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Review

Remote sensing using GNSS signals: Current status and future directions

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Abstract

The refracted, reflected and scattered signals of global navigation satellite systems (GNSS) have been successfully used to remotely sense the Earth's surface and atmosphere. It has demonstrated its potential to sense the atmosphere and ionosphere, ocean, land surfaces (including soil moisture) and the cryosphere. These new measurements, although in need of refinement and further validation in many cases, can be used to complement existing techniques and sensors, e.g., radiosonde, ionosonde, radar altimetry and synthetic aperture radar (SAR). This paper presents the current status and new developments of remote sensing using GNSS signals as well as its future directions and applications. Some notable emerging applications include monitoring sea ice, dangerous sea states, ocean eddy and storm surges. With the further improvement of the next generation multi-frequency GNSS systems and receivers and new space-based instruments utilizing GNSS reflections and refractions, new scientific applications of GNSS are expected in various environment remote sensing fields in the near future.

Keywords: GNSS; Remote sensing; Refractometry; Reflectometry; Bistatic radar

Contents

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1. Introduction

The Global Positioning System (GPS)[1] has provided an unprecedented high accuracy, flexibility and tremendous contribution to navigation, positioning, timing and scientific questions related to precise positioning on Earth's surface, since it became fully operational in 1993. For example, the southern California Permanent GPS Geodetic Array (PGGA) was the first established in early 1990s across the Pacific-North America plate boundary to continuously monitor crustal deformation, providing the first temporal-spatial details of crustal movements before, during and after a major earthquake (Bock et al., 1997). Since GPS is highly precise, continuous, all-weather and real-time with signals that travel through the Earth's atmosphere, additional scientific applications of GPS were being explored by scientists and engineers. Notably, Ware (1992) suggested limb sounding the Earth's atmosphere and ionosphere using GPS atmospheric refracted delay signals. Following, the GPS/Meteorology Mission (GPS/MET) using the GPS radio occultation technique was launched and successfully provided accurate, all weather, global refractive index, pressure, temperature and the ionospheric total electron content (TEC) measurements and electron density profiles, which have been widely applied in the atmosphere and ionosphere (Rocken, 1997; Hajj and Romans, 1998).

In addition, as GPS's potential as a highly precise, continuous, all-weather and near-real-time microwave (L-band) bistatic radar became apparent more and wider applications began to emerge. One of the first proposals of this nature was PARIS (PAssive Reflectometry Interferometric System, also called GNSS-Reflectometry) which was designed to use GPS reflected signals from Earth's surface to act as multiple passive altimetric ranging signals. Following soon afterward was a proposal to use GNSS reflected signals from the sea as a bistatic scatterometer (Katzberg and Garrison, 1996). The wave height, wind speed and (occasionally) direction were determined from GNSS reflected signals under well developed sea conditions as well as soil moisture, snow and ice thickness (Komjathy et al., 2000; Rius et al., 2002; Germain et al., 2004; Masters, 2004; Komjathy et al., 2004; Belmonte-Rivas et al., 2010). Some new objectives and results of GNSS reflectometry and remote sensing have been presented by Jin and Komjathy (2010). It is expected that that the surface reflected and atmospheric refracted GPS signals will revolutionize various atmospheric sounding, ocean remote sensing and land/hydrology mapping, especially for various Earth's surfaces and the atmosphere.

With the development of the next generation of multi-frequency and multi-system GNSS constellations, including the U.S.'s modernized GPS-IIF and planned GPS-III, Russia's restored GLONASS, and the coming European Union's GALILEO system and China's Beidou/COMPASS system as well as a number of Space Based Augmentation Systems, such as Japan's Quasi-Zenith Satellite System (QZSS) and India's Regional Navigation Satellite Systems (IRNSS), more applications and opportunities will be exploited and realized using new onboard GNSS receivers on future space-borne GPS reflectometry and refractometry missions in the near future. In this paper, the current status of GNSS remote sensing in the atmosphere, oceans, land, hydrology and cryosphere is introduced. Furthermore, the future development of GNSS systems and receivers and planned missions of GNSS refractometry, reflectometry and scatterometry are presented as well as some new GNSS remote sensing applications.

