a higher altitude. Even with a single scan, the precision between 10 and 20 m s$^{-1}$ is achieved at an altitude above 70 km. The vertical resolution for those altitudes is around 6–8 km, which is limited by the inversion model setting. By contrast, the $^{13}$CO line provides sensitivity to the lower altitudes around 40–60 km. Below 40 km, accumulation of several scans is necessary to obtain reasonable sensitivity to the LOS wind. By averaging 25 limb scans (the lower panels in Fig. 18), the lower limit of sensitivity goes down to ~20 km. To measure the LOS wind below 20 km, further suppression of the measurement noise becomes critical, and from this point of view, the application of a cooled receiver, such as HIFI or SMILES, must be considered. With the current instrumental design of an ambient temperature receiver, the LOS wind measurement works most effectively at the middle and upper atmospheres.

6.6. $\text{H}_2\text{O}_2$ and HO$_2$

Hydrogen peroxide and HO$_2$ are photochemically important species, as described in Section 3. We plan to observe the $\text{H}_2\text{O}_2$ 591.4 GHz line, which exists in the window region of H$_2$O and CO emission. Within the 1 GHz bandwidth of this $\text{H}_2\text{O}_2$ line, there are relatively intense HO$_2$ lines at 591.757 and 591.760 GHz. Therefore, these key species of the Martian atmospheric chemistry can be measured simultaneously with a single backend instrument. In addition, there is another $\text{H}_2\text{O}_2$ transition at 599.7 GHz, whose line intensity is one of the strongest in the submillimetre domain, and can be detected within the same spectral bandwidth as the HDO 599.9 GHz observation.

We investigated the 3-σ upper limits on $\text{H}_2\text{O}_2$ and HO$_2$ abundances, which can be inferred from nadir and limb scan observations of the 591 GHz window. The left plot in Fig. 19 shows the expected upper limit (3-σ) with respect to the $\text{H}_2\text{O}_2$ and HO$_2$ abundances in the nadir looking observation. The warm atmospheric scenario was adopted and vertical constant profiles were assumed for $\text{H}_2\text{O}_2$ and HO$_2$, respectively. The change in the upper limit along the integration time is shown in the plot. If several tens of ppb of $\text{H}_2\text{O}_2$ exist on Mars, as indicated from
Fig. 18. Sensitivity to LOS wind from limb scan observations of $^{12}$CO and $^{13}$CO. Upper panels show the case for a single limb scan, while the lower are the case when 25 scans are averaged. The left panels show the measurement response in solid lines, and the vertical resolution scaled by a factor of 10 in dashed lines. The right ones display the total retrieval errors. Different colours indicate the cases for $^{12}$CO and $^{13}$CO, respectively, as labeled on the upper left panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 19. (Left) Expected 3-$\sigma$ detection level of H$_2$O$_2$ (plotted in solid line) and HO$_2$ (dashed line) with nadir looking measurements as a function of the integration time. (Right) 3-$\sigma$ sensitivity to H$_2$O$_2$ and HO$_2$ at each tangential height assuming a single limb scan and an average over 25 scans.
previous IR observations (e.g., Encrenaz et al., 2008), then a single-second exposure of the submillimetre sounder facilitates the $> 3\sigma$ detection of such H$_2$O$_2$ distributions. Regarding HO$_2$, a 1-min integration results in the detection of abundance less than 5 ppbv.

The sensitivity for limb scan observations is shown in the right panel of Fig. 19. The expected sensitivity at each tangential height was calculated for a single limb scan and for averaging over 25 scans. Thanks to the long LOS in the atmosphere, we achieved a significant improvement in sensitivity to H$_2$O$_2$ and HO$_2$. A single limb scan enables the detection of 0.5 ppbv H$_2$O$_2$ and HO$_2$ at an altitude around 10 km, and by averaging 25 scans we can potentially measure sub-ppbv order abundances of these species from the surface up to between 40 and 50 km.

7. Conclusion

Table 5 shows a summary of our OEM retrieval simulations of the H$_2$O mixing ratio, temperature, [HDO]/[H$_2$O], and LOS wind velocity. In addition to the results described in the previous section, the table includes completed data for all the cases we studied, i.e., the warm and cold or extremely dry atmospheric conditions and two cases of data integration time, 2 and 25 s, for the nadir geometry. Compared with previous proposals of sub-millimetre instruments, such as MAMBO (operated at 320–350 GHz), our instrument/FIRE is advantageous in terms of measuring the water vapour at high altitudes. Thanks to the better sensitivity to H$_2$O and HDO, [HDO]/[H$_2$O] ratios are also expected to be derived with much higher precisions ($1-\sigma$ precision of $\sim 0.1$ SMOW) than those expected in the MAMBO proposal. Regarding temperature sounding, the expected retrieval precision of FIRE is similar to that of MAMBO, but with a higher upper-altitude limit of sensitivity. The LOS wind will be derived with $10–20$ m s$^{-1}$ precision from a single limb scan at altitudes around 80 km. As described in Section 6.5, the LOS wind retrieval simulations presented in this paper were conducted with a limited spectral range of the measurement spectra. By improving the implementation algorithm of the LOS winds into the forward model, more information from the full spectral bandwidth of the measurement spectra become usable in the retrieval analysis; thus, sensitivity can be improved.

