0254-6124/2020/40(2)-151–18 *Chin. J. Space Sci.* 空间科学学报

LIU Congliang, KIRCHENGAST Gottfried, SUN Yueqiang, WANG Xin, LÜ Daren, BAI Weihua, DU Qifei, LÖSCHER Armin, SYNDERGAARD Stig, TIAN Longfei, ZHANG Zhihua. Exploring greenhouse gases water and climate changes: scientific opportunities for the climate and atmospheric composition exploring satellites mission. *Chin. J. Space Sci.*, 2020, **40**(2): 151-168. DOI:10.11728/cjss2020.02.151

Exploring Greenhouse Gases Water and Climate Changes: Scientific Opportunities for the Climate and Atmospheric Composition Exploring Satellites Mission*

LIU Congliang[1,3] KIRCHENGAST Gottfried[2,3]

SUN Yueqiang[1,3,8] WANG Xin[4] LÜ Daren[4,8]

BAI Weihua[1,3,8] DU Qifei[1,3]

LÖSCHER Armin[5] SYNDERGAARD Stig[6]

TIAN Longfei[7] ZHANG Zhihua[4]

1(*Beijing Key Laboratory of Space Environment Exploration, National Space Science Center, Chinese Academy of Sciences, Beijing* 100190)

2(*Wegener Center for Climate and Global Change and Institute for Geophysics, Astrophysics, and Meteorology/Institute of Physics, University of Graz, Graz A-8010*)

3(*Joint Laboratory on Occultations for Atmosphere and Climate, Beijing* 100190)

4(*Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029)

5(*Future Missions and Instrument Division, European Space Agency, Noordwijk, NL-2200*)

6(*Danish Meteorological Institute, Copenhagen, DK-2100*)

7(*Innovation Academy for Microsatellite of Chinese Academy of Sciences, Shanghai* 201210)

8(*University of Chinese Academy of Sciences, Beijing* 100049)

Abstract The Essential Climate Variables (ECVs), such as the atmospheric thermodynamic state variables and greenhouse gases, play an important role in the atmosphere physical processes and global climate change. Given the need of improvements in existing ground-based and satellite observations to successfully deliver atmosphere and climate benchmark data and reduce data ambiguity, the Climate and Atmospheric Composition Exploring Satellites mission (CACES) was proposed and selected as a candidate mission of the Strategic Priority Research Program of Chinese Academy Science (SPRPCAS). This paper presents an overview of the key scientific questions and responses of ECVs in relation to global change; the principles, algorithms, and payloads of microwave occultation using centimeter and millimeter wave signals between low Earth orbit satellites (LEO-LEO microwave occultation, LMO) as well as of the LEO-LEO infrared-laser occultation (LIO); the CACES mission with its scientific objectives, mission concept, spacecraft and instrumentation.

Key words Climate, Greenhouse gases, Water, Microwave occultation, Infrared-laser occultation

Classified index P 352

---

* Supported by the National Natural Science Foundation of China (41775034, 41606206), and the Strategic Priority Research Program of Chinese Academy of Sciences (XDA15012300)

Received December 31, 2019

E-mail: lcl@nssc.ac.cn

0 Introduction

GNSS Radio Occultation

The concept of Radio Occultation (RO) originated from interplanetary space exploration in the 1960s for probing the atmosphere of Mars[1]. Decades later, with the emergence of the Global Positioning System (GPS) constellation, scientists suggested that RO could also be used to probe the Earth's atmosphere, with the source being the available GPS signals, and the receiver is in a Low Earth Orbit (LEO). In this paper, we refer to this as the Global Navigation Satellite System RO (GNSS RO) technique. The GNSS RO technique was demonstrated using GPS signals in the proof-of-concept GPS/Meteorology (GPS/MET) mission[2], subsequently, many GNSS RO missions have been launched, such as the Challenging Minisatellite Payload (CHAMP)[3], Gravity Recovery and Climate Experiment-A (GRACE-A)[4], Meteorological Operational satellite-A (MetOp-A)[5], the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)[6], and Fengyun-3C/3D GNSS Occultation Sounder (FY-3C/3D GNOS)[7].

In the RO data validation and assessment, GNSS RO's excellent features of global coverage, all weather capability, high accuracy, high vertical resolution, no need for calibration, very high precision, long-term stability, low structural uncertainty, negligible satellite to satellite bias were proven[8−10].

Due to these positive features, GNSS RO has been recognized as an important data source for improving weather forecasts and for monitoring climate change. Today GNSS RO products, in particular, bending angle and refractivity, are widely used for numerical weather prediction (NWP)[11−13] and Global Climate Monitoring (GCM)[14,15].

LEO-LEO Occultation

While many scientists have reported significant positive impacts of GNSS RO products on NWP and GCM, GNSS RO has an inherent limitation, which is the inability to separate the contributions of temperature and humidity to the total refractivity[16,17]. Therefore, in the troposphere where the contribution from humidity cannot be neglected, the temperature and humidity variables can only be retrieved separately from refractivity by co-using a priori humidity and/or temperature information[18]. This is the main reason why scientists started to explore and suggested microwave occultation using centimeter and millimeter-wave signals between LEO satellites.

The LMO technique exploits both the refraction and the absorption of the signals to solve the temperature-humidity ambiguity in the troposphere. Thus, LMO promises to enable the retrieval of temperature, pressure, and humidity profiles without auxiliary background information, by using various X/K band and M band frequencies around the 22 GHz and 183 GHz water absorption lines[19−22]. Similarly, ozone profiles can be retrieved by absorption measurements of signals near the 195 GHz ozone line[23,24]. Furthermore, the liquid water and ice cloud variables, as well as turbulence strength can also be retrieved as by-products[23,25].

The LIO technique, proposed as part of ACCURATE mission[26], uses laser signals in the short-wave infrared (SWIR) band from 2 to 2.5 μm between LEO satellites, to accurately observe key trace species for chemistry and climate (*i.e.*, greenhouse gases H_2O, CO_2, CH_4, N_2O, O_3, CO, including key isotopes), line-of-sight wind speed, and also profiles of cloud layers and aerosols as by-products[26]. An overview of the GNSS RO and LEO-LEO occultation measurement concept and geometry are shown in Figure 1.

Figure 2 shows the spectral bands and distribution of the LMO and LIO (LMIO) channels. Channels

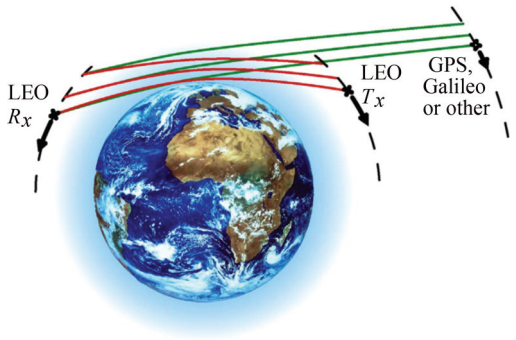

Fig. 1 Schematic view of the GNSS RO (green signal paths) and LEO-LEO occultation (red signal paths) event geometry