2. Current status

GNSS satellites are constantly broadcasting radio signals to Earth's surface through the atmosphere. Ground-based, aircraft based and GPS receivers on Low Earth Orbit (LEO) satellites can receive refracted signals that travel through the atmosphere and reflected signals that scatter off the surface. The refracted and reflected signals can then be used to estimate the atmosphere and Earth surface characteristics. The current status of several GNSS remote sensing applications is discussed below.

2.1. Atmospheric sensing

Ground-based and space borne GPS observations have been widely used in atmospheric sounding, including sensing tropopsheric precipitable water vapor (PWV), ionospheric total electron content (TEC) and atmospheric profile information (e.g., pressure, temperature, humidity, tropopause and ionospheric electron density). These observations have facilitated greater advancements in meteorology, climatology, numerical weather model, atmospheric science and space weather (e.g., Jin et al., 2007; Jin and

[1] This paper contains a large number of abbreviations and acronyms. The abbreviations of GPS Occultation Missions are listed in Table 1. A list of acronyms is given in Appendix A.

Luo, 2009; Schmidt et al. 2010). For example, the dual frequency ground GPS array could detect ionospheric response and its processes during large geomagnetic storms (Jin et al., 2008). Meanwhile, ground GPS also observed the plasma bubbles and retrieved reliable propagation characteristics of the depletions without assumptions about the mapping of the depletion along magnetic field lines to large latitudinal distances, comparable with airglow data (Haase et al., 2011).

Additionally, space-borne GPS receivers have proven very successful in making high vertical resolution and global atmospheric measurements using the radio occultation (RO) technique (Ao, 2009). The existing GPS radio occultation (RO) missions (Table 1) have been widely used to estimate the detailed vertical profile information, including pressure, temperature, gravity waves and sporadic E-layers as well as their variation characteristics, particularly six satellites of the Taiwan/US FORMOSAT-3/COSMIC (FORMOsa SATellite mission-3/Constellation Observing System for Meteorology, Ionosphere and Climate) mission with more than 2000 radio occultation profiles per day. Schmidt et al. (2010) was the first to observe upper tropospheric warming and lower stratospheric cooling using GPS RO data (2001–2009) (Fig. 1). Although a number of progresses in atmospheric and ionospheric sensing have been made using GPS RO missions in the past few years, they still do not satisfy actual requirements for short-time scales and higher temporal-spatial resolution monitoring together with ground GNSS observations. For instance, the tropospheric or ionospheric profile information cannot be directly estimated from GPS tomography due to the lack of enough line-of-sight GPS signals passing each grid cell (Jin et al., 2006; 2008; Nesterov and Kunitsyn, 2011). Moreover, most current RO satellite missions are approaching their end of operations. With the increase of future GNSS satellite constellations and more GNSS RO missions, the goal of improved temporal-spatial resolution will enable more detailed profile information and evolution processes of the atmosphere and ionosphere.

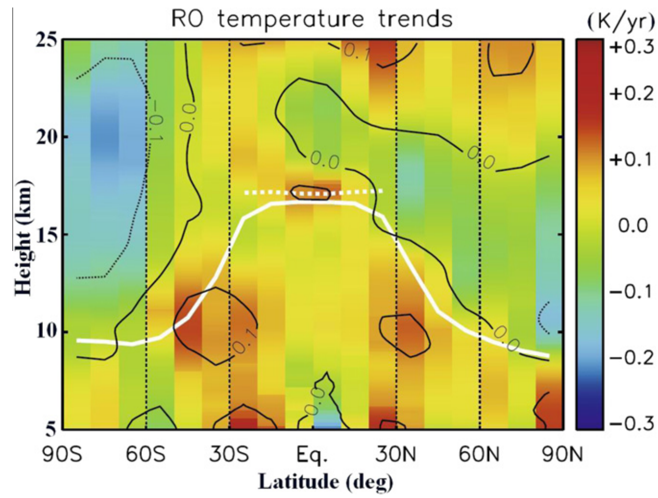

Fig. 1. Absolute temperature trends [K/yr] from CHAMP and GRACE data (May 2001-August 2009) (modified from Schmidt et al., 2010).

