REPORT ON SURVEYING USER NEEDS AND REQUIREMENTS

OUTCOME OF THE EUSPA USER CONSULTATION PLATFORM

GALILEO EGNOS Copernicus

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01 INTRODUCTION AND CONTEXT OF THE REPORT

The surveying sector, being central in addressing important societal and economic challenges (e.g. urbanisation and high demand for fuel), strongly relies on GNSS-enabled solutions in a number of applications. GNSS user requirements, strongly interlinked with the growing and evolving market trends, are driven by:

- Significant improvements in High-Accuracy solutions (e.g. multi-constellation, multi-frequency, Galileo High-Accuracy Service);
- Increased availability of low-cost equipment (e.g. performant handheld devices, more affordable GNSS RTK solutions);
- Heavy investment in infrastructure and construction works (especially in emerging markets such as India and China), but also by leading companies in capital-intensive sectors (e.g. mining and oil & gas);
- Integration of GNSS with other complementary technologies such as RPAS, LIDAR and laser scanners;
- Continuous development of IT hardware and software solutions for handling large amounts of data.

In this framework, E-GNSS solutions, especially Galileo, could hold a significant role in the evolution of the utilisation of GNSS by surveyors across the various disciplines.

The User Consultation Platform (UCP) is a yearly organised forum for interaction between end users, user associations and representatives of the value chain, such as receiver and chipset manufacturers, application developers and the organisations and institutions dealing, directly and indirectly, with Galileo and EGNOS. In this context, the objective of this document is to constitute a reference for the general surveying community by collecting and analysing the most up-to-date GNSS user needs and requirements in the surveying market segment. The document should serve as a key input to the UCP so that main included outcomes can be validated and subsequently updated.

The analysis is aimed to provide the EUSPA with a clear and up-to-date view of the current and potential future user needs in order to:

- Reflect the latest trends and developments and anticipate impact on future E-GNSS therefore preparing the future E-GNSS (G2G);
- Ensure the E-GNSS market uptake.

Finally, as the analysis will be publicly available, it will serve also as reference for users and industry supporting the planning and decision-making activities for what concerns the use of location technologies.

1.1 METHODOLOGY

Figure 1 details the methodology adopted for the analysis of the surveying user requirements.

1.2 SCOPE

This document is part of the User Requirements documents issued by the European GNSS Agency for the Market Segments where Position Navigation and Time (PNT) play a key role. Its scope is to cover user requirements on PNT solutions from the strict user perspective and the market conditions, regulations, and standards that drive them. Therefore, the document includes an analysis of the market trends on this particular segment, then performs a detailed analysis including the prospective uses of GNSS in this market finalising with a specification of user requirements in a format that can be used for System Engineering activities.

THE OBJECTIVE IS TO CONSTITUTE A REFERENCE FOR THE GENERAL SURVEYING COMMUNITY BY COLLECTING AND ANALYSING THE MOST UP-TO-DATE GNSS USER NEEDS AND REQUIREMENTS.

In more detail, the document is laid out as follows. It starts with a market overview for Surveying (**section 4**), focussing on market evolution and key trends, and presenting the main market players and user communities. It then moves on with an analysis of GNSS user requirements for surveying (**section 5**). This is organised as follows:

- Section 5.1.1 identifies and defines the main GNSS user level criteria.

Figure 1: High-level methodology for the analysis of Surveying User Requirements

OVERALL METHODOLOGY

1 Desk Research

Identification and detailed description of all existing surveying applications

- All surveying applications covered in Market Report v.5
- Surveying applications found in other sources

Identification of user communities and key actors in value chain

- Presentation of main market players and key user communities
- Identification and definition of GNSS performance criteria relevant to the various surveying applications

Segmentation of Surveying Applications

- Analysis of GNSS utilisation in different surveying techniques
- Definition and classification of applications

Definition of the functions and level of performance required for each application

- Surveying user requirements analysis based on open secondary research information
- GNSS limitations, regulatory considerations, market/techno trends and drivers
- Table matching the main applications with the performance criteria

User requirement analysis – *draft 1*

SECONDARY RESEARCH INFORMATION

GNSS magazines- Coordinates, GPS World, Inside GNSS; ESA website; Articles on Google Scholar; Thesis and dissertations on; European regulation or standard; Google

2 Stakeholders Consultation

Validation interviews

- Interview guide
- Selection of the consulted stakeholders
- Primary research: Interviews and reporting

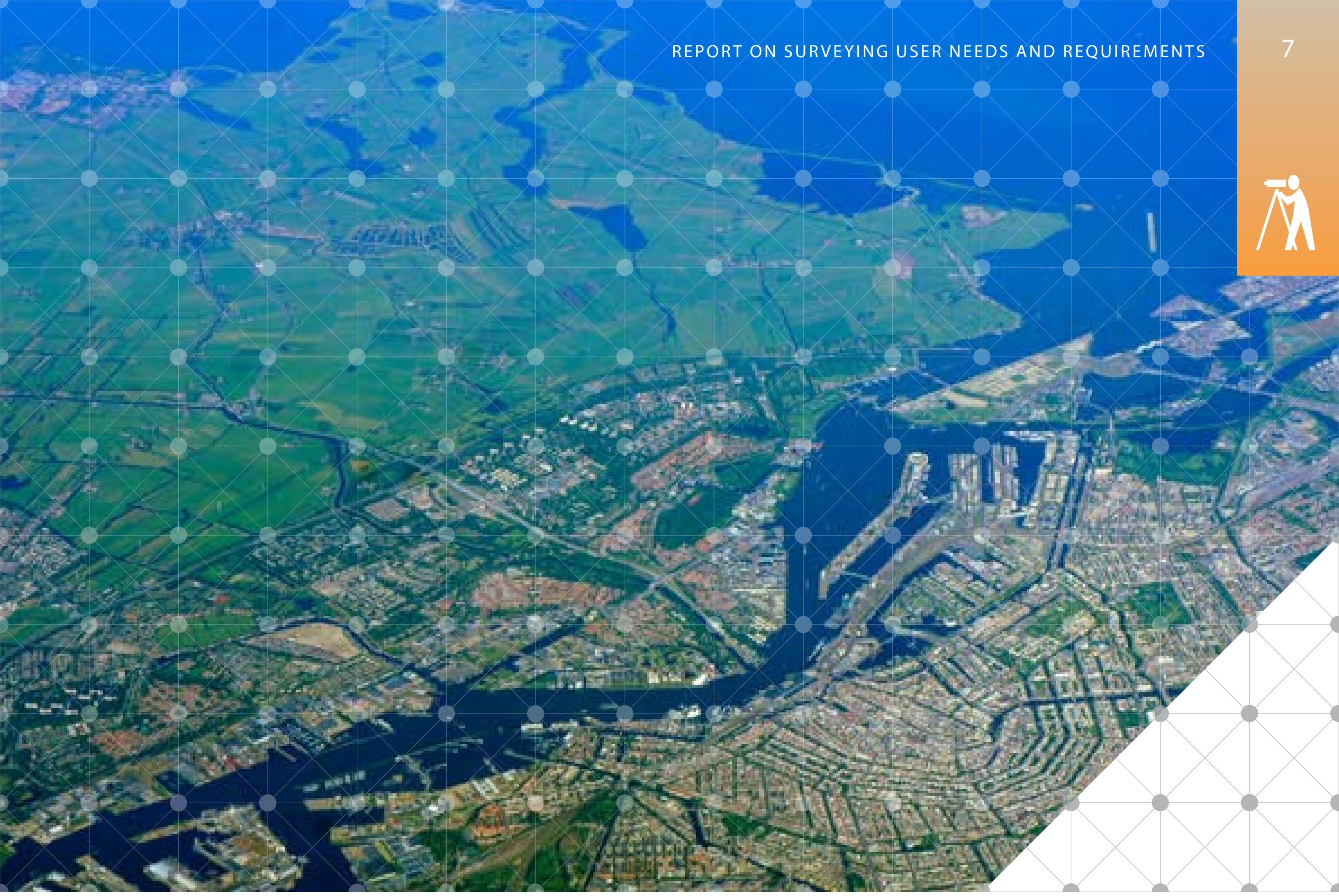
User requirement analysis – *final version*