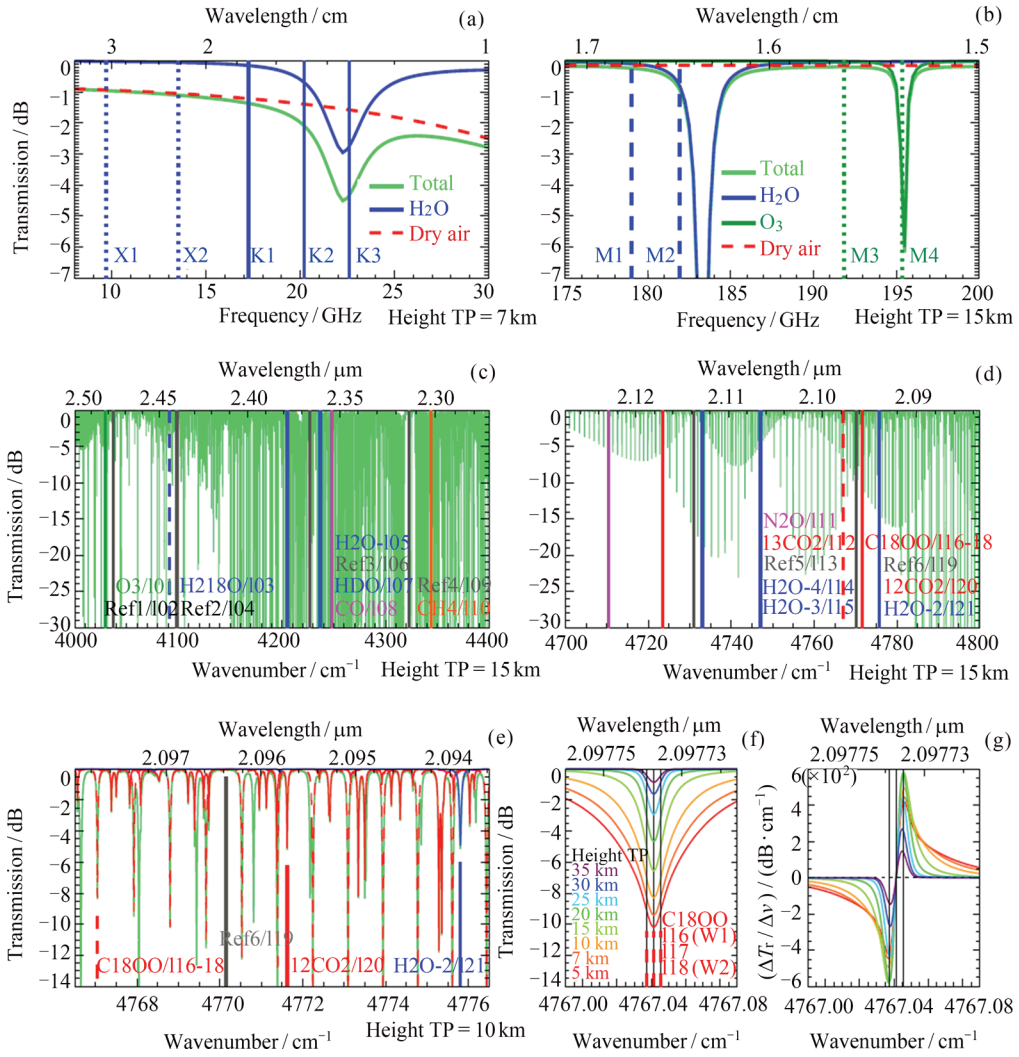

Fig. 2 Spectral bands and distribution of the LMO and LIO (LMIO) channels

at the wings of the 22 and 183 GHz water absorption lines (Figure 2a and 2b) were investigated and suggested for the LMO signals. LMO channels including (a) centimeter-wave signals in X/K band (core channels K1∼K3), exploiting the 22 GHz water vapor absorption line, and (b) millimeter-wave signals in M band (primary channels M1, M2), exploiting the 183 GHz water vapor line and the 195 GHz ozone line.

Furthermore, SWIR frequency channels were carefully selected for the LIO signals to match desired absorption lines of trace species of interest. All channels include suitable reference channels, or in case of LMO, use nearby channels as reference, for enabling effective use of differential transmission between channels (Figure 2c and 2d). Figure 2(e)∼(g) highlight specific LIO channels. LIO channels including shortwave-infrared (SWIR) laser signals Figure 2 (c) in the 2.3 to 2.5 μm SWIR-B band, exploiting absorption lines of stratospheric ozone and water vapor, water isotopes, carbon monoxide and methane, and Figure 2(d) in the about 2.1 μm SWIR-A band, exploiting lines of nitrous oxide, carbon dioxide, isotopes, and water vapor. Figure 2(e) zoom into a narrow sub-range of the SWIR-A band, highlighting a special demonstration band of only about 4 nm (10 cm^{-1}) width, suitable to probe the key variables CO_2 and isotopes, H_2O, and line-of-sight wind within the mode-hop free tuning range of single SWIR diode lasers. Figure 2(f) and (g) further refined zoom in SWIR-A, highlighting the "wind line" band of only about 40 pm (0.1 cm^{-1}) width. The selected two wind measurement channels sit at the inflection points of

the highly symmetric and stable $C_{18}OO$ line (Figure 2f) and the spectral derivative of the transmission (Figure 2g) confirms that the wind channels are located at the maximum gradient providing highest sensitivity to wind-induced Doppler shift of the line[26].

Climate, Greenhouse Gases, and Water Scientific Challenges

A deeper understanding of how greenhouse gases and water vapor impact and respond to global climate change is one of the outstanding challenges in Earth climate science. As the community gains the consensus of global warming and a deeper understanding of the many processes involved, greenhouse gases and water vapor are playing critical roles. Reduction of uncertainties in greenhouse gases climate feedbacks as well as improved understanding of processes governing these effects will result from profiling of the atmospheric thermodynamic state variables (*i.e.*, pressure, temperature, and humidity), greenhouse gases (*i.e.*, H_2O, CO_2, CH_4, N_2O, O_2, CO, including key isotopes), and line-of-sight wind speed with improved accuracy and vertical resolution compared to existing ground-based and space-based measurements. Therefore, expanding the observational foundation for climate change studies by accurate, long-term, consistent benchmark data is a fundamental need for climate science.

In-situ observing stations, mainly deployed on land, buoys, ships, balloons or aircraft can be highly accurate but suffer from poor representativeness as they offer point or line measurements in space and time. They are very irregularly distributed around the globe, particularly their density is poor over remote regions and oceans, and vertical profiles are rare.

Earth observation from space is the key approach to obtain such data globally. Current methods of satellite remote sensing of Earth's free atmosphere (above boundary layer) do collectively enable global observations of ECVs, including thermal state (temperature, pressure, humidity), dynamics (wind), and composition (ozone, carbon dioxide, methane, other greenhouse gases), but are struggle to provide them as consistent climate benchmark dataset. The latter requires joint sensitivity to all essential variables, measurement stability over decades and longer, high accuracy tied to international metrological standards and unbiased spatio-temporal sampling. Despite the demand and having GNSS RO as a valuable starting point for refractivity, such a fundamentally needed "full atmospheric state" method did not exist so far.

1 Challenging Requirements in Climate Science and Key Observations

The Intergovernmental Panel on Climate Change (IPCC) reported that scientific evidence for warming of the climate system is unequivocal, such as global temperature rise, warming oceans, shrinking ice sheets, glacial retreat, decreased snow cover, sea level rise, ocean acidification and so on. IPCC also concluded there's a more than 95 percent probability that human activities over the past 50 years have warmed our planet by emitting greenhouse gases *i.e.*, CO_2, CH_4, NO, *etc.*, into the Earth atmosphere. However, the consequences of changing the natural atmospheric greenhouse are difficult to predict, as well as the physical and chemical impacts and feedbacks of the atmospheric composition and climate change are uncertain.

The atmospheric thermodynamic state variables and greenhouse gases are Essential Climate Variables (ECVs) and significant in physical and chemical processes of the atmosphere, which play very important roles in the Earth system, ecosystem, and human society. The impacts and feedbacks of these ECVs to global change are one of the key questions in the Earth and climate science.

However, the existing ground-based and satellite observations are still far from fully supporting properly the atmospheric physics and global climate change research that requires a long-term stable, global coverage, high spatial resolution and simultaneous measurement of ECVs, to deliver atmosphere and climate benchmark data. The benchmark observations are also helpful to understand the exchanges

among the atmospheric water vapor, ice liquid water and ice crystals, under strong convection conditions. Based on the work of Kirchengast *et al.*[27], who introduced the scientific objectives versus impact matrix approach as a method for effectively assessing the value of observing systems, Table 1 summarizes the scientific objectives and provides a convenient shortcut form for them that is then used in the Impact Level matrix (Table 2).

GNSS RO has become a major method to ob-

Table 1 Scientific objectives used in the impact level matrix

Scientific objective shortcut form	Scientific objective description
Climate	
Monitor climate trends and variability	Monitoring of climate trends and variability in thermodynamic, dynamics/wind, green-house gases, reactive gases, aerosol, cloud/precipitation, and radiation variables, for contributing to accurate long-term observations of climate in the atmosphere
Diagnose and predict climate change	Diagnostics, including detection and attribution, of anthropogenic climate and composition changes in the atmosphere, as well as of changes in the global carbon and water cycles, and support to climate change predictions through accurate data
Validate, test and improve climate GCMs	Validation of Global Circulation Models (GCMs), in simulated mean climate and variability seen in atmospheric physics/composition/radiation variables, and testing and improvement of their process formulations
Understand climate forcing and feedbacks	Improvement of the understanding of climate forcing variations (*e.g.*, greenhouse gases and aerosol) and of climate feedbacks determining magnitude and characteristics of climate changes
Chemistry and Processes	
Study atmospheric processes near-surface and in the LT	Study of atmospheric processes near surface and in the Lower Troposphere (LT), in the context of atmospheric chemistry and physics research, including also aerosol, cloud, and dynamical variability studies
Study atmospheric processes in the UTLS	Study of atmospheric processes in the UTLS region at high resolution, in the context of atmospheric chemistry and physics research, including also aerosol, cloud, and dynamical variability studies
Improve atmospheric composition forecasting	Improvement of forecasting and analysis of atmospheric composition including greenhouse gases, reactive gases, and aerosols by atmospheric constituent model and data assimilation systems
Test and improve atmospheric constituent models	Testing of constituent models and improvement of their process formulations, in order to enhance their composition forecasting skill
NWP	
Improve NWP forecasting	Improvement of forecasting and analysis of weather conditions, including in thermodynamic, dynamic/wind, cloud/precipitation, and radiation variables, by Numerical Weather Prediction (NWP) and data assimilation systems
Test and improve NWP models	Testing of NWP models and improvement of their process formulations, in order to enhance their weather forecasting skill
Others	
Calibrate data from other atmospheric observing systems	Provide reference data for the calibration, validation, and analysis of data from other space missions or airborne/ground-based observing systems
Demonstrate a novel observing technique	Demonstrate the science value of a novel satellite-based atmospheric remote sensing technique not yet used before