Table 1
Actual and planning GPS Radio Occultation missions.

Mission	Launch time	Profile per day	Country	Note
GPS/MET	April 1995	125	USA	First GPS /Meteorology radio occultation experiment
CHAMP	July 2000	250	Germany	CHAllenging Minisatellite Payload for gravity, magnetic and radio occultation
SAC-C	November 2000	300	USA/ Argentina	Satellite de Aplicaciones Cientificas-C (SAC-C)
IOX/PICOSat	September 2001	~300	USA	Ionospheric Occultation Experiment (IOX), of US Air Force Space Test Program (STP) PICOSat[1] satellite
GRACE	May 2002	500	USA/ Germany	Gravity Recovery and Climate Experiment
FORMOSAT-7/ COSMIC	April 2006	2000	USA/Taiwan	FORMOsa SATellite mission - 3/Constellation Observing System for Meteorology, Ionosphere and Climate
MetOp-A	October 2006	500	Europe	Meteorological Operational satellite programme (MetOp)-A
OceanSat-2	September 2009	500	India	Indian Space Research Organisation (ISRO) OceanSat-2
TanDEM-X	June 2010	400	Germany	TerraSAR-X add-on for Digital Elevation Measurement
KOMPSAT-5	2011	300	South Korea	KOrea Multi-Purpose SATellite-5
SAC-D	2011	400	Argentine	Satelite de Aplicaciones Cientificas-D
CICERO	2011-2016	>10000	USA	Community Initiative for Continuing Earth Radio Occultation
EQUARS	2012	400	Brazil	Equatorial Atmosphere Research Satellite
MetOp-B	2012	600	Europe	Meteorological Operational satellite programme (MetOp)-B
FORMOSAT-7/ COSMIC-II	2014-2016	>8000	USA/Taiwan	FORMOsa SATellite mission - 3/Constellation Observing System for Meteorology, Ionosphere and Climate-II
MetOp-C	2016	600	Europe	Meteorological Operational satellite programme (MetOp)-C
CLARREO	2017-2020	1000	USA	Climate Absolute Radiance and Refractivity Observatory (CLARREO) Mission

2.2. Ocean sensing

GNSS-Reflectometry (GNSS-R) is an innovative and promising approach in ocean remote sensing and holds many potential advantages, including primarily global coverage and long-term satellite mission lifetime. In the last few years, several experiments were carried out and numerous advancements have been made. For example, the National Oceanic and Atmospheric Administration (NOAA) Hurricane Hunter research aircraft carrying a GPS reflectometry instrument flew into Hurricane Michael off the South Carolina coast in October 2000 (Katzberg et al., 2001). The first GPS signals reflected from the sea surface inside tropical cyclones were analyzed and the wind speed results were obtained (Katzberg et al., 2001). In November 2002, the United Kingdom (UK) launched satellite as part of the disaster monitoring constellation (DMC). UK-DMC carried a GPS reflectometry experiment as a secondary payload. The onboard GPS receiver was operated in a scatterometric approach to detect Earth's reflected signals. It has successfully inferred geophysical parameters (e.g., sea surface roughness) of the Earth surface (Gleason et al. 2005).

Currently, the GPS reflected signals from the ocean surface can be used to make altimetric sea surface height measurements with the achievable accuracy an active topic of research (Martin-Neira et al., 2001; Katzberg and Dunion, 2009). Some of the difficulties in using GNSS signals to make altimetry measurements involve the relatively long "chipping" rate and spreading code applied to all currently available GNSS signals (Gleason et al, 2010). Good altimetry accuracy results have been obtained in very calm sea states with GPS reflected signals. Further research is needed in the field including more detailed analysis of the electromagnetic field scattering theory, power and Delay-Doppler parameter retrieval methods (Lowe et al., 2002) and characterizing the L-band surface slopes' probablility density function. Good examples of ocean roughness and wind sensing using GPS signals have also been retrieved by Armatys et al. (2000) and Cardellach and Ruis (2007). However, the data of several GNSS-R experimental missions are not open to the public and the spatial-temporal resolution is low. More GNSS-R missions are needed for the entire globe in the future, especially missions providing data free to the scientific community.