User Consultation Platform

- User requirements submitted to the first UCP forum for review and finalisation
- Update, validation and expansion of the User requirement analysis at each UCP

2019 update

Content figure updated in 2019



- Sections 5.2 to 5.4 provide a detailed overview of the user requirements across the various surveying applications. This follows closely the classification adopted in Market Report v5 whilst providing insights to additional sub-segments. The analysis has relied on extensive desk research and has been validated through interviews with key surveying stakeholders.
- Prospective use of GNSS in surveying is addressed in section 5.5. It assesses GNSS technology trends, along with the other complementary technologies.
- GNSS limitations for surveying are described in section 5.6, followed by key drivers in section 5.7.
- Section 5.8 provides an account of policy, regulation and standardisation considerations.
- Section 5.9 provides a summary of conclusions.

The specification of user requirements across each segment and sub-segment is provided in **Section 6;** this includes a detailed account of performance requirements (6.1) and an analysis of additional considerations across the three main segments (land, mapping, marine). The report concludes with a table of PNT system requirements (6.3) informed by the various analyses performed in the previous sections.

THE SURVEYING SECTOR, BEING CENTRAL IN ADDRESSING IMPORTANT SOCIETAL AND ECONOMIC CHALLENGES, STRONGLY RELIES ON GNSS-ENABLED SOLUTIONS IN A NUMBER OF APPLICATIONS.

The document is intended to serve as an input to more technical discussions on Systems Engineering and evolution of the European GNSS systems so that space infrastructures are effectively linked to user needs.

02 EXECUTIVE SUMMARY

This report, prepared in the frame of the *Specific Contract N°8 "Market and Technology Monitoring Process update, expansion and validation 2015"*, aims at enhancing the understanding of market evolution, strongpoints, limitations, key technological trends and main drivers related to the uptake of GNSS solutions across the different surveying disciplines. These elements are essential in order to frame the appropriate technology and service offering development vis-à-vis the requirements of the respective users.

To that end, the report starts (chapter 4) with an overview of the GNSS surveying market trends. The surveying market in general and the use of GNSS within it in particular, are expected to show significant growth in the coming years especially in regions of the world where there are no alternative legacy systems or dense geodetic ground networks. Moreover significant growth is expected in regions that have intense construction activity, for example India and China. In these same regions, the importance of cadastral surveys will also increase as a function of the increasing GDP and population. In this context, GNSS-enabled surveying addresses some of the most immediate economic and societal concerns such as increased urbanisation, increased demand for hydrocarbons and modernised transportation needs. To better understand market dynamics, the report provides a brief description of the landscape of market players, typically large multi-national players such as Trimble, Hexagon and Topcon, serving a wide range of users (cadastral agencies, surveyors, oil & gas companies, etc.).

CADASTRAL, CONSTRUCTION, MAPPING, MINE AND MARINE SURVEYING ARE ALL COVERED BY GNSS-ENABLED SOLUTIONS.

GNSS-enabled solutions cover a wide range of applications including cadastral surveying (delineation of property boundaries), construction surveying (precise drawing of the future work sites for buildings and infrastructure), mapping (charts that contain points of interest and are typically integrated in Geographic Information Systems), mine surveying and marine (offshore and hydrographic) surveying. These applications are relying mostly on GNSS technologies, however there are still applications where traditional surveying methods are preferred; for example, in situations where a clear view of the sky is not available or if vertical accuracy is particularly important. In such cases, GNSS is used complementarily with emerging applications, such as optical, multispectral or LiDAR, RPAS, terrestrial laser scanning, IMU, SLAM, AR, mobile and crowdsourced mapping. The GNSS user requirements per application, together with potential constraints and drivers for the use of GNSS and the evolution of user requirements accordingly, are presented in Chapter 5.

2019 update

Taking all this into account, the report concludes with a detailed analysis of the current GNSS performance levels and takes particular stock on some "qualitative" considerations that impact the uptake of GNSS solution across the different applications.

Finally, the report concludes with a series of tables summarising the PNT system requirements for the various applications analysed herein.

Content text updated in 2019

03 REFERENCE DOCUMENTS

Id.	Reference	Title	Date
[RD1]	GSA Market Report 5	GSA GNSS Market Report Issue 5	May 2017
[RD2]	Positioning of Galileo impact towards other GNSS and complementary technologies	GSA Market development strategy and implementation plan (Surveying)	November 2014
[RD3]	RICS Guidelines	RICS Guidelines for the use of GNSS in land surveying and mapping	November 2010
[RD4]	Surveyor's General Guidelines	New South Wales Government - *GNSS for Cadastral Surveys*	May 2014
[RD5]	Practical Considerations	C. Roberts - *GPS for cadastral surveying - practical considerations*	September 2005
[RD6]	Trimble White Papers	*Series on White Papers on Satellite Tracking, Integrated surveying, etc.*	NA
[RD7]	Cost Effective GNSS Positioning Techniques	FIG - *Cost Effective GNSS Positioning Techniques*	January 2010
[RD8]	Introduction to GNSS	Novatel - *An introduction to GNSS*	2010
[RD9]	Surveying with GPS for Construction Works	Ahmed El-Mowafy - Surveying with GPS for Construction Works Using the National RTK Reference Network and Precise Geoid Models	July 2014
[RD10]	RTK Networks for Machine Control	Keenan et al - *RTK Networks for competitive advantage in Machine Control and Site Positioning*	January 2010
[RD11]	GNSS Machine Control	Fastellini et al - *GNSS machine control with RTCM corrections from permanent networks*	May 2009
[RD12]	Guidelines for GNSS positioning in the oil & gas industry	IMCA/OGP - *Guidelines for GNSS positioning in the oil & gas industry*	June 2011
[RD13]	Precise Positioning in the mining sector	ACIL Allen Consulting - *Precise Positioning in the mining sector*	June 2013
[RD14]	S-44	IHO - *Standards for Hydrographic Surveys*	February 2008
[RD15]	GNSS Hydrographic Surveying	Ligteringen et al - *GNSS Based Hydrographic Surveying: clear advantages and hidden obstacles*	2013
[RD16]	GIS and GNSS integration	Salem - *GIS and GNSS Integration*	November 2007
[RD17]	EGNOS Bulletin	*EGNOS Bulletin - story on bathymetry in Barcelona*	Q4-2015
[RD18]	Maritime Boundaries	Fraser et al - *Positioning maritime boundaries with certainty - a rigorous approach*	2002

