GNSS positioning services of the future

Future GNSS users, requirements and national geodetic infrastructure

AJ Geomatics for Lantmäteriet

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1. Introduction

1.1 Background and format

The purpose of this report is twofold, first to outline expected users of future Global Navigation Satellite System (GNSS) positioning services and the requirements from users to the services. Secondly, the conclusions on future users form the basis for recommendations to the future national geodetic infrastructure in support of such services as well as recommendations to the future role of national geodetic authorities.

The report is based on the global and European development, but it has a specific focus on Sweden, on Lantmäteriet and on SWEPOS.

The report commences with an overall review of the technological development of society followed by a brief outline of the current development in GNSS and high accuracy GNSS services. Section 2 provides a review of past and current SWEPOS users, followed by a review of the most important findings of the Market Report from the European GNSS Agency (GSA). This concludes with an identification of the expected GNSS user groups in Sweden for the next five to ten years.

These preliminary conclusions provide the basis for interviews with a number of stakeholders representing expected future user groups in Sweden. The stakeholders represent end users, municipalities, government organisations as well as Ericsson and Leica Geosystems. A total of 19 persons were interviewed and in Section 4 summaries of the interviews are provided followed by concluding remarks on future GNSS users and their requirements in Section 5.

Subsequently, Section 6 outlines the expected need for national geodetic infrastructure in the future, while Section 7 provides a perspective on the expected role of the national geodetic authorities of the future as well as a special focus on Lantmäteriet and the future role of SWEPOS. Finally, conclusions are provided in Section 8.

A list of the external references used in the text is provided at the end of the document.

1.1.1 Limitations

User groups which are not discussed in the current work include the use of GNSS in space, for instance for positioning and navigation of satellites and other space crafts, because mostly a global (not national) infrastructure is needed for such applications.

Further, the use of GNSS for monitoring of earthquakes, landslides and other natural phenomena is not included along with the use of GNSS for weather prediction services because the number of users within these fields is relatively small.

The use of GNSS for military, security, and intelligence applications is omitted because of the secrecy and security clearances needed to reveal relevant requirements and plans.

1.2 Towards a data driven smart society

The development in GNSS technology, applications and users is an integral part of the overall development towards a data driven smart society. Important trends in this contemporary technological development are *Internet of Things* (IoT) where objects, devices, vehicles etc. are connected to the internet allowing for remote access or control relying on a wide range of sensor technologies. Also, *Smart Cities* which describe an integrated system of for collecting, processing, measuring and broadcasting data from and about the city for use by citizens, governments and city planners is part of this development.

The *Big Data* concept is an important element of both IoT and Smart Cities where new systems and technologies are needed to deal with the massive amounts of data being produced which must be processed, analysed or evaluated. Finally, *Augmented Reality* (AR) is also an important trend affecting the development of GNSS applications and also being affected by the GNSS development. AR uses the real environment (i.e. not a virtual reality) and overlays information on top to be used both for entertainment (e.g. *Pokemon Go*) and for more professional applications for instance in city planning and construction works.

All of these development trends affect the development of GNSS applications, but they also rely on GNSS for providing real time geo-location and timing information. For IoT and the Big Data concepts, positioning is important for moving objects and vehicles, and GNSS based timing is important for many stationary objects and devices. The same is the case for Smart Cities where GNSS is the most important source of geo-location information about moving objects and dynamic motion patterns of people and cars. For AR, GNSS is one among many sensors being integrated for the next level of AR to provide seamless indoor-outdoor location information supporting the continuity requested for many AR applications. For outdoor use of AR, GNSS is currently the most important positioning sensor which combined with digital camera and inertial sensors, e.g. in smart phones, provides the user with references to specific real objects in the applications.

These international trends in technological development are in Sweden further supplemented by a large focus on digitalisation and seamless data flow in building and construction activities as well as in management and maintenance of the built environment. Through the strategic innovation program *Smart Built Environment*, the Swedish government has invested a substantial amount in research and development with the overall goal of driving Sweden to the forefront of the new opportunities of digitalisation in order to achieve intelligent, sustainable cities and to be able to manage resources more efficiently in the future. This is followed up by related initiatives in the combination of Building Information Modelling (BIM), Geographic Information Systems (GIS) and 3D geodata for environmental applications as well as for building and construction work. All of these initiatives rely on geo-location information where GNSS is a crucial contributor.

1.3 Technical development of GNSS

As a background for the following discussion on GNSS users and their requirements toward GNSS services, the global development within GNSS systems is briefly reviewed in this section.

The term GNSS covers global navigation satellite systems as well as regional navigation satellite systems and augmentation systems.

1.3.1 Global Navigation Satellite Systems

Of the four global GNSS, the American GPS and the Russian GLONASS are fully operational and undergoing further development and modernisation. The European Galileo and the Chinese BeiDou are still being developed but will soon be fully operational.

For **GPS** the implementation of a new civil code on the L2 frequency (L2C) and use of a third frequency (L5) is ongoing as new satellites are launched. Currently 19 satellites transmit the L2C code, and 12 satellites employ the L5 frequency. Development of the next generation GPS satellites, called GPS III, is well underway with the first GPS block III satellite launched in December 2018. Also, the Next Generation Operational Control Segment (OCX), i.e. the control system for GPS, is undergoing a major review and modernization in order to support full utilization of the new GPS block III satellites including e.g. a new civil code on the L1 frequency (L1C).

For **GLONASS**, modernization activities are centred around adding a third frequency and changing the coding structure on the satellite signals for a better interoperability with GPS and Galileo in the future. The new generation of satellites, called GLONASS-K satellites, are beginning to be launched. Currently two K-satellites are in orbit, and more are planned to be launched during the coming years along with the remaining three satellites of the previous generation.

Galileo Initial Services was declared in 2016 based on 12 operational satellites. Currently 22 Galileo satellites are operational. More satellites will be launched in 2020, and full operational capability is expected when these are operational. Galileo differs to GPS by a more robust signal structure and more stable clocks in the satellites. Also, Galileo will include both authentication services and a high accuracy service - these are further discussed in Section 1.3.5 below.

The **BeiDou** system is composed of satellites in medium earth orbit (MEO), as the other global GNSS, but supplemented with five satellites in geostationary orbit (GEO) and five in inclined geosynchronous orbits (IGSO). Thereby BeiDou could be established first as a regional navigation system, and it has been available as such in China and neighbouring countries since 2011. With many MEO satellites being launched these years, a global coverage is soon available. It appears that currently 29 BeiDou satellites are in orbit, a combination of MEO, GEO and IGSO satellites. Totally, the system shall be composed of 37 satellites and a global navigation service is expected in 2020.

1.3.2 Regional Navigation Satellite Systems

The Indian Regional Navigation Satellite System (IRNSS) is the only autonomous regional satellite-based navigation system which does not rely directly on any of the global systems. IRNSS operates based on seven dedicated satellites distributed in GEO and IGSO orbits, providing a navigation service with an anticipated accuracy better than 10 meter in India.

1.3.3 Augmentation systems

Satellite based augmentation systems (SBAS) are providing supplementary data which is used together with data from the global GNSS systems. The current list of systems comprise the European Geostationary Overlay System (EGNOS), American Wide Area Augmentation System (WAAS), the Japanese Multi-functional Satellite Augmentation System (MSAS) and Quazi Zenith Satellite System (QZSS), the Indian GPS Aided Geo Augmented Navigation (GAGAN), the Geoscience Australia Test-Bed Project (GATBP) and the Nigerian Satellite Augmentation System (NSAS) in test mode. These are all augmenting GPS.

The Russian System for Differential Corrections and Monitoring (SDCM) augments both GPS and GLONASS

The SBAS systems provide integrity information along with extra ranging information for improved navigation performance. Most of these are mainly developed for aviation, but are also used for maritime and land-based applications with accuracy requirements at the level of a few meter. Use of SBAS is limited at high latitudes because the geostationary satellites often used for the data distribution are located at low elevation angles above the horizon, and data reception is therefore easily blocked by the topography in Northern and Southern latitudes. Some of the SBAS systems also distribute data via the internet.

Current development of SBAS systems is towards augmentation of data on more frequencies and also towards augmentation of more GNSS constellations. For instance, EGNOS is being developed towards augmenting both the GPS and Galileo constellations, and towards a dual frequency augmentation for both the L1/E1 and the L5/E5a frequencies.

1.3.4 High accuracy positioning services

Since the mid 1990'ies real time high accuracy GNSS positioning has been obtained by means of the **real time kinematic (RTK)** positioning technique, where data from one or more permanent GNSS reference stations is used for generation of RTK correction data which is distributed to end users and applied in the positioning process. The RTK data provides corrections for atmospheric effects on the satellite signals as well as for inaccuracies in the GNSS navigation messages (i.e. estimates of satellite position and clock errors). RTK corrections are transmitted to users via terrestrial communication, mostly cell phone networks or UHF radio. RTK can provide an uncertainty in the position estimate of 1-5 cm after a short initialisation of a few seconds.

RTK services based on networks of permanent GNSS reference stations (network RTK) exist as local or national services in most parts of the world. The service provider operates a processing centre and a number GNSS reference stations within the geographic area of interest. Also, the service provider manages data communication and support to end users. The Swedish SWEPOS is an example of such a service.

Different approaches for estimation of RTK corrections exist one of them being the Virtual Reference Station (VRS) approach [11] where corrections are estimated for the approximate user location in the form of data from a virtual reference station which is then transmitted to the user.

Most current RTK services provide corrections for GPS and GLONASS, and implementation of Galileo and BeiDou as well as the use of data from all available frequencies in the operational RTK services is well underway. Another important development activity is focused on the models used for estimating corrections for the various error sources. The concept of **state space representation (SSR)** implies a separate estimation of the error sources allowing for the use of more advanced models in the data processing. This also allows for a more efficient data distribution since different error sources can be corrected at different time intervals leading to an overall reduction in the amount of data to be distributed to end users.

Real time **precise point positioning (PPP)** is another approach for providing high accuracy positioning services. PPP requires a global network of permanent GNSS reference stations for precise estimation of satellite positions, clock corrections, and code and phase hardware biases. The correction data is normally distributed by means of geostationary satellites. Due to the global nature of the technique, PPP services provide global coverage and are operated by companies with a global business agenda. Real time PPP services provide position accuracies at the level of 5-10 cm with an initialisation time of some minutes [9].

Recently, the techniques of RTK and PPP are being combined in order to take benefit of the higher accuracy and shorter initialisation time of RTK as well as the less dense network of reference stations required for PPP. In the simplest way the two techniques are used separately to supplement each other, i.e. if connection to a local RTK service is lost, the user equipment can switch to using a global PPP service until connection to the RTK service is re-established.

More advanced combination of RTK and PPP is in the data processing both in the control centre and in the end user equipment. For instance, the models used for estimating corrections for the satellite positions and clock errors can be based on the PPP methodology, whereas estimates for atmospheric errors can be based on the RTK methodology. For this to work out, the SSR approach must be applied in both the data processing, the data distribution and in the end user equipment.

International standardisation work within e.g. the Radio Technical Commission for Maritime Services (RTCM) is ongoing, and even though combined RTK and PPP does exist to some extent in operational services, the standards are not yet finalized.

The GNSS positioning services require data from permanent GNSS reference stations, also referred to as Continuously Operating Reference Stations (CORS). Such stations exist in almost every country of the world. Originally high quality CORS stations were established by government organisations as the backbone for geodetic reference frames, and they are used also for geodynamic monitoring and modelling. However, CORS stations also provide an excellent infrastructure for positioning services, and in Sweden the SWEPOS network of CORS forms the basis for the SWEPOS positioning services.

Integrity as a quality or performance parameter in GNSS positioning is becoming increasingly important for many user groups, especially within the field of autonomy. Integrity is a measure of the trust which can be applied to the correctness of data from a positioning service. The integrity concept for GNSS based positioning was originally developed for SBAS services and has been applied to some of the operational PPP services.

1.3.5 Operational global high accuracy GNSS positioning services

In this section, some examples of commercial global providers of high accuracy GNSS positioning services are briefly reviewed. Parts of the text in this section originate from an NKG White Paper on Future Positioning Services [10].

Many of the services listed below are not "truly global", but the service providers operate in several countries, and the services are established so they can be expanded.

- Hexagon AB operates a number of high accuracy positioning services: Veripos is a global PPP service targeting offshore applications while TerraStar C is a global PPP service aimed at farming. HxGN SmartNet is a network RTK service based on GNSS reference stations in Europe, North America, Australia, Russia and Kazakhstan. Service is provided in the areas covered by the networks of reference stations, and the service relies on local actors within the service areas. HxGN SmartNet is in Sweden based on data from the SWEPOS network of CORS.

- Topcon operates a PPP service, TopNET global, which is a global service mainly for Topcon-equipped platforms. The RTK service TopNET live is a network RTK service. The service is available through Topcon distributers in large parts of North and South America as well as in several countries in Europe and Australia. TopNET live is in Sweden based on data from the SWEPOS network of CORS.

- Trimble operates a number of positioning services with different levels of performance. Focusing on the high accuracy services, OmniStar-HP is a PPP service where the corrections are modelled on a worldwide network of reference stations using carrier phase measurements to maximise accuracy. It is used mainly for agricultural machine guidance and many surveying tasks. The CenterPoint RTX service is a satellite-delivered global positioning service with an expected positioning accuracy better than 4 cm. The service VRS Now is based on network RTK, and is available in much of North America, as well as in several countries in Europe, Australia and New Zealand. VRS Now is in Sweden based on data from the SWEPOS network of CORS.