2.3. Land sensing

The power level of the GPS reflected signal from the land contains information about the soil moisture, dielectric constant, surface roughness, and possible vegetative cover of the reflecting surface (Masters, 2004). Some experiments using GPS reflected signals have made estimates of the soil moisture. For example, Katzberg et al. (2006) obtained the soil reflectivity and dielectric constant using a GPS reflectometer installed on an HC130 aircraft during the Soil Moisture Experiment 2002 (SMEX02) near Ames, Iowa, which were consistent with results found for other microwave techniques operating at L-band. In addition, the multi-path from ground GPS networks is possibly related to the near-surface soil moisture. Larson et al. (2008) found nearly consistent fluctuations in near-surface soil moisture from the ground GPS multi-path, comparable with soil moisture fluctuations in the top 5 cm of soil measured from conventional sensors. However, GPS multipath signals are very complex due to various factors, e.g., vegetable, foliage, and glass debris. To infer the soil moisture parameters from ground GPS multipath, it is necessary to further remove the other factors' effects. Additionally, simulations have been performed by Ferrazzoli et al. (2010) which have opened up the possibility of sensing forest biomass using GNSS reflections. This is another area where validation data is needed to further assess the feasibility of this application.

2.4. Cryosphere mapping

As the ice and snow thickness are related to the amplitude of the reflected signal as a function of the incidence angle or relative amplitudes between different polarizations, the snow and ice thickness can be retrieved from the GPS reflected signals. Komjathy et al. (2000) has derived the condition of sea and fresh-water ice as well as the freeze/thaw state of frozen ground from aircraft experiments with GPS reflections over the Arctic sea ice and ice pack near Barrow, Alaska, USA. The correlation was quite consistent for forward-scattered GPS returns and RADARSAT backscattered measurements. This behavior of the reflected signal showed clearly the sensitivity to ice condition, indicating that the GPS reflected signals can well determine the ice status and features. The potential of sensing sea ice from low Earth orbit was explored using two signals from two different ice concentrations by Gleason (2010a). This result showed some agreement between GPS measurements and estimates of ice concentration from the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) instrument, but due to the small amount of data no conclusions could be made. In addition, the change in snow depth is also related to the corresponding multi-path modulation of the ground-based GPS signal. Fig. 2 shows the measurement and theoretical results for a 0.3 cm thick snow layer on top of 12.7-, 26.7-, 39.4-, 54.7-, and 68.7 cm-thick ice layer from the GPS satellite PRN 10 (Jacobson, 2010). It has shown that a theoretical ice thickness of 39.4 cm agrees best with the measurements with regards to the first deep fade shape.

3. Future developments

3.1. GNSS network and satellite constellations

Nowadays, more and more permanent GNSS stations are being established around the globe, including more than 300 permanent worldwide IGS stations ((Fig. 3) and

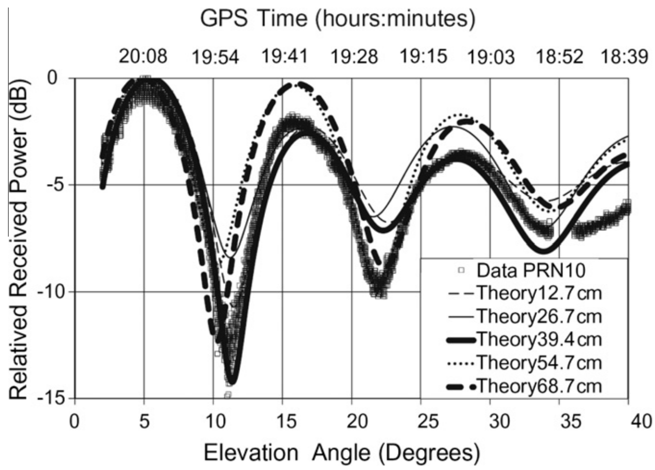

Fig. 2. Theoretical (lines) and measured (squares) elevation plots for a reservoir covered by a 0.3 cm thick snow layer on top of 12.7-, 26.7-, 39.4-, 54.7-, and 68.7 cm-thick ice layers with h = 50.5 cm for the GPS satellite PRN 10 (Jacobson, 2010).