Table 2 Scientific objectives versus observation information impact level matrix for LMIO

Scientific objectives	Atmospheric observation information						
	ThDyn	DynWind	GHGs	RAGs	Aerosols	Cls+Prec	Radiation
Climate							
Monitor climate trends and variability	$***$	$***$	$***$	$**$	$**$	$*$	$*'$
Diagnose and predict climate change	$***$	$**$	$***$	$*$	$*$	$*$	$*'$
Validate, test and improve climate GCMs	$***$	$**$	$***$	$*$	$*$	$*'$	$*'$
Understand climate forcing and feedbacks	$***$	$**$	$***$	$*$	$*$	$*'$	$*'$
Chemistry and Processes							
Study atmospheric processes near-surface and in the LT	$*$	–	$*$	$*$	$*$	–	$*'$
Study atmospheric processes in the UTLS	$***$	$**$	$***$	$**$	$**$	$*$	$*'$
Improve atmospheric composition forecasting	$**$	$*$	$***$	$**$	$*$	–	$*'$
Test and improve atmospheric constituent models	$**$	$*$	$***$	$*$	$*$	–	$*'$
NWP							
Improve NWP forecasting	$**$	$**$	$*$	$*$	$*'$	$*'$	$*'$
Test and improve NWP models	$**$	$*$	$*$	$*$	$*'$	$*'$	$*'$
Others							
Calibrate data from other atmospheric observing systems	$***$	$***$	$***$	$**$	$*$	$*'$	$*'$
Demonstrate a novel observing technique	$***$	$***$	$***$	$***$	$**$	$*$	$*'$

Remarks: ThDyn (Thermodynamics), DynWind (Dynamic Wind), GHGs (Greenhouse Gases), .
RAGs (Reactive Atmospheric Gases, *e.g.* O_3), Cls+Prec (Clouds and Precipitation).
$***$ unique impact (superior to all other known observation systems for the objective).
$***$ major impact (co-leading impact amongst all other known observation systems).
$**$ significant impact (adding significant information to that of all other observation systems).
$*$ contributing impact (contributing useful information to that of all other observation systems).
$*'$ indirect impact (providing useful indirect information). – no impact.

serve the atmospheric thermodynamic state variables, which demonstrated that the occultation observations have the atmosphere and climate benchmark data features. However, the GNSS RO has a temperature and humidity ambiguity problem. Fortunately, as an advanced technique LMO can exploit both the refraction and absorption of the signals to solve the temperature-humidity ambiguity in the troposphere. Thus LMO enables to retrieve pressure, temperature, and humidity profiles without background information. Liquid water and rain rate profiles, as well as turbulence and complementary 3D cloud information, can be co-observed. Additionally, the LIO, using laser signals in the short-wave infrared band from $2\sim2.5\,\mu$m, between LEO satellites, has been designed to accurately observe key trace gas species for chemistry and climate (*i.e.*, greenhouse gases H_2O, CO_2, CH_4, N_2O, O_3, CO, *etc.*), line-of-sight wind speed,

and also profiles of cloud layers and aerosols as by-products. LIO measures the absorption of the signals to retrieve Volume Mixing Ratio (VMR) profiles of the greenhouse gases. In order to mitigate the effects of foreign species absorption, aerosol extinction, scintillation, and scattering on the retrieved trace species profiles, LIO uses the differential transmission principle between carefully selected pairs of absorption signals and reference signals. This enables accurate retrieval of the pure absorption profile due to the target species and hence accurate greenhouse gas profiles.

Among further potential, the LMIO method enables to rigorously monitor how greenhouse gas and climatic changes evolve from monthly to decadal scales and it can serve as independent observational constraint for model testing, re-analyses and forecasting, and anthropogenic change detection and attribution.

In the last decade, several LMO and LIO missions for atmosphere and climate change have been proposed to ESA and NASA, which resulted in many pre-studies. In China, the Climate and Atmospheric Composition Exploring Satellites (CACES) mission concept has been proposed to the Strategic Priority Research Program of the Chinese Academy of Sciences (SPRPCAS). A mission for benchmark monitoring of the Earth's atmospheric thermodynamic state variables, greenhouse gases and climate change by LMIO combined with 3D clouds imaging from low Earth orbits.

Table 2 shows the Impact level matrix for the LMIO occultation technique. As is obvious, its unique and major strengths fall mainly into the field of climate science *via* observing thermodynamic variables, greenhouse gases, and wind from space with climate benchmark quality and with focus on the Upper Troposphere and Lower Stratosphere (UTLS). Due to the accuracy and high vertical resolution, the ACCURATE data will have a unique and major impact on atmospheric chemistry and process studies in the UTLS, GHG composition modeling, and calibration of data from other observing systems. Furthermore, it is a very novel technique therefore also its demonstration is unique and of significant relevance.

2 Studies for LEO-LEO Observations from Space

After the GNSS RO technique having been demonstrated by the GPS/MET mission, there have been many GNSS RO missions to observe the atmospheric variable profiles from space, such as CHAMP, GRACE-A, MetOp-A/B, COSMIC-1/2 and FY-3C/3D GNOS, *etc.*

The work to develop the LEO-LEO occultation technique has been ongoing for the last two decades, and a number of LMO proposals and missions have been put forward mainly by U.S. and European scientists. In the following, we give a brief chronological history of these efforts, in part drawing from the report[28].

In 1997, researchers at the Jet Propulsion Laboratory (JPL) and the University of Arizona in the U.S. began exploring how frequencies significantly higher than those of the GPS could be used to measure the absorption of water vapor due to its 22 GHz water vapor resonance line[29,30]. This led to two large proposals being submitted in 1998. The first, the Atmospheric Moisture and Ocean Reflection Experiment (AMORE) responded to the NASA Earth System Science Pathfinder (ESSP) Announcement of Opportunity (AO). The second, the Active Tropospheric Ozone and Moisture Sounder (ATOMS) was in response to the NASA Instrument Incubator Program (IIP) AO. AMORE was piggybacked on the COSMIC mission satellites, yielding a combined mission titled COSMIC-AMORE, but later it was promoted as a separate mission[17]. While AMORE was highly ranked scientifically, it was considered technically immature and was not selected.

In 2007, the US NSF funded a proposal for the development of the Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS) instrument and an aircraft-to-aircraft occultation demonstration, with NASA providing the aircraft[23]. While the aircraft demonstration never occurred due to funding limitations, this effort successfully developed a prototype ATOMMS instrument that probed both the 22 and 183 GHz water vapor absorption

lines and has been used to demonstrate a number of key ATOMMS capabilities through ground measurements[31,32].

The LMO concept was also translated to Mars in a mission concept named Mars Atmospheric Climate Observatory (MACO) whose development began with seed funding from NASA in 2000[33]. MACO was designed to characterize the Martian atmosphere and climate, and in particular, its hydrological, CO_2, methane, energy and dust cycles using satellite-to-satellite microwave occultation complemented by solar occultation and IR and microwave thermal radiance observations.

In Europe, the retrieval strategy to separate water vapor from the temperature in the troposphere by adding Ku-band signal crosslink measurements was proposed as early as in 1996, as part of the first End-to-end GNSS Occultation Performance Simulator (EGOPS) functionality definition document for ESA[34]. Responding to an ESA call for Earth Explorer Core Missions, a mission named Water vapor and Temperature in the troposphere and Stratosphere (WATS) was proposed by a European consortium in 2001[35]. The WATS LMO concept was subsequently combined with an earlier GNSS RO mission concept (named Atmosphere Climate Experiment, ACE) in a new mission proposal, the so-called Atmosphere and Climate Explorer Plus (ACE^+), selected as top priority in ESA's 2nd Call for Earth Explorer Opportunity Missions in 2001[36,37].