Examples of other services providers available in (parts of) Sweden not relying on SWEPOS data but on other GNSS infrastructure are:

- Fugro which operates several different services with global coverage. The StarFix services G2, G2+ and G4 are high accuracy PPP services based on a global network of GNSS reference stations. The services are provided for offshore applications.

- NavCom, a subsidiary of John Deere, offers StarFire subscription. This is a PPP service with global coverage for use on land only and aimed at farming. Position accuracy typically better than 5 cm.

1.3.6 Upcoming high accuracy GNSS positioning services

Internationally, it is expected for the field of autonomy, including autonomous vehicles, machines, drones, vessels, robots etc., that the positioning and navigation solutions will be developed around high accuracy GNSS-based positions. It is also expected that the business area of autonomy will be global and that it will be very large. This had led to an increasing level of activity with respect to development of existing, and establishment of new, global high accuracy positioning services. Some of these are discussed in the following.

- Sapcorda, a recently launched joint venture between Bosch, Geo++, Mitsubishi Electric and u-blox, is creating a new GNSS correction service with coverage on a global scale expected to be operational early 2020. The services from Sapcorda will be broadcasted using cellular networks as well as satellite links. Also, the Sapcorda services will include integrity information, and data will be distributed in an open format. Sapcorda is targeting self-driving and autonomous cars as well as drones and various IoT applications.

- Hexagon AB has recently launched the TerraStar X service which is presently operated in North America and Europe. It is based on a combination of orbit and clock corrections estimated from a global PPP reference station network, with ionospheric corrections estimated from the HxGN Smartnet reference stations (see Section 1.3.5). TerraStar X also provides integrity and authentication, and the service is aimed at autonomous driving. Some results of using the new service were presented at the ION GNSS+ conference in the USA in September 2019 [12].

Also, at the ION GNSS+ conference in USA in September 2019 [13], a number of initiatives from other service providers were presented. Some of these are reviewed below.

- In France, Centre national d'études spatiales (CNES) operates a PPP service and has developed a related app called PPP-WizLite for Android smart phones [14]. Currently, the service and app used in combination provide position accuracies at the sub-meter level with the newest generation of smart phones. The service is further developed for dual frequency multi GNSS positioning.

- In Canada, Natural Resources Canada has been operating a post processing PPP service for a number of years. They have investigated the use of data from smart phones, and based on a number of modifications in relation to e.g. weighting scheme and better a priori tropospheric parameters, it has been possible to obtain cm-level position accuracy with post processing of data from a Huawei smart phone as collected in static mode [15]. So far, this has been demonstrated in a test mode only, but it illustrates the expected future development within the field of PPP positioning services in relation to smart phones.

- In China, the company Qianxun Spatial Intelligence Inc. which is a joint venture partly owned by the Alibaba Group, operates a high accuracy GNSS positioning service based on a global network of 300 reference stations along with 2200 CORS in China [16]. The service provides corrections for both orbits, clocks and hardware biases as well as atmospheric corrections using the SSR concept. Low cost end user equipment can not yet apply SSR data, and the company has therefore developed a method to convert SSR data into VRS-like data which is transmitted to end users via mobile internet. This has been tested with a low cost GNSS receiver and cm-level position accuracy is shown.

The above developments are just examples of ongoing activities. There are, especially in the USA and Asia, more companies currently developing high accuracy positioning services aimed at the mass market users such as for example autonomous vehicles and high accuracy LBS.

1.3.7 Galileo services

As mentioned above, Galileo will provide at least one authentication service and a high accuracy service (HAS). The **Galileo Open Service Navigation Message Authentication (OSNMA)** is based on using a few bits of the navigation message as check bits which can be used by the GNSS receiver to verify that the signal received does indeed originate from a Galileo satellite. This open service authentication will be available for free for all Galileo users. A more advanced authentication service, based on navigation code encryption, is being planned for the future most likely as a commercial authentication service available for a subscription fee.

The **Galileo High Accuracy Service (HAS)** will be a PPP service based on a global network of GNSS reference stations, where the technically most novel part is that the data distribution will be via the Galileo MEO satellites on the E6-B frequency. This means that the service will have better availability at higher latitudes compared to existing PPP services using GEO satellites for the data distribution.

Data from the Galileo HAS will available free of charge as opposed to existing PPP services, and according to Fernandez-Hernandez et al. [8] it has been decided by the European Commission (EC) that the positioning error of the Galileo HAS service shall be "less than 2 dm". Normally, PPP can provide a better positioning performance, but the limitation has been decided by the EC in order for the Galileo HAS to coexist with commercial PPP services. Galileo HAS will initially provide corrections for GPS and Galileo satellite positions, clock errors, and code and phase biases for use global usage. The global service is expected to be available in 2020. Further, as a next development step, distribution of ionospheric corrections over the EU region is being considered as a European regional service.

1.4 User Technology Development

According to the GSA User Technology Report [3] the technical development in user GNSS technology including GNSS receivers and antennae is developing rapidly towards multi constellation units and also multi frequency especially for the professional applications.

In terms of multi constellation units the GSA User Technology Report estimates that more than 30% of all GNSS receivers support both GPS, GLONASS, Galileo and BeiDou (see Figure 1), and this number is expected to further increase in the future.

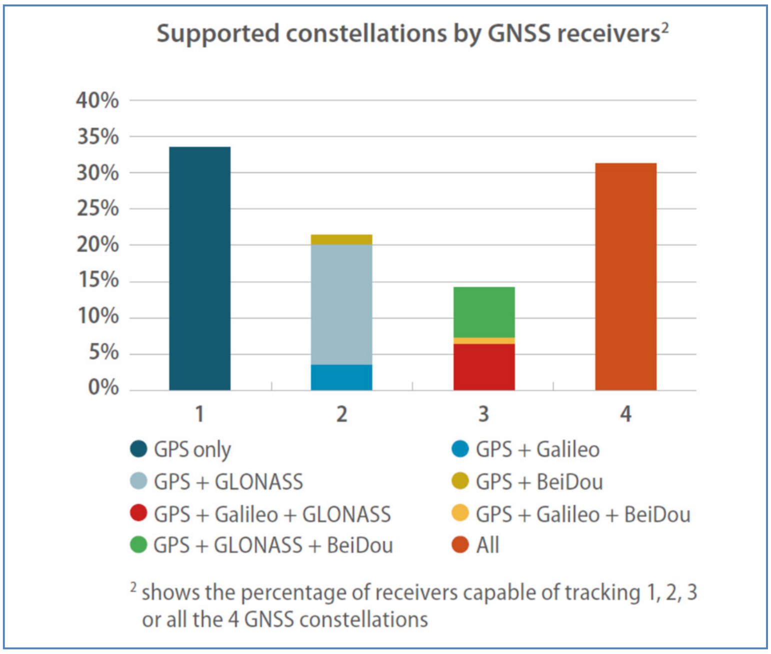

Figure 1. Percent of GNSS receivers tracking one to four GNSS constellations. Source: Galileo Technology Report Issue 3 © European GNSS Agency, 2018.

For professional use, most GNSS receivers have, for a number of years, been able to track both GPS and GLONASS and most of the multi constellation units in use today are indeed used by professional GNSS users. The development among professional users is therefore more focused on multi frequency where the receivers and antennae are moving away from the dual frequency concept towards tracking signals on three or four frequencies simultaneously. This is discussed in the GSA User Technology Report [3], and Figure 2 shows that currently only around 10% of all GNSS receiver units are able to track signals on three or four frequencies.

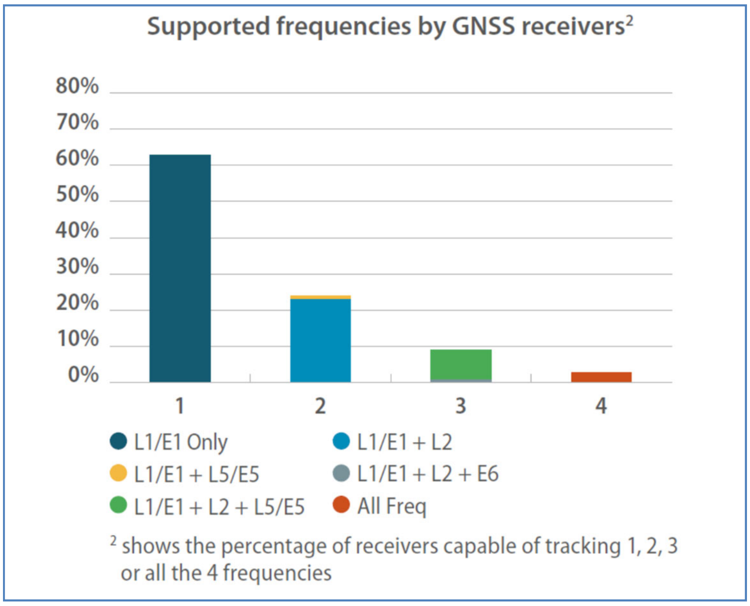

Figure 2. Number of GNSS receivers in percent tracking one to four frequencies. Source: Galileo Technology Report Issue 3 © European GNSS Agency, 2018.

2. SWEPOS user groups

Lantmäteriet is operating SWEPOS which is a network of permanent GNSS reference stations in Sweden. These stations form the backbone of a number of positioning services offered by Lantmäteriet to GNSS users in Sweden. Most important in this context is the high accuracy real time kinematic (RTK) service which augments GNSS by providing RTK correction data enabling end users to obtain cm-level GNSS positioning accuracy in real time.

Based on statistics from Lantmäteriet an overview of the composition of users of the SWEPOS RTK service is provided in the following. Figure 3 shows the current (by the end of 2018) main user groups of the SWEPOS RTK services.

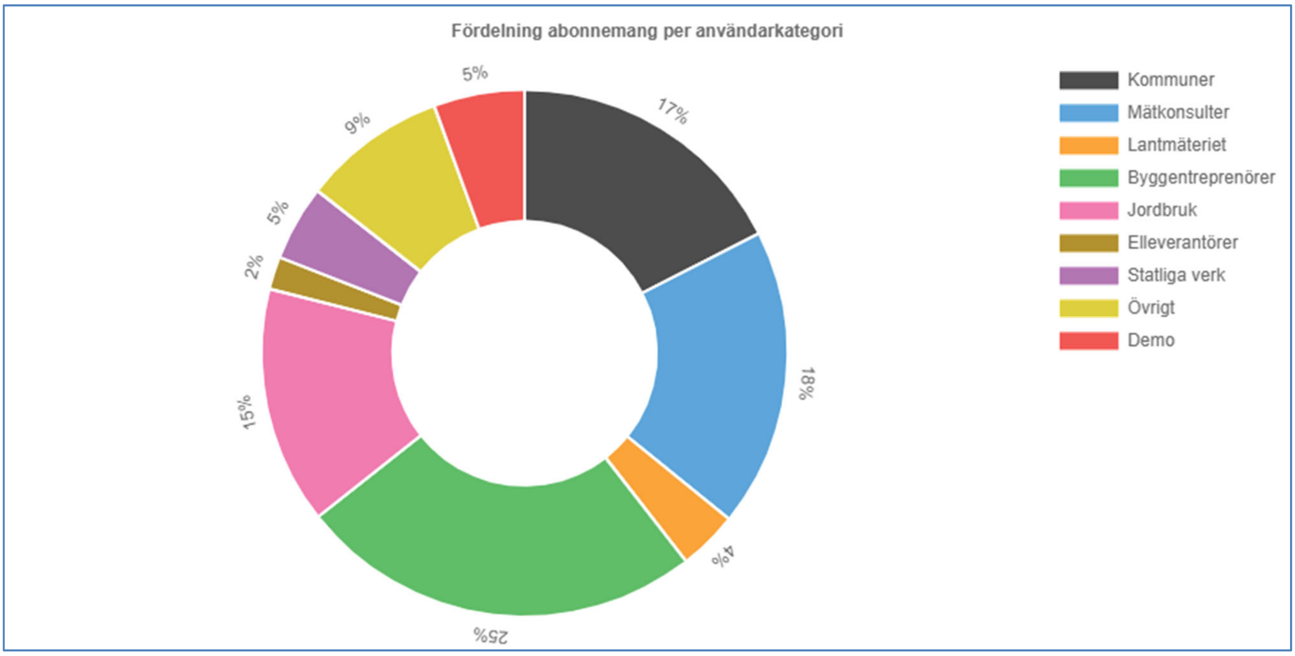

Figure 3. SWEPOS RTK users by end of 2018. Data from Lantmäteriet.

The status by end of 2018 was a total of 4099 paying users distributed in groups as follows:

25% construction companies, 18% land surveying companies, 17% municipalities,
15% farming, 5% government organizations, 5% demonstration users,
4% Lantmäteriet, 2% power companies, 9% other

Assuming that Lantmäteriet mainly use the services for land surveying (real estate and property boundaries) and that the municipalities also mainly use the services for land surveying (real estate, construction control, mapping), then land surveying amounts to 18 + 17 + 4 = 39% of the current users. Grouping land surveying users with the construction companies lead to 64% of the RTK SWEPOS users operating within the areas of building and construction (in Swedish *samhällsbyggnad*). This becomes an even larger share (i.e. 71%) of the users if government organizations and power companies also belong in this group.

If these assumptions are correct, there are three main areas of application for the SWEPOS RTK services are:

- 71% building and construction (Swedish *samhällsbyggnad*)
- 15% farming
- 14% other (other + demonstration)

2.1 Development of SWEPOS user groups 2004 - 2018

Data on the various user groups has been provided back to 2004, and it is relevant to outline the development of the various user groups.