thousands of regional continuous GNSS network stations, e.g., ~1000 continuous GPS stations of the GPS Earth observation network in Japan and more than 300 continuous GPS stations in China. Moreover, the new navigation systems, including Russia's modernized GLONASS, European Union's GALILEO system, and China's Beidou/COMPASS, are being developed, particularly with multi-frequencies (Wu et al., 2010). Along with Space Based Augmentation Systems (e.g., QZSS and IRNSS), the ground-based GNSS network can receive more line-of-sight (LOS) signals from future multi-frequency GNSS satellite constellations (over 30) through the atmosphere and ionosphere. These new signals will mean great improvements in the temporal-spatial resolution coverage of the atmosphere. With these new measurements it will be possible to monitor more detailed processes and evolutions of the ionospheric profiles at global and regional scales. Furthermore, multi-path from ground GPS networks could provide useful estimates of the near surface soil moisture. In the future, the continuously increasing International GNSS Service (IGS) networks together with regional GPS network around the world may provide a new tool to estimate global land soil moisture in near real-time for hydrology and climate studies.

With the increase of future GNSS satellite constellations and LEO satellite missions, the additional reflected and refracted signals received by aircraft or LEO satellites (Fig. 3), will enable scientists to monitor more detailed processes across land and ocean surfaces and the atmosphere.

3.2. Advanced GNSS receivers

The Blackjack GPS receiver developed by the Jet Propulsion Laboratory (JPL) has been widely used in most current space-borne GNSS missions for precise orbit determination and radio occultation (Montenbruck and Kroes, 2003), e.g., Satellite de Aplicaciones Cientificas-C (SAC-C, 2000), CHAllenging Minisatellite Payload for gravity, magnetic and radio occultation (CHAMP, 2000), JASON-1 (2000), ICESat (2001), and Gravity Recovery and Climate Experiment (GRACE, 2002). This receiver is an unclassified and high-precision space-rated GPS receiver with dual-frequency tracking capability, which is controlled through flexible and versatile software implementations of various receiver functions. In order to satisfy new mission requirements and quasi real-time data processing capabilities in the near future, additional GNSS receivers are needed for emerging applications. New receivers should also have the ability to track signals from not only GPS, but also, GALILEO, GLONASS and other new GNSS systems, like China Beidou/COMPASS. Now JPL is developing the next generation multi-antenna GNSS receiver

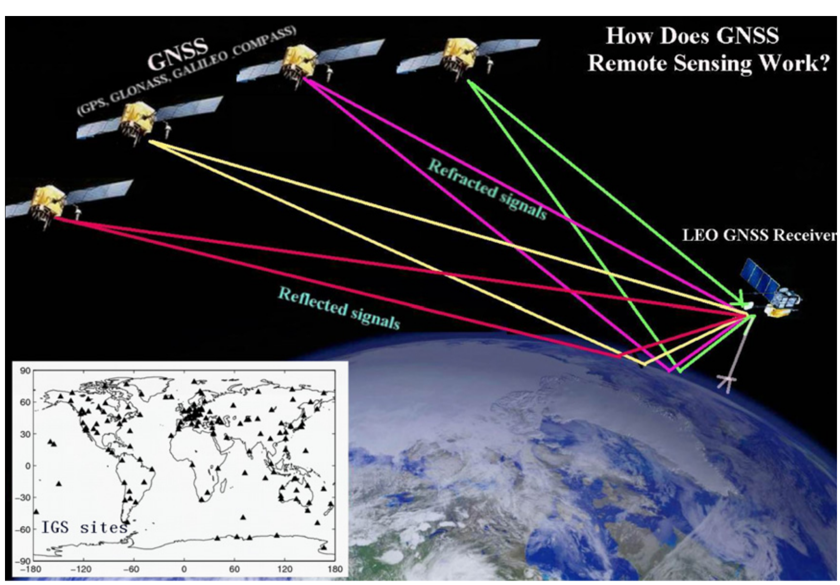

Fig. 3. Remote sensing using future denser GNSS network and more satellite constellations. The left lower corner shows the global IGS sites distribution.