Id.	Reference	Title	Date
[RD19]	CLGE Regulation	CLGE - *Position Paper in favour of the regulation of the surveying profession*	March 2014
[RD20]	European Requirements for cadastral surveyor activities	EuroGeographic, CLGE and Geometer Europas - *European Requirements for cadastral surveyor activities*	June 2008
[RD21]	Residential Drones	RICS - *Property Journal (story on residential drones p.44)*	August 2015
[RD22]	PPP versus DGNSS	Rizos, C., Janssen, V., Roberts, C. and Grinter, T. - *PPP versus DGNSS*	October 2012
[RD23]	RTK GNSS Receivers	Gakstatter, E. - *RTK GNSS Receivers: A Flooded Market?*	March 2013
[RD24]	Galileo CS GNSS High Accuracy and Authentication	InsideGNSS - *Galileo's Commercial Service: Testing GNSS High Accuracy and Authentication*	February 2015
[RD25]	Precise Point Positioning (PPP)	Murfin, T. - *Look, No Base-Station! – Precise Point Positioning (PPP)*	March 2014
[RD26]	User Requirements Interviews	VVA - *User Requirements Interviews*	April 2016
[RD27]	Environmental Monitoring	Awange, J. – *Environmental Monitoring using GNSS*	January 2012
[RD28]	Satellite Clock estimation for PPP	Chen *et al*, Efficient High-Rate Satellite Clock Estimation for PPP Ambiguity Resolution Using Carrier-Ranges	Nov 2014
[RD29]	Galileo's surveying potential	GPS World – Galileo's Surveying Potential	Mar 2012
[RD30]	Exploiting Galileo E5	Diessongo et al - Exploiting the Galileo E5 Wideband Signal	Sep 2012
[RD31]	Comparative analysis of measurement noise and multipath	Cai et al - A comparative analysis of measurement noise and multipath for four constellations: GPS, BeiDou, GLONASS and Galileo	Dec 2014
[RD32]	GNSS Technology Report	GNSS User Technology Report issue 1	Oct 2016
[RD33]	User Requirements Interview	UCP follow-up validation interview with industry	Jan 2018
[RD34]	UCP 2017	Surveying Session at the UCP MoM (Ref. doc. GSA-MKD-MS-MOM-236055-Professional-Mapping-and-Surveying)	December 2017
		Stakeholder consultation	
[RD35]	GSA-MKD-MS-MOM-246195	User Consultation Platform 2018 – Minutes of Meeting of the Surveying and Mapping Panel	03.12.2018
		GNSS User Requirements Analysis	
[RD36]	QZSS transmits SBAS-like signal	Quasi-Zenith Satellite System Performance Standard (PS-QZSS-001)	05.11.2018
[RD37]	SBAS in Australia and New Zealand	Satellite Based Augmentation System test-bed project	May 2018

2019 update

Content table updated in 2019

04 MARKET OVERVIEW AND TRENDS

4.1 MARKET EVOLUTION AND KEY TRENDS

Thanks to its high-purchasing power, the surveying sector has been an early adopter of cutting-edge technological innovations amongst which GNSS holds a seminal role, both as a centrepiece of several current solutions and as a driver for their evolution. **Price-dependent trends** are observed in a four-fold fashion: **(i)** on one hand, expensive solutions first tested and adopted in the high-end surveying applications are taken up in other markets once they become more affordable; **(ii)** on the other side global leaders of capital intensive industries (i.e. mining and oil & gas) invest heavily in the vanguard of technological development; **(iii)** GNSS performance improvements in consumer-grade devices enable greater uptake in large emerging markets (e.g. China and India) and in less-accuracy-dependent sectors (i.e. mapping); and lastly, **(iv)** the availability of more affordable high-precision GNSS data and the infrastructure to collect, process and analyse it.

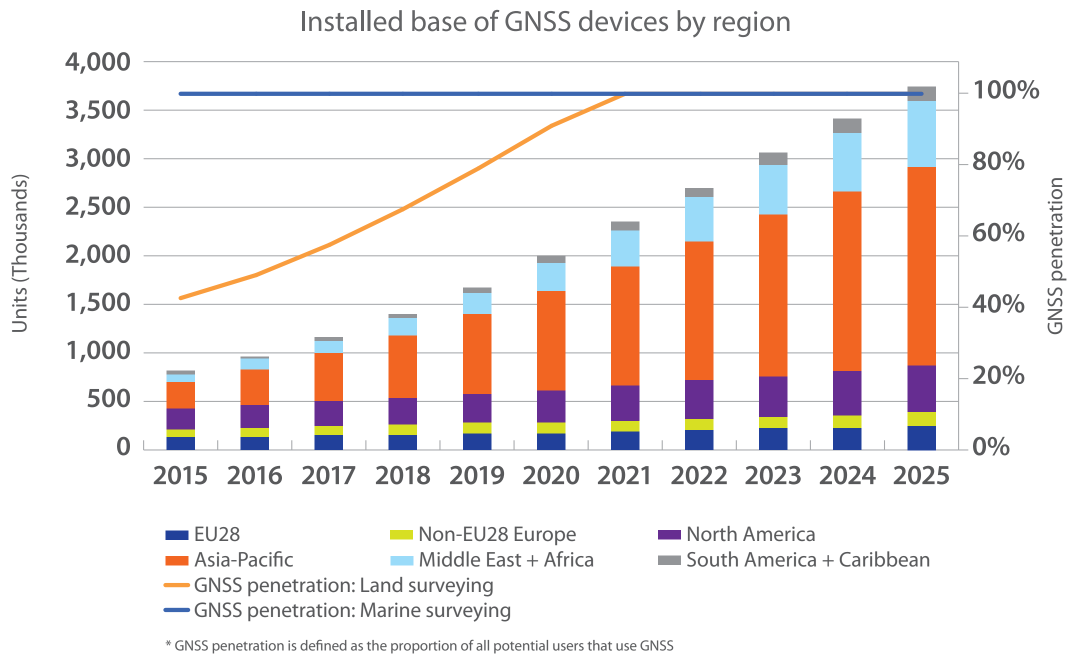
The evolution of the surveying market at large, and of GNSS in surveying in particular, is further characterised by **geographic trends**, i.e. increased uptake of GNSS-based solutions in emerging markets owing to heavy investments in infrastructure and construction projects[1]. According to the Global Construction 2025 report[2], sponsored by PwC, the volume of construction output will grow by more than 70% to $15 trillion worldwide by 2025. This will be mainly concentrated in China, India and the US - the latter investing in re-building of major works (dams, bridges, etc.) that have reached the end of their life cycles. Furthermore, mature markets such as the US, Western Europe and Australia, are driving demand for highly-sophisticated solutions, especially in sectors such as mining (see for instance the Rio Tinto investment in fully autonomous mining trucks[3]), and oil & gas exploration (due to rising global demand for hydrocarbons[4]).

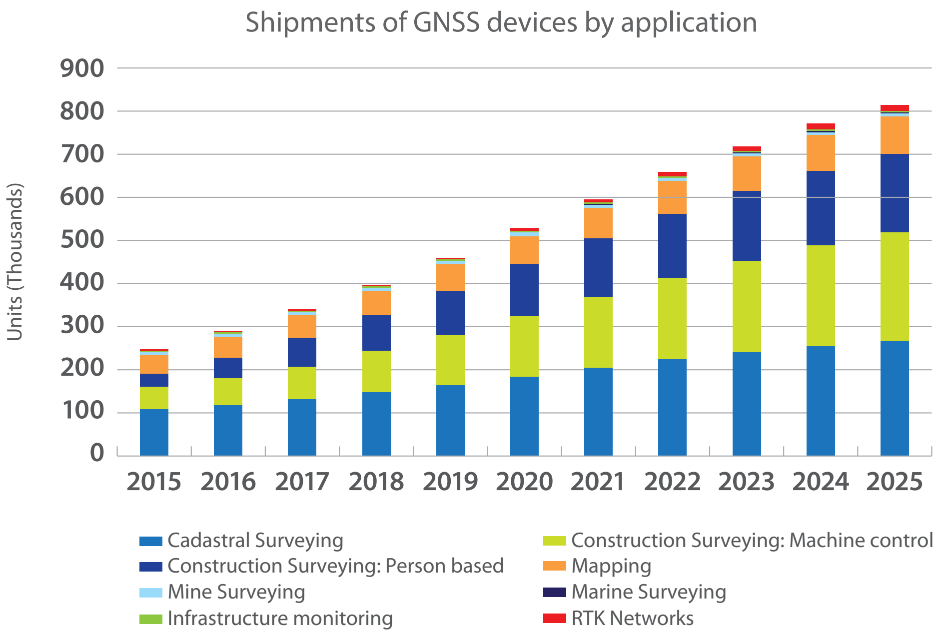
1 A prime example is Beijing's new airport mega project awarded to Trimble http://gpsworld.com/trimbles-beijing-airport-construction-contract-extended-with-machine-control/
2 http://www.pwc.com/gx/en/industries/engineering-construction/publications/global-construction-2020.html
3 http://www.abc.net.au/news/2015-10-18/rio-tinto-opens-worlds-first-automated-mine/6863814
4 http://www.lukoil.com/materials/doc/documents/Global_trends_to_2025.pdf