In 2004 there were 200 users of the SWEPOS RTK services. The number of users has increased every year since then. The rate of change of number of users per year is increasing with relatively more new users since 2015. Especially during the last year, the number of users has increased a lot with 560 new users. This means that 14% of all users by the end of 2018 had signed up during the year.

Looking at the various user groups, the largest user group in 2004 was municipalities followed by demonstration and land surveying companies.

In 2004, 47% of the users were municipalities and their share of users has been reduced every year since then reaching the level of 17% of the users today, because the number of users in the other user groups has increased in numbers.

Land surveying companies was the second largest user group in 2004 and amounted to 16% of the users. In terms of percentage of users, this group has remained rather stable since then varying between 16% and 25% of the total number of users. Today land survey companies compose 18% of the users.

Power companies were present with 1% in 2004, and also this user group has remained at almost the same level varying between 1% and 3% of the total number of users since then. Today it is 2%

Construction companies is the user group which has increased the most since 2004 when it was 2%. The ratio has increased almost every year to the level of 25% of the total number of users today.

Farming came in as a new user group in 2010 with 2% of the users. Since then the ratio of farming users has increased every year to the level of 15% today.

Looking at the last five years (2013-2018), the most significant changes are found for:

- Farming - has increased 5% -> 15%
- Construction - has increased 22% -> 25%
- Surveying - has decreased 21% -> 18%
- Municipalities - has decreased 21% -> 17%

It must be noted that the percentages provided describe the relative distribution of users. The absolute number of users in each user group has not been provided, but it is expected that the number of users has increased for all of the user groups since 2004 because the total number of users has increased as a consequence of the more widespread use of GNSS in society in general.

It is expected that the number of SWEPOS users will continue to increase in the future, and that all user groups will increase, because there are still many new applications being developed for GNSS. However, some of the future SWEPOS users will most likely come from user groups not yet represented in the statistics from Lantmäteriet such as users that rely on high accuracy positioning and navigation of drones as well as the users of GNSS for high accuracy road and rail applications. This is further discussed in Section 3 and 4 of this report.

3. Expected global development in GNSS users 2015 - 2025

The European GNSS Agency (GSA) publishes a GNSS Market Report at regular intervals. The latest report, issue number 5, was published in May 2017 [1]. The report provides a review of the current base of GNSS users, globally and across all GNSS i.e. GPS, GLONAS, Galileo, BeiDou and augmentation systems. The report also provides analyses of current trends in development, and it provides predictions, or expectations, to the development of the user base for a ten-year period. For the latest report, current status is provided for 2015 and the expectations are forecast until 2025.

The full GSA Market Report is available at the web site of the GSA:
https://www.gsa.europa.eu/market/market-report

The text in this section is mainly based on the GSA Market Report reviewing the main conclusions with respect to different user groups, development trends, requirements from the various user groups to GNSS, and finally the expected development in number of users towards 2025. Where other references are used in the text, these are explicitly mentioned.

For discussions of the user requirements, the terms and definitions applied by the GSA Market Report are also applied in this report. The most important of these are accuracy, availability, and integrity. But also, time to first fix, robustness and authentication are included. For the definitions used, please refer to Appendix A of this report.

In the following, the large consumer user groups are discussed first, i.e. the private or personal use of GNSS. This is followed by a discussion of the professional user groups where GNSS is used for surveying, agriculture, maritime applications etc.

3.1 GNSS for non-professional users

The two main non-professional user groups are the use of GNSS for Location Based Services (LBS) and the use of GNSS for road-based applications. Figure 4 shows the expected development in total number of units on a global basis during 2015 to 2025.

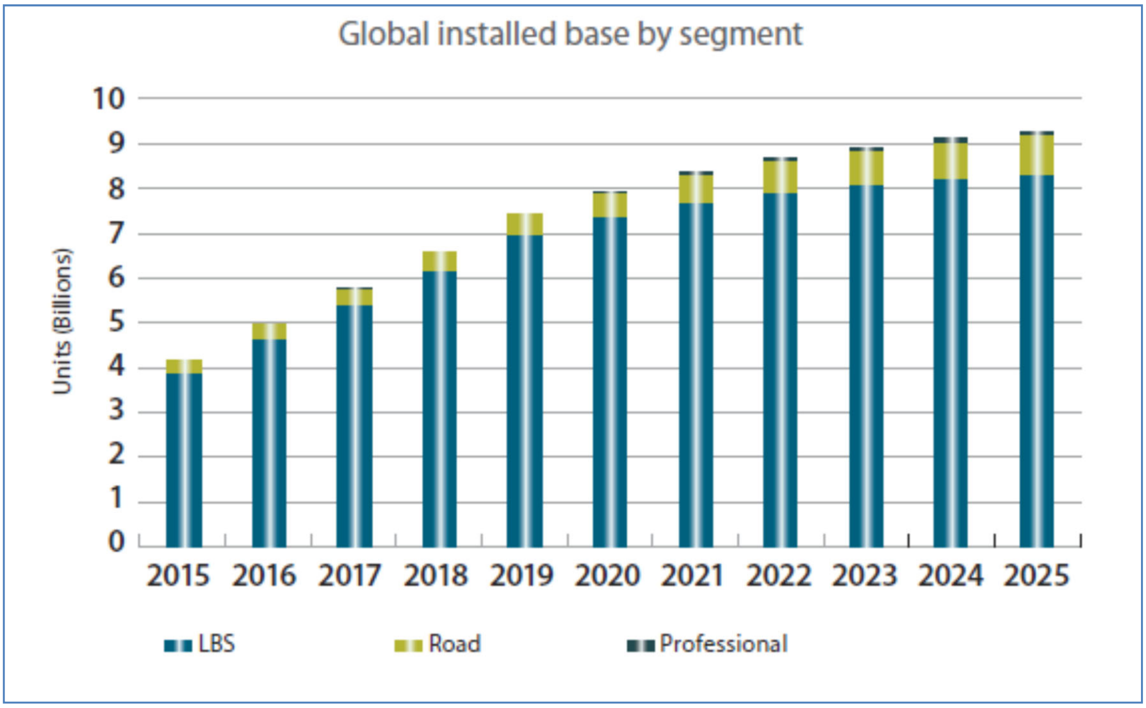

Figure 4. Number of GNSS units installed globally. Source: GNSS Market Report, Issue 5, copyright © European GNSS Agency, 2017.

3.1.1 LBS - Location Based Services

Use of GNSS for LBS is considered a non-professional group of users because the professional users of GNSS for LBS are outnumbered by the private and personal applications. In terms of platforms for the GNSS units in this user group, smart phones are by far the largest platform. Other types of platforms are for instance tablets, portable computers, digital cameras, personal tracking devices, sporting equipment and also "wearables" where GNSS receivers are integrated into clothes, shoes, watches etc.

The absolute number of GNSS units to be used for LBS globally is expected to increase from 3.9 billion units in 2015 to around 8.1 billion units in 2025 where the development is expected to attenuate (see Figure 4). The expected increase in units corresponds to a factor of 2.1 over the ten years from 2015 to 2025. It should be noted that the largest increase in number of units is expected within the first five years until 2020 mainly driven by an increase of LBS users in Asia.

It is also noted that according to the United Nations, the number of people in the world is expected to be around 8.1 billion in 2025 [2], the same number as the expected number of GNSS units for LBS. This does not mean that every person in the world will have a GNSS unit by 2025. Still many people will be without a smart phone, but as the GSA points out in the Market Report, many other people will have multiple GNSS devices.

Examples of applications where GNSS is used for LBS are:

- Personal navigation and route guidance
- Geo marketing and advertising
- Safety and emergency
- Sports, games, and augmented reality
- Social networking
- Enterprise applications (i.e. LBS for professional use e.g. mobile workforce management)
- mHealth e.g. patient monitoring and guidance for visually impaired

Trends and drivers in the development of the number of users of GNSS for LBS are for instance the new possibilities with the opening of the use of raw measurements (code and carrier phase) for app developers, more complexity in apps relying on augmented reality, integration of multi-GNSS units which provide increasing accuracy and availability, and LBS in mHealth which is driving the development and sophistication of wearables and apps in smart phones for health care.

It is noted that LBS does not only rely on GNSS but also on WI-FI, bluetooth, cell-ID location, virtual beacons etc. to provide information about the user location. Hybrid positioning, i.e. seamless indoor - outdoor navigation, brings the different technologies together in order to provide the user with continuity in the LBS services.

A growing number of LBS applications require high accuracy, and with the integration of multi constellation GNSS the LBS units can approximate performance of low-end professional receivers. In the future, this could lead to "democratisation of some professional activities" for instance rural cadastral surveying ([1] page 30). According to the GSA User Technology Report [3] the LBS users which currently set the highest requirements to accuracy and continuity are the augmented reality and mapping/GIS applications. The GSA user consultancy report on LBS [7] also mentions Mobile Location Based Gaming (MLBG) or just "games" as an application area with an increasing request for high accuracy.

A limiting factor in the development of high performance LBS applications is power consumption because GNSS requires a considerable amount of energy and the platforms used, e.g. smart phones, have limited capacities [7]. The development within batteries and power sources is therefore also important in this context.

Key requirements to GNSS from LBS users in the future are mainly availability and time to first fix. Requirements of accuracy and authentication are, however, increasing as the number of high performance applications increase for instance for mHealth, geo marketing, fraud management and billing. Connectivity, interoperability and power consumption is also important for this user group. Whereas integrity is not mentioned as an important requirement.

As mentioned, the number of GNSS units for LBS applications is expected to grow with a factor of 2.1 from 2015 to 2025 on a global basis. The largest increase is expected for GNSS in smart phones but also the use of GNSS in tablets will increase significantly. GNSS in sports equipment and wearables as well as in digital cameras and tracking devises will also increase but not as much. GNSS for portable computers and for personal search and rescue is not expected to increase from the current number of units in use.

3.1.2 Road

Use of GNSS for road related applications is mainly a non-professional user group because the professional use of GNSS for road is outnumbered by the use of GNSS in private cars and vehicles.

The absolute number of GNSS units to be used for road applications globally is expected to increase from 300 million units in 2015 to around 870 million units in 2025 (see Figure 4), an increase with a factor of 2.9.

Use of GNSS for road covers mainly the following types of applications:

- Smart mobility including use of GNSS for navigation, fleet management and road traffic monitoring
- Safety critical applications such as intelligent transport systems (ITS), advanced driver assistance systems (ADAS), and tracking of dangerous goods
- Liability critical applications including road user charging and insurance telematics

- Regulated applications governed by national or international legislation such as eCall (automatic messages sent to 112 in case of emergency), and smart tachographs for automatic recording of speed, distances etc.

The main driver of the development in this sector, is the research and development in autonomous driving where all the large car manufacturers are currently investing in autonomous driving technologies. But also, as mentioned by the European Radio Navigation Plan, eCall will be mandatory for all cars sold in Europe in the future and smart tachographs will be mandatory in all trucks sold in Europe from 2019 [4]. These are examples of how political decisions may also affect the development in number of GNSS users for road applications.

Key requirements to GNSS from this user group cover basically all the different types of requirements defined by the GSA depending on the type of application. Authentication and integrity stand out as being important for all the various uses. Accuracy is important for safety critical and payment critical applications, time to first fix is important for safety critical applications and for regulated applications etc. Also, connectivity is listed as an important requirement for all road uses for GNSS.

The US Federal Radio Navigation Plan notes that for future highway applications of GNSS, high accuracy services with integrity will be requested. The lack of such service is identified as a shortfall in the present US national positioning, navigation and timing (PNT) architecture along with the challenges such as for instance jamming, spoofing and cyber threats [5].

As mentioned, the number of GNSS units for road applications is expected to globally grow with a factor of 2.9 from 2015 to 2025. The largest increase is expected for in-vehicle systems and for units installed for eCall applications. The use of personal navigation devises in vehicles is expected to decrease as the use of in-vehicle systems increases. The use of GNSS for insurance telematics, road user charging, fleet management, and advanced driver assistance systems is also expected to increase during 2015 to 2025.

3.2 GNSS for professional users

Referring back to Figure 4 the number of GNSS units installed for professional use is much smaller than the number of units for non-professional use. The GSA Market Report therefore provides a separate review of the number of units for professional use and the main user groups within this field.

Figure 5 provides a zoom into the distribution of the professional users on different applications in 2015 and the expected distribution in 2025.