called the TriG (Tri-GNSS, GPS+Galileo+GLONASS) receiver for precision orbit determination and radio occultation observations. The TriG receiver has a modular design to obtain multi-GNSS refraction and reflection measurements with tracking L1 C/A, L2 Codeless, and the new L2C and L5 signals from GPS as well as new GNSS signals from Galileo and GLONASS (Tien et al., 2010). To improve the percentage of profiles reaching into the lowest regions of the atmosphere, the digital beam steering, wideband open loop tracking, and Blue Shift signal processing algorithm are realized in the TriG receiver to improve the precision in the atmosphere and to increase the signal-to-noise ratio (SNR) from the lower regions of the atmosphere.

For fully deriving scientifically relevant geophysical parameters such as ocean altimetry, sea state or soil moisture using GPS reflected signals, the Departament de Teoria del Senyal i Comunicacions (TSC) of the Universitat Politècnica de Catalunya (UPC) has developed the GNSS Reflectometer Instrument for the Passive Advanced Unit (griPAU). The griPAU instrument is a real-time and high resolution Delay-Doppler Map (DDM) reflectometer operating at the GPS L1 frequency with the C/A codes, which computes 24×32 complex points DDM with configurable resolution and selectable coherent as well as incoherent integration times. The high sensitivity of griPAU instrument will improve the quality of the retrieved geophysical parameters (Valencia et al., 2010). For the coming higher number of satellite constellations, new signals, and frequencies of GNSS systems, e.g., the modernized multi-frequency GPS and the future Galileo system, the ICE (IEEC-CSIC, Spain) is also actively engaged in GNSS-R instrument development and scientific understanding of the GNSS scattering and reflected signals applications.

Additionally, the Surrey Satellite Technology Limited (SSTL), together with partners from the National Oceanography Centre (NOC), the University of Bath and the Surrey Space Centre (SSC) of the University of Surrey, is developing a next generation Space GPS Receiver-Remote Sensing Instrument (SGR-ReSI) to further exploit GNSS potential for remote sensing in the fields of land, ocean, cryopshere and atmospheric science (Unwin et al., 2010). The SGR-ReSI is a highly versatile and multi-frequency GNSS navigation receiver for both Reflectometry and Radio Occultation applications.

Lastly, a simple alternative that will provide data publicly to the entire scientific community for use in application validation is the software receiver based approach being pursued by several Universities in Canada (Gleason, 2010b). Although this strategy would not provide the high performance of some of the other instruments, it will be capable of capturing both RO and reflections data for both ground-based and on on-board processing. Notably, the reflection data and the instrument design will be released in the public domain under an open source license. This type of small, inexpensive, low power instrument is expected to be capable of flying on University built nano-satellites. It is expected one or more of these new instruments will be flown on a satellite mission in the next few years.

3.3. New missions and systems

Space-borne GPS reflectometry and refractometry experiments have been successful in providing estimates of a number of the Earth's surface characteristics and atmospheric and ionospheric information, e.g., the Taiwan/US FORMOSAT-3/COSMIC mission with six satellites. However, these missions still have some restrictions due to low temporal-spatial resolutions and are approaching their end of operations. In order to fully utilize these new GNSS remote sensing tools, more and more new missions and systems are being developed (see Table 1). For example, the FORMOSAT-3/COSMIC mission will reach the end of its design life in about 2011, and the National Oceanic and Atmospheric Administration (NOAA) and National Space Organization (NSPO) intend to launch the next generation follow-on FORMOSAT-7/COSMIC-2 mission between 2014 and 2017 (Yen, 2010). This follow-on mission has a new constellation of 12 satellites with GNSS RO receiver to receive GPS, GLONASS and GALILEO satellite signals. It will collect a large amount of occultation point data primarily for weather forecasting including typhoons and hurricane and space weather monitoring as well as meteorological, climate, ionospheric, and geodetic research.

