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**Radionavigation-satellite service
applications in the 1 164-1 215 MHz,
1 215-1 300 MHz and 1 559-1 610 MHz
frequency bands**

M Series
**Mobile, radiodetermination, amateur
and related satellite services**



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Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

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RA	Radio astronomy
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Note: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.

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**Radionavigation-satellite service applications in the 1 164-1 215 MHz,
1 215-1 300 MHz and 1 559-1 610 MHz frequency bands**

(Questions ITU-R 217-2/4 and 288/4)

(2019)

1 Introduction

Recommendation ITU-R M.1787 provides descriptions of systems and networks in the radionavigation-satellite service (RNSS) and technical characteristics of transmitting space stations operating in the bands 1 164-1 215 MHz, 1 215-1 300 MHz and 1 559-1 610 MHz, which are referred to in this Report as the 1-GHz RNSS bands. Recommendations ITU-R M.1905, ITU-R M.1902, ITU-R M.1903 and ITU-R M.1904 provide technical and operational characteristics of, and protection criteria for, receiving stations in the RNSS (space-to-Earth and space-to-space) operating in the 1 GHz RNSS bands. For the purpose of providing protection criteria for RNSS systems, RNSS receiver types for particular applications were described in the above referenced M-Series Recommendations.

The RNSS continues to evolve, as new systems come on line and additional applications are developed. This Report provides further information on the current and planned RNSS applications for the 1-GHz RNSS bands, including additional RNSS applications not addressed in the M-Series Recommendations.

2 RNSS systems

The detailed descriptions of RNSS systems operating or planned to operate in the 1-GHz bands, including signal plans, are provided in Recommendation ITU-R M.1787. The included systems generally fall into one of four categories: 1) Global Navigation Satellite Systems; 2) Regional RNSS Systems; 3) RNSS Satellite-Based Augmentation Systems; or 4) Assisted RNSS (A-RNSS) systems. Following a general overview, a brief description of each of these categories is provided in §§ 2.2 through 2.5 for convenience.

2.1 Overview**a) Economic benefits of RNSS**

RNSS is used around the globe, with an estimated 5.8 billion RNSS devices in use in 2017. This number is expected to grow to 8 billion by 2020¹.

Although the globally installed base of RNSS devices is greatly dominated by smartphones, followed a distant second by automobiles, the number of RNSS devices in use for professional applications continues to grow and serve a critical role in national economies, public safety, science, etc. Billions of people globally benefit from these high-end RNSS devices on a day-to-day basis, e.g. enjoying the produce of sustainable and cost-effective agriculture, using efficiently coordinated transport networks, and leveraging RNSS-synchronized telecommunication networks.

¹ GNSS Market Report, 2017, at 5, available at <http://www.gsa.europa.eu/market/market-report>.

A 2015 study by ASCR Federal Research and Technology Solutions, LLC, has estimated that U.S. GPS contributed more than \$68 billion to the U.S. economy alone in 2013². This study found that “more than \$26 billion was from vehicle location services, \$13.7 billion was from grain-related precision farming, \$11.9 billion was from fleet vehicle connected telematics, \$11.6 billion was from surveying, and \$5 billion was from GPS-based guidance of earth-moving equipment.” The study added that these estimates did not capture the full economic benefits of the GPS signals. This study did not include some sectors due to lack of information on productivity and cost savings. A more comprehensive estimate comes from the European GNSS Agency (GSA). Its 2017 GNSS Market Report projects a global revenue of 60 billion euros in 2020 for devices and augmentation services, and a revenue of 120 billion euros for added-value services.

b) RNSS receiver considerations

RNSS receivers measure radionavigation signals delivered by satellite. They are very different from receivers used in radio communications systems, where the incoming message is not known to the receiving device whose goal is to find the message and determine whether each signal bit is a one or a zero using sophisticated methods to correct errors. The RNSS incoming signal sequence (ones and zeros) is known to the RNSS receiver. The primary measurement in RNSS systems is the precise timing of bit transitions in the navigation signal. Precise positioning requires sub-nanosecond measurement of bit edges and effective multipath rejection. Both, in turn, require wide receiver bandwidth.

As provided in the relevant ITU-R Recommendations referenced above (specifically Recommendations ITU-R M.1902, ITU-R M.1903, ITU-R M.1904 and ITU-R M.1905), many RNSS receivers, which are ubiquitously deployed, are designed to acquire and track their associated satellite signals in the presence of interference from all non-RNSS sources that degrades C/N_0 by no more than 1 dB³.

2.2 Global navigation satellite systems

Global Navigation Satellite Systems (GNSS) operate in the RNSS, and in particular in frequency bands allocated to that service, and provide coverage on and above the entire Earth’s surface. Examples of GNSS systems include China’s Compass/Beidou system, Europe’s Galileo system, Russia’s Global Navigation Satellite System (GLONASS) and USA’s Global Positioning Satellite (GPS) system.

2.3 Regional RNSS systems

Regional RNSS systems provide coverage on and above only limited portions of the Earth’s surface. Examples of Regional RNSS systems include IRNSS (India’s Regional Navigation Satellite System) and QZSS (Japan’s Quasi-Zenith Satellite System).

2.4 RNSS satellite-based augmentation systems

RNSS with Satellite-Based Augmentation Systems (SBAS) provide enhanced regional service. Examples of RNSS SBAS systems include WAAS (USA’s Wide-Area Augmentation System, of which the LM-RPS networks are part), EGNOS (Europe’s SBAS), GAGAN (India’s GPS-Aided GEO-Augmented Navigation system), Omnistar, StarFire, MSAS (Japan’s SBAS), SDCM (Russian Federation’s SBAS) and NIGCOMSAT (Nigeria). These systems augment the RNSS

² <http://www.insidegnss.com/node/4535>.

³ For example, for receivers operating with RNSS systems in the 1 559-1 610 MHz RNSS band, this restricts the maximum interference level as provided in Table 2 of Recommendation ITU-R M.1903.

services by improving accuracy, availability, continuity, and/or integrity by reporting RNSS satellite status (signal integrity).

2.5 Assisted RNSS (A-RNSS) systems

A-RNSS refers to commercial-grade handheld and assisted RNSS receivers. This class of receivers operate within “stressed” environments, such as under heavy foliage, indoors or in urban canyons.

They are sometimes “cell-phone assisted”, since aiding information (Doppler, timing, navigation data) is provided in real-time to enable RNSS signal acquisition and tracking through significant attenuation (such as building walls). These receivers provide position information for E911 services in the United States of America, and the equivalent 112 number in Europe.

3 RNSS applications

This section contains information on many RNSS applications in current use.