ACE^+ was selected for Phase A studies taking place from 2002 to 2004, but was not continued after a mission down-selection round in 2004 though the scientific and technical feasibility studies showed the potential for implementation. A comprehensive summary of the results coming out of the ACE^+ Phase A study[38] can be found. Two other microwave occultation studies, namely Alternative Measurement Techniques for LEO-LEO Radio Occultation (AlMeTLEO) [39,40] and Galileo Atmospheric Data Enhancement Mission (GADEM)[41,42], were funded by ESA and EU respectively from 2004 to 2006.

In late 2004, the Atmospheric Climate and Chemistry in the UTLS Region And climate Trends Explorer (ACCURATE) mission was conceived at Wegener Center (WEGC), which inherited the LMO technique from the ACE^+ mission and employed a novel concept of LIO yielding LEO-LEO Microwave and Infrared-laser Occultation (LMIO)[25]. This initial ACCURATE mission concept was submitted to an ESA selection process for the next Earth Explorer Missions in 2005[43−45]. Although ACCURATE was not selected for a Phase A study, it received very positive evaluation and was recommended for further development and demonstration[25]. Therefore, a project called Aid to ACCURATE Climate Satellite Mission Preparations (ACCURAID) was supported by the Austrian Aeronautics and Space Agency from 2005 to 2007, which resulted in refinement of the mission concept and consolidation of its instrumentation[44].

In 2010, a more mature mission concept was then proposed to ESA in response to the Call for Proposals for Earth Explorer Opportunity Mission EE-8[27]. It was not selected but highly rated again and therefore supported for further studies, in particular, ground-based demonstration of infrared-laser occultation. Such initial ground-based demonstration of the LIO method was conducted by a campaign at the Canary Islands in 2011[46,47], which was funded by the ESA's Support to Science Element (STSE) and supported by the Earth Observation Future Missions program, including ESA's OGS facility.

Yinghuo-1 (YH-1) is a microsatellite developed by Chinese Aerospace Industry, and planned to be launched together with Russian spacecraft, Phobos-Grunt, to a Mars orbit to explore the Martian space environment. A satellite-satellite occultation experiment had been planned for the collaboration, radio frequencies of the signals are near 415.5 MHz and 833 MHz would be transmitted by Phobos-Grunt and received by the YH-1 micro-satellite to carry out the occultation experiment[48]. The joint Chinese-Russian satellite-to-satellite Martian radio occultation experiment to be used to sound the Martian ionosphere to derive electron density profiles. Compared with the satellite-to-Earth radio occultation technique, the satellite-to-satellite radio occultation

technique has a better ability to receive a higher signal-to-noise ratio radio signal and acquire more accurate profiles in a wider range (especially in areas of solar zenith angle of less than 43° and angle of larger than 138°). The flight models of the satellite-satellite transmitter and receiver were developed by Russia and NSSC of CAS, respectively. The indoor testing of the transmitter and receiver showed that both of them were working well. However, they were not successfully launched into the Martian orbit in 2011.

There have been many GNSS RO missions and their data produces have been widely used for NWP and GCM. Nowadays, clear evidence emerges from the range of studies reviewed in this paper that the LEO-LEO occultation performance for pressure, temperature, and water vapor retrievals can meet NWP and GCM requirements; and the data processing software and instrument studies indicate mission feasibility. However, there is no space-borne LEO-LEO occultation mission so far.

3 Measurement Principles and Retrieval Methodologies

3.1 Measurement Principles and Retrieval Approach

As an advanced occultation technique beyond GNSS RO, LMO promises to solve the temperature-humidity ambiguity problem by exploiting both the refraction and absorption of various X/K and M band signals transmitted between transmitters and receivers onboard LEO satellites[19,49]. Additionally, the frequencies close to 195 GHz can be used to observe ozone profiles[19]. The LMO measurement principle can be assumed to have reached a quite high level of maturity from a technical point of view and exhibits a high level of robustness.

The LIO technique uses laser signals in the Short-Wave Infrared (SWIR) band 2∼2.5 μm between LEO satellites, to accurately observe key trace species for chemistry and climate (*i.e.*, greenhouse gases H_2O, CO_2, CH_4, N_2O, O_3, CO, including key isotopes), line-of-sight wind speed, and also profiles of cloud layers and aerosols as by-products[25,50].

ACCURATE combines the highly synergetic LMO and LIO techniques into LEO-LEO Microwave and Infrared-laser Occultation (LMIO), in which the LMO thermodynamic state retrieval output is the input for the LIO greenhouse gases and line-of-sight wind retrieval, to guarantee the self-calibrating and independent characteristics of the full mission concept[15]. Therefore, the LMIO occultation technique not only inherits the GNSS RO's positive features, *e.g.*, global coverage, high vertical resolution, long-term stability, and self-calibration, but also can independently provide a full state vector of thermodynamic variables, wind speed, and trace gas species of the atmosphere[15]. The LIO observation principle poses more challenges from a technical point of view than the LMO approach. Nevertheless, the technical advances during the last years concerning seed lasers, amplifiers, and integrated fiber technology would allow implementing such an instrumentation with a good prospect of success. Figure 3 shows this synergistic combination of the LMO and LIO retrieval procedures based on the work of Proschek *et al*[51].

3.2 LMO Retrieval Methodology and Algorithms

The LMO technique can independently retrieve thermodynamic state variables *i.e.*, pressure, temperature, and humidity by using complex refractivity, of which the real and imaginary parts can be inverted from phase and amplitude measurements, respectively, by using suitable Abel transforms.

The real part of the refractive index as a function of impact parameter a can be retrieved by using the classical refractive Abel transform,

$$n'(a) = \exp\left[\frac{1}{\pi}\int_a^\infty \frac{\alpha(x)}{\sqrt{x^2-a^2}}\mathrm{d}x\right], \tag{1}$$

where α is the bending angle.

The difference in volume absorption coefficient, Δk, as a function of impact parameter, a, can be retrieved through an absorptive Abel transform[19]

$$\Delta k(a) = -\frac{1}{\pi}\frac{\mathrm{d}a}{\mathrm{d}r}\int_a^\infty \frac{\mathrm{d}\Delta\tau/\mathrm{d}x}{\sqrt{x^2-a^2}}\mathrm{d}x. \tag{2}$$

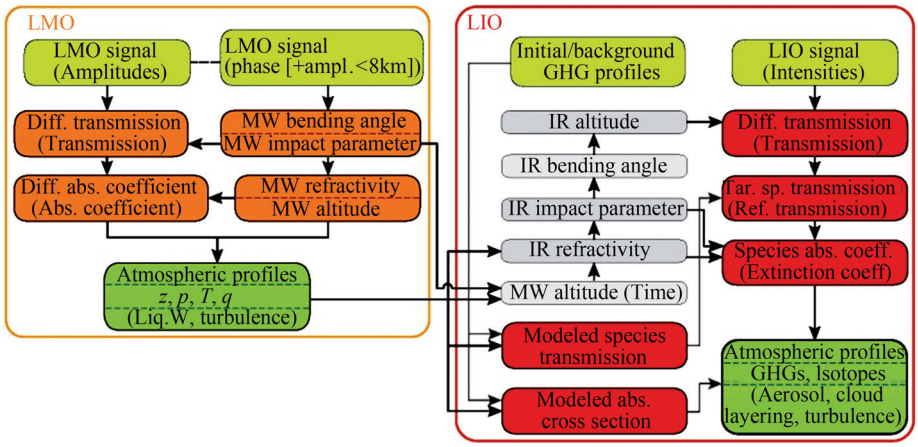

Fig. 3 LMIO retrieval processing chain

The above-retrieved refractivity and differential absorption coefficient profiles are finally used to derive the atmospheric profiles of pressure, temperature, and water vapor partial pressure.

3.3 LIO and LMIO Retrieval Methodology and Algorithms

As shown in Figure 3, the LMIO technique synergistically combines LMO and LIO to retrieve profiles of atmospheric thermodynamic variables, greenhouse gases, and line-of-sight wind velocity in the UTLS.

In order to mitigate the effects of foreign species absorption (the species that are not retrieved target species), aerosol extinction, scintillation, Rayleigh scattering, *etc.*, on the retrieved atmospheric trace gas profiles, the LIO technique utilizes the differential transmission principle between carefully selected pairs of absorption and reference signals. That is

$$T_{\mathrm{r}}(a) = T_{\mathrm{r,abs}}(a) - T_{\mathrm{r,ref}}(a). \tag{3}$$

Then the target species absorption coefficient profile $k(z)$ can be derived from such a target species transmission profile $T_{\mathrm{r}}(a)$ by the absorptive Abel transform

$$k(z_i) = \frac{1}{\pi}\frac{\mathrm{d}a}{\mathrm{d}r}\Big|_{a=a_i}\int_{a_i}^{a_{\mathrm{top}}} \frac{\mathrm{d}\ln T_{\mathrm{r}}(a)}{\mathrm{d}a}\frac{1}{\sqrt{a^2-a_i^2}}\mathrm{d}a. \tag{4}$$

Then the target species VMR profile $V(z)$ can finally be calculated as

$$V(z) = 10^6 R\frac{k(z)}{\sigma(z)}\frac{T(z)}{p(z)}, \tag{5}$$

where R is the universal molar gas constant, $\sigma(z)$ is the modeled molar absorption cross section of the target species, and T and p are the temperature and pressure profiles (from LMO).