CICERO (Climate Community Initiative for Continuing Earth Radio Occultation) is a follow-on mission to the COSMIC as a self-supporting enterprise for the greater GNSS-RO science and wider user communities who will share in its design, evolution, and success (www.geooptics.com). The CICERO project changes the way to collect and disseminate Earth observational data with 100 micro-satellites in Low-Earth Orbit (LEO) performing GNSS atmospheric radio occultation (GNSS-RO) and GNSS Surface Reflection (GNSS-SR) measurements (see Fig. 4). The CICERO constellation is designed with lower cost of acquiring data essential to understand our planet and expands the possibilities for obtaining new types of data from space. The plan is to initially launch 20 satellites with follow-on launches to reach a sustained array of 100 spacecrafts. The full CICERO constellations are expected to deliver nearly 100,000 atmospheric profiles per a day (Yunck et al., 2007). Meanwhile, since CICERO has GNSS Surface Reflection (GNSS-SR), it is expected to detect more detailed Earth's surface characteristics and time-varying evolutions.

The past UK-DMC GPS Reflectometry experiment launched in 2003 has successfully showed that GNSS signals can be used from space in a bi-static radar configuration to analyze reflections off the ocean, ice and land. In order to further test and implement GNSS-R, a new UK satellite with a GNSS-R instrument on-board, TechDemoSat-1, is planned for launch in the near future (Unwin

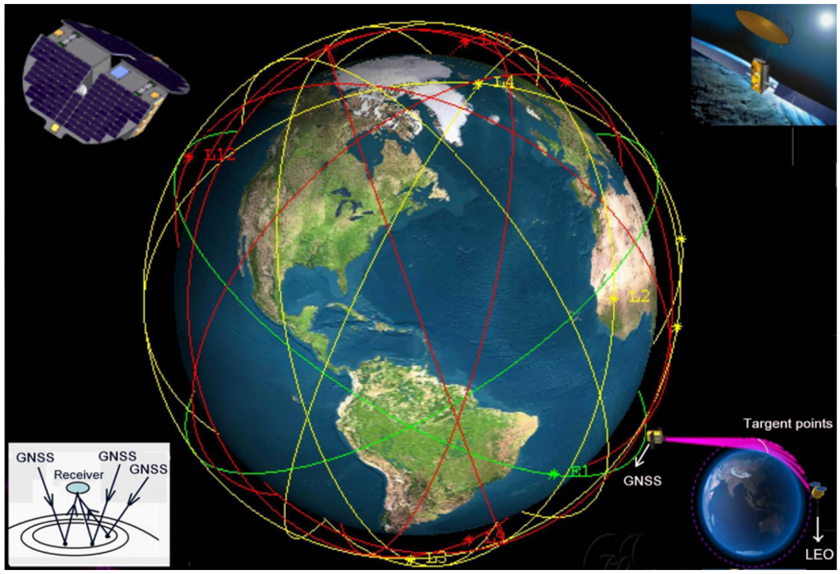

Fig. 4. CICERO (Climate Community Initiative for Continuing Earth Radio Occultation) with about 100 satellites (Yunck et al., 2007). The left lower corner shows the GNSS-Reflectometry and the right lower corner represents GNSS Radio Occultation.

et al., 2010). It will be designed to estimate several Earth observables, including Directional Mean Square Slope (DMSS), ice edge detection, ice freeboard measurement, and ionospheric delay (e.g., total electron content), in a format that allows proper verification of inversion models by relevant scientists. The DMSS of the ocean is an important parameter that has interest from both operational users (shipping, off-shore energy) and scientific users (wave, weather and climate modelling). Other parameters that potentially can be measured using GNSS-R include ocean states, ice edge, ice concentration, ionospheric mapping and soil moisture.