As per the latest GSA GNSS Market Report [RD1], the **overall growth in GNSS device shipments** is mostly attributed to cadastral surveying, mapping and construction (both person-based and machine control), together accounting for 95% of the installed base in 2016. Similarly, the **future growth in shipments will be mostly driven by cadastral and construction surveying activities.**

North America holds the largest share of GNSS devices, followed by Europe; however, the fastest growth pace is found in Asia-Pacific region[5]. It is worth noting that even if marine surveying represents a niche market compared to land surveying (which holds 99% of the total GNSS market), Europe's hydro survey equipment market holds the global lead.

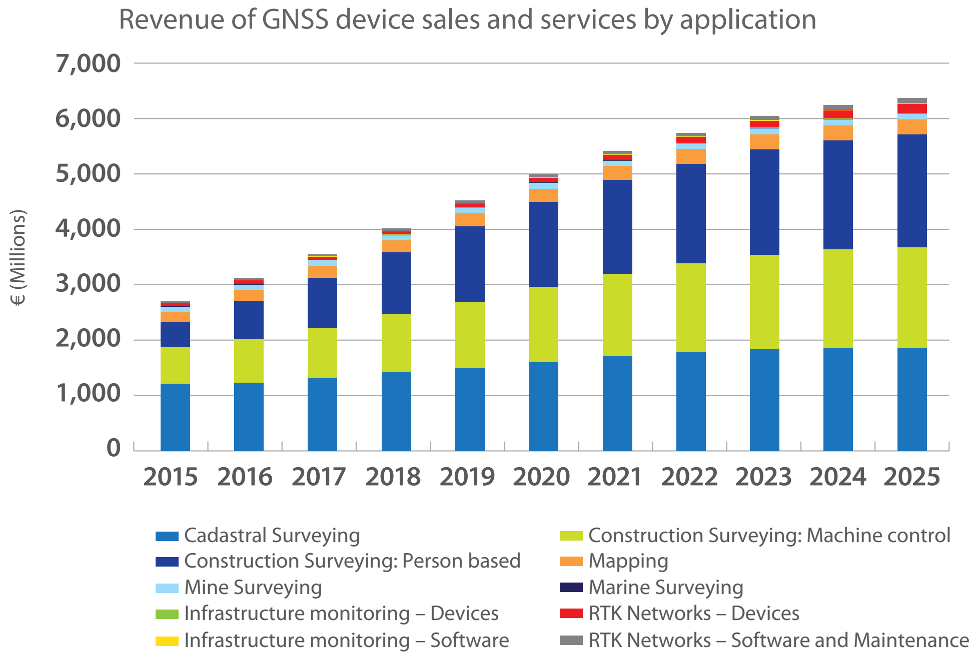
Figure 2: Shipments by region (left) and by application (right) - source [RD1]





5 Furthermore, according to the latest Markets&Markets study, the overall Asia-Pacific surveying (i.e. not only GNSS-enabled) is expected to grow at 7.3% CAGR in the period 2014-2020.

Figure 3: Revenue of GNSS device sales and services by application - source [RD1]



Another clear trend in surveying is that of the steady decrease in the average price of devices. This is due to increased competition, not only amongst the leading manufacturers but also stemming from the so-called "OEM syndrome". This encompasses, for instance, the increasing number of companies buying RTK GNSS boards from the limited number of original designers, and then making their own finished products with similar capabilities to the original ones. This market phenomenon exerts additional pressure to OEMs who need to compete against - predominantly - Chinese-equivalent products that cost 1/4 of the original price. Additional competition resulting to reduced prices arises from the need to migrate to L1/L5 capable receivers, given that GPS will not support legacy L2 (P/Y) signals beyond 2020.

The evolving dynamics in the surveying market are further characterised by a **significant widening of survey solution providers' customer base**; thus, whilst the lion's share amongst user groups is still held by surveyors and construction contractors, other users such as government agencies (including National Mapping and Cadastral Authorities - NMCAs), utility actors, oil & gas companies, mining and railway actors are becoming increasingly relevant. With this in view, a concise overview of the main market players and the respective user communities follows in the following sections.

4.2 MAIN MARKET PLAYERS

The GNSS surveying value chain consists of commercial augmentation providers, component manufacturers (receivers, antennas, integrated solutions, etc.), system integrators, and application or added-value service providers, serving a wide range of professional users who in turn work or are contracted by a number of end-customers (see figure 4).

ONE CLEAR TREND IN SURVEYING IS THAT OF THE STEADY DECREASE IN THE AVERAGE PRICE OF DEVICES.

Multinational companies with an established portfolio of solutions across various applications are leading the various "links" of the global surveying value chain. Amongst receiver and component manufacturers, Trimble Navigation Ltd. (US) holds the lead, followed by Hexagon AB (Sweden) - including Leica and Novatel[6], and Topcon Corporation (Japan). Fugro NV (Netherlands) is the global leader in offshore surveying offering a comprehensive suite of services[7], with 78% of its revenue in 2014[8] coming from its oil & gas business. Amongst system integrators, Kongsberg Gruppen ASA (Norway) is amongst world leaders in sonar seabed surveying equipment.

6 Hexagon acquired SCCS, a leading UK-based supplier of surveying equipment - https://www.businesswire.com/news/home/20160113005481/en/Hexagon-Acquires-SCCS-Leading-Supplier-Leica-Geosystems
7 http://www.fugro.com/our-expertise/our-services/survey/satellite-positioning
8 http://www.fugro.com/docs/default-source/investor-publications/2014/annual-report-2014.pdf?sfvrsn=10

Figure 4: The GNSS surveying value chain - source [RD1]

AUGMENTATION SERVICE PROVIDERS

- FUGRO (STARFIX)*
- HEMISPHERE (ATLAS)
- HEXAGON (SMARTNET)*
- JOHN DEERE (STARFIRE)
- TOPCON (TOPNET LIVE)
- TRIMBLE (RTX, OMNISTAR)

NATIONAL AND REGIONAL RTK NETWORK PROVIDERS

COMPONENTS AND RECEIVER MANUFACTURERS

- BEIJING BDSTAR NAVIGATION CO
- BEIJING UNISTRONG SCIENCE & TECHNOLOGY
- CHC
- GNSS-GPS
- HEXAGON (LEICA GEOSYSTEMS, NOVATEL)*
- HI-TARGET SURVEYING INSTRUMENT CO.
- HOLUX TECHNOLOGY, INC.
- JAVAD
- JOHN DEERE
- KONGSBERG*
- LAIRD PLC*
- NORTH SURVEYING*
- RAKON
- SEPTENTRIO*
- SHANGHAI HUACE NAVIGATION
- SOUTH
- SUZHOU FOIF CO. LTD
- TECHNOLOGY
- TOPCON
- TRIMBLE
- YAGEO CORPORATION

SYSTEM INTEGRATORS (RELEVANT ESPECIALLY FOR MACHINE CONTROL)

- BEIJING BDSTAR NAVIGATION
- CATERPILLAR
- HEXAGON*
- HITACHI
- HI-TARGET SURVEYING INSTRUMENT
- J.C.B. SERVICE*
- JOHN DEERE
- KOMATSU
- KONGSBERG*
- TOPCON
- TRIMBLE