3.1 Agriculture

Precision agriculture uses high accuracy, real-time RNSS on-board agricultural machinery to manage distribution of fertilizer and pesticides, and planting and harvesting of crops. Using RNSS precision guidance, farmers can plant rows closer together and with greater precision, to increase crop yields and reduce waste due to overlaps or gaps. When used on harvesting machines, the collection of RNSS precise positioning data, combined with information about crop yields, is applied to seeding and fertilization plans for the following season’s crops. The RNSS positioning adds precision to weed and insect control, allowing farms to decrease the use of potentially toxic pesticides and herbicides by as much as 80 percent. Precision agriculture requires 24/7 delivery of continuous real-time position accuracies with Key Performance Indicators (KPI) from 1 cm to 10 cm during agricultural operations. This positional capability enables the grower to operate a range of farm machinery, including at night that carefully follows precision farming plans requiring repeatable KPI throughout the growing cycle, from tilling through harvesting. Many precision agriculture receivers require a real-time differential data stream, often delivered by integrated MSS receiver equipment.

3.2 Construction – Heavy and civil engineering

RNSS construction machine control systems consist of rugged, high-precision RNSS receivers mounted on construction machines of various types. With reference to a computer model of a job grading plan, the RNSS system is required to determine the precise position of the machine’s blade continuously (24/7) to within one inch or less using the on-board computer to continuously compare the blade’s precise position to the design plan. By watching a display in the machine’s cab, the operator controls the machine to produce the desired results.

In some applications, the machine control system handles the steering and blade positioning automatically through hydraulic interfaces, with the operator functioning as a monitor and safety check. Off-machine high-precision RNSS is also used extensively on construction sites for site measurement, layout and dimensional control functions.

3.3 Aviation

Aviation use of RNSS is not limited to navigation. RNSS on a receive-only basis is also used to support other aviation applications as well. These applications enhance aviation operational capabilities such as efficiency, availability, accuracy and integrity. In addition, aviation safety is enhanced by RNSS both by facilitating surveillance in areas where ground-based radar is not available, and, where radar is available, by providing immediate navigation to the closest airport.

Systems such as LNAV, LNAV/VNAV (Lateral Navigation/ Vertical Navigation), LPV (Localizer Performance with Vertical Guidance) instrument approach, ADS-B Out and TAWS (Terrain Awareness and Warning System) utilize RNSS position information to perform or assist the traditional avionics functions of landing approach, collision avoidance and terrain avoidance.

En route and terminal area navigation – RNSS is widely used by aircraft for navigation to and from airports, both under visual and instrument conditions. For many aircraft, RNSS is one of the means used to navigate from point to point. The area navigation provided by RNSS allows direct, and therefore more efficient, routing for those using certified aviation receivers instead of going from one ground-based navigation station to the next. In the event of an in-flight emergency, RNSS systems can provide immediate navigation to the closest airport, even in areas where there are no ground-based navigation aids.

Instrument precision approaches and flight procedures – RNSS-based approaches, augmented by SBAS/GBAS, allow aircraft suitably outfitted with certified aviation receivers to fly precision approaches at certain airports throughout the country. These augmented RNSS approaches require significantly less ground infrastructure than approaches utilizing ground-based navigation aids, and they can be accommodated at a larger number of airports than traditional ground based (ILS) approaches. In addition, un-augmented RNSS-based approaches, like LNAV or LNAV/VNAV, provide significant benefits to aviators and improve aviation safety.

Surveillance – Automatic Dependent Surveillance-Broadcast (ADS-B) equipment broadcasts RNSS-derived aircraft position reports which are received by suitably equipped aircraft in the vicinity for situational awareness, and by Air Traffic Control centres on the ground for airspace monitoring. ADS-B also provides increased safety, aircraft position accuracy, capacity, and surveillance capability to Air Traffic Control in areas where there is no ground-based surveillance radar. Space-based reception of ADS information is envisioned to further enhance the surveillance and the tracking of aircraft over the oceans and in remote areas.

Airborne Collision Avoidance System (ACAS-X) – Traffic Alert and Collision Avoidance System (TCAS) provides enhanced safety by providing pilots with timely alerts of potential collisions with other aircraft and provides a resolution as needed to avoid a mid-air collision. The next generation of TCAS, referred to as the Airborne Collision Avoidance System-X (ACAS-X) is intended to be more flexible for evolving airspace, and may move from the beacon-only surveillance of TCAS to satellite-based next-generation technologies (e.g., RNSS surveillance data, radar, and electro-optical sensors) to track aircraft with higher precision, enabling smaller safe separation distances.

Terrain Awareness and Warning – RNSS supplies position and altitude information to many terrain awareness systems. Such systems greatly reduce the likelihood of controlled-flight-into-terrain incidents by providing the pilot with a picture of the aircraft's position relative to the surrounding terrain and obstacles.

Cockpit Position Display – Many aircraft are equipped with electronic multi-function displays that depict the aircraft's location on a map. RNSS is a source of position data for these displays. These displays reduce pilot workload by improving situational awareness, showing the aircraft position on a map that can be overlaid with weather radar and traffic information. Such systems also help reduce runway incursions because they provide an unambiguous display of the aircraft position relative to active runways and other airport landmarks at airports with state of the art surface surveillance systems. Further, some commercial services provide this capability at many airports that do not have such state of the art surface surveillance systems.

Low-cost Attitude and Heading Reference Systems – RNSS is used in conjunction with low-cost inertial sensors to provide reliable, inexpensive and lightweight attitude and heading systems. While some are not certified for navigation, these devices are used to replace spinning-mass gyroscopic instruments that have notoriously poor reliability and provide the pilot's primary means for determining attitude and heading during instrument flight.

Emergency Location and Airborne Search and Rescue – RNSS is used for airborne search and rescue operators. RNSS allows search and rescue aircraft to fly precise pre-determined search patterns at any location, day or night, under a wide range of weather conditions. RNSS position may be used as an input to 406 MHz Emergency Locator Transmitters (ELTs) which transmit downed aircraft location to COSPAS-SARSAT satellites.

3.4 Environment

Positional data; evaluation of wildlife and human activities; mining, forest logging, oil spill and resource management; migratory patterns.

RNSS is widely adopted within environmental disciplines. One example is animal tracking. For example, RNSS-based devices can be directly attached to wild or house-trained animals which can be used to achieve a better understanding of animal movement over time. This is vital for biodiversity research, predicting conservation hotspots, identifying human-animal conflict zones, rebuilding and sustaining productive ecosystems and understanding the spread of pandemic disease and invasive species.