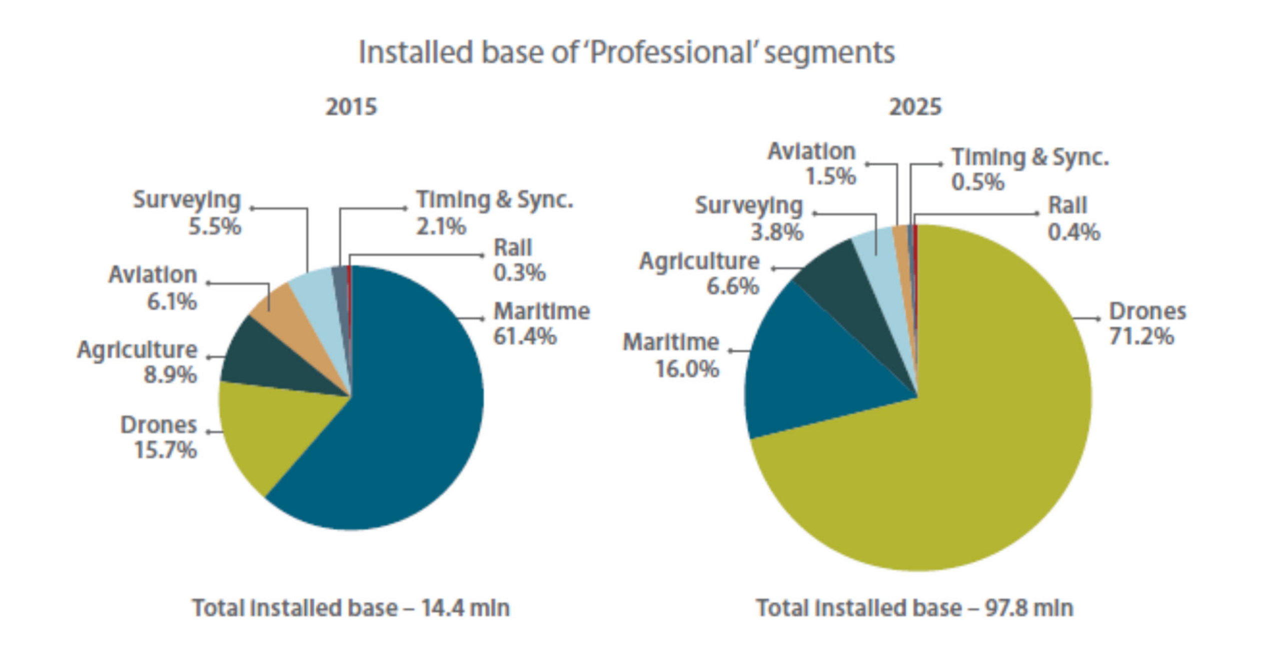

Figure 5. Relative distribution of professional GNSS units per user group. Source: GNSS Market Report, Issue 5, copyright © European GNSS Agency, 2017.

Each of the user groups are further discussed in the following in terms of expected development in number of users during 2015 to 2025 as well as key requirements to GNSS from the user groups. This text is also based on the GSA Market Report [1] unless otherwise noted.

3.2.1 Surveying

On a global basis use of GNSS for surveying applications amounted to 5.5% in 2015 and is expected to decrease to 3.8% of the total number of professional users in 2025 (see Figure 5). However, the absolute number of users is expected to increase from around 0.8 million units in 2015 to 3.7 million units in 2025 (see Figure 6) an increase of a factor of 4.6 globally.

The term surveying covers the following types of GNSS applications:

- Cadastral surveying
- Construction surveying including machine control
- Mapping
- Mining
- Infrastructure monitoring
- Marine surveying

Trends of development within this field are an increased integration and request for interoperability of surveying GNSS receivers with other sensors such as lasers scanning, lidar, inertial units, robotics etc. Also, an increased competition among manufacturers drives the development especially because of increasing activities in Asia where new and cheaper products appear on the market. Finally, the increasing use of drones is expected to change the classical approach to land surveying in the future.

Other trends affecting the development are easier to use equipment which means that high accuracy receivers can be used by more and more people without specific education (this is also referred to as democratisation of surveying applications). Further, crowd sourcing, smart cities and the increasing use of PPP are considered by the GSA as trends that are affecting the development in the number of GNSS units used for surveying applications.

The European Radio Navigation Plan also notes that a decrease in the price of RTK GNSS receivers is expected, due to the competitive pressure from emerging PPP solutions [4, page 29], and the lower prices may further contribute to a more widespread use of GNSS for surveying applications.

For surveying users, the key requirements to their GNSS applications are: Accuracy, Availability, Continuity and time to first fix. Other factors are connectivity and interoperability.

For high end users, price is less important and also requirements such as integrity and authentication are not so important for this user group.

As mentioned, the number of GNSS units for surveying applications is expected to globally grow with a factor of 4.6 from 2015 to 2025. All types of GNSS users within this user group will increase, but the largest increase is expected in the use of GNSS for cadastral surveying, machine control and person based surveying for construction. Use of GNSS for mapping purposes will also grow significantly (see Figure 6).

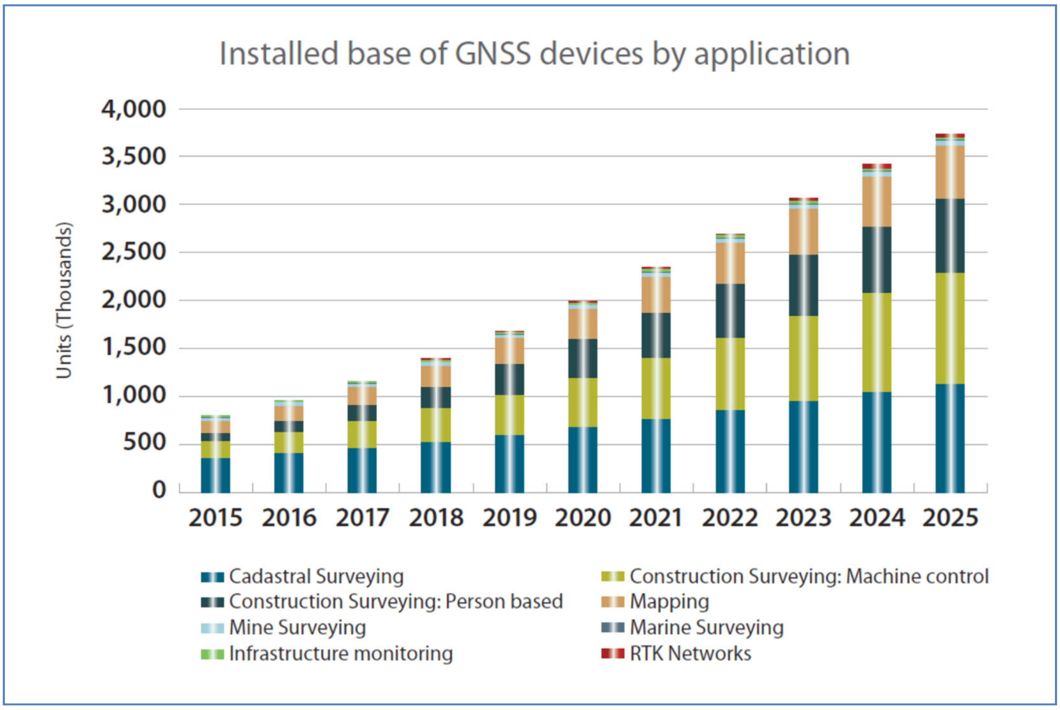

Figure 6. Development in number of GNSS units installed for surveying applications. Source: GNSS Market Report, Issue 5, copyright © European GNSS Agency, 2017.

3.2.2 Agriculture

Globally, use of GNSS for agriculture amounted to 8.9% of the professional users in 2015, and is expected to decrease to 6.6% of the total number of professional users in 2025 (Figure 5).

However, the absolute number of users will increase on a global basis from around 1.3 million units in 2015 to 6.4 million units in 2025 (Figure 6), corresponding to an increase with a factor of 4.9.

Agricultural use includes the following types of applications:

- Farm machinery guidance
- Automatic steering
- Variable rate application for distribution of e.g. chemicals
- Yield monitoring
- Biomass and soil condition monitoring
- Life stock tracking and virtual fencing
- Asset management
- Forestry

Characteristic for agricultural use of GNSS is a very rapid development in new applications including for instance integrated farm management where different types of data are integrated throughout all the activities on a farm. Important trends driving the development are interoperability, i.e. the use of GNSS in combination with other sensors on farming equipment as well as for instance earth observation data. A challenge in this context is a lack of standards for data to be used in sensor fusion, fostering a number of projects currently aimed at introducing the use of for instance ISO standards in agriculture.

Use of GNSS in forestry is relatively new and it is one of the growing areas of application of GNSS within agriculture as defined by the GSA. Also, the use of drones in agriculture is increasing a lot and is, together with the increasing use of technology for agriculture in emerging economies, important drivers for the increasing use of GNSS in agriculture as a whole.

The GSA user consultation report on agriculture [6] underlines the overall global development with more wealthy people with an increased calorie intake in the future. This development does require a more efficient and sustainable agriculture globally, and this is a very important driver for the technological development within agriculture.

According to GSA Market Report [1], for future agricultural machine guidance, automatic steering and monitoring applications the key requirements to GNSS are accuracy, availability and continuity. Other factors are connectivity and interoperability.

But requirements such as integrity and time to first fix is not so important for this user group.

As mentioned, the number of GNSS units for various agriculture applications is expected to grow with a factor of 4.9 from 2015 to 2025 on a global basis. All types of GNSS applications within this user group will increase, but the largest increase is expected in the use of GNSS for tractor guidance, automatic steering and variable rate applications (Figure 7).

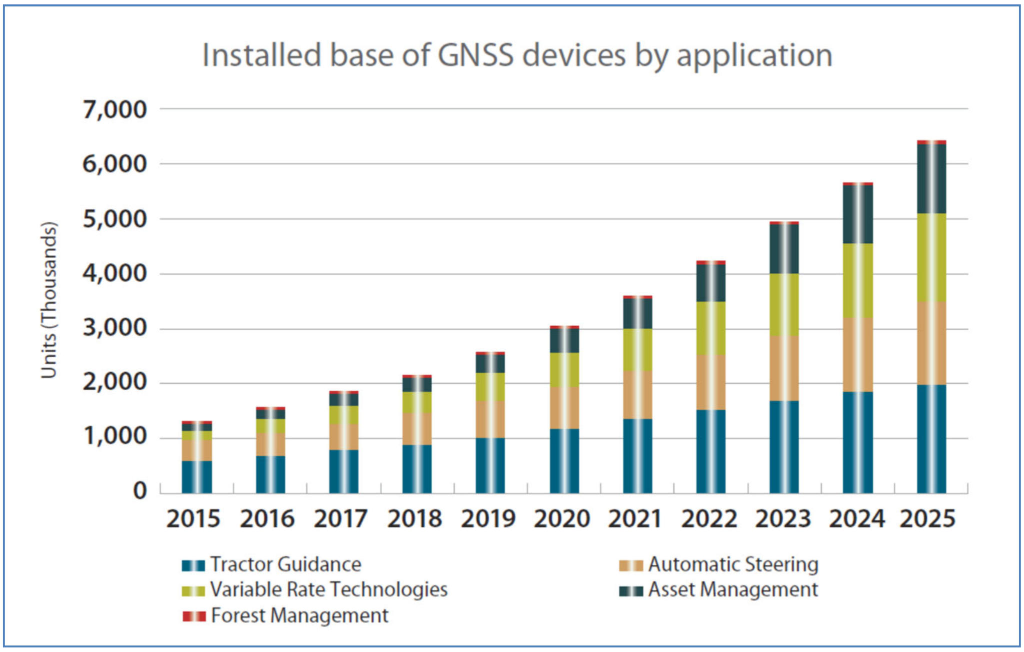

Figure 7. Development in number of GNSS units installed for agriculture applications. Source: GNSS Market Report, Issue 5, copyright © European GNSS Agency, 2017.

3.2.3 Maritime

Use of GNSS for maritime applications amounted to 61.4% of the professional users in 2015 and is expected to decrease to only 16.0% of the of professional users on a global basis in 2025 (Figure 5). However, the absolute number of users will increase from around 9 million units in 2015 to 16 million units in 2025 (Figure 8). This is an increase of a factor of 1.8.

Maritime use covers the following types of applications:

- Recreational navigation which is by far the largest group of users
- Search and rescue (SAR)
- Traffic management
- Homeland security (customs, coast guard etc.)
- Port operations
- Marine engineering e.g. cable laying (note that marine surveying is included in the surveying user group Section 3.2.1)
- Fishing vessels - monitoring and control
- Navigation in inland water ways (IWW)
- Merchant fleet navigation

Characteristic for maritime use of GNSS is that it is very well rooted in the community, and GNSS is by far the primary mean for positioning, navigation and timing at sea. Equipment for search and rescue (SAR) is under rapid development to include multi GNSS. Also, many new applications for maritime use of GNSS are being developed including an increasing use of drones and the development of "smart ships".

There is much regulation of maritime navigation both at international and European level, and the regulation does to some extent drive the development. The most relevant regulations at European level are listed in the European Radio Navigation Plan and the regulations include for instance requirements that all passenger ships must have a GNSS receiver installed, for navigation in inland waterways the position must be displayed in an electronic chart with an uncertainty better than 5 meters, positions of fishing vessels must be logged with an error less than 500 meter (99%) etc. [4].

Most of the maritime applications of GNSS require only meter level positioning (DGNSS) or even un-augmented GNSS positioning. But according to the GSA Market Report [1] especially port operations and marine engineering does require high accuracy. These user groups also point to key requirements being availability, integrity, continuity and robustness, and for marine engineering also time to first fix is important. Interoperability is also mentioned as important for these user groups.

Of all the key requirements to GNSS as listed by the GSA only authentication seems to be less important for the maritime use of GNSS.

For navigation in inland water ways (IWW) the European Radio Navigation Plan points out that there is reason to believe that because of the very constricted narrow environment, the vertical dimension is becoming important for instance for calculating bridge clearance, and such applications of GNSS will require a high accuracy service in the future [4].

As mentioned, the number of GNSS units for maritime applications is expected to grow globally with a factor of 1.8 from 2015 to 2025. All types of GNSS applications within this user group will increase, but the largest increase is expected in the use of GNSS for recreational navigation. Further, the use of GNSS for SAR will increase significantly and also the use of GNSS for IWW traffic information and IWW navigation will be more than doubled during the ten years. The use of GNSS for port operations will also increase whereas the use of GNSS for marine engineering is expected to remain at the current level with respect to the number of GNSS units installed globally, see Figure 8.