SOFTWARE, APPLICATIONS AND ADDED-VALUE SERVICES

- CARLSON
- FUGRO*
- HEMISPHERE
- HEXAGON (LEICA GEOSYSTEMS)*
- HYPACK
- JAVAD
- SEPTENTRIO*
- SOUTH
- STONEX*
- TOPCON
- TRIMBLE

PROFESSIONAL USERS

- CONSTRUCTORS
- ENGINEERS
- ENVIRONMENT PROFESSIONALS
- FARMERS
- MINING COMPANIES
- OIL & GAS COMPANIES
- SCIENTISTS
- SURVEYORS

CUSTOMERS OF SURVEYING SERVICES

- HYDROGRAPHIC OFFICES
- NATURAL RESOURCES MANAGEMENT FIRMS
- OFFSHORE WIND FARMS
- PRIVATE COMPANIES (CONSTRUCTION COMPANIES, INSURANCES, ETC.) INDIVIDUALS
- PUBLIC ORGANISATIONS
- UNDERWATER CABLE & PIPELINE INSTALLERS

The landscape of RTK GNSS receivers, serving the high-precision user community, is driven by solutions provided[9] by Trimble, Leica/Novatel, Topcon/Sokkia, Hemisphere GNSS (US), JAVAD GNSS (US), Septentrio (BE). At the same time, network RTK services are proliferating; European examples include OS Net, SmartNet and SAPOS.

Several of the aforementioned companies are also competing - or in some cases cooperating[10] - in the commercial augmentation providers' arena. For example:

- Trimble owns Omnistar, offering different 24/7 subscription-based services[11], that achieve between 10cm (HP) and metre (VBS) accuracies, and having worldwide coverage. Trimble also offers CenterPoint® RTX[12], a PPP solution that achieves under 4cm accuracy.
- NavCom - a subsidiary of John Deere - offers StarFire[13] subscription service, achieving global coverage and accuracy up to 5cm.
- Veripos - now acquired by Hexagon, offers the TerraStar[14] DGNSS services at the level of 10cm accuracy, targeting especially the oil and gas sector[15].

9 This list is not exhaustive. For a comprehensive overview see GSA GNSS User Technology Report.
10 http://gpsworld.com/hexagon-enters-into-agreement-with-topcon-for-terrastar-network/
11 http://www.omnistar.com/SubscriptionServices.aspx
12 http://www.trimble.com/positioning-services/centerpoint-RTX.aspx
13 https://www.navcomtech.com/navcom_en_US/products/equipment/cadastral_and_boundary/starfire/starfire.page
14 http://www.terrastar.net/
15 http://www.veripos.com/dp-drilling.html

Main world-wide commercial augmentation services are listed in the Figure 5.[16]

Figure 5: Main world-wide commercial augmentation services

Name	Service	Stated performance	Supported Constellations	Method	Owned by
OmniStar	VBS	<1m	GPS	DGNSS	Trimble
	HP	10cm	GPS	LR-RTK	
	XP	15cm	GPS	PPP	
	G2	<10cm	GPS + GLONASS	PPP	
RTX	ViewPoint	<1m	GPS + GLONASS + BDS	PPP	Trimble
	RangePoint	<50cm	GPS + GLONASS + BDS	PPP	
	FieldPoint	<20cm	GPS + GLONASS + BDS	PPP	
	CenterPoint	<4cm	GPS + GLONASS + BDS	PPP	
StarFix	HP	10cm	GPS	Phase DGNSS	Fugro
	G2	10cm	GPS + GLONASS	PPP	
	G2+	3cm	GPS + GLONASS	PPP	
	G4	5-10cm	GPS + GLONASS + BDS + Galileo	PPP	
	L1	1.5m	GPS	DGNSS	
	XP2	10cm	GPS + GLONASS	PPP	
Atlas	H100	1m	GPS + GLONASS + BDS	PPP	Hemisphere
	H30	30cm	GPS + GLONASS + BDS	PPP	
	H10	8cm	GPS + GLONASS + BDS	PPP	
StarFire	SF2	5cm	GPS + GLONASS	PPP	John Deere
C-Nav	C1	5cm	GPS	PPP	Oceaneering international
Veripos	C2	5cm	GPS + GLONASS	PPP	Hexagon AB
	Apex	10-20cm	GPS	PPP	
	Apex^2	5cm	GPS + GLONASS	PPP	
	Ultra	15cm	GPS	PPP	
	Ultra^2	8cm	GPS + GLONASS	PPP	
	Standard	1m	GPS	DGNSS	
	Standard^2	1m	GPS + GLONASS	DGNSS	
TerraStar	TerraStar D	10cm	GPS + GLONASS	PPP	Hexagon AB
	TerraStar M	1m	GPS + GLONASS	DGNSS	
	TerraStar C	2-3 cm	GPS + GLONASS	PPP	

16 https://www.gsa.europa.eu/system/files/reports/gnss_user_technology_report_webb.pdf

The products and services offered by the various actors in the competitive GNSS surveying landscape, are tailored to the specific requirements of the diverse user groups, ranging from cadastral agencies and construction site managers, to large multi-national companies active in the extractive industries. These requirements are often incorporated in guideline or best practice handbooks issues by the professional associations representing the various groups. A brief overview of these groups as well as the licensing and accreditation bodies (for surveyors) is provided below.

4.3 MAIN USER COMMUNITIES

4.3.1 PROFESSIONAL ASSOCIATIONS

Within the surveying profession (and in its neighbouring sectors), there are a number of organisations which represent the interests of professionals in the sector and its thematic sub-divisions. They federate the collective interests of surveyors at different levels (global, EU, national):

INTERNATIONAL

- **The International Federation of Surveyors (FIG)** is a global non-governmental organisation, recognised by both the United Nations and the World Bank, which represents surveyors worldwide through its national member associations, covering the range of professional fields within the global surveying community. Its aim is to ensure that the disciplines of surveying (and their practitioners) meet the needs of the markets and communities that they serve. FIG through its thematic working groups publishes guidelines and best practices for surveyors in a range of thematic sectors.
- **The International Federation of Hydrographic Societies (IFHS)** is a partnership of national and regional hydrographic societies, which represents - amongst others - the profession of hydrographic surveyors;
- **The International Society for Mine Surveying (ISM)** is an international non-profit association of specialists in mine surveying or related fields;
- **The International Association of Geodesy (IAG)** is a scientific organisation in the field of geodesy which promotes scientific cooperation and research in geodesy on a global scale and contributes to it through its various research bodies. It is an active member of the International Association of Geodesy and Geophysics (IUGG) which itself is a member of the International Council for Science (ICSU). The IAG maintains services such as the International Geoid Service and the International GNSS Service;
- **The International Society for Photogrammetry and Remote Sensing (ISPRS)** is a non-governmental organisation devoted to the enhancement of international cooperation between the worldwide organisations with interests in the photogrammetry, remote sensing and spatial information sciences.
- **The International Association of Oil and Gas Producers (IOGP)** represents the global upstream oil and gas exploration and production industry. The Geodesy Subcommittee of IOGP's Geomatics Committee maintains

the **EPSG Geodetic Parameter Dataset**. In coordination with IMCA (see below), IOGP has issued the *Guidelines for GNSS positioning in the oil & gas industry* [RD12].

- **The International Marine Contractors Association (IMCA)** is an international trade association representing companies and organisations engaged in delivering offshore, marine and underwater solutions, aiming to improve performance in the marine contracting industry by championing better regulation and enhancing operational integrity;
- **The International Hydrographic Organisation (IHO)** is a global hydrographic body which aims to ensure that all the world's seas, oceans and navigable waters are surveyed and charted, to advance maritime safety and efficiency and to support the protection and sustainable use of the marine environment. The IHO publishes standards and specifications, including for hydrographic surveys (e.g. S-44).