On the other hand, RNSS is a relevant enabler of Geographic Information Systems (GIS) which represent a cost-efficient and powerful tool for resource analysis towards sustainable management of forests, open air mines, water reservoirs, logging, assessing fisheries, crops and many other resources. Within these applications, RNSS is used to geo-reference relevant data collected both through remote sensing platforms and in-field. A particular case of remote sensing under development, called GNSS-Reflectometry (GNSS-R) remote sensing, uses RNSS signals as electromagnetic radiation reflected on earth surface to monitor forest biomass development.

3.5 Maritime

Maritime applications of RNSS include open water, harbours and inland waterways. RNSS receivers with electronic marine charts provide depth contours and locations of hazards and other features. The RNSS position data can be combined with marine radar to show non-stationary objects such as other vessels on the charts.

The availability of precise position allows for the placement and recovery of such items as fishing nets and traps, buoys, scientific and hydrographic instruments and drilling equipment. RNSS also plays a key role in marine safety and serves as the basis for the position information used in services like DSC (Digital Selective Calling) and EPIRBs (Emergency Position-Indicating Radio Beacon).

In a scenario in which maritime users need to navigate fast and in a cost-effective way yet without compromising safety and security, RNSS has become the primary means of obtaining PNT information at sea. In view of its enhanced capabilities, multi-constellation RNSS are especially important for a wide range of maritime applications. RNSS applications can be split into navigation and positioning:

Navigation

- Sea
 - SOLAS vessels: All passenger ships, cargo ships larger than 500 gross tonnage or larger than 300 tons if engaged on international voyages are regulated and rely heavily on RNSS to support navigation activities. At least three devices are typically fitted on vessels for redundancy reasons.
 - Non-SOLAS vessels: RNSS-based systems for maritime navigation are widespread not only across commercial, but also recreational vessels. They are used both for overseas and high traffic areas.
- Inland Waterways (IWW): RNSS is used to ensure safe navigation also in inland waterways (rivers, canals, lakes and estuaries).

Positioning

- Traffic management and surveillance: These activities are supported by RNSS-based systems including Automatic Identification System (AIS) and Long-Range Identification and Tracking (LRIT) both in sea and inland waters.
- Search and Rescue is the search for and provision of aid to people in distress or danger. Different types of devices can make use of RNSS positioning:
 - In the frame of the Cospas-Sarsat programme, ship and person-registered beacons, i.e. Emergency Position Indicating Radio Beacons (EPIRBs) and Personal Locator Beacons (PLBs) transmit, once activated, the necessary information for rescue to authorities via satellite communication.
 - When activated, AIS Search and Rescue Transponders (AIS-SART) and AIS Man Overboard (AIS-MOB) devices continuously transmit an alert message including ID number and RNSS-based location, which triggers an alarm on all AIS equipped vessels within the Very High Frequency (VHF) range.
- Fishing vessel control: RNSS positioning enables Vessel Monitoring Systems to check the position of fishing vessels, as well as the time spent in international and foreign waters, protected marine areas, etc.
- Port operations: Transit progress, docking and loading-unloading operations are monitored through RNSS-based technologies.
- Marine engineering: RNSS is widely used to support marine construction activities (e.g. cable and pipeline laying).

3.6 Public safety and disaster relief

Search and rescue; wildfire management; earthquake prediction; emergency requests; tracking.

By integrating accurate RNSS position information into distress beacon signals, RNSS is also enhancing search and rescue (SAR) operations. By 2020, all Cospas-Sarsat Emergency Personal Location Beacons (registered personal devices that can be used in any remote location or situation where people may require rescue) are expected to be using precise RNSS positioning, helping to reduce response times and save lives.

RNSS is being increasingly used as an essential enabling technology to monitor and provide early warnings for natural phenomena such as earthquakes, landslides, volcanoes and flood hazards. In that context, the most established application is RNSS land deformation monitoring. It typically relies on measurements acquired through Continuously Operating Reference Stations (CORS) positioned in selected areas (e.g. boundary zones of tectonic plates). The data collected by each of the CORS network's stations are transmitted via GSM or radio modems to a relevant centre. Given that land

deformation (especially the one associated with tectonic motions) is often of the order of a few millimetres per year, the sensitivity of the system, i.e. its ability to distinguish land deformation from monumentation deformation (i.e. movement of the station due to other reasons such as temperature excursion, wind, etc.), is critical.

Finally, RNSS data is also used within specialized smartphone applications for disaster management integrating crowdsourcing data from users and from other systems such as Earth Observation (e.g. Copernicus) and/or weather stations allowing civil protection services and policymakers to effectively prevent and/or react against natural disasters (e.g. European-funded projects iReact and Floodis).

3.7 Rail

Rail car tracking; railroad command and control (part of the PTC⁴ system); information updates; track inspection and defect detection.

An important number of rail applications rely on RNSS data:

- Asset Management: Includes several functions such as fleet management, needs-based maintenance, infrastructure changes and intermodal logistics. RNSS is increasingly seen as a standard source of positioning and timing information in these systems.
- Signalling and train control applications:
 - Low Density Line Command & Control Systems will provide full signalling capabilities supported by RNSS on lines with small to medium traffic. These lines are usually located in rural areas, where cost savings can be vital for the viability of a service.
 - Main Line Command & Control Systems assist train command and control on main lines, referring primarily to the European Train Control System (ETCS)⁵ in Europe and some regions in the rest of the world, as well as Positive Train Control (PTC) in North America. RNSS can also be a source of additional input, e.g. for enhanced odometry in ETCS.
- Passenger Information Systems: On-board trains show the real-time location of a train along its route. The location of a train, determined using RNSS, also supports online passenger information platform and services.
- Driver Advisory Systems: Provide additional information to the train driver based on accurate position acquired through RNSS fused with other track reference data and operational characteristics to enable energy-efficient driving.

3.8 Consumer RNSS uses

Consumer use of RNSS regards mainly positioning applications that take into account a given device's geographical location at a certain point in time. RNSS is a crucial technology that is ubiquitously used in applications ranging from navigation and mapping over geo marketing to Augmented Reality

⁴ PTC = Positive Train Control system. The PTC effort is designed to improve safety by reducing the risk of train-to-train collisions. RNSS is used for positioning, timing and speed, principally in locating the lead locomotive of a train. Multiple inputs are fed into location filters to improve accuracy and smooth inputs into reliable safe output of train location, speed and confidence factor. These systems are designed to detect when a locomotive is in danger of a collision and will apply the brakes without human intervention.