Another essential complementary retrieval part, integrated into the LIO retrieval, is line-of-sight wind profiling[52].

A detailed description of the LMO, LIO and LMIO measurement approaches and detailed algorithm descriptions of the steps in the retrieval processing chain are provided by Liu *et al*[53].

4 CACES Mission

According to the challenging requirements of climate science that are addressed in Section 2, it's significant to monitor the atmospheric thermodynamic state variables (*i.e.*, pressure, temperature and humidity), greenhouse gases (*i.e.*, H_2O, CO_2, CH_4, N_2O, O_3, *etc*), and line-of-sight wind speed with improved accuracy and resolution as benchmark climate data. In this context, a concept mission named Climate and Atmospheric Composition Exploring Satellites (CACES) has been proposed by Lü Daren and Wang Xin and accepted by Strategic Priority Research Program of Chinese Academy of Sciences (SPRPCAS) in 2016 for observing the benchmark climate data.

Moreover, the optimized payload configuration and design enable CACES mission to observe the

atmosphere using LEO-LEO occultation, as well as Clouds and Water Vapor Imager (CWAVI) camera nadir imaging techniques, which can provide global coverage, high vertical and horizontal resolution atmospheric observations. The CWAVI camera imaging is also valuable to best interpret the LMIO data, isolate the cloud information, *etc.*, and facilitates the processing.

If CACES mission will be selected and implemented in 5 years, it would be the first scientific satellite mission to combine the LEO-LEO occultation and nadir imaging techniques for benchmark climate observations in the world.

4.1 Scientific Objectives

Based on the high observation accuracy and high vertical resolution benchmark climate datasets, one can investigate the climatic, as well as atmospheric physical and chemical scientific issues. So the scientific objectives of this mission are as following.

(1) To monitor the multiple parameters simultaneously with high accuracy, high vertical resolution, to provide a new understanding of spatial-temporal distribution and variation.

(2) To know the transport and exchange of atmospheric water vapor, liquid water, possibly including ice crystals, in clouds under strong convections.

(3) To reveal the physical and chemical processes of different atmospheric composition at the key interface between troposphere and stratosphere, and to study their impacts and feedbacks on global climate change.

(4) To study the impact of atmospheric composition change on the Earth's ecosystem and the interaction mechanisms.

4.2 Orbit and Spacecraft

CACES mission will use Sun Synchronous/near-polar counter-rotating Orbits (SSO) of transmitter and receiver satellites. The higher orbit is 550 km and the lower one is 500 km, both crossing each other. Two transmitter satellites flying in the higher orbit and two receiver satellites flying in the lower orbit. Figure 4 shows the orbit simulation. Table 3 shows the constellation parameters in terms of the orbit height, inclination, time of descending node and period.

Based on the CACES mission orbit parameters shown in Table 3, an LEO-LEO occultation events simulation has been conducted, and Figure 5 shows the LEO-LEO occultation events distribution and statistics. One can see that, in 72 h, the occultation events cover the Earth very well, and have a good spatial distribution in different latitude zones.

After a carefully design, the preliminary accommodation design is completed, which demonstrates the feasibility of the design of CACES satellites. Figure 6 illustrates the satellite configuration, launch accommodation and in-orbit accommodation of CACES satellites, which take a transmitter satellite as an example (the other three satellites are quite similar to this one).

With the designed accommodation, the Kuaizhou-11 launcher would be selected, which have the capability of maximum mass of 1100 kg for 550 km SSO orbit. It is sufficient to launch two of the CACES transmitter (or receiver) satellites at one time. Two

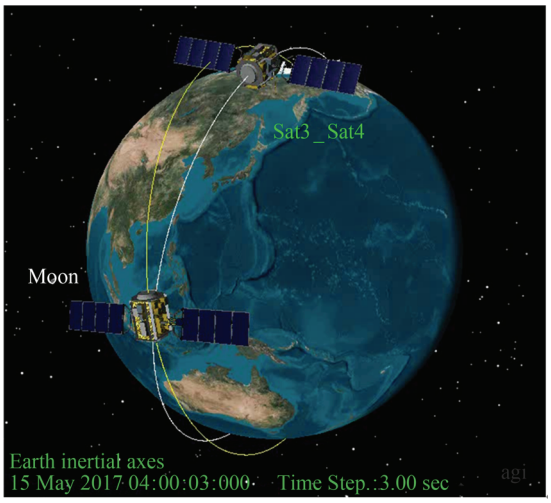

Fig. 4 CACES orbits

Table 3 Orbit parameters of CACES mission

Orbits	$2\,R_x$	$2\,T_x$
Height/km	500	550
Eccentricity	0	0
Inclination/(°)	97.41	97.60
LT*	12:00	00:00
Period/s	5676.98	5738.99

Remarks: * Time of descending node.

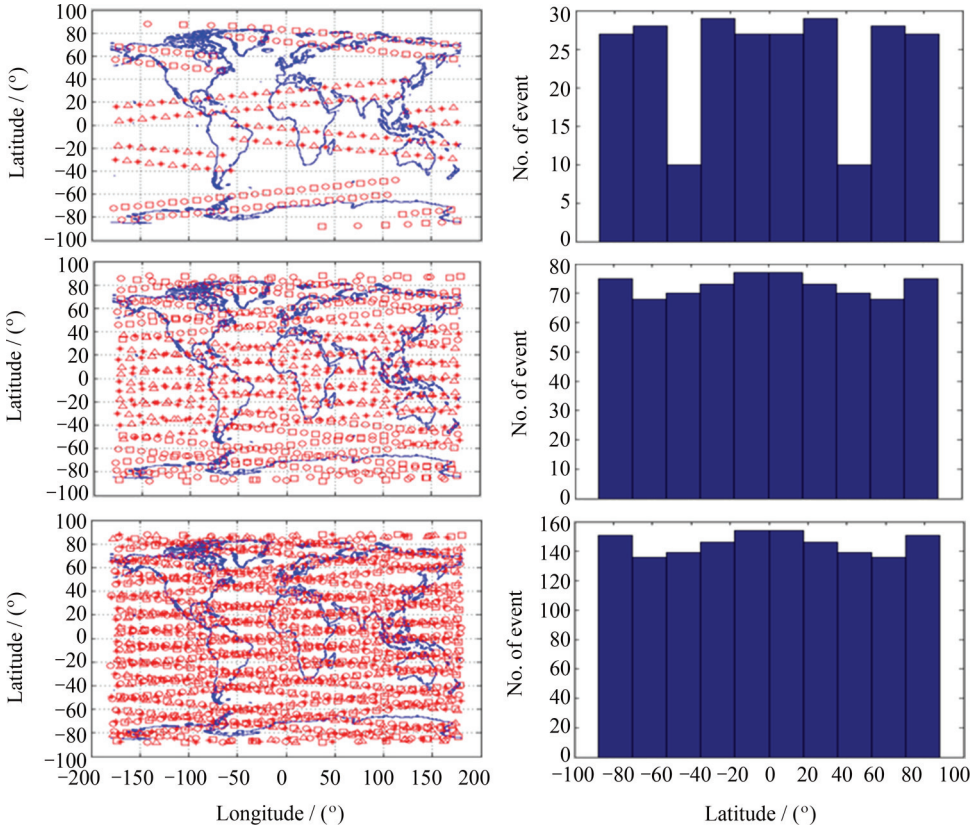

Fig. 5 Global distribution and statistical analysis of the LEO-LEO occultation events of CACES mission for 24, 72, 144 h

launch sites, *i.e.*, Jiuquan and Taiyuan in China can be used for launching the satellites, where lots of meteorological, oceanic satellites have been launched in the last three decades.