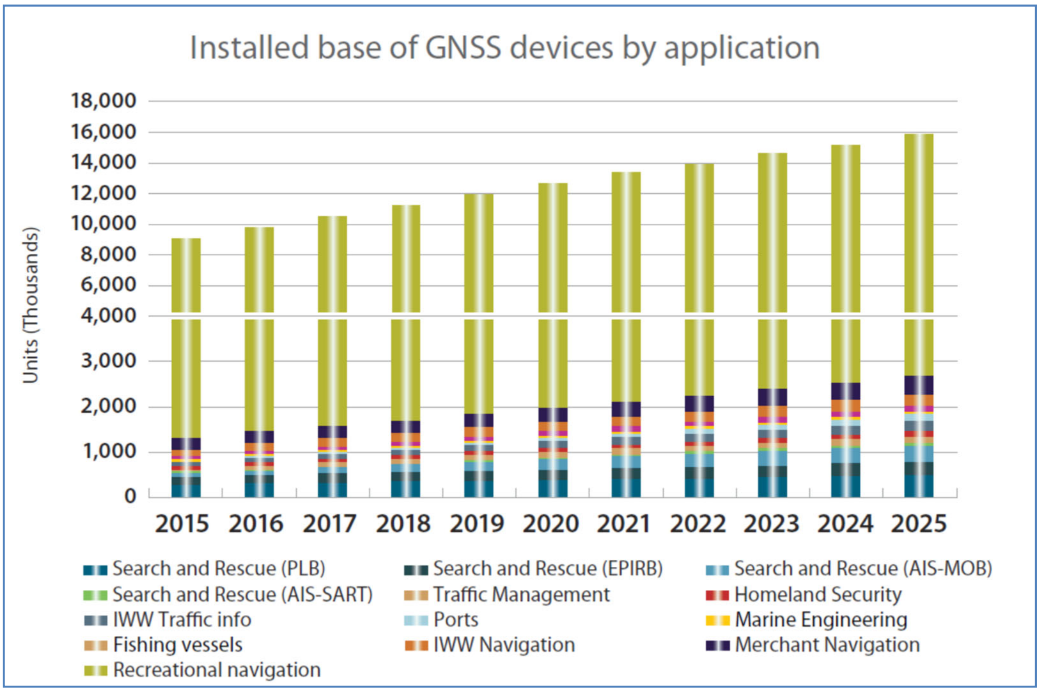

Figure 8. Development in number of GNSS units installed for maritime applications. Source: GNSS Market Report, Issue 5, copyright © European GNSS Agency, 2017.

3.2.4 Aviation

Use of GNSS for aviation applications globally amounted to 6.1% of the professional GNSS users in 2015 and is expected to decrease to 1.5% of the total number of professional GNSS users in 2025 (see Figure 5).

The absolute number of users will, however, increase from around 0.9 million units in 2015 to 1.4 million units in 2025. This is an increase with a factor of 1.6.

Note that drones, although these are aerial vehicles, are not included in the description of aviation related GNSS applications. Drones are discussed separately in Section 3.2.7.

Aviation use includes the following types of applications:

- Regulated applications in professional aviation:
    - Navigation, in particular Performance Based Navigation (PBN) which is the most modern type of air navigation
    - Emergency transmitters
    - Surveillance and monitoring
- Un-regulated applications mainly in recreational aviation including not only light sport aircrafts but also for instance home-built airplanes, gliders and hot air balloons. These aviation users reply on GNSS for instance for:
    - En route navigation
    - Alarm systems
    - Beacons for search and rescue operations

Characteristic for aviation use of GNSS is that the market is increasing globally, and especially in Asia and the Middle East aviation activities are increasing. Also, the use of GNSS for rotorcrafts (helicopters) is increasing both for land and off-shore operations. The use of GNSS for aviation moves towards the use of multi-constellation and multi-frequency GNSS, both in the regulated and un-regulated applications.

The European Radio Navigation Plan further notes that development in uses of GNSS for aviation is also driven by a desire to improve performance of air traffic management, increase airport capacity, and improve environmental and economic efficiency [4].

Key requirements for aviation users are mainly availability, continuity and integrity. Accuracy matters, but is less important for aviation users than for many other professional GNSS user groups. High accuracy at the cm-level is mainly required for ground operations and surveillance in the airports.

Connectivity and resilience are, however, requirements which are also mentioned as important for aviation users.

As mentioned, the number of GNSS units for various aviation applications is expected to grow with a factor of 1.6 from 2015 to 2025 on a global basis. All types of GNSS applications within the aviation sector will increase, but the largest increase is expected in the use of GNSS for general aviation (regulated as well as un-regulated). Further, the number of GNSS units installed for emergency and rescue operations will also increase significantly on a global basis, as well as the use of GNSS for surveillance.

3.2.5 Rail

The use of GNSS for rail related applications cover a relatively small number of users compared to other user groups. But the number of GNSS units installed for rail applications is growing significantly and it is therefore also discussed in this context. According to the GSA market report 0.3% of the professional GNSS users in 2015 were related to rail and this is expected to be 0.4% in 2025 (see Figure 5).

However, the actual number of rail users is expected to increase from around 0.2 million units in 2015 to around 1.6 million in 2025. This is an increase with a factor of 8.

Rail related use of GNSS include the following types of applications:

- Command and control systems for train control, mainly in Europe and North America
- Asset management
- Passenger information
- Driver Advisory Systems used for instance to provide information to the driver on speed management and power consumption

Characteristic for rail related applications of GNSS is that this is still are relatively new market since there is no long tradition for the use of GNSS in safety critical rail applications. Development trends indicate that this may change and a number of projects and experiments are carried out to define and develop requirements for GNSS to be used in rail safety applications.

Nevertheless, the use of GNSS is increasing for non-safety rail applications where important requirements to GNSS are mainly accuracy and availability as well as connectivity. For safety critical operations also integrity is very important along with robustness.

The largest growth in rail applications of GNSS during 2015 to 2025 is expected for asset management which accounts for the absolutely largest number of installed GNSS units used for rail applications. The other rail related applications as listed above are also expected to increase towards 2025.

The US Federal Radio Navigation Plan lists requirements to GNSS as set by various user groups and in connection with rail applications, tectonic monitoring and monitoring of bridge deformations are listed. These are examples of rail related GNSS applications that require position accuracy at the sub-cm level in real time with a very high availability [5]. However, the number of such uses of GNSS is relatively small and disappear in the overall statistics.

3.2.6 Timing and synchronisation

Use of GNSS for timing and synchronisation is also a small user group amounting to around 2.1% of the professional users in 2015 and expectedly 0.5% in 2025 (Figure 5).

The absolute number of GNSS units to be used for timing and synchronisation globally is expected to increase from 1.3 million units in 2015 to 3.5 million units in 2025, an increase with a factor of 2.7.

Use of GNSS for timing and synchronisation covers the following three main sectors:

- Telecom
  - GNSS is used for timing, synchronisation, and frequency control between base stations in the networks. By far the most GNSS units are used for terrestrial telecom. Satellite communication composes a smaller part of this user group.
- Energy
  - GNSS is used for timing in the monitoring of energy flow within power networks
- Banking and finance
  - GNSS is used for time stamping functions in tracing and logging of operations in banking and stock exchange

Within this group of users, the telecom sector represents around 90% of all the GNSS units installed. The use of GNSS in the telecom sector is mature, but development of new technologies (e.g. 5G) drive a continued development of the GNSS equipment used within this sector.

An overall key requirement to GNSS used for timing and synchronisation is authentication. This is supplemented with requirements to accuracy, robustness and availability depending on the applications. Resilience is also mentioned as important by all application areas within this user group.

As mentioned, the number of GNSS units for various applications in timing and synchronisation is expected to grow globally with a factor of 2.7 from 2015 to 2025. The absolutely largest increase is expected in the use of GNSS in the telecom sector. The use of GNSS in banking and finance is already mature and the increase in this sector is expected to be relatively small.

3.2.7 Drones

In an overall context the GSA is expecting the use of GNSS for drones to account for the largest relative increase in GNSS users from approximately 15.7% of the professional users in 2015 to 71.2% in 2025 (see Figure 5).

In absolute numbers GNSS units installed in drones is expected to increase from approximately 0.3 million units in 2015 to 70 million units in 2025 (see Figure 9). This corresponds to an increase with a factor of 233, by far the largest increase factor for any of the GNSS user groups within this ten-year interval.

In the GSA Market Report, drones are not considered as a distinct user group and are therefore not analysed to the same level of detail as the user groups discussed above. Drones are used by virtually all of the user groups including surveying, agriculture, maritime applications etc., and deployment is expected to increase for all user groups. But it is not possible to say, from the Market Report, within which of the user groups, deployment of drones will increase the most towards 2025.

Regardless of user groups, the increase in the number of GNSS units installed in drones is currently limited by regulatory framework including e.g. authorisation, certification, and spatial limitations for operation. In Europe there are differences between member states with some member states applying "drone-friendly" regulation, whereas other member states apply a more constrained regulation.

According to the GSA Market Report, it is expected that the evolution of the technical and operational rules by 2024-2028 will have reached a level where drones can be mixed with manned aviation following the same Air Traffic Management (ATM) procedures ([1] page 91).

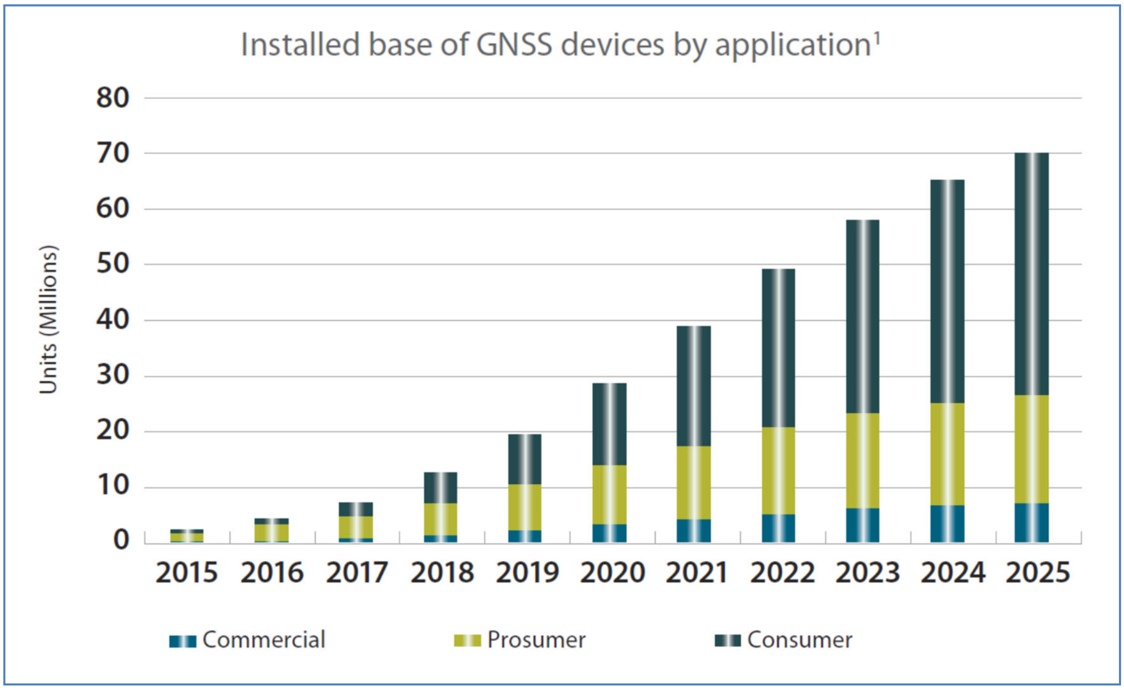

Figure 9. Development in the number of GNSS units installed for drone applications. Source: GNSS Market Report, Issue 5, copyright © European GNSS Agency, 2017.

3.3 Summary of expected future GNSS users

Referring to the GSA Market Report [1], in absolute numbers, the largest growth in future GNSS users is expected in the use of GNSS for LBS and for road related applications, and it is reasonable to believe that this will also be the case in Sweden.

However, the largest *relative* growth on a global basis is expected in the following user areas:

- Rail applications, expected increase with a factor of 8 during 2015-2025
- Agriculture, expected increase with a factor of 4.9 of during 2015-2025
- Surveying, expected increase with factor of 4.6 during 2015-2025

Rail is a small user area, and the expected increase is closely tied to the developments in asset management i.e. tracking of wagons and cargo.

Focusing on the high accuracy applications, agriculture and surveying are the user groups where the largest development is expected in the coming years. For agriculture the growth will be mainly in tractor guidance, automatic steering and variable rate applications, and for surveying the growth will be in construction and cadastral surveying.

Even though the global numbers to a large degree are driven by development in the emerging economies, it is reasonable to expect that these user groups will also (continue to) grow in Sweden.

It is also reasonable to believe that the use of drones in Sweden, e.g. for agriculture and surveying, will increase significantly during the coming years, if rules and regulations follow in support of the technical development.

3.3.1 Which user groups are expected to be important for SWEPOS in the future?

Based on the review performed in the previous sections, the following groups of users are considered most important for the future SWEPOS services: Surveying, agriculture, maritime, drones, road and mobility. Swedish representatives from these user groups are relevant to interview to obtain more detailed information about their expectations and requirements to future GNSS services:

Of the user groups discussed in the previous sections, the following are not selected for interviews:

- Aviation, not selected because the means for positioning and navigation in commercial aviation is highly regulated and the development in number of users within the near future will be driven mostly by development in the regulations
- Rail, not selected because the largest growth is expected in asset management which is already a mature user area with respect to location and tracking of objects and goods
- Time and synchronisation, not selected because even though the use of GNSS for timing and synchronisation in the telecom sector will be growing with development of new technologies (e.g. 5G), the number of professional users within this field is relatively small

4. Interviews with stakeholders

In connection with this report, several interviews with stakeholders have been performed. A total of 19 professionals have been interviewed.