⁵ ERTMS = The European Rail Traffic Management System is the system of standards for management and interoperation of signaling for railways by the European Union (EU). The main objective of ERTMS is to promote the interoperability of trains in the EU in order to enhance safety, increase efficiency of train transports and enhance cross-border interoperability of rail transport in Europe. This is done by replacing former national signaling equipment and operational procedures with a single new Europe-wide standard for train control and command systems.

applications. In the consumer segment, RNSS applications are supported by multiple categories of devices, including widespread technologies such as smartphones and tablets as well as more specific equipment such as tracking devices, smart glasses and fitness gear, and new applications are constantly emerging.

3.8.1 Outdoor/Recreation

Outdoor activities like fishing or hiking; improving skills like golfing; mobile gaming; finding recreational spots like restaurants or waypoints; route planning. RNSS systems also enable many action cameras.

RNSS receivers can be combined with mobile-satellite service (MSS) transmitters enabling the ability to advise family and associates of whereabouts during recreational activities. These devices can include the means of summoning aid in the case of a user becoming lost or suffering a medical emergency. These devices also find application in protecting “lone workers” in areas outside the range of other communications means.

3.8.2 Health and fitness

RNSS technology plays a pivotal role in the health and fitness marketplace. RNSS devices serve to assist runners, cyclists, and swimmers in a variety of ways. RNSS also plays a key role in the “Activity Tracker” market.

RNSS also plays an important role in health promotion and disease prevention. The increasing penetration of wearable devices for both leisure and professional purposes, is part of a general trend towards pre-emptive healthcare and maintaining personal well-being. Measurements of effort, distance and speed of movement enabled by RNSS devices are employed in specific sport applications (e.g. rowing, golf, athletics, soccer training, skiing, cycling) allowing identification of specific sport aptitudes and improvements. The process of monitoring activity, including everything from simple pedometers to advanced RNSS-based sports devices has been found to increase physical activity by 27%. Additionally, new available platforms allow the synchronization of data to a personal health record that could eventually provide medical professionals with real-time vision into the lives of their patients, integrating yearly medical check-ups with constant monitoring.

RNSS positioning information integrated into navigation-assistance systems will also allow blind and visually impaired people to better understand the surrounding environment and support their mobility. Such systems require higher accuracy compared to current mass market receivers (e.g. to have access to the names of shops being passed, streets being crossed, or demarcation for the pavement/sidewalk).

3.8.3 Automotive navigation

From “In-Dash” to “On-the-Dash,” RNSS technology is the enabling technology for all automotive navigation. Integration with other sensors and communications networks is common, making RNSS integral to the development of smart cars and autonomous vehicles.

3.8.4 Social media

RNSS technology plays an important role in many social media applications. Provision of location and timing information allows for more tailored utilization of many applications, and facilitates increased accuracy and relevance of many interactions over multiple social media platforms, including Facebook, Instagram, and Twitter.

Friend locators incorporated into online social networks typically use near real-time RNSS information provided by a user's mobile device, for example to help keep in touch with friends and for sharing travel information. This RNSS location data can be used by some social networks for determining whether a user is in an area subject to an on-going natural disaster or crisis event that can then trigger a request to that user to mark themselves "safe." This can act to reassure friends and

relatives and may in itself reduce local network voice and data traffic that is likely to be stressed by the event.

The trend for online social networks to seek revenue streams is seeing greater use of positioning and navigation data to provide their users with location specific adverts or offers, and with tailored directions. More precise positioning and navigation data provided by RNSS is expected allow even more focused information to be presented to users.

3.9 Government: Transportation and environmental management

Commercial high-precision RNSS is used widely by national and local governments, including within the departments for administration of transportation, agriculture, forest and land management, and security as well as by emergency services/first responders and other departments and bureaus.

Local government uses of high-precision RNSS include mapping, surveying and other transportation uses, Geographic Information Systems (GIS) for asset management, emergency preparedness, disaster response and E911 mapping, public sector water, wastewater and electric utilities, public works, environmental management, dam and structure monitoring, environmental health, insurance rating districts, flood zones, tax appraisals, the provision of geodetic control networks, and other functions.

High-precision RNSS is used in response and disaster planning to capture the location of critical infrastructure for utilities, transportation and emergency services. By combining RNSS measurements with elevation models, planners can identify areas susceptible to flooding or other damage. The information is stored in Geographic Information Systems (GIS) where it can be accessed by emergency managers and response organizations.

3.10 Utilities, energy, mining, oil and natural gas

High-precision RNSS is used by electric, gas and water utilities to map and manage their widely dispersed assets, in the avoidance and management of major power, water, or gas outages, in vegetation management, rapid location of damaged equipment, in pipeline integrity inspections and in tasks related to environmental and safety compliance. In Energy and Natural Resources, RNSS is used extensively in the construction of sustainable energy projects such as wind farms and solar power sites, seismic exploration and production of domestic oil and gas reserves, mine surveying, measurement and safety monitoring, pipeline construction, pipeline integrity and safety monitoring, drill location and environmental monitoring, measurement and compliance.

The development of smart grids relies also on RNSS technology which provides the accurate timing that smart grids require for synchronization, to adjust demand to the distribution across a wide geographical area. The purpose of such synchronization is to augment power system monitoring, control and protection functions. A disruption of synchronization could potentially lead to wide-scale blackouts and consequently affect a high number of people.

3.11 Science

Scientific applications of RNSS are widespread and include environmental and atmospheric monitoring, animal behaviour studies, botanical specimen location recording, meteorology and climate research, where the RNSS signal propagation characteristics are used to measure tropospheric and ionospheric activity. RNSS is used to generate position tags for weather balloons and buoys for monitoring atmospheric and ocean parameters such as temperature and iceberg location. Animal behaviour researchers use RNSS equipped tracking collars to monitor herd migration, polar bear movements, wolf movements and large marine mammals.

The western United States of America and Japan are blanketed with arrays of high-precision RNSS receivers. Information from these receivers is used to study the motion of the Earth's tectonic plates. These arrays include more than 1 100 GPS receivers in the western United States of America and 1 200 in Japan, and their continuous observations can detect and measure crustal plate motion to within a few millimetres per year.

3.12 Space-guidance systems

Satellite tracking and management; navigation; low-cost attitude solutions; timing; constellation control.

RNSS-based navigation – Trajectory and orbit determination in space may be accomplished using RNSS signals, either as stand-alone or in combination with measurements from other sources such as, but not limited to, ground-based and space-based communication channel tracking, Inertial Navigation System (INS), and star trackers. One space agency has demonstrated it is feasible to broadcast RNSS differential corrections to users in space with the objective to improve the accuracy of RNSS-based spacecraft positioning. RNSS may be used in definitive (i.e. near-real time) or predictive (filtered and/or post-processed) applications for navigation, precise time, and attitude determination.