EUROPEAN

- **The Council of European Geodetic Surveyors (CLGE)**, similarly to the FIG, represents the geodetic surveying profession at the European level. CLGE includes a number of Interest Groups, one of which (IG-PARLS - Publicly Appointed and Regulated Liberal Surveyors) emerged from the former "Geometer Europas" and represents the interests of liberal surveyors within CLGE, who are entrusted with public missions in the field of property guarantee by their country of origin;
- **The European Group of Surveyors (EGoS)** represents non-geodetic European surveying professionals in particular.

EUROGI is the European umbrella organisation for Geographic Information. It represents the needs of all organisations in Europe who use such information. It aims to promote the compatibility, sharing and re-use of, and improve access to, geo-spatial data, to promote the development of innovative geo-spatial services, build relevant technological, political, and human capacity and contribute to the development of worldwide spatial data infrastructures. These organisations maintain a direct link with surveying, geodetic and cartographic professionals and provide a platform for their collective concerns. They also maintain reference systems and standards (see Section 5.8.4), publish guidelines and best practises, and thereby stand to serve as a source of "bottom-up" user requirements for technologies which have an impact on the fundamental activities of the profession, such as GNSS. For example, the FIG is attempting to incorporate the use of GNSS in surveying as a starting point for land administration and cadastral registration, especially in developing countries (see [RD9]).

4.3.2 LICENSING AND ACCREDITATION BODIES

Surveying as a profession has a long history, and in many countries is still governed by royal charter or decree. Publicly appointed and regulated surveyors act on behalf of the competent public authority in determining the boundaries of property, thus giving them a legally binding status. Real estate cadastre is an area subject to government control and legislation, and cadastral surveyors are required to work within the laws of particular jurisdictions relating to professional standards and competency, and within the profession's own code of conduct. Surveying (particularly cadastral surveying, being related to property rights and legal land ownership) is therefore generally considered a liability-critical profession. Against this background, there are a number of organisations and associations which provide professional accreditation to surveyors in the various sectors within the profession:

- **The Chartered Institution of Civil Engineering Surveyors (ICES)** is an international qualifying body dedicated to the regulation, education and training of civil engineering surveyors;
- **The Royal Institution of Chartered Surveyors (RICS)** is a global professional accreditation and standards body for surveyors in the land, property and construction sectors. RICS regulates and promotes the profession, maintains the educational and professional standards, protects clients and consumers via a strict code of ethics, and provides impartial advice and guidance to its qualified professionals. It maintains a list of accreditation bodies in countries across the world. RICS has issued comprehensive guidelines on the use of GNSS in surveying and mapping (see [RD3]).

SEVERAL COMPANIES ARE COMPETING, OR IN SOME CASES COOPERATING, IN THE COMMERCIAL AUGMENTATION PROVIDERS' ARENA.

By upholding and promoting standards and principles of professional conduct and good practice within the sector, these organisations are also well-placed to serve as a source of user requirements for emerging technologies, particularly where these technologies can support or improve the accuracy, reliability and trustworthiness of the surveyor's output, and therefore its credibility for use in legal proceedings or matters of public interest. Galileo's authentication feature, for example, is highly relevant to the work of the surveyor for this reason.

05 GNSS USER REQUIREMENTS ANALYSIS

5.1 GNSS USE IN SURVEYING

5.1.1 GNSS USER LEVEL CRITERIA

The performance of GNSS may be evaluated/perceived according to several criteria. **Each criterion** may include **several performance parameters** or non-measurable parameters. Only those criteria and performance parameters that are relevant for the analysis of Surveying user requirements have been retained, i.e. **accuracy**, **service area**, **availability, integrity, robustness, relevance of the surveying method, time to first accurate fix (TTFAF), and size, weight and autonomy.** The proportion of GNSS usage in each application category has also been assessed in this analysis.

Accuracy is given in terms of horizontal and vertical position accuracy, however timing accuracy is not considered in this report. **Service area** is defined in terms of geographical coverage. **Availability** covers both physical environmental conditions such as urban canyon and canopy (natural obstruction caused by a layer of branches of trees), and the time required to make a first accurate fix (**TTFAF**) and the fix update type. **Resilience, or robustness**, covers susceptibility to environmental conditions as well as susceptibility to interference and susceptibility to spoofing. **Integrity** provides the user with a probability that the position provided is (or is not) correct and it also provides the time required before an incorrect position can be determined and signalled to the user. **Power consumption** is not strictly a GNSS performance parameter, and it is also relevant in this analysis only for the hand-held devices such as for GIS as GNSS is considered one of the heaviest drain on batteries.

The description of each criterion and its performance level is described in the Table 1.

Table 1: List of criteria / performances relevant to user

Criterion	Description	Performance Level	
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	Horizontal	mm-level
			cm-level
			dm-level
			m-level
		Vertical	mm-level
			cm-level
			dm-level
			m-level
Availability	Availability: the percentage of time the position, navigation or timing solution can be computed by the user. Values vary greatly according to the specific application and services used, but typically range from 95-99.9%. There are two classes of availability: System: the percentage of time the system allows the user to compute a position – this is what GNSS Interface Control Documents (ICDs) refer to Overall: takes into account the receiver performance and the user's environment (for example if they are subject to shadowing).	Urban Canyon Canopy	Yes/No
		Better than 95%	Low
			Medium
			High
		Better than 99%	Low
			Medium
			High

Criterion	Description	Performance Level
Robustness	Robustness is a qualitative, rather than quantitative, parameter that depends on the type of attack or interference the receiver is capable of mitigating. It can include authentication information to ensure users that the signal comes from a valid source (enabling sensitive applications). Note: 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 or spoofing.	Low Medium High
Integrity and reliability	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.	Low Medium High
Size, weight, autonomy	Power consumption and size are not strictly a GNSS performance parameters, however they are also considered in this analysis, especially for GIS and Mapping. Most GIS devices are handheld or rugged tablets/phones, which implies that they must remain small and lightweight and GNSS is considered one of the heaviest drain on smartphones batteries.	Relevance: Yes/No The length of time a device can run: >1h >5h a few days
TTFaF	A measure of a receiver's/solution's performance covering the time between activation and output of a position within the required accuracy bounds.	few seconds a few min >20min
Coverage service Area	Service area is defined in terms of geographical coverage.	Global Regional Local
GNSS contribution to the PNT solution	Level of the GNSS contribution to the final PNT solution	Low/Medium/High

5.1.2 OVERVIEW OF SURVEYING APPLICATIONS

The Surveying applications considered in this analysis are consistent with GSA Market Report 5 [RD1] having been further completed with additional specific applications (listed in the last in column in random order) collected from complementary sources **[RD3], [RD4], [RD9], [RD10], [RD11], [RD12], [RD15], [RD20].**