Interviews have been performed with representatives from the following user groups:

- **Machine control** in construction work by representative from a company providing software and support to the business area
- **Municipality** by representative from a municipality in a greater city region
- **Surveying** by representative from a consulting company performing surveying tasks
- **Agriculture** by three representatives working with machinery and GNSS in farming in two different companies
- **Road applications** by representative from a company developing software for vehicle navigation systems and by representative from a car manufacturer
- **Drone applications** represented by a researcher working with navigation systems for drones
- **Maritime applications** and offshore surveying by four representatives from the Swedish Maritime Administration (*Sjöfartsverket*)
- **Transport infrastructure** building and maintenance as represented by two employees of the Swedish Transport Administration (*Trafikverket*) and by a consultant working for Trafikverket on e.g. project adapted network RTK

Also, a representative from **Ericsson** has been interviewed as developer of solutions for data distribution, and finally two representatives from **Leica Geosystems** have been interviewed both in the role as providing positioning services and support for such, and in the role of developing hardware and software for permanent GNSS stations and end user equipment.

4.1 Review of interviews with stakeholders

This section provides a review of all the interviews performed. After the interviews, the information has been grouped and structured into sub sections as outlined below.

4.1.1. Trends in development of the use of GNSS positioning services

The interviews point towards an increasing use of GNSS services in the future within all of the fields represented.

Among professional users there is much focus on development of new methods for the use of GNSS. For land surveying there is for instance focus on integration of GNSS with other sensors for e.g. simultaneous localization and mapping (SLAM) and on the use of smart phones with high accuracy carrier phase-based positioning.

For the use of GNSS in machine control at construction sites there is much focus on increased autonomy at the sites with more self-guiding machinery and a smoother automated data flow. Also, an increasing demand for documentation drives the development, increasing the need for e.g. smart phones with high accuracy positioning capabilities.

Also, in the municipalities, a more seamless digital workflow for the future, e.g. including the use of BIM, is a driving factor in the development.

The use of drones in many different areas of applications such as land surveying, at construction sites, in agriculture and in the maritime sector is also driving the development towards more use of high accuracy GNSS services.

Autonomy is mentioned by all of the interviewees as becoming important in the future and for requiring GNSS services. This is especially the case for machine control in construction work, for agriculture and for maritime applications.

Among the non-professional user segments autonomous mobility is a very large driving factor. Much focus is on autonomous vehicles because the car industry is an important driver. But also e.g. lawn movers and drones for the non-professional users are relying on GNSS positioning and are driving the development.

In terms of GNSS service providers, Leica Geosystems sees a tendency towards service providers becoming larger, in the sense that in the future, service providers will cover larger geographic areas and support more users. This development is driven by increasing requirements from users to availability and continuity of the GNSS services.

Ericsson points to the development of the broadcast principle for terrestrial distribution of high accuracy GNSS corrections which will accommodate a much larger number of users of GNSS services in the future.

4.1.2. Performance parameters for GNSS services

Integrity is considered important for user representatives from surveying, municipalities, machine control in construction, marine applications, drones, road applications and also by Leica Geosystems.

For the representatives from land surveying, municipalities, drones and road applications, integrity is considered the most important or the second most important performance parameter in the future. Leica Geosystems rates integrity as one of the three most important parameters (along with availability and accuracy) for the future, and the same is the case for machine control in construction work.

For marine applications, integrity is considered increasingly important for the future in order to reduce the risk with the advent of autonomous vessels and a more widespread use of GNSS services among un-educated users. The municipality representative points to the same issue with un-educated users especially in relation to real estate registrations, and the land surveying representative also points to the need for integrity because of more un-educated users working with high accuracy GNSS services in the future.

Especially for the representatives from land surveying, municipalities, and marine applications it is considered important as a quality parameter to have information about the significance or confidence level of the position provided, for instance that a height may be estimated with an uncertainty of 2 cm at 95% significance level. Other user representatives are not so specific, but for both of the representatives from the road applications area, integrity is clearly underlined as being the most important performance parameter for the future.

Availability and continuity are considered important for machine control in construction work, for drones, road applications, and agriculture. It is also considered important by Leica Geosystems.

For both machine control and agriculture it is pointed out that a 24/7 availability is highly important because the machinery is operating continuously, and high availability will become even more important in the future with more autonomous machines.

For both road and marine applications, short term outages of the GNSS services can be bridged by use of other navigation sensors. There is a request for high availability, but integrity is considered more important.

For the marine area as a whole, availability is not considered the top priority. But there are applications where availability of the GNSS service is very important in critical situations e.g. for manoeuvring in narrow water ways and mooring in harbours. It is also pointed out that availability of GNSS based timing is important for synchronisation in the navigation systems and for the Automatic Identification Service (AIS).

Leica Geosystems consider the increasing request from users for a 24/7 availability as one of the largest challenges for GNSS service providers in the future.

In terms of geographic availability (or coverage) Trafikverket points to challenges with high accuracy positioning in the large areas of Sweden covered by forest where they would like to see better availability. From some of the representatives from agriculture as well as for machine control, availability of high accuracy positioning services at high latitudes, i.e. in the Northern parts of Sweden, is pointed out as being important.

Accuracy is considered a very important quality parameter for the municipalities; they need high accuracy in the positioning in order to make use of the GNSS-services. If the accuracy is not sufficiently good, they must use other surveying techniques. Also, for Trafikverket and for machine control in construction work, high accuracy is considered very important.

Further, accuracy is considered important for the representatives from the drone and road applications. For drone applications, accuracy is not important for all users, but many applications do require high accuracy for instance for autonomous landing. For road applications high accuracy is required in particular for automatic road lane identification.

For municipalities, Trafikverket and machine control, accuracy in the **height component** is pointed out as being very important. Also, for some applications in agriculture, marine surveying and for drones, a high accuracy in the height component is important. It is mentioned by some of the people interviewed that a lower uncertainty in the height component will become important in the future.

For the representatives from land surveying and machine control it is pointed out that the relative accuracy is more important than the absolute accuracy. This means that it is important that positions close to each other (e.g. within a construction site) are coordinated correct in relation to each other.

Leica Geosystems rates accuracy as one of the three most important parameters (along with availability and integrity) for the future.

Time to first fix or time to re-acquisition is considered important for the representatives from drone applications and road applications.

But for agriculture and machine control this is not considered a top priority because there are many other systems which must be initiated upon start of the machines, and also because the machinery is operating for many hours at a time.

Authentication is considered important for marine applications, drones, and for road applications as a mean to mitigate consequences of spoofing of GNSS signals and corrections.

Robustness and resilience are considered important for the representatives from municipalities, machine control, marine applications, drones, and road applications because of an increasing risk for interference and jamming in the future.

4.1.3 Geodetic reference frame, height system and geoid model

For the interviewed representatives from municipalities, Trafikverket and machine control in construction, use of the Swedish SWEREF 99 reference frame is essential, and the high accuracy GNSS service of use (i.e. SWEPOS) must operate within this reference frame.

For marine applications it is important that the GNSS positioning service complies with the chart datum which in Swedish nautical charts is SWEREF 99. Most important is, however, that relevant coordinate transformation algorithms, or relations, between international and national geodetic reference frames are available for the future dynamic reference frames.

A similar point of view is given by the land surveying representative who points out that a global international reference frame is important, but it is also important that the reference frames are easily available to users by means of transformation algorithms.

For the users in need of high accuracy in the height component, i.e. land surveying, municipalities, machine control, and drone applications, the importance of a high-quality geoid model in the future is considered very important.

For marine applications in Sweden the geoid model is important as reference surface at sea, and a high-quality geoid model will be increasingly important in the future also for inland waterways.

Many users of high accuracy drone applications do not hold any geodetic training at all, so geodetic reference frames and height systems are considered a large challenge for the drone community in the future.

Also, the representatives from road applications consider geodetic reference frames and height system a challenge for the future. For seamless cross border navigation, a global reference frame used for the GNSS service is preferable. But it is also important that the reference frame is accurate and up to date, and that the reference frame used for geodata applied in the navigation systems is compliant with the reference frame used for the GNSS positioning service.

Both Ericsson and Leica Geosystems foresee that the GNSS services will operate in global reference frames in the future, and conversions or transformations to national reference frames will be carried out in the software on the user side. They also point to the need for (more) international cooperation on standards within this field, e.g. through the RTCM committee, and they note a potential future legal question around the responsibility for using correct geodetic reference frame and geoid model.

4.1.4 Education and information

As mentioned above, some of the interviewees express concern towards the increasing number of un-educated users of high accuracy GNSS positioning services for instance in marine navigation, real estate surveying, other types of surveying, machine control and drone operations.

The development is caused both by an increasing number of GNSS users in general, but also because high accuracy positions will become more easily available in the future for instance with smart phones.

The need for information and GNSS-literacy for end users is stressed, and the request for quality information (e.g. integrity) from the GNSS service provider for documentation of coordinate quality is based on this concern.

For the mass market, as represented by the vehicle industry, education of end users is not a big concern because the software implemented to handle positioning and navigation must be free of user interaction as an important step towards autonomy.

4.1.5 Considerations around future GNSS positioning services

Among the Swedes interviewed there is an overall content with SWEPOS as of today. There are requests for improvements and expectations for the future, but most support that the Swedish government, by Lantmäteriet, operates a high accuracy GNSS service as a national infrastructure.

It is pointed out by several of the people interviewed that Lantmäteriet holds a very high level of expertise in geodesy and GNSS. Such level of expertise is considered important for establishment and operation of geodetic GNSS reference stations as well as a high accuracy GNSS service.

Several of the representatives interviewed consider global PPP services with distribution of GNSS corrections from satellites very interesting for the future, preferably in combination with a national RTK service for higher accuracy. Others express concern about the poor coverage of PPP services at high latitudes where signals from the geostationary satellites providing PPP correction data can be difficult or impossible to receive.

Despite the advent of global PPP services, Leica Geosystems, which operates a global GNSS service but also supports RTK service providers, points to the need for national RTK services for many years still to come. This is because of the need for support and knowledge about national / local requirements such as e.g. geodetic reference frame and geoid model.

5. Concluding remarks on future users

Concluding on the analyses provided in Section 3 and 4, the deductions provided in the following are made.

5.1 Expected users of high accuracy GNSS services and their requirements

It is expected that the future main user groups of high accuracy cm-level GNSS services in Sweden will be machine control and guidance in construction work, land surveying for building, construction, cadastral and environmental applications, and maritime use for applications in harbors, inland waterways, and coastal areas. Also, a large increase in agricultural use is expected.

The use of high accuracy GNSS services for navigation and positioning of drones will increase a lot if rules and regulations support the technical development. Increased use of drones will be within all of the application areas mentioned above with specific requirements to the GNSS services from the various fields of application.

Road applications, mobility and LBS will also request high accuracy GNSS services in the future. Most of these users will be personal or private (e.g. for augmented reality and gaming) and GNSS will be combined with other sensors e.g. inertial navigation and motion sensors. For these applications GNSS performance is perhaps not so critical, and it is likely that these users will be satisfied with global positioning services.

However, it is expected that many of the professional users today relying on high accuracy GNSS services, will request such services in smart phones, tablets etc. in the future. This is evident from some of the interviews discussed in Section 4, where it is revealed that high accuracy GNSS services in smart phones are expected to be utilized e.g. for documentation in construction work or for cadastral surveying in the future.

Also, in autonomous driving high accuracy GNSS is requested. Previously, there has been a focus on developing autonomous vehicle navigation by means of other sensors. But it appears that the car industry today is paying much attention to high accuracy GNSS services in their development work, mainly because of the future possibility of obtaining integrity information from the services, and because of the more wide spread availability of global services. Integrity is very important for autonomous driving, but a global coverage is also important and it is expected that this field of application will prefer global, as opposed to national, services for easy cross border use. High accuracy GNSS is not important for the entire field of vehicle use, but for some applications, such as road lane identification of autonomous vehicles, high accuracy GNSS is very important.

The most important performance parameters requested by users are integrity, availability and accuracy. There is a difference in which of the parameters are considered most important by the various user groups. For instance, integrity is most important for autonomous vehicle navigation, availability is most important for agriculture and machine control, and accuracy is most important for use of GNSS in municipalities. But all professional user groups request these three performance parameters.

Further, there is a focus on robustness, resilience, and authentication from many users because of the risk for interference, jamming and spoofing. Especially in the areas of application where autonomy is an important development trend, the request for these performance parameters is essential. This is for instance within the fields of autonomous vehicles in land and marine applications, autonomous machine control in construction and farming, and autonomous navigation of drones.

Time to fist fix is mentioned by a few user groups, but it appears to not hold the same importance as some years ago, perhaps because the technology today does meet most of the user requirements.

From some of the stakeholders interviewed, education, information and support is very important. These aspects are normally not included among performance parameters for GNSS services which are often focused on technical aspects only. But the request for education, information and support is strongly underlined by some stakeholders to a degree which makes it relevant to include in this conclusion. Also, it is noted that support and information is mentioned by Leica Geosystems as one of the reasons why there is still a need for local or national high accuracy GNSS services despite the increasing number of global services.