Space-qualified RNSS receivers – Standard RNSS receivers are inadequate for certain space applications above Low Earth Orbit (LEO) due to survivability in space issues and reduced signal power levels and reduced availability. To address these issues, a space agency has developed specialty RNSS receivers to support real-time on-board navigation. In addition, the latest generation of this space agency's space-borne receivers are software programmable units and capable of tracking multiple signals from multiple RNSS constellations. The ability to obtain multiple sets of RNSS signals from multiple RNSS constellations will improve performance and robustness.

Guidance during launch - Navigation for launch vehicles is provided by an INS using multiple redundant Inertial Measurement Units (IMU) and RNSS receivers. IMU measurements are considered to be the primary source for navigation and RNSS measurements provide backup, confirmation, and position updates to the navigation solution. The reason for this reliance on INS during launch is to mitigate the effect of potential interference or other disruptions that may occur to RNSS signals.

Orbit determination – Once in orbit, communication-channel tracking, supplied from space agency SRS (space research service) space and ground-based communication networks, is typically used as the primary means for navigation. Measurements (specifically particular angle and distance) from the tracking networks, and on-board observables, are sent to a ground facility for analysis and to generate navigation products, such as trajectory analysis and orbit determination, in support of the space missions. This involvement of the ground facility is sometimes referred to as 'ground-in-the-loop'. On-board observables may include the orientation of the sun/stars, variations in the magnetic field, etc. Individual missions, however, depending on the mission requirements may include RNSS measurements to be used in the generation of spacecraft navigation products. The key advantage of RNSS-based navigation is that the hardware, while not currently as accurate as other sensors, is more cost-effective than other navigational sensors because of its low size/mass characteristics and its inherent capability to directly support spacecraft navigation from on-board the spacecraft rather than relying on ground-in-the-loop facilities to generate the required navigation products. A goal of space exploration is to develop autonomous navigation and flight technology for spacecraft with high-precision space positioning while operating independent of ground facilities. At least one administration's space agency is currently using on board RNSS measurements, albeit with ground-in-loop, to support spacecraft navigation requirements.

RNSS Space Service Volume (SSV) – Between the surface of the Earth and its 3 000 km altitude at least four signals from a RNSS constellation are continuously available to enable stand-alone real-time autonomous spacecraft navigation. This situation is used for spacecraft navigation during launch and operations while in LEO, such as rendezvous operations of spacecraft with the International Space Station (ISS). However, at altitudes greater than 3 000 km the number of available main-lobe RNSS signals decreases below four because of RNSS antenna pointing geometry. At these higher altitudes the “spill-over” energy radiating over-the-limb of the Earth defines the limits of RNSS utility and access for spacecraft navigation. This more challenging signal processing environment is known as the SSV, which is defined as the volume of space between 3 000 km altitude and Geosynchronous Orbit (GEO) altitude (approximately 36 000 km). The performance of RNSS reception in the SSV is specified in terms of RNSS signal User Range Error (URE), Minimum Received Power, and Minimum Signal Availability.

Fortunately, due to the predictive ephemeris of the spacecraft, specialty RNSS receivers are available to provide the necessary navigation data in this environment, but not with the same level of position accuracy that can be obtained in the lower than 3 000 km orbit altitude where at least four RNSS signals are available at all times. At least one administration’s space agency is working with a RNSS provider to empirically measure the performance of RNSS signals in the SSV, and use those measurements to update the performance specifications that space mission planners rely on in mission plans and objectives.

Multi-RNSS SSV – There are on-going efforts within the United Nations (UN) International Committee on GNSS (ICG) to characterize the SSV performance of all RNSS constellations and regional systems. The objective of this effort is to, eventually, develop a fully interoperable Multi-RNSS SSV definition that aggregates the capabilities provided by all RNSS and their regional augmentations. Efforts are also underway to develop and conduct flight experiments to validate the performance of these signals to support space users.

3.13 Surveying and mapping

High-precision RNSS is used in many surveying functions necessary for civil engineering and architectural design, production and maintenance of maps and Geographic Information Systems (GIS), land management and title transactions, and management of critical assets such as utility infrastructure, pipelines, dams, roads, rail and waterways. High-precision RNSS is also used to provide services to cities and counties for tax appraisal purposes and flood zone mapping.

Survey work may be commissioned at any geographic location and predictable RNSS coverage and operation is critical given the unpredictable work locations. Accuracies of 1-2 cm are required and accuracy standards are often dictated by regulation and law.

RNSS lowers the need for complex and costly equipment, including software solutions and the investment in the required infrastructure of augmentation service providers. For GIS and many mapping applications, the metre level accuracy provided by SBAS is sufficient. These applications include thematic mapping for small and medium municipalities, forestry and park management, and surveying utility infrastructures (e.g. electrical power lines). The application of RNSS tools and equipment makes simpler to geo-reference set of points and areas, enabling cost-efficiency and reduction of the needed personnel.

RNSS is the enabler of high-precision augmentation networks offering cm-level positioning such as Real-Time Kinematic (RTK) and Precise Point Positioning (PPP) essential for surveying applications requiring high precision: cadastral, mining, infrastructure monitoring and construction.

3.14 Timing

The extreme precision in the clocks required for accurate positioning can be transferred to an RNSS timing receiver and utilized wherever accurate frequency or absolute time is required. RNSS timing is used across a range of civilian and government activities due to its ability to reliably transfer precise time synchronization to global standards over very large distances with low-cost, very low maintenance user equipment.

RNSS provides precise timing and synchronization for most critical infrastructures. Telecommunication networks use the RNSS timing function for handover between base stations in wireless communications, time slot management and event logging. The main applications are:

- Satellite Communication
- Professional Mobile Radio
- Digital Cellular Network
- Public Switched Telephone Network

Telecommunication networks are continuously evolving toward higher capacity, increased transmission speeds and exploitation of higher frequencies. Consequently, the request for timing and synchronization requirements continuously gets more demanding.

Power grids use RNSS timing in systems providing measurements relevant to the network status. Smart grid development is underway all over the world. Phasor Measurement Units (PMUs) are pivotal to the development of network automatic protection systems. PMUs are deployed across remote locations of power networks requiring microsecond-level accuracy. The internal time references are currently based on RNSS receivers.

The finance sector, i.e. banks and Stock Exchanges, uses RNSS to timestamp financial transactions, allowing tracing of causal relationships and synchronizing financial computer systems. The main applications are financial transaction timestamps.