Table 2: Surveying applications and definitions

Surveying Application categories	Application	Application description	Specific Application
Land Surveying	Cadastral Surveying and Geodesy	**Cadastral surveying** is the sub-field of land surveying that involves the determination of the legal boundaries of land properties. Thus, in order to establish or re-establish the property boundaries, land surveyors proceed with the three steps, i.e. research, field operations and (legal) drafting. Once the appropriate evidence found in land deeds, cadastral registers, recorded past surveys, subdivision plats, topographic maps, etc. has been analysed, the surveyors set out into the field to gather horizontal (and potentially vertical) data of physical objects on the property in question and those adjacent to it, for comparison to the research (historic) data. Geodesy is the earth science of accurately measuring and understanding three of Earth's fundamental properties: its geometric shape, orientation in space, and gravitational field. The field also studies of how these properties change over time. Geodynamical phenomena include crustal motion, tides, and polar motion, which can be studied by designing global and national control networks, applying space and terrestrial techniques, and relying on datums and coordinate systems.	National/international networks and reference frame survey
			Geodetic surveys
			High-order control surveys
			Low-order control surveys
			DGNSS or RTK reference station positioning
			High-order detail surveys and positioning
			Cadastral surveys
			Land seismic, dimensional control and source positioning
			Land Survey, real time topographic detailing and profiling
			Low-order detail surveys and positioning
			Temporary DGNSS reference for monitor station positioning
	Construction Surveying	Construction surveying involves the staking out of reference points and markers that will guide the execution of the construction project (e.g. road, buildings, etc.). This includes establishing basic lines, grade control and principal points, positioning for corners, delineating the working areas, determining ground profiles and the placement of utilities, and preparing large-scale topographic maps for drainage and site design. Staking also serves as a base for verification of location and quantities of completed work. GNSS-RTK solutions are the preferred solution for several construction activities (e.g., road construction, topographic measurements and surveying of the construction sites, etc.) as they allow for significant cost savings, whilst maintain the desirable level of accuracy in the horizontal dimension. GNSS machine control refers to the control and semi-automatic guidance of vehicles; in the case of construction sites this entails mainly earth-moving machines, i.e. dozers, diggers, graders. Using RTK corrections machine operations can be undertaken at centimetre level accuracy, with increased productivity (fewer passes needed to achieve grade specifications) and at significantly less cost (reduced labour, fuel and maintenance).	Setting-out/staking, alignment, trajectory, Machine control
			Vehicle tracking and asset management
			Asset positioning at 3m level
			Low order control survey
			High-order control survey
			Temporary DGNSS reference for monitor station positioning

Surveying Application categories	Application	Application description	Specific Application
Land Surveying	Mapping/GIS	Whether, scanning paper maps and survey plans, or processing information captured through photogrammetry, remote sensing or GNSS-enabled field-work, GIS technologies enable the digitisation and visualisation of spatial and attribute data. Indeed, by combining different layers of raster images or vector data, GIS applications generate different types of maps (e.g. thematic, contour, change, etc.) carrying a wealth of information. In recent years, GNSS has been increasingly used in combination with and in support of GIS solutions.	Photogrammetry/remote sensing high-order ground control
			Photogrammetry, photo control points
			High-order topographical profiles
			Automated mapping/facilities management (AM/FM); utilities mapping
			Update of special database, digital mapping
			GIS, assets positioning and attribute collection
			GIS - high-precision asset positioning and attribute collection
			Topographic mapping
			Photogrammetry camera positioning and photo control
	Mining	This discipline includes all measurements, calculations and mapping which serve the purpose of ascertaining and documenting information at all stages from prospecting to exploitation and utilizing mineral deposits both by surface and underground working. Both static and dynamic GNSS-based solutions are used for exploration and mine site surveying; for autonomous mining and operations control; for remote control of machines (incl. haul trucks and drillers); for environmental surveying; and for material tracking and loading. Whilst most applications in the mining sector require accuracies at decimetre level, more stringent accuracy demands are found in mine site surveying and mine machinery guidance (especially when autonomous).	Slope stability, volumetric surveys
			Machine Control
			Vehicle tracking and asset management
Marine Surveying	Marine cadastre	Marine cadastre is thus defined as a system enabling the boundaries of maritime rights and interests to be recorded, spatially managed and physically defined in relationship to the boundaries of other neighbouring or underlying rights and interest. However, contrary to land cadastre where the position of boundaries can be determined by prior evidence or by physical monuments, maritime boundaries exist as virtual objects without visible or tangible demarcation. Thus, to establish the location of the boundaries GNSS-based solutions must be dep loyed. Differential GNSS methods are typically used to determine maritime boundaries.	

Surveying Application categories	Application	Application description	Specific Application
Marine Surveying	Hydrographic Survey	Hydrographic surveying entails a number of activities ranging from reconnaissance (e.g. when designing a construction project) to payment of underwater work (e.g. dredging or reclamation). In essence, hydrographic surveying is concerned with the accurate measurement of water depth below a stated datum and the exact position of this measured depth. The collected information is normally projected onto a bathymetric contour map, which presents the sea bed in a way that allows the identification of areas of equal depth (isobaths). Hydrographic surveying is also concerned with the determination of the sea bottom type and the positioning of "intertidal" and shoreline features above a stated datum.	Real-time tidal monitoring
			Vessel positioning
			Hydrographic survey and vessel navigation
	Off-shore Survey	During off-shore surveying and exploration activities, GNSS is typically used for the determination of the positions and heights of the survey equipment and the sensors used to record the survey data (e.g. seismic source and receiver locations in seismic surveys, BES on bathymetric surveys). It is also used to determine the positions of certain points of interest such as the drill centre position (during a rig move).	Off-shore exploration

The section 5.2 to 5.4.3 gather all available information on GNSS user requirements for each Surveying application listed in Table 2.

5.1.3 INTRODUCTION AND MAIN SURVEYING TECHNIQUES

GNSS-enabled equipment has been an integral component of the surveyors' and mappers' toolbox already since the late 1980s. Today, thanks to significant improvements in receiver technologies, higher availability of signals in the advent of the multi-GNSS era and marked progress in terms of price and usability, GNSS systems are used in a wide variety of surveying and mapping tasks. Several sectors including land surveying (cadastral, construction and mine), mapping and marine surveying (marine cadastre, hydrographic and offshore surveys) benefit from the proliferation of high-accuracy GNSS-based solutions. Multi-constellation and multi-frequency receivers, as well as various differential correction techniques (SBAS, RTK and DGNSS) are currently deployed in the surveying and mapping sector.

In surveying, GNSS is used for the accurate determination of the three-dimensional position of points, the distances between them and the corresponding angles. Two techniques are utilised:

- **Relative positioning** involves the reception of signals from common satellites, recorded simultaneously at two or more survey control stations using high-accuracy GNSS receivers. Real-time or post-fieldwork processing of these measurements enables the derivation of GNSS baselines that are used to estimate the three-dimensional position, the error sources and the uncertainty for each control station. This allows for the atmospheric effects on the propagation of the signal from satellite to receiver, to effectively cancel out (especially if the baseline between receivers is short). Relative positioning can be performed only if there are source control stations with well-known coordinates. These are provided by Continuously Operating Reference Stations (CORS) established nationally or by using data from the International GNSS Service (IGS)[17]; by utilising commercial or public DGNSS/RTK networks or if none of the above is available, by establishing a DGNSS/RTK reference station for a given project.