5.2 Geodetic requests from users of GNSS positioning services

It is clear from the interviews that, in general, users do not want to care too much about reference frames, geoid models etc. It is considered complicated. Preferably geodesy should be something which is part of a setup or an installation process once, where after users should not have to worry about it.

The representatives interviewed from land surveying, municipality and machine control in construction work do, however, care about reference frames and geoid models, but they also worry about consequences because of the increasing number of users without a geodetic background.

It appears likely that future GNSS services, also local and national services, will operate in global reference frames with subsequent coordinate transformations carried out on the user side.

The height component seems to be increasingly important for high accuracy users in the future as new applications are developed. This is the case for some applications of drones, for instance autonomous precise landing, and for some maritime applications for instance requiring information about under keel clearance. Also, for land surveying and machine control, the height component is pointed out as very important. This implicitly means that there will be a request for accurate geoid models in the future.

It is pointed out by several of the stakeholders interviewed, that high accuracy GNSS services are expected to be a vital part of the national infrastructure of the future, in line with the infrastructure for power, communication, water etc. Because of the complexity around high accuracy GNSS and geodesy it is also pointed out that the operation of high accuracy GNSS services resides well with a national geodetic government organization.

6. National geodetic infrastructure for future positioning services

The importance of a geodetic infrastructure and the importance of contributions from national agencies is clearly highlighted in the UN Resolution 69/266 *A Global Geodetic Reference Frame for Sustainable Development* adopted in 2015 [17]. The resolution points to the need for maintaining a global geodetic reference frame and invites nations to commit to improving and maintaining appropriate national geodetic infrastructure.

The American National Academy of Sciences in a report from 2010 entitled *Precise Geodetic Infrastructure National Requirements for a Shared Resource* [18] defines geodetic infrastructure as consisting of two principal components: (1) the network of observation instruments for each geodetic observation technique; and (2) associated international services composed of various scientists, technicians and administrators that support each technique. Examples are ground and space-based equipment and facilities for data collection and processing such as Very Long Baseline Interferometry (VLBI) and GNSS including the CORS stations used for tracking of GNSS data. A board entitled "Evolving the Geodetic Infrastructure to Meet New Scientific Needs" was established in 2018 by the American Academy of Sciences to update the requirements set in the 2010-report.

In this present report, the definition of the term geodetic infrastructure is expanded and slightly turned in order to be seen from the point of view of society. The definition of geodetic infrastructure as used within the geodetic community is here broadened to not only include the instrumentation, facilities and people involved in the geodetic data collection and data processing, but also the models and the products thereof.

This means that geodetic infrastructure herein is defined as the geodetic observation facilities for terrestrial and space based geodetic data collection and analyses, as well as the results and geodetic products developed for the society.

The term geodetic infrastructure thereby does not only include e.g. permanent GNSS reference stations, but also the geodetic reference frame developed based on data from the stations. For the society, important elements of a geodetic infrastructure are the national geodetic reference frame, geoid models, land motion models, physical ground markers for traditional geodetic observations, and also high accuracy GNSS positioning services.

A most basic requirement to the future geodetic infrastructure is to support the needs of society. This is a very broad requirement and includes for instance the need for a sufficient geodetic infrastructure in relation to the establishment, maintenance and operation of the built environment with the elements of e.g. the cadaster, the building and construction activities, the transport infrastructure etc. A geodetic infrastructure is also needed for the operation of satellite services such as remote sensing, satellite communication, satellite-based positioning like GNSS etc.

But also, the monitoring of climate change, water level changes, land uplift etc. becomes increasingly important for the future society, and a geodetic infrastructure is crucial for these purposes. Further, the fast-developing concepts like Internet of Things (IoT), Smart Cities and autonomy will need, and rely on, a precise and timely geodetic infrastructure.

It is important to note that society in general, e.g. many users of IoT and autonomy, are not aware that a geodetic infrastructure is necessary in order to use and operate the units and devices on which they rely. Requests from these users towards a geodetic infrastructure are therefore not likely to appear.

6.1 National versus international geodetic reference frame

Currently, local and national GNSS positioning services normally operate using a national geodetic reference frame. SWEPOS, for example, is operated in the SWEREF 99 reference frame. On the other hand, global positioning services, like PPP services, normally operate in an international geodetic reference frame, typically the latest realisation of the International Terrestrial Reference Frame (ITRF). Both solutions are the most convenient for the respective type of positioning services - it is convenient that services with a global business agenda operate in an international frame, and it is convenient that a national positioning service operates in a national frame given that most of the end users need positions in a national reference frame.

Referring to the interviews discussed in Section 4, both Leica Geosystems and Ericsson foresee that in the future, positioning services will be operated in international reference frames with coordinate transformations to national or local reference frames carried out by the end user (in practise, by the end user's equipment or software).

In terms of data processing, using an international geodetic reference frame in the estimation of satellite orbits and clocks provides the best fit on a global scale, and it therefore makes good sense that the central data processing of future positioning services, covering larger areas, is carried out using a global reference frame.

National geodetic reference frames, on the other hand, provide the best fit to the actual conditions within a given country. A national frame is fitted considering local surface deformations caused by for instance post glacial rebound, regional land uplift or subsidence effects as well as effects of volcanoes, earthquakes and other natural phenomena. These are all examples of local or regional geodynamic activity which, to varying degree, are mitigated or eliminated in the definition of the international reference frames.

In order to maintain both international and national reference frames, the necessary facilities for data collection, analyses and modelling must be maintained. In Sweden, this includes for instance a continued development and operation of the Very Long Baseline Interferometry (VLBI) facilities at Onsala Space Observatory and a continued development and operation of the SWEPOS network of CORS stations.

6.2 Coordinate transformations

Geodynamic activity is also the main reason for the need of dynamic coordinate transformations. The coordinate transformation parameters used to convert between national and international reference frames must comply with local conditions in considering velocity fields and relatively frequent updates of the parameters. It is mentioned in the interview with the car industry that for instance in the event of an earthquake it is important for autonomy that reference frames, coordinate transformations and relevant geodata is quickly updated to comply with the new physical reality after sudden changes in the Earth's surface have occurred.

Compliance of a high accuracy positioning service with the location information of geodata is also of importance. National databases of geospatial data are normally based on national geodetic reference frames. Such databases can be transformed between geodetic reference frames just as positions of a high accuracy positioning service. But important is that the two elements; coordinates from a positioning service and coordinates for geodata should be available for the end user applications in the same geodetic reference frame. This can be handled by either on the fly coordinate transformations, or by use of, and storage in, the same geodetic reference frame.

6.3 Height system and geoid model

As mentioned in Section 4, it is pointed out by several stakeholders interviewed that the third dimension, the height, becomes increasingly important as output from GNSS positioning services in the future. Also, it is expected from the users that the uncertainty of heights determined with GNSS will be reduced in the future. This, in turn, sets increasing requirements to the uncertainty of both height reference system and geoid model. To obtain the level of uncertainty required, fitted geoid models must be national or even local, since global models are not sufficiently accurate.

Especially important in this context is the use of GNSS in relation to water e.g. for surveying of water courses, streams and sewages where it is important that the heights determined comply with the actual physical conditions, so the height differences derived from the GNSS positioning services can reveal in which direction the water is running. Also, in relation to marine navigation in inland waterways and for offshore surveying, the heights determined with GNSS must relate to mean sea level in a well-defined and precise manner.

In order to ensure an accurate height system and geoid model, the necessary facilities for data collection, analyses and modelling must be maintained. In Sweden, this includes for instance development and maintenance of the network of both absolute and relative gravity observations, as well as tide gauges and precise levelling.

7. Role of national geodetic authorities in the future

Internationally, the field of geodesy currently attracts more attention than it has done for many years. This is evident for instance by the UN Resolution from 2015 [10] and by an increasing level of activity in many national geodetic authorities worldwide. There are several reasons, some examples are:

- Geodetic observation methods are excellent for monitoring the effects of climate change
- Geodetic reference frames and geoid model are crucial for the operation of GNSS systems and for high accuracy GNSS positioning services
- The use of geodetic methods is applied by an increasing number of new users in fields not traditionally applying advanced geodetic methods such as gravity field models and high accuracy GNSS observations

The role of the national geodetic authorities is therefore expanding in the coming years.

The classic tasks of establishing, maintaining, operating and developing a fundamental geodetic infrastructure consisting of e.g. geodetic reference frame, height system, geoid model, coordinate transformations, map projections, high grade permanent GNSS stations etc. will remain. This is seen as a task for national government authorities because it is expensive to establish and maintain such infrastructure and at the same time difficult to commercialise. But as discussed in the following there are more roles to be taken on, and tasks to be carried out, in the future.

Due to the global nature of geodetic reference systems, reference frames, geoid models etc. a strong international cooperation is required. The International Association of Geodesy (IAG) and the UN Committee of Experts on Global Geospatial Information Management (UNGGIM) are important organisations in this context along with the IAG Reference Frame Sub-Commission for Europe (EUREF). For the Nordic and Baltic region, the Nordic Geodetic Commission (NKG) is an important forum for cooperation on geodetic research and development as well as for exchange of experiences and best practices. It is important, also in the future, for national geodetic authorities to cooperate internationally and to participate in the international communities established for the purpose.

Explicitly for Sweden, the future role of Lantmäteriet and of SWEPOS is discussed in the following.

7.1 Role of Lantmäteriet in the future

As mentioned above it is important for Lantmäteriet to continuously ensure and develop a high-quality geodetic infrastructure in Sweden, and it is important for Lantmäteriet to participate in international geodetic cooperation.

In relation to this, many other tasks as discussed in the following are also important for Lantmäteriet in the future.

It is important that Lantmäteriet works on making the geodetic infrastructure available to users i.e. Swedish citizens and Swedish companies as well as foreign companies operating in Sweden. Making geodetic infrastructure available and accessible for users include not only information provided via web site, education and training. It can also include making for instance coordinate transformations available for software developers in the form of open source software libraries, it can involve making geoid models available in standardised data formats, and it can involve operating a high accuracy positioning service in order to make the geodetic reference frame available in the form of positions for end users.

Also, it becomes increasingly important for Lantmäteriet in the future to continue cooperation with other government organisations in Sweden. The main reason being the advent of autonomy in the form of autonomous vehicles, autonomous vessels, autonomous drones etc. Regulation around autonomy requires a cross disciplinary cooperation at governmental level, and the geodetic infrastructure becomes crucial for ensuring a safe and secure future environment with autonomous units.

At a more technical level it is expected to be important, also in the future, for Lantmäteriet to cooperate with Trafikverket on project adapted network RTK (SWE: *projektanpassat nätverks-RTK*, PaNRTK) for large infrastructure projects, and to cooperate with Sjöfartsverket on high accuracy positioning and navigation in inland waterways and near coastal regions of Sweden as well as on geoid model and mean sea level.

Lantmäteriet can take a lead on this and take initiatives towards such intensified cooperation among government organisations.

7.1.1 Geodata

Collection, processing and analyses of high accuracy geospatial data (geodata) for instance for digital terrain models, 3D city models, some mapping and charting as well as for some applications of Geographic Information Systems (GIS) is part of geodesy. This is for instance data collection using classical geodetic surveying methods as well as RTK-GNSS, terrestrial and airborne laser scanning and InSAR.

In the future, much geodata will be collected by commercial companies such as Google, Amazon, Here etc. Crowd sourcing, where data is collected for instance *en route* with autonomous vehicles, will also be a large source of geodata in the future and this will reduce the need for national geodetic agencies to perform such data collection. However, an increasing need for verification, analyses and quality control of the data collected commercially or by crowd sourcing will arise. This will be important and can therefore be a task for Lantmäteriet to ensure that geodata used, for instance for navigation of autonomous vehicles and drones, is accurate and reliable. Such control and verification of geodata will be an important part of the work with the national geodetic infrastructure in the future.

Further, there will be an important role of national geodetic agencies in collecting geodata in remote and sparsely populated areas where crowd sourcing and commercial data collection will be too sparse. Also, more sophisticated geodetic data collection for purposes such as monitoring of climate change or land movements will be carried out by Lantmäteriet in the future. Development of new methods for geodetic high accuracy data collection and analyses will therefore continue to be an important task for Lantmäteriet in the future.

7.1.2 Competences and support

A high level of competence and qualification at Lantmäteriet is important in order to maintain and develop the geodetic infrastructure for a country the size of Sweden. It is important that the knowledge and competences needed are available with the national geodetic authority. There are only a few other organisations where such high level of competence in geodesy is present, for instance in academia and in some of the more specialised engineering consulting companies. In essence, this means that also university education becomes a topic of importance for the national geodetic authorities in order to ensure a continued recruitment base. The importance of capacity building is also emphasized by the United Nations in the UN Resolution on geodesy from 2015 [17].

Given the increasing use of location based services (LBS), there will be many new users of geodetic infrastructure including reference frames and coordinate transformations in the future. Not everybody needs to have knowledge about geodesy, but stakeholders, key users, relevant software developers etc. must have a certain level of geodetic knowledge in order to apply e.g. coordinate transformations correctly. This induces an increasing need for support and information to such professionals in the future.

Lantmäteriet could establish a closer cooperation with software developers as well as engineers active in the fields of autonomy, robotics, and drone navigation systems as well as software developers in the vehicle industry. A close cooperation with such professionals will contribute to a proper use of the geodetic infrastructure, and at the same time provide Lantmäteriet with indications of the technical development within these fields. This, in turn, can strengthen further development of the geodetic infrastructure to better support the autonomous society of the future.