Through this work, we are confident that submillimetre observations from the near-Martian orbit will open a new frontier of Martian atmospheric science, specifically with (1) high sensitivity to the vertical profiles of atmospheric temperature and

<table>
<thead>
<tr>
<th>Physical parameter</th>
<th>Condition</th>
<th>Altitude range (km)</th>
<th>Vertical resolution (km)</th>
<th>1-σ precision</th>
</tr>
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<tr>
<td><strong>Limb, single scan (0.5 s integration on each spectrum)</strong></td>
<td></td>
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<tr>
<td>Temperature</td>
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<td>3</td>
<td>$&lt; 2$ K</td>
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<td>30–60</td>
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<td>2–6 K</td>
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<td></td>
<td>60–110</td>
<td>8–10</td>
<td>6–10 K</td>
</tr>
<tr>
<td></td>
<td>Cold</td>
<td>0–30</td>
<td>3–4</td>
<td>$&lt; 3$ K</td>
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<td>30–60</td>
<td>4–8</td>
<td>3–6 K</td>
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<td>60–110</td>
<td>8–10</td>
<td>6–10 K</td>
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<td>$&lt; 1%$</td>
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<td>3–6</td>
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<td></td>
<td>60–80</td>
<td>6–8</td>
<td>1–10%</td>
</tr>
<tr>
<td></td>
<td>Extremely dry</td>
<td>0–20</td>
<td>3</td>
<td>$&lt; 2%$</td>
</tr>
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<td></td>
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<td>20–80</td>
<td>3–8</td>
<td>$&lt; 1$ ppmv at near surface</td>
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<td>[HDO]/[H$_2$O]</td>
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<td>3</td>
<td>0.1 SMOW</td>
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<td>20–40</td>
<td>3–4</td>
<td>0.2–1.0 SMOW</td>
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<tr>
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<td>3</td>
<td>0.5–3.0 SMOW</td>
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<td>LOS wind</td>
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<td>6–8</td>
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<td>6–8</td>
<td>10–20 m s$^{-1}$</td>
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<tr>
<td>Nadir geometry, 2 s integration</td>
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<td>Warm, cold</td>
<td>0–10</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10–40</td>
<td>8–14</td>
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<td>6</td>
<td>10–20%</td>
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<td>15–30</td>
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<td>5–10%</td>
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<td></td>
<td></td>
<td>30–40</td>
<td>10</td>
<td>10–40%</td>
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<tr>
<td></td>
<td>Extremely dry</td>
<td>0–10</td>
<td>8–10</td>
<td>3–30%</td>
</tr>
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<td></td>
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<td>10–20</td>
<td>10–15</td>
<td>10–80%</td>
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<tr>
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<td>8</td>
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<td>6</td>
<td>$&lt; 5$ K</td>
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<td>20–40</td>
<td>6–10</td>
<td>1–10%</td>
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<td>0–10</td>
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<td>1–10%</td>
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<tr>
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<td>Extremely dry</td>
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<td>10–15</td>
<td>10–80%</td>
</tr>
<tr>
<td>[HDO]/[H$_2$O]</td>
<td>Warm</td>
<td>0–40</td>
<td>10–20</td>
<td>0.5–3 SMOW</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5–3 SMOW at 15 km</td>
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compositions, (2) capability of direct measurement of winds, and (3) continuous observations independent of local time and dust opacity. A specific feasibility study is now under way as preparation for the real data analysis. This study will include the optimisation of the backend spectrometer configuration (binning width), and more realistic error analysis than the one presented here. In the presented sensitivity study, we only took the measurement error and null space error into account. However, in practise, there are more error sources such as the model parameter error and calibration error. In fact they become in some cases dominant error sources in the retrieval. For example, a significant impact of the antenna pointing error in the Earth limb emission sounding is reported in Baron et al. (2011). In order to evaluate the real precision and accuracy of the FIRE measurement, all potential error sources should be examined.

The next stage of hardware development is to optimise the instrumentation of FIRE, as well as the operational mode, to agree with the entire mission concept of MELOS. The miniaturisation of the instrument is also planned to satisfy the limited resources of the orbiter. The antenna sizes and its scanning mechanism will be determined after the overall design of the orbiter is approved. The scientific targets may change depending on new findings from ongoing Mars observations such as the Herschel guaranteed time programme. All these developments will make FIRE a better and more unique instrument.

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