2019 update

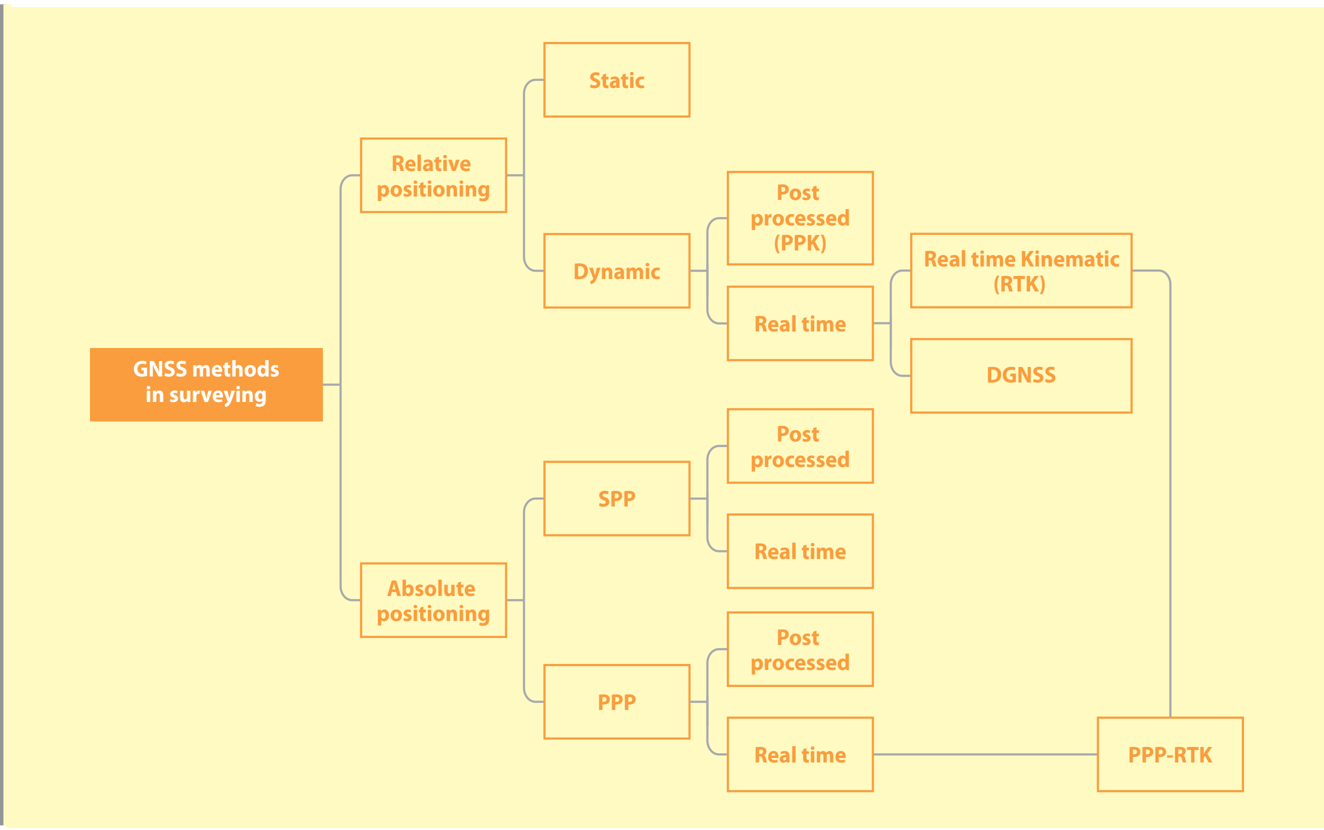
- **Absolute positioning** is the standard method used for standalone GNSS receivers and does not require the existence of a control station with known location. Instead, it involves processing the data from a single receiver for the determination of the three-dimensional Cartesian coordinates in respective reference frame.

2019 update

17 http://igs.org/network

Table 3: Overview of different GNSS techniques deployed in surveying (source: [RD2])

2019 update



Both methods involve the collection of precise code measurements, often coupled with precise carrier phase measurements for activities with high accuracy requirements. Different variations of these techniques have been developed in the context of surveying that can be classified according to the type of operations performed (i.e. **static** or **dynamic)** and the time for data processing (i.e. **real time** or **post-processed**). In all cases, the key to achieving higher accuracy is to mitigate the effects from several error sources ranging from ephemeris and clock parameters to atmospheric delays, multipath and operating environment (incl. errors by the surveyor). This involves the utilisation of different technologies that require different equipment, rely on different configurations and ambiguity resolution processes, and subsequently offer different levels of accuracy.

2019 update

A schematic overview of the different methods deployed in surveying is provided in Table 3, followed by some additional details on the most relevant methods.

Static surveying has been the original method used by surveyors in the field and still remains the most widely used, especially when high-accuracy is required. In this case, two or more receivers (and antennas) remain stationary during the observation time; the period for which the rover receiver remains stationary is referred to as occupation. The longer the occupation, the better the systematic errors are resolved and the better the positional accuracy achieved. Typical occupation times range from 10 minutes to 6 hours. Shorter times for the effective elimination of ionospheric errors are achieved by using double frequency receivers (e.g. L1/L2), whereas greater accuracy is supported by the use of carrier-phase techniques. Provided that certain conditions apply[18], surveyors can perform **rapid static surveying** which can achieve good - but lower compared to classical static surveying - accuracies in shorter timeframes. In both cases the logged survey data are post-processed (often to include actual ephemeris).

Dynamic surveys achieve the highest rate of coordinate generation at the cost of lower accuracy (compared to static). Different dynamic survey methods (e.g. **kinematic, on-the-fly**) entail one receiver remaining fixed at a known location (base) whilst the rover (or rovers) move around on the site observing the same set of satellites. The main difference between kinematic and on-the-fly methods lies in the tolerance or lack thereof of periodic lock of the satellites' signal; in kinematic both receivers must initialise on a known baseline and then maintain the lock to at least 4 satellites throughout the survey session; this is not necessary for on-the-fly where

18 Dual frequency data are used, sophisticated algorithms for the computation of the baselines are available, good satellite geometry, no multipath and interference, baselines limited to 40 km

integer ambiguity is resolved whilst the rover moves between points. Dynamic surveys can be post-processed or carried out in real time. The latter is ensured via a suitable communication link between the base station and the rover; this is typically the case for RTK or DGNSS techniques. Nowadays several vendors (both public and commercial) enable access to RTK or DGNSS networks, making this type of surveying one of the most widespread solutions.

REAL TIME KINEMATIC (RTK)

Real Time Kinematic solutions enable highly-accurate, highly-repeatable positioning in the vicinity (typically up to 40km) of a base station receiver placed on a - ideally immobile - mount. The main principle behind RTK services relies on the assumption that positioning errors (due for example to clock bias, atmospheric delays, satellite orbital errors, etc.) computed at the base station under local field conditions, are the same as those occurring for the mobile receiver (rover). RTK utilises a real-time communication channel (usually short-range radio) to transmit the corrections from the base station, whose location is well known, to the rover thus eliminating the errors that typically tamper standalone positioning. The base station broadcasts its well-known location together with the code and carrier measurements in two frequencies (e.g. L1/L2)[19] for all in-view satellites. This information allows the rover equipment to fix the phase ambiguities and determine its location relative to the base with precision up to 2 cm. By adding up the location of the base, the rover is positioned in a global coordinate framework.

The corrections are as accurate as the known location of the base station and the quality of the base station's satellite observations. Also important is the operating environment (to minimise environmental effects such as interference and multipath) and the quality of the receivers (rover and base station). In addition, the actual accuracy achieved at the rover receiver is a function of its distance from the base station. To alleviate this limitation, networks of several widely spaced base stations have been deployed, especially in countries of more advanced maturity. In fact, RTK networks are the preferred option in industrialised countries, where commercial and public initiatives have been long established. The network RTK corrections are distributed via internet which can limit the usage of the service in areas with connectivity white spots (mostly rural and mountain areas).

PRECISE POINT POSITIONING (PPP)

Unlike RTK, Precise Point Positioning (PPP), employs readily available satellite orbit and clock correction data, generated from a network of global reference stations, to perform absolute positioning using measurements from a single GNSS receiver. The corrections are delivered to the end user via geostationary satellite(s) or over the internet ensuring worldwide coverage. PPP can achieve decimetre-level accuracy without the need for a base station in the proximity. This comes however at a price; PPP requires a rather long time (15-30 min) resolving any local biases such as the atmospheric conditions, multipath environment and satellite geometry, to converge to decimetre-level accuracy. However, a number of solutions are emerging that can mitigate this problem. This includes *inter alia* the exploitation of ionospheric corrections, which under favourable conditions and when combined with regional networks can achieve a convergence to 10-cm horizontal accuracy in a few seconds (see for example Banville 2016). Other solutions entail the utilisation of more powerful computation in chipsets, the use of several constellations and the use of more than two frequencies. The most common and optimized technique in terms of bandwidth for real-time PPP is to send orbits and clock corrections