4.3 Mission Concept and Payloads Designs

In order to achieve the scientific objectives, CACES combines the microwave and infrared laser occultation and clouds and water vapor imager techniques. LMO and LIO limb sounding for vertical profiles of T, P, W_v, CO_2, CH_4, *etc.*, at the high vertical resolution, and the complemented CWAVI camera for down-looking multi-angle images over occultation event regions. Two Visible and Near-Infrared (VIS-NIR) channels (near about 0.6 μm and 0.9 μm) and two Thermal Infrared channels (near about 7 μm and 11 μm), each just yielding 320×240 pixels 8-bit camera sensor images with about 1 km resolution in nadir view; for imaging clouds and water vapor in the LEO-LEO occultation event plane region about tangent point locations at three angles (+45°, nadir, −45°) during T_x and/or R_x over-flight. Table 4 summarizes the CACES mission main observations and their accuracy and resolution requirements. Table 5 shows the technical parameters of the CACES satellites and payloads.

After a frequency selection and performance estimation study, a pair of prototype LMO transmitter and receiver (Figure 7) has been manufactured at NSSC, and a mountain-based LMO experiment is being prepared. Table 6 shows the technical parameters of the LMO instruments.

5 Next Steps to Realize the CACES Mission

5.1 Recommendations from the Forum to the CACES

In this 2-day ISSI Beijing forum on 24—25 July 2019, particularly the discussion sessions, the CACES research team obtained lots of valuable and construc-

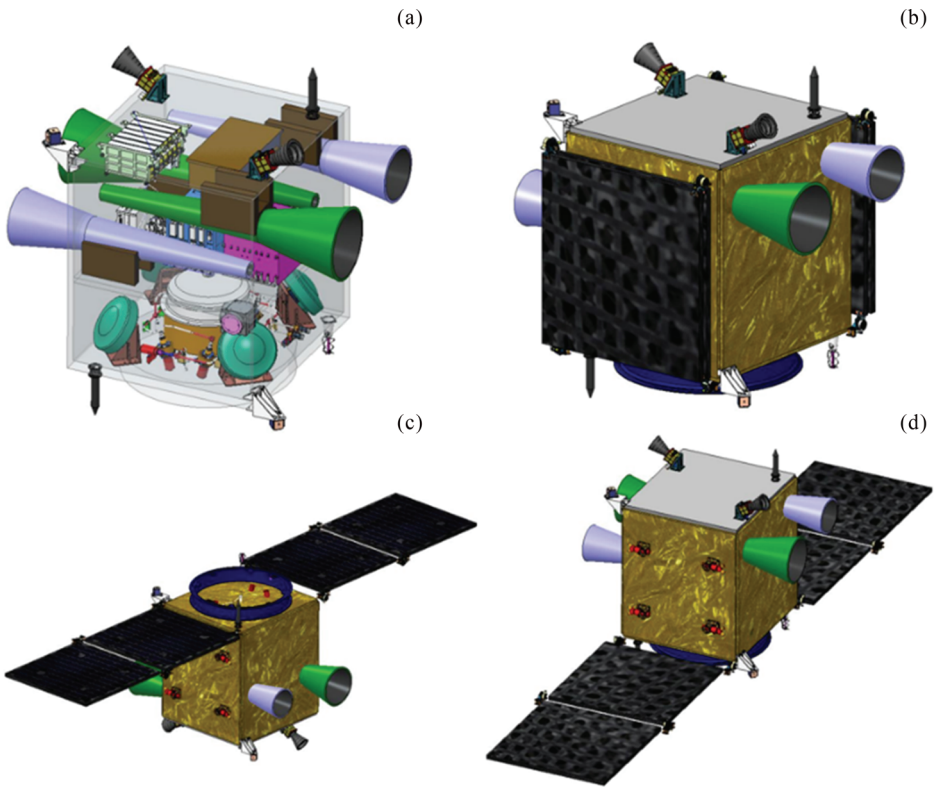

Fig. 6 CACES mission satellites in different scenarios. (a) Satellite configuration, (b) launch accommodation, (c) (d) in-orbit accommodation



Fig. 7 LMO transmitter, receiver, and antenna made by NSSC

tive recommendations in the following aspects.

5.1.1 To Specify the CACES Mission Scientific Objectives

As the first and pioneering scientific experimental LEO-LEO occultation mission, it is better to focus the scientific objectives, to demonstrate this brand new LEO-LEO occultation atmospheric observation techniques scientifically and technically. And the fairly simple CWAVI camera instrument would provide high added value for an LMO-focused mission.

5.1.2 To Select Key Observation Variables

In order to achieve the specified scientific objectives, the thermodynamic state variables *i.e.*, temperature, water vapor and density will be measured by LMO. For the greenhouse gases, it is better to profile the major greenhouse gases such as CO_2, CH_4, instead of observing all the atmospheric composition.

5.1.3 To Select Specific Channels

For implementing this first LEO-LEO technical demo mission scientifically and economically, it is better to reduce the number of frequency channels to observe essential climate variables, *e.g.*, LMO to select the 23 GHz water vapor absorption band frequency channels to detect the thermodynamic state variables *i.e.*, temperature, water vapor, and density. And for LIO,

Table 4 CACES mission observation requirements

		LMO				LIO			
		Temperature		Specific humidity		Trace species		Line-of-sight wind	
Requirement		TA	TH	TA	TH	TA	TH	TA	TH
VD/km		1∼80	3∼40	1∼15	3∼10	5∼40	5∼30	5∼40	5∼30
VSR/km	LT	0.5	1	0.5	1	0.5	1	0.5	1
	UT	0.5	1	0.5	1	0.5	1	0.5	1
	LS	0.5	1	0.5	1	0.5	1	0.5	1
	US	1	2	–	–	1	2	1	2
RMS	LT	Best-effort basis				Best-effort basis			
	5∼10 km	1 K	2 K	10%	20%	To be confirmed			
	10 km (TP)	0.5 K	1 K	10%	20%				
	LS	0.5 K	1 K	10%	20%				
	US	1.5 K	3 K	–	–				

Remarks: TA (Targe), TH (Threshold), VD (Vertical Domain), VSR (Vertical Sampling Resolution), RMS (RMS of Accuracy).

Table 5 Technical parameters of the CACES satellites and payloads

System		Mass/kg	P_{mean}/W	P_{peak}/W
Platform	AOCS	30.00	40.00	76.0
	Power	28.00	10.00	10.0
	Satellite keeping	8.00	12.00	12.0
	Measurement control	6.00	23.00	23.0
	Data transmission	8.00	6.00	60.0
	Structure	80.00	0.00	0.0
	Thermal	7.00	30.00	40.0
	Cables	9.00	–	–
	Orbit control	15.00	–	–
	Propellant	15.00	–	10.0
Payloads	LIO (T_x/R_x)	60/40	5/4	100/30
	LMO (T_x/R_x)	40/30	5/4	50/30
	In total (T_x/R_x)	306/276	131/129	381/291

Remarks: AOCS (Attitude and Orbit Control System)

Table 6 Technical parameters of LMO transmitter and receiver

Frequency/GHz	9.4	14.6	17.4	22.6
Antenna gain/dB	$\geqslant$ 26	$\geqslant$ 27.5	$\geqslant$ 28.5	$\geqslant$ 30
Transmit power/W	$\geqslant$ 2	$\geqslant$ 2	$\geqslant$ 2	$\geqslant$ 2
Amplitude measurement accuracy	Less than 0.022 dB (0.5%) RMS (within 15 s)			
Phase measurement accuracy	Better than 1% per cycle			
Clock short-term frequency stability	Better than $10^{-12}\,\mathrm{s}^{-1}$			
Sampling rate/Hz	$\geqslant$ 500			
Weight/kg	30 (T_x, R_x)			
Power consumption/W	60 (T_x), 40 (R_x)			
Antenna size/mm	X/Ku: Internal diameter 270, Length 920 Ku/K: Internal diameter 200, Length 900			

to select the specific infrared frequency pairs to sound the CO_2 and CH_4 profiles. This would mean to focus on the LIO observation on a narrow band at the shorter end of the wavelength interval of interest.

5.1.4 To Investigate the LMO Measurement Capabilities at High Altitude

Previously, the CACES was proposed to explore the thermodynamic state variables and greenhouse gases from the near Earth surface to about 40 km altitude. Since the microwave frequencies are affected by the ionosphere slightly, it has the potential to measure the higher atmosphere accurately. The discussion concluded that the K band signal LEO-LEO occultation can detect the higher atmospheric temperature and density, further validation and analysis should be conducted.

5.2 SPRPCAS Candidate Mission Application for CACES

As a new concept satellite mission in China, CACES has been studied as a half-year concept design project in 2017, and then as a 2-year feasibility research project from 2018 to 2019.

The next step, at the end of 2019, is the SPRPCAS candidate mission application for CACES according to the recommendations from this ISSI Beijing forum. If the CACES mission will be selected and funded as a SPRPCAS candidate mission study, then according to the study outcomes, it will probably be listed in the preparing for launch SPRPCAS missions.

In terms of scientific, satellites and instruments research, the CACES science team will continue the studies according to this ISSI Beijing forum discussions and recommendations.