7.2 Role of SWEPOS in the future

SWEPOS composes both a network of GNSS reference station (CORS stations) and a high accuracy positioning service. The GNSS stations constitute a geodetic reference network, and some of the stations form the backbone of the Swedish national geodetic reference frame SWEREF 99 and are as such absolutely vital for the Swedish national geodetic infrastructure.

The SWEPOS high accuracy positioning service provides users with positions directly in the SWEREF 99, and the positioning service is thereby a mean for making the reference frame available and accessible for the Swedish society.

The interviews, discussed in Section 4, revealed that a reliable high accuracy and high quality GNSS positioning service is seen as a very important part of the basic infrastructure for a modern society. Also, the interviews show that stakeholders find it important that high accuracy positioning services are operated by personnel with a high level of knowledge and competence within the fields of geodesy and GNSS in order for the services to be trustable. Most of the stakeholders interviewed acknowledge that such high level of competence is held by Lantmäteriet today. It can therefore be considered as an important task for Lantmäteriet also in the future to maintain and develop the high accuracy SWEPOS positioning service.

Many professional users of the SWEPOS high accuracy positioning service rely strongly on the quality of service and the support provided by Lantmäteriet. Referring to the interviews, this is for instance GNSS users in municipalities, in engineering geodesy, and users of GNSS positioning services in building and construction work. These professional users will require the high accuracy positioning services of SWEPOS for many years into the future.

The SWEPOS user base could be expanded to include also the mass market, e.g. autonomous driving, by modifying the structure around generation and dissemination of the SWEPOS correction data to end users. For the mass market applications, the role of SWEPOS could also be to provide raw GNSS data in real time from the SWEPOS stations to the commercial national and international high accuracy positioning services discussed in Section 1.

A cooperation within the EU around the Galileo High Accuracy Service (HAS) may be a possibility. If the HAS in the future shall provide a positioning service with position accuracies at the cm-level in Europe, then it will be necessary with a relatively dense network of GNSS reference stations within the service area. It would make sense to use the already existing SWEPOS stations in Sweden, instead of establishing new stations. A number of political obstacles as well as measures of security would have to be overcome, but technically this could be feasible.

On the other hand, it may also be possible to improve the SWEPOS positioning service by integration with the Galileo HAS. This is technically more challenging, but could be further explored as a future development of SWEPOS.

The interviews in Section 4 show that the most important performance parameters for users of high accuracy GNSS positioning services are availability, accuracy and integrity. Also, it is expected that the requirements set to these parameters, e.g. the level of availability, will increase in the future. This means that Lantmäteriet and SWEPOS should focus on development initiatives towards ensuring compliance with these parameters for future SWEPOS users.

In the following the future role and tasks of Lantmäteriet and SWEPOS in relation to these key performance parameters, i.e. availability, accuracy and integrity, are discussed.

7.2.1 Availability

In relation to GNSS positioning services, availability is normally referred to as availability over time, and it has been pointed out by several of the stakeholders interviewed that a high level of end user positioning availability is important. SWEPOS users are generally satisfied with the level of availability today, but especially for the applications where SWEPOS is used for machine control and autonomy a service with no outages is requested for the future. To fully comply with such a request on 24/7 availability the control centre for SWEPOS should be manned around the clock, the GNSS stations, communication lines and server setup must be sufficiently robust and resistant to service breakdowns etc.

Availability can also be interpreted geographically. For Sweden, this means that the SWEPOS positioning service must be available in all of Sweden, and there is an important role for Lantmäteriet to ensure SWEPOS availability especially in the parts of Sweden where other positioning services are not available. This is for instance at high latitudes where data from geostationary satellites of global PPP services can not be received, and in remote rural areas where there are not enough users for a commercial RTK service to be feasible.

Another role for Lantmäteriet related to availability is in making SWEPOS data available, not only for the geodetic reference frame and the SWEPOS positioning service, but also for the increasing number of private positioning services (local and global) which rely on the streaming of real time raw data from the SWEPOS stations. Data for these services should also hold a very high level of availability. Making the real time SWEPOS data available and attractive for commercial operators increases the quality of the GNSS based positioning services in Sweden.

7.2.2 Accuracy

With respect to accuracy, two main requests regarding the position accuracy obtainable from the SWEPOS positioning service were revealed with the interviews. The first is an increasing focus on, and importance of, the height component. When using high accuracy positioning services in Sweden today, the height component is determined with an uncertainty which is slightly worse than for the horizontal position (latitude and longitude, or Northing and Easting coordinates). This is caused mainly by the GNSS satellite geometry but also by limitations in the data processing algorithms e.g. with respect to the effect of the troposphere on the GNSS satellite signals. It is clear from the interviews, that many professional users of SWEPOS request a lower uncertainty in the height component, and they expect that research and development on this is carried out to the future benefit of the end users. Implicitly this also means that there will be a request for better geoid models in the future and probably a need for a densification of the gravity network in Sweden

The other request revealed by the interviews is a request for a (horizontal) positioning quality better than 1 cm at the level of 95% significance (also referred to as two times the standard deviation, or statistically; the expanded uncertainty with a coverage factor of two). Today this is difficult to obtain with "normal" observation conditions and it requires a very dense network of reference stations. This is therefore also a field where more research and development is required to meet end user requests.

7.2.3 Integrity

Integrity information, or an integrity service, is requested by many of the current and future SWEPOS users. Currently, there is no standard for providing integrity in network RTK services such as SWEPOS, but there are research activities in the field focusing on both the user side (integrity as estimated in the end user equipment) and on the system side (integrity estimated by the service provider).

The software used for operation of the SWEPOS services should be able to provide such integrity service in the future. If this does not become available, or if the service is not suitable for all applications, then Lantmäteriet should consider developing its own SWEPOS integrity service. This is a new field of work for Lantmäteriet, and it may be necessary to set aside resources for looking into this now, as the request from the SWEPOS users is already relatively strong.

Another field which is indirectly related to integrity, is the use of SWEPOS facilities as an infrastructure for monitoring of spoofing and jamming of GNSS satellite signals. Such monitoring can be performed by automatically analysing data received from the GNSS satellites and raise flags or issuing warnings when certain threshold levels are exceeded. The warnings will be relevant for a small area around a SWEPOS station where the incident is detected, but the SWEPOS network is dense in the larger cities and along some of the transportation corridors in Sweden where jamming and spoofing is most likely to occur.

Such a monitoring service will be relevant for all GNSS users. This is not only for the users of the SWEPOS services but also for users relying on standalone GNSS with no augmentation for instance for IoT, Smart City applications and LBS. Thus, a jamming and spoofing monitoring service may reach a much broader part of the Swedish society than SWEPOS does today.

Safety and security around the SWEPOS stations is also a topic which should be considered by Lantmäteriet as part of the future development of SWEPOS. This relates to access to the SWEPOS stations and the SWEPOS data, not only in a physical and juridical sense but also electronically. Cyber security must be considered in relation to all of the national geodetic infrastructure, but especially in relation the GNSS stations and services. Given that also jamming and spoofing are already well-known threats to GNSS services, it is important that the necessary precautions are taken to ensure the availability, accuracy and integrity of SWEPOS data at all times.

8. Conclusion

GNSS positioning services of the future including expected users and their requirements as well as the national geodetic infrastructure required and the future role of the national geodetic agencies is presented in this report.

The number of users of high accuracy GNSS positioning services will increase during the next 5 to 10 years, and an increase is expected within all of the current user groups such as for instance agriculture, machine guidance and control in construction work, land surveying for building, construction, cadastral and environmental applications, as well as maritime use for applications in harbors, inland waterways, and coastal areas. Also, a large increase in the use of positioning services for drones is expected.

Future units for mobility and autonomous navigation of vehicles, vessels, drones, robots etc. will be a new and very large group of users of GNSS positioning services in the near future. The use of GNSS positioning services for autonomous machinery in e.g. agriculture and construction work will also increase in the future

Most important performance parameters as requested from users to the GNSS positioning services are accuracy, availability and integrity. These three performance parameters are requested by all user groups, but there are differences in which ones of the parameters are considered most important.

Other performance parameters such as robustness, resilience and authentication are also considered important in order to reduce the risk for or the consequences of interference, jamming and spoofing of the GNSS satellite signals.

It is expected that the role of Lantmäteriet within the field of geodesy will be expanded compared to the current role. The classical tasks with maintenance and development of the national geodetic infrastructure will still be very important, but many new tasks can be undertaken by Lantmäteriet and SWEPOS in the future.

For Lantmäteriet there will be an important future role in verification and quality control of geodata collected commercially or by crowd sourcing. In relation to the use of geodata and related regulation for navigation of autonomous vehicles and drones in cities and populated rural areas, Lantmäteriet could take on a leading role in ensuring cooperation and coordination at the governmental level.

Lantmäteriet could establish a closer cooperation with software developers and engineers active in the fields of autonomy, robotics and drone navigation as well as in other user areas to support proper use of the geodetic infrastructure. At the same time Lantmäteriet could learn more about the technical development within these fields, knowledge which in turn can be used for ensuring that the geodetic infrastructure sufficiently supports the autonomous society of the future.

For SWEPOS there are many considerations and preparations to make regarding the future role in relation to the mass market. Further, requirements regarding availability, accuracy and integrity from current and future users of the high accuracy positioning service should be met by SWEPOS, and there are initiatives to take, and work to do, for SWEPOS in relation to these three key performance parameters.

In terms of geodetic infrastructure, there is a need for both national and international geodetic reference frames to support GNSS positioning services of the future, and timely, accurate and dynamic coordinate transformations for on the fly real time conversion between the geodetic reference frames become crucial.

National height systems and high accuracy fitted geoid models will be increasingly important in the future as more GNSS users will rely on not only the horizontal position but also the vertical dimension, the height, as determined with high accuracy GNSS positioning services.

Finally, it is important to mention safety and security around the SWEPOS stations and the SWEPOS positioning service and also in relation to other national geodetic facilities in Sweden. Cyber security at large must be considered in relation to all of the national geodetic infrastructure. Given that also jamming and spoofing are already well-known threats to GNSS, it is important that the necessary precautions are taken to ensure the availability, accuracy and integrity of SWEPOS data as well as the entire Swedish national geodetic infrastructure at all times.

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Appendix A - Definition of key performance parameters from GSA Market Report Issue 5

Annex 2: Definition of key performance parameters

The definitions given below are to explain the key performance parameters as mentioned on the User Perspective page of each market segment. **Important notice: the definitions below are applicable to this report only, and are not meant to be used for any other purpose.**

Key GNSS requirements and performance parameters

Availability: percentage of time over a specified time interval that a sufficient number of satellites are transmitting a usable ranging signal within view of the user. Values vary greatly according to the specific application and services used, but typically range from 95-99.9%.

Accuracy: the difference between true and computed position (absolute positioning). This is expressed as the value within which a specified proportion of samples would fall if measured. Typical values for accuracy range from tens of meters to centimetres for 95% of samples. Accuracy is typically stated as 2D (horizontal), 3D (Horizontal and height) or time.

Continuity: ability to provide the required performance during an operation without interruption once the operation has started. Continuity is usually expressed as the risk of a discontinuity and depends entirely on the timeframe of the application (e.g. an application that requires 10 minutes of uninterrupted service has a different continuity figure than one requiring two hours of uninterrupted service, even if using the same receiver and services). A typical value is $1x10^{-4}$ over the course of the procedure where the system is in use.

Integrity: the measure of trust that can be placed in the correctness of the position or time estimate provided by the receiver. This is usually expressed as the probability of a user being exposed to an error larger than alert limits without warning.

The way integrity is ensured and assessed, and the means of delivering integrity related information to the user are highly application dependent.

Throughout this report, "integrity" is to be understood at large, i.e. not restricted to safety-critical or civil aviation definitions but also encompassing concepts of quality assurance/quality control as used by other applications and sectors.

Time To First Fix (TTFF): a measure of a receiver's performance covering the time between activation and output of a position within the required accuracy bounds. Activation means subtly different things depending on the status of the data the receiver has access to.

Robustness: the ability of systems or system elements to withstand a level of interferences and/or jamming without significant degradation or loss of performance.

For some users robustness may have a different meaning, such as the ability of the solution to respond following a severe shadowing event. For the purpose of this document, robustness is defined as the ability of the solution to mitigate interference.

Authentication: the ability of the system to assure the users that they are utilising signals and/or data from a trustworthy source (e.g. GNSS constellation), and thus protecting sensitive applications from spoofing threats.

Other requirements and performance parameters

Power consumption: the amount of power a device uses to provide a position. The power consumption of the positioning technology will vary depending on the available signals and data. This requirement is important for devices with a limited battery life-span such as smartphones and tablets, drones and asset management devices.

Resiliency: the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions; includes the ability to recover from deliberate attacks, accidents, or naturally occurring threats or incidents. A resilient system will change its way of operations while continuing to function under stress, while a robust system at the end will reach a failure state without being able to recover.

Connectivity: this requirement refers to the need for a communication and/or connectivity link of an application to be able to receive and communicate data to third parties. Connectivity comprises long-range communication technologies such as 3G and LTE as well as short-range technologies such as Bluetooth and NFC.

Interoperability: refers to the characteristic of a product or system, whose interfaces are completely understood, to work with other products or systems, in either implementation or access, without any restrictions (e.g. ability of GNSS devices to be combined with other technologies and the possibility to merge the GNSS output with the output coming from different sources).

Traceability: A traceable measurement is one that can be related to national or international standards using an unbroken chain of measurements, each of which has a stated uncertainty. For Finance applications, knowledge of the traceability of the time signal to UTC is essential to ensure regulatory compliance at the time-stamp.