3.15 Meteorology

RNSS signals contain precise timing information. RNSS systems transmit this information simultaneously on two or more frequencies. In addition, the ephemeris of RNSS satellites is also precisely known and made available to RNSS receivers. These intrinsic characteristics of RNSS operation have proven to be unique and invaluable for the purpose of obtaining measurements of the Earth's atmosphere by low-Earth orbit (LEO) satellite-based RNSS (space-to-space) receivers and ground-based RNSS (space-to-Earth) receivers. Atmospheric temperature and water vapour profiles derived from this use of RNSS signals aid meteorologists to observe, research and forecast hurricanes, typhoons and other storm patterns over the oceans and improve many areas of weather prediction. These meteorological measurements are used in Numerical Weather Models and improve weather forecast predictions.

The following two sections provide descriptions of RNSS (space-to-space) and RNSS (space-to-Earth) applications which generate these meteorological measurements.

3.15.1 Radio occultation: RNSS (space-to-space)

Radio occultation is a space-based measurement technique whereby the RNSS space-to-space signal passing through the Earth's atmosphere is received by another LEO satellite and the characteristics of the received signal are used to determine physical characteristics of the intervening atmosphere. The precise knowledge of the position and velocity of both the LEO and RNSS satellites is used to compute a profile of the atmospheric refractivity in the position where the individual ray path between the transmitter and receiver has passed closest to the surface of the Earth. The positioning information used by the LEO satellite is: 1) the precise instantaneous positioning determination arrived at by an

examination of a series of position determinations; and 2) the residual error of the instantaneous RNSS positioning measurements obtained during an occultation. By using both the LEO positioning information and the refracted characteristics derived from the RNSS signal, the residual error between the actual LEO position and the measured position from the RNSS signal is used in calculations to determine the density of the atmosphere resulting in a temperature and water vapour profile for that signal's transition of the atmosphere.

The duration of a typical analysed occultation through the neutral atmosphere (below the ionosphere from roughly 100-km altitude to sea level) is less than 100 s. On average, over the entire globe 80 percent of the radio occultation measurements of the atmosphere extend to within 1 km of the surface, and 60 percent extend to within 1/2 km. A proof of concept constellation of six LEO satellites was deployed in 2006. Operational deployment of LEO satellite constellations commenced in 2016 for the purpose of collecting atmospheric radio occultation measurements on a global basis. RNSS receivers taking radio occultation measurements using the RNSS (space-to-space) link are subject to RR Nos. **5.328A**, **5.328B** and **5.329A**. These space-to-space radio occultation measurements of the atmospheric refractivity via RNSS-LEO can be used to augment ground-based RNSS measurement.

3.15.2 Ground-based RNSS meteorology: RNSS (space-to-Earth)

In a ground-based RNSS meteorology system, the RNSS positioning inaccuracy (residual error) that results from signal delays through the atmosphere are used to determine the Integrated Precipitable Water (IPW) in the zenith direction of the RNSS receiver. RNSS radio signals are slowed as they pass through layers of Earth's atmosphere; the ionosphere and the neutral atmosphere.

This slowing delays the arrival time of the transmitted signal from that expected if there were no intervening media. It is possible to correct for the ionospheric delay, which is frequency dependent, by using dual L1/L2 RNSS receivers. The delays due to the neutral atmosphere are dependent on the constituents of the atmosphere which are a mixture of dry gasses and water vapour. Since the errors due to the neutral atmosphere are not correctable through RNSS signal processing these errors remain as "residual error" and result in positioning inaccuracy.

In order to determine the Integrated Precipitable Water (IPW) in the zenith direction of the RNSS receiver, a number of RNSS L1/L2 signal measurements are taken from multiple RNSS satellites and compared against the extremely precise location coordinates of the RNSS receiver. When all system-related errors are accounted for, the residual error is presumed to come from the mixture of dry gasses and water vapour in the atmosphere. This residual "error" is combined with other local measurements to calculate the zenith direction IPW. These RNSS signal-derived local IPW measurements are input into Numerical Weather Models and improve weather forecasting.

3.16 Asset tracking and management

RNSS technology plays an increasingly broad role in the area of asset tracking and management. Sections 3.7 and 3.10 include some examples of individual asset tracking and management applications. Additionally, assets such as shipping containers, vehicles and boats can be actively tracked, even across borders, by teaming an RNSS receiver with a satellite transmitter. Such applications can provide real-time indication of normal or illegal asset movement.

4 RNSS application trends

This section contains information on trends for planned RNSS applications. In many of the applications mentioned in § 3, there is almost constant expansion and evolution of the applications of RNSS. These trends are expected to continue unabated for the foreseeable future. There is a significant trend to develop various receivers that simultaneously track the signals from more than one RNSS constellation for many applications.

4.1 Civil aviation RNSS application trends

The use of RNSS systems within civil aviation has evolved rapidly and has enabled new navigation capabilities and operations in all phases of flight. In particular, RNSS is an essential element of the International Civil Aviation Organization (ICAO) Performance Based Navigation (PBN) Concept and, as the performance of RNSS and avionics capability has progressed, has allowed the evolution of new PBN Navigation specifications.

4.2 Dual-frequency, multi-RNSS constellation use for aviation

It has long been recognised that the inclusion of a second RNSS frequency band together with multiple RNSS constellations has the potential benefit of improving the robustness of RNSS positioning by providing mitigations to identified RNSS vulnerabilities through the provision of additional ranging sources in different frequency bands.

The aviation industry and regulatory agencies have already begun laying the groundwork to certify the simultaneous use of signals from multiple RNSS constellations to enhance flight navigation. Following recommendations on GNSS of the 12th Air Navigation Conference of the International Civil Aviation Organization (ICAO), the ICAO Navigation Systems Panel (NSP) prepared a Concept of Operations (CONOPS) for the use of dual-frequency, multi-constellation (DFMC) GNSS in aviation. The main goal is to build consensus among stakeholders on how new RNSS technology will be introduced in air traffic management (ATM) in a cost-efficient manner, bringing operational benefits while addressing identified technical and regulatory challenges.⁶

The main principle of this CONOPS is to adapt the current operational concept of using RNSS in ATM introducing the minimum necessary evolutions. The key points from the CONOPS are summarized as:

- The combination of DFMC signals has the potential to improve RNSS performance and robustness to bring significant operational benefits for all CNS applications that are currently based on single-frequency, single-constellation RNSS. The development of DFMC RNSS antenna and receiver minimum operational performance standards (MOPS) provides an opportunity for implementing enhanced techniques to further reduce the susceptibility to interference.
- The potential operational benefits offered by DFMC receivers can only be realized if States approve the use of new RNSS signals in their airspace and those approvals are promulgated within the national AIPs. It is therefore recommended that ICAO provide additional technical guidance to assist States in their approvals for the use of new RNSS elements. Maintaining interoperability between aircraft and RNSS systems deployed at global, regional and local levels presents technical challenges, such as:
 - Backwards compatibility with Legacy L1 avionics will need to be maintained.
 - Future aviation systems (e.g. ABAS (e.g. RAIM), SBAS and GBAS) will augment different combinations of core constellations and signals and will provide different performance levels that will need to be accommodated operationally.
 - RNSS systems and receivers will need to have nominal and degraded modes of operation to enable increased robustness provided by DFMC RNSS.
 - To ensure global interoperability some aircraft implementations will be required to process different combinations of constellations in both dual frequency and single frequency modes of operation.