3.4. New and emerging applications

Various methods have been proposed for determining the ocean roughness and cryosphere, but there are insufficient spaceborne data to validate the methods or monitor more details. Moreover, the traditional instruments have a long delay with low spatial resolutions. In next few years, more space-borne GPS reflectometry and refractometry experiments will be launched with the next generation GNSS Receiver-Remote Sensing Instrument (e.g. Shuttle measurements). Some new scientific applications of the utilization of the GNSS-R are expected in various environment remote sensing fields with high spatial-temporal resolution and near real time in the near future, particularly some notable emerging applications include monitoring sea ice, sea states, ocean eddy and geohazards. These near-real-time GNSS reflection data are expected to be open in the public domain. The analysis of these real-time data may play a key role in predicting high winds, dangerous sea states, risk of flooding, ocean eddy and storm surges. Furthermore, high-sampling ocean surface roughness will be estimated from future denser GNSS reflected signals, which may improve our understanding of the air-sea exchanges, the floe ridges, frost flowers, broken ice, and fine-scale roughness at the snow-ice interface, particularly for inaccessible and atrocious sea ice cover.

Also the GNSS reflectometry together with ground observation networks of seismology and geodesy are expected to be applied in a geohazard warning system. The German Indonesian tsunami early warning system for the Indian Ocean was established after the Sumatra earthquake of December 2004 (www.gitews.de). It will later be extended to the Mediterranean and the Atlantic Ocean using new space-based GNSS reflectometry and scatterometry with all available signal sources, including the modernized GPS, the restored GLONASS, the establishing Galileo and the upcoming Compass GNSS. Moreover, future GNSS reflected signals may be used to monitor crustal deformation, like Synthetic Aperture Radar (SAR), and GNSS reflectometry is expected to observe the global-scale geodynamic processes together with other sensors.

4. Conclusion and discussion

The refracted, reflected and scattered GNSS signals have been used as a remote sensing tool in the atmosphere, ocean, land, hydrology and cryosphere. With continuously increasing global permanent IGS stations and regional continuous GNSS stations and more satellite constellations of the future multi-frequency GNSS and Space Based Augmentation Systems, such as GPS, GLONASS, Galileo, Beidou/COMPASS, QZSS and IRNSS, the denser ground GNSS stations can receive more multi-path signals and line of sight signals of GNSS satellites through the atmosphere and ionosphere. It can monitor more detailed ground surface characteristics and processes and evolutions of the atmospheric and ionospheric profiles at global and regional scales.

With more and more space-borne GPS reflectometry and refractometry missions in the near future (e.g., follow-on FORMOSAT-7/COSMIC-2 mission, CICERO and TechDemoSat-1), these missions will monitor more detailed Earth's surface characteristics and atmospheric and ionospheric information with high temporal-spatial resolutions. Furthermore, some advanced GNSS receivers are being developed with improved algorithms for the various possible applications and quasi real-time data processing capabilities to satisfy the future space-based high-performance missions (e.g., next generation TriG (Tri-GNSS) receiver with the ability to generate multi-GNSS refraction and reflection). It is also possible in the next few years a low cost instrument will be made public capable of operating on limited resource satellites, such as those being developed by Universities. New remote sensing applications using GNSS signals are expected to continue expanding over a global scale in the coming years.

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Appendix A

AMSR-E	Advanced Microwave Scanning Radiometer for Earth Observing System
DDM	Delay-Doppler Map
DMC	Disaster Monitoring Constellation
DMSS	Directional Mean Square Slope
GNSS	Global Navigation Satellite Systems
GNSS-R	GNSS-Reflectometry
GPS	Global Positioning System
griPAU	GNSS Reflectometer Instrument for the Passive Advanced Unit
IGS	International GNSS Service
IRNSS	India's Regional Navigation Satellite Systems
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LOS	Line-Of-Sight
NOAA	National Oceanic and Atmospheric Administration
NOC	National Oceanography Centre
PARIS	PAssive Reflectometry Interferometric System
PGGA	Permanent GPS Geodetic Array
PWV	Precipitable Water Vapor
QZSS	Quasi-Zenith Satellite System
RO	Radio Occultation
SAR	Synthetic Aperture Radar
SGR-ReSI	Space GPS Receiver-Remote Sensing Instrument
SMEX02	Soil Moisture Experiment 2002
SNR	Signal-to-Noise Ratio
SSC	Surrey Space Centre
SSTL	Surrey Satellite Technology Limited
TEC	Total Electron Content
TriG	Tri-GNSS (GPS+Galileo+GLONASS)

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