6 International Collaborations and Further Mission Activities

6.1 Collaborations for CACES Mission

Climate change and monitoring are international issues. The scientific outlook of CACES is consistent with several planned international satellite missions. CACES gives much more emphasis on integrated scientific aims through synchronous and highly accurate observations for essential climate variables. This forum provided a good opportunity to discuss and establish an international collaboration working group for CACES. Detail information about international collaboration will be described in the following.

The CACES Science Team will collaborate extensively with international partners in retrieval algorithm development. For the LMO thermodynamic state variables retrieval, the science team will collaborate closely with that of WEGC and DMI. The CACES science team will also collaborate with WEGC for the infrared laser occultation retrieval. Preliminary collaborating work has been undertaken in the development of a simulator for CACES through utilizing the EGOPS software.

For the instrument development, the CACES instrument team from the NSSC of CAS has established a good collaboration relationship with WEGC and ESA is aware of the ongoing activities following them with interest and is prepared to support the European side of the collaboration.

After launch, for the product validation, international partners are encouraged to participate in these experiments in the future. As all CACES products will be freely released to the community. The ultimate and challenging scientific aim of CACES can only be achieved with the effort of the whole community. The expected CACES data set has the potential to raise significant international interest and exhibit the potential of high scientific value and visibility.

6.2 Collaboration Activities Independent of CACES Mission

Besides the CACES mission, as an LEO-LEO occultation scientific and technical international work group, we will collaborate to improve the LEO-LEO occultation technique and its applications further through the following activities.

(1) Establishment of a better LEO-LEO occultation simulation system and retrieval approaches.

(2) Continue to hold LEO-LEO occultation workshops or forums for further discussions and other outreach activities.

(3) Publish relevant journal papers.

(4) Foster international exchange by building up

and maintaining a group of experts.

(5) Application of other international co-funding projects to achieve an LEO-LEO occultation mission.

7 Summary and Outlook

The CACES satellite mission focuses on benchmark climate and atmospheric composition observation, as well as the atmospheric physics/chemistry and their impact and feedbacks on global climate change research. If implemented, CACES will be the first space-born mission that combines the limb sounding, nadir down looking, multi-microwave, multi-infrared channels measurements on essential climate variables. Through the development of a combination of multi-frequency sensors, we are able to develop high performance retrieval algorithms based on synergetic use of multi-source data. The implementation of the CACES mission will significantly improve the capability for high accuracy and high vertical resolution observation of the atmospheric thermodynamic and composition variables. Improved atmosphere observation capabilities will significantly drive the development of many branches of Earth system science research, thereby improving the ability of global change trend prediction and better understanding the impacts and feedbacks among the atmospheric variables, human activities and climate change.

In China, the series of Fengyun meteorological satellites is developing rapidly. On one hand, together with the Fengyun atmospheric measurements, particularly the GNSS RO observations, the CACES mission would be a very important contributor to the global climate change research as a benchmark climate data provider. In that respect, the CACES mission has a significant potential to achieve a very high level of international visibility and will raise the potential for international collaboration at several levels. On the other hand, after demonstrated through CACES mission, the LEO-LEO occultation will be a powerful atmospheric observation technique for the operational Fengyun satellites to enhance the numerical weather prediction and climate monitoring capabilities.

Acknowledgement The content of this paper is based on the contributions presented at the ISSI-Beijing forum on exploring greenhouse gases, water and climate changes by LEO-LEO occultation, which was held on 24—25 July 2019 in Beijing. The authors are grateful to all the participants for their contribution, namely, FAN Quanlin, CAHOY Kerri, CHENG Long, DU Xiaoyong, LIAO Mi, LIU Yan, LIU Lijun, MENG Xiangguang, TIAN Yufang, WAMG Xianyi, WICKERT Jens, XIA Junming, YANG Guanglin, YANG Zhongdong, ZHAO Danyang. Special thanks are given to Prof. FALANGA Maurizio, Executive Director of ISSI-Beijing, for his great effort and high efficiency in organizing the successful forum, as well as EN Lijuan, BONNET Anna and BALDIS Laura.

References

[1] KLIORE A, CAIN D L, LEVY G S, *et al*. Occultation experiment: results of the first direct measurement of Mars's atmosphere and ionosphere [J]. *Science*, 1965, **149**(3689): 1243-8

[2] KURSINSKI E R, HAJJ G A, BERTIGER W I, *et al*. Initial results of radio occultation observations of Earth's atmosphere using the global positioning system [J]. *Science*, 1996, **271**(5252): 1107-1110

[3] WICKERT J, REIGBER C, BEYERLE G, *et al*. Atmosphere sounding by GPS radio occultation: first results from CHAMP [J]. *Geophys. Res. Lett.*, 2001, **28**(17): 3263-3266

[4] BEYERLE G. GPS radio occultation with GRACE: atmospheric profiling utilizing the zero difference technique [J]. *Geophys. Res. Lett.*, 2005, **32**(13): L13806

[5] LUNTAMA J P, KIRCHENGAST G, BORSCHE M, *et al*. Prospects of the EPS GRAS mission for operational atmospheric applications [J]. *Bull. Am. Meteorol. Soc.*, 2008, **89**(12). DOI: 10.1175/2008BAMS2399.1

[6] ANTHES R A, ECTOR D, HUNT D C, *et al*. The COSMIC/FORMOSAT-3 mission: early results [J]. *Bull. Am. Meteorol. Soc.*, 2008, **89**(3): 313-333

[7] LIAO M, ZHANG P, YANG G L, *et al*. Preliminary validation of the refractivity from the new radio occultation sounder GNOS/FY-3C [J]. *Atmosph. Meas, Tech.*, 2016, **9**(2): 781-792

[8] SCHREINER W, ROCKEN C, SOKOLOVSKIY S, *et al*. Estimates of the precision of GPS radio occultations from the COSMIC/FORMOSAT-3 mission [J]. *Geophys. Res. Lett.*, 2007, **34**(4): L04808

[9] STEINER A K, HUNT D, HO S P, *et al*. Quantification of structural uncertainty in climate data records from GPS radio occultation [J]. *Atmos. Chem. Phys.*, 2013, **13**(3): 1469-1484

[10] SCHERLLIN-PIRSCHER B, STEINER A K, KIRCHENGAST G, *et al*. The power of vertical geolocation of

atmospheric profiles from GNSS radio occultation [J]. *J. Geophys. Res. Atmos.*, 2017, **122**(3): 1595-1616

[11] HEALY S B, THÉPAUT J N. Assimilation experiments with champ GPS radio occultation measurements [J]. *Quart. J. Roy. Meteorol. Soc.*, 2006, **132**(615): 605-623

[12] CUCURULL L, ANTHES R A. Impact of infrared, microwave, and radio occultation satellite observations on operational numerical weather prediction [J]. *Mon. Weather Rev.*, 2014, **142**(11): 4164-4186

[13] APARICIO J M, LAROCHE S. Estimation of the added value of the absolute calibration of GPS radio occultation data for numerical weather prediction [J]. *Mon. Weather Rev.*, 2015, **143**(4): 1259-1274

[14] FOELSCHE U, PIRSCHER B, BORSCHE M, *et al.* Assessing the climate monitoring utility of radio occultation data: from CHAMP to FORMOSAT-3/COSMIC [J]. *Terr. Atmos. Ocean. Sci.*, 2009, **20**: 155-170

[15] LACKNER B C, STEINER A K, HEGERL G C, *et al.* Atmospheric climate change detection by radio occultation data using a fingerprinting method [J]. *J. Clim.*, 2011, **24**: 5275-5291

[16] KURSINSKI E R, HAJJ G A, SCHOFIELD J T, *et al.* Observing Earth's atmosphere with radio occultation measurements using the global positioning system [J]. *J. Geophys. Res.*, 1997, **102**: 23429-23465

[17] YUNCK T P, HAJJ G A, KURSINSKI E R, *et al.* AMORE: an autonomous constellation concept for atmospheric and ocean observation [J]. *Acta Astron.*, 2000, **46**(2/3/4/5/6): 355-364

[18] HAJJ G A, KURSINSKI E R, ROMANS L J, *et al.* A technical description of atmospheric sounding by GPS occultation [J]. *J. Atmos. Sol.: Terr. Phy.*, 2002, **64**: 451-469

[19] KURSINSKI E R, SYNDERGAARD S, FLITTNER D, *et al.* A microwave occultation observing system optimized to characterize atmospheric water, temperature and geopotential via absorption [J]. *J. Atmos. Ocean. Technol.*, 2002, **19**(12): 1897-1914