⁶ www.icao.int/Meetings/anconf13/Documents/WP/Navigation_Systems_Panel_CONOPS_for_DFMC_GNSS.pdf.

- At the time of the initial CONOPS, the DFMC standardisation activities within RTCA and EUROCAE were not inclusive of all RNSS core constellations. Therefore, it was suggested that further studies be undertaken to investigate possible solutions toward the goal of global interoperability of the ICAO CONOPS.
- This initial version of the CONOPS presents a preliminary, high-level implementation timeline covering RNSS systems developments, standardisation (MOPS and SARPS), receivers and certification, approval of the use of RNSS elements by States, and operational implementation in ATM.

The timeline suggests that realistically the operational introduction of DFMC RNSS could start in the 2025-2028 timeframe.

A DFMC RNSS receiver that accommodates all constellations and signals and delivers all of the potential benefits will be more complex than current receivers and may include the following features and capabilities:

- Processing of CDMA and FDMA signals.
- Processing of dual frequencies for each constellation and computing the ionosphere delay.
- Processing of multiple RNSS core constellations.
- Management of different constellation system times.
- Processing of DFMC and single Frequency GBAS and SBAS.

4.3 Synthetic vision for aviation

Synthetic vision systems provide a virtual 3D image of the surrounding terrain that enhances situational awareness when flying under instrument conditions. RNSS provides the position information so that the 3D images can be properly located.

4.4 Intelligent highway trends

Although fully autonomous vehicles will use RNSS as the primary navigation source, there will likely be semi-autonomous vehicle fleets available in the much nearer future. These vehicles will drive themselves on uncomplicated roads such as highways. They will exchange RNSS-derived position and velocity data with nearby vehicles so as to enable optimum separation distances. Such multi-vehicle systems have been demonstrated to be capable of safe and consistent operation at higher speeds than with human drivers.

4.5 Maritime trends

e-Navigation, an IMO (International Maritime Organization) initiative aiming to integrate all navigational tools in one only bridge system in order to enhance safety and ease of navigation to be implemented from 2020 onwards also tackling standardization and interoperability issues, is expected to spread the use of multi-constellation RNSS receivers.

The IMO operational performance requirements for RNSS towards the development of a multi-system receiver performance standard and of harbour services with high precision and robust positioning systems is expected to fuel the spread of multi-constellation receivers.

4.6 Public safety and disaster relief trends

There are four technological trends in which RNSS is expected to add and contribute to SAR missions:

- By providing more satellites carrying a SAR payload relaying the Forward Link Service (FLS), thus enabling the build-up of the MEOSAR system that is expected to replace the aging LEOSAR system. The MEOSAR will be backward-compatible and is expected to provide enhanced performance for all 406 MHz beacons currently in operation, to include global, near-instantaneous alerting and locating capabilities, and provide greater resilience to beacon-to-satellite obstructions. The MEOSAR Full Operational Capability is planned for 2018-2020.
- Cospas-Sarsat 406 MHz distress beacons will increasingly include an internal RNSS receiver. This is enabled by the “ever smaller, ever less power” trend of RNSS chipsets.
- In the case of Galileo satellites, by providing a Return Link Service (RLS) in addition to the Forward Link Service, thus acknowledging the receipt of the distress call to the beacon (within 15 minutes), enabling the possibility of detecting false alarms and reducing the stress of people awaiting rescue (PLBs). The RLS is planned to be operational by 2018.

4.7 Rail trends

Today, RNSS systems in the railway domain are predominantly used for non-safety related applications. Passenger information systems is the main application whereas RNSS is used, with asset management gaining importance. In the coming years, safety relevant applications, signalling and train control, based on RNSS are expected to be increasingly developed, to complement traditional technologies. These applications require a very high level of performance. Depending on the strategy towards them, RNSS may be used as:

- Primary means as foreseen in the US with PTC.
- A back-up solution as planned in Europe.
- One of the means within a hybrid solution.

The increasing demand for additional capacity of railway lines is expected foster the development and adoption of RNSS solutions. New solutions will need to be competitive, with minimum infrastructure and operational costs, which will also play a major role forming future demand for RNSS in rail applications.

4.8 Consumer trends

Smartphones are the primary platform for consumer applications, followed by wearables and tracking devices. The growing and diversifying usage of applications, such as the integration of positioning information in augmented reality scenarios and context-aware apps, will continue to drive the growth in consumer applications of RNSS.

The need for ubiquitous access to positioning, navigation, and timing (PNT) information is increasingly requiring navigation and timing capabilities to be available anywhere, anytime. To fulfil that objective, the only option is the hybridization of receivers, making use of all the data coming from RNSS, communication networks and stand-alone sensors, to offer the best PNT information possible to the end-user. In this scenario all sensors work collaboratively, providing a seamless stream of PNT information, irrespective of user location (e.g. RNSS in open areas, LTE in high-density city centres and tunnels, Wi-Fi indoors, embedded sensors in electromagnetic degraded environments, etc.).

4.9 Government: transportation and environmental management trends

The emergence of the smart cities concept is expected to drive the adoption of RNSS-enabled applications in urban environments in view of:

- The complementarity of RNSS with additional smart cities-enabling technologies.
- The enhanced performances in urban environment offered by the proliferation of multi-constellation receivers.
- The fact that RNSS still constitutes the most effective location technology in outdoor environments.

In particular, RNSS is an important component of Mobility As A Service (MAAS) solutions. On the one hand, it enables service providers to manage and optimise the use of the assets required to provide the different transport options. On the other hand, it enables the provision of smart mobility solutions to the users, including navigation, traffic information and journey planning directly. In the frame of MAAS, accuracy and availability in urban areas, as well as the need of trustable transactions, represent important requirements.

In Europe, the mandatory uptake of regulated applications will bring communication and positioning platform on all vehicles, opening the way for new telematics applications:

- e-Call⁷ based on RNSS will become mandatory in all new cars and vans sold in Europe from 2018.
- Smart tachographs based on RNSS will become mandatory in all trucks sold in Europe from 2019.

Within emergency services applications, enhanced accuracy and availability offered by are expected to be at the service of authorities to locate distressed persons in the shortest time. In fact, in Europe it is under study the implementation of E112 service. E112 is a location-enhanced version of 112, the European emergency number, introduced within the EU 2002 Universal Service Directive. It requires cellular network operators to provide emergency services managers with the location information of the caller. Already employed in local architectures, in Europe at least, it is expected that RNSS, and Galileo in particular, will be increasingly adopted.

4.10 Surveying and mapping trends

Being a demanding market domain, the main driving principle for adoption of RNSS will be the capability to offer increasingly better performances in terms of accuracy, availability, continuity and reliability, given the continuous demand for them by users.

The need for integrated solutions that make the best complementary usage of different technologies (including LIDAR and scanner), allowing for interoperability and software flexibility, will feed the demand for RNSS-enabled mapping and surveying equipment. RNSS receivers are integrated together with these technologies (also including total stations and photogrammetric cameras) to provide an absolute geo-reference to the local data acquired by those systems.

The landscape of Real Time Kinematic (RTK) applications is evolving with respect to:

- The proliferation of RTK RNSS receiver boards.
- The widespread availability of active and passive reference stations and RTK reference station networks operated by several national mapping agencies and commercial vendors.

⁷ eCall is an European initiative intended to bring rapid assistance to motorists involved in a collision anywhere in the European Union.

- Significant decrease in the price of RTK RNSS receivers, due to a congested market and the competitive pressure from emerging Precise Point Positioning, PPP, solutions.

These elements drive the trend towards low-cost, dual-frequency (L1/E1 and L5/E5 signal) receivers capable of cm-level horizontal and vertical precision. As these become widely available, they will enable the proliferation of RTK for a range of high accuracy applications.

Despite the challenges in delivering PPP solutions, particularly in a real-time environment, low-cost dual-frequency receivers are increasingly seen as a viable alternative to RNSS solutions using differential corrections solutions and are becoming popular amongst users who need sub-decimetre accuracy. This is especially true for users operating in environments where RTK is not an option (further from the coast), but also in areas where permanent networks are not available and the investment required for a full RTK system (two receivers plus a datalink) has to be compared with the lower cost of a PPP solution (one receiver only). Thus, in the context of centimetre accuracy applications, while RTK remains the premium option and offers immediate solution convergence, the minimal equipment needs and global accessibility make PPP an interesting alternative, providing opportunities also for the Galileo Commercial Service.

4.11 Timing trends

There is an increased RNSS interest for Small Cells synchronisation. Small cells are low-powered radio access nodes that operate in licensed and unlicensed spectrum that have a range between several metres up to 1 or 2 kilometres. Small Cell base stations can be deployed at street-level or within buildings and are key elements of the LTE deployment. The Small Cells market is therefore growing very rapidly to support the need for greater coverage and increasing mobile broadband traffic. LTE Small Cells networks synchronisation can rely on RNSS. This is a potentially promising RNSS market as the outdoor Small Cells market is expected to grow by 43% CAGR from now until 2020.

The timing and synchronisation community is facing many challenges linked to an increased need for resilience, reliability and security. The frequency and severity of threats to RNSS systems is evolving from unstructured experiments to more organised attacks that are better funded and more motivated. The technology to disrupt RNSS has become much more accessible. Examples include increases in websites selling low-cost “personal protection” jammers and GPS starting to gain attention at hacker conventions.

4.12 Agriculture trends

The market uptake of RNSS-enabled precision agriculture applications is expected to increase along with the need for increased food production caused by rising population, intensified urbanisation and adoption of western-lifestyle habits by developing countries.

SBAS-based solutions, improving the accuracy, integrity and availability of basic RNSS signals, are becoming increasingly available in precision agriculture applications, frequently being the preferred option for farmers entering the precision agriculture market. Available over continental scales, free of subscription fees or additional investment costs, SBAS-based solutions are widespread amongst farmers requiring accuracy to sub-metre levels. This is expected to lead to a further penetration of SBAS within agriculture RNSS receivers (currently at 80%).

The integration of RNSS positioning in Farm Management Information Systems (FMIS) together with the use of additional information coming from various sensors, including Earth Observation, is due to change precision farming and further drive its uptake. FMIS is a system for collecting, processing, storing and providing data enabling informed decision-making and management strategy elaboration for farmers. RNSS links this data to specific geographical coordinates. Within this context, whereas data collected comes from different equipment supplied by different hardware brands, interoperability and ease of use are key requirements of precision farmers.

The market uptake of multi-constellation receivers, enabling better performance and reliability of positioning in RNSS-degraded environments, is expected to further guide adoption of RNSS in the agriculture domain.

Accuracy will remain the most fundamental RNSS parameter for farmers. Reliability, availability, authenticity and coverage will also have relevance for specific applications.

4.13 Science trends

The unique characteristics of RNSS signals are extremely useful for exploitation in many science applications. These characteristics are availability on a global basis from RNSS MEO spacecraft, precise timing and navigation, low atmospheric attenuation, penetration of vegetation biomass and top levels of soil surface, and also the long-term deployment and stability of the RNSS constellations themselves. New science concepts incorporating RNSS signalling are found every year and development of those concepts spans many years before funding and deployment. One such concept under development is the use of RNSS signal timing for the real-time correlation of astronomy microwave observations from globally deployed Very Long Baseline Interferometry (VLBI) sites. The successful use of RNSS signal timing could obviate the need for VLBI site synchronized atomic clocks and dedicated terrestrial communication lines between the VLBI sites.

4.14 Other RNSS application trends

Other areas where, in particular, the use of RNSS signalling continues to be explored for enhanced or new applications include: Autonomous parcel delivery (by land and air), utilities monitoring, clean energy deployment and operation, mining, oil and natural gas extraction, space-guidance systems, environmental monitoring, and construction – heavy and civil engineering.

4.15 RNSS as element of innovative technology development

As an independent, globally available, and cost-effective source for positioning, navigation and timing information in outdoor environments, RNSS has become an essential element of major contemporary innovative technology development, such as the Internet of Things (IoT), Big Data, Augmented Reality, Smart Cities, and Multimodal Logistics. Additionally, advances in mobile technology, Automated Driving, Smart Cities, and IoT will spawn a further proliferation and diversification of RNSS-enabled added-value services.

5 Summary

This Report provides information on some current and planned RNSS applications for the 1-GHz RNSS bands (1 164-1 215 MHz, 1 215-1 300 MHz and 1 559-1 610 MHz). It includes RNSS applications not addressed in the current set of ITU-R M-Series Recommendations addressing 1-GHz RNSS issues as well as additional information on RNSS applications that have been previously addressed.