[20] KIRCHENGAST G, HOEG P. The ACE$^+$ Mission: an Atmosphere and Climate Explorer Based on GPS, GALILEO, and LEO-LEO Radio Occultation [M]//Occultations for Probing Atmosphere and Climate. Berlin Heidelberg: Springer, 2004: 201-220

[21] GORBUNOV M E, KIRCHENGAST G. Processing X/K band radio occultation data in the presence of turbulence [J]. *Radio Sci.*, 2005, **40**(6). DOI: 10.1029/2005rs003263

[22] GORBUNOV M E, KIRCHENGAST G. Fluctuations of radio occultation signals in X/K band in the presence of anisotropic turbulence and differential transmission retrieval performance [J]. *Radio Sci.*, 2007, **42**(4). DOI: 10.1029/2006rs003544

[23] KURSINSKI E R, WARD D, OTAROLA A, *et al.* The Active Temperature, Ozone and Moisture Microwave Spectrometer (ATOMMS) [M]//New Horizons in Occultation Research: Studies in Atmosphere and Climate. Berlin: Springer, 2009: 295-313

[24] FENG D D, SYNDERGAARD S, HERMAN B M, *et al.* Deriving atmospheric water vapor and ozone profiles from active microwave occultation measurements [J]. *Sens., Syst., Next-Gener. Satellites IV*, 2000, **4169**: 299-308

[25] SCHWEITZER S, KIRCHENGAST G, SCHWAERZ M, *et al.* Thermodynamic state retrieval from microwave occultation data and performance analysis based on end-to-end simulations [J]. *J. Geophys. Res.*, 2011, **116**: D10301

[26] KIRCHENGAST G, SCHWEITZER S. Climate benchmark profiling of greenhouse gases and thermodynamic structure and wind from space [J]. *Geophys. Res. Lett.*, 2011, **38**(13): 142-154

[27] KIRCHENGAST G, BERNATH P, BUEHLER S, *et al.* ACCURATE-Climate Benchmark Profiling of Greenhouse Gases and Thermodynamic Variables and Wind from Space (ESA Earth Explorer Opportunity Mission EE-8 Proposal) [R]. Graz: Wegener Center Verlag, 2010

[28] SYNDERGAARD S, RUBEK F, SCHWEITZER S, *et al.* Review of Active Occultation Techniques from L-Band to the SW-Infrared [R]. Copenhagen: DMI, 2009

[29] HAJJ A G, KURSINSKI E R, Walter S J. Examining the Appropriate GPS Science Signal Suitable for Radio Occultation Measurements of Atmospheric Water Vapor (Abstract G22C-04) [R]. AGU Fall Meeting, 1997

[30] HERMAN B, FENG D, XUN X. GPS Remote Sensing Using a Third Frequency for Water Vapor Profiles of the Atmosphere (Abstract G22C-05) [R]. AGU Fall Meeting, 1997

[31] KURSINSKI E R, WARD D, STOVERN M, *et al.* Development and testing of the active temperature, ozone and moisture microwave spectrometer (ATOMMS) cm and mm wavelength occultation instrument [J]. *Atmos. Meas. Tech.*, 2012, **5**(2): 439-456

[32] KURSINSKI E R, WARD D, OTAROLA A C, *et al.* Atmospheric profiling *via* satellite to satellite occultations near water and ozone absorption lines for weather and climate [C]//Earth Observing Missions and Sensors: Development, Implementation, and Characterization Iv, 2016

[33] KURSINSKI E R, FOLKNER W, ZUFFADA C, *et al.* The Mars Atmospheric Constellation Observatory (MACO) Concept, in Occultations for Probing Atmosphere and Climate [M]. Berlin-Heidelberg-New York: Springer, 2004: 393-405

[34] KIRCHENGAST G. End-to-end GNSS Occultation Performance Simulator Functionality Definition-EGOPS [R]. Inst. Meteorol. Geophys., Univ of Graz, Austria, 1996

[35] WATS-Water Vapor and Temperature in the Troposphere and Stratosphere (3rd report of Reports for Mission Selection [R]. Noordwijk: Spec. Public, 2001

[36] HOEG P, KIRCHENGAST G. ACE$^+$-Atmosphere and Climate Explorer Based on GPS, GALILEO, and LEO-LEO Radio Occultation (ESA Earth Explorer Opportunity Mission Proposal) [R]. Graz: University of Graz, 2002

[37] KIRCHENGAST G, HOEG P. The ACE$^+$ Mission:

an Atmosphere and Climate Explorer Based on GPS, GALILEO and LEO-LEO Radio Occultation. In Occultations for Probing Atmosphere and Climate [M]. Berlin-Heidelberg-New York: Springer, 2004: 201-220

[38] KIRCHENGAST G, SCHWEITZER S, GORBUNOV M E, *et al.* The ACE$^+$ Phase A Scientific Support Study ACEPASS-LEO-LEO Occultation Characterisation Study (Summary Report) [R]. Graz: University of Graz, 2005

[39] CUCCOLI F, FACHERIS L. Global water vapor estimate in the lowest troposphere by attenuation measurements on LEO-LEO satellites at 17.25 GHz [C]//IGARSS 2004: IEEE International Geoscience and Remote Sensing Symposium Proceedings, 2004: 2748-2751

[40] FACHERIS L, CUCCOLI F, ARGENTI F. Normalized Differential Spectral Attenuation (NDSA) measurements between two LEO satellites: performance analysis in the Ku/K-bands [J]. *IEEE Trans. Geosci. Remote Sens.*, 2008, **46**(8): 2345-2356

[41] SCHWÄRZ M, RAMSAUER J, KIRCHENGAST G. End-to-end Scientific Performance Analysis for Retrieval of Atmospheric Data from GALILEO K-band Radio Links [R]. Graz: University of Graz, 2006

[42] KIRCHENGAST G, SchwÄrz M. Scientific Applications of GaliLEO K-bandRadio Links [R]. GJU GADEM Project-Tech. Note WP1200, 2006: 16

[43] KIRCHENGAST G. ACCURATE-Atmospheric Climate and Chemistry in the UTLS Region and Climate Trends Explorer, Earth Explorer Core Mission Proposal to ESA [R]. Graz: University of Graz, 2005

[44] KIRCHENGAST G, Schweitzer S. ACCURATE LEO-LEO Infrared Laser Occultation Initial Assessment: Requirements, Payload Characteristics, Scientific Performance Analysis, and Breadboarding Specifications [R]. Graz: University of Graz, 2007

[45] SCHWEITZER S. The ACCURATE Concept and the Infrared Laser Occultation Technique: Mission Design and Assessment of Retrieval Performance [R]. Graz: Wegener Center, 2010

[46] BROOKE J S A, BERNATH P F, KIRCHENGAST G, *et al.* Greenhouse gas measurements over a 144 km open path in the Canary Islands [J]. *Atmos. Meas. Tech.*, 2012, **5**(9): 2309-2319

[47] PROSCHEK V, KIRCHENGAST G, SCHWEITZER S, *et al.* Retrieval and validation of carbon dioxide, methane and water vapor for the Canary Islands IR-laser occultation experiment [J]. *Atmos. Meas. Tech.*, 2015, **8**(8): 3315-3336

[48] SUN Y Q, DU Q F, ZHU G W. Joint Russian-Chinese satellite-to-satellite martian radio occultation experiment [J]. *Chin. J. Space Sci.*, 2009, **29**(5): 475-479

[49] SCHWEITZER S, KIRCHENGAST G, PROSCHEK V. Atmospheric influences on infrared-laser signals used for occultation measurements between low Earth orbit satellites [J]. *Atmos. Meas. Tech.*, 2011, **4**(10): 2273-2292

[50] PROSCHEK V, KIRCHENGAST G, EMDE C, *et al.* Greenhouse gas profiling by infrared-laser and microwave occultation in cloudy air: Results from end-to-end simulations [J]. *J. Geophys. Res.*: *Atmos.*, 2014, **119**(21): 12372-12390

[51] PROSCHEK V, KIRCHENGAST G, SCHWEITZER S. Greenhouse gas profiling by infrared-laser and microwave occultation: retrieval algorithm and demonstration results from end-to-end simulations [J]. *Atmos. Meas. Tech.*, 2011, **4**(10): 2035-2058

[52] SYNDERGAARD S, KIRCHENGAST G. An Abel transform for deriving line-of-sight wind profiles from LEO-LEO infrared laser occultation measurements [J]. *J. Geophys. Res.*: *Atmos.*, 2016, **121**(6): 2525-2541

[53] LIU C L, KIRCHENGAST G, SYNDERGAARD S, *et al.* A review of low Earth orbit occultation using microwave and infrared-laser signals for monitoring the atmosphere and climate [J]. *Adv. Space Res.*, 2017, **60**(12): 2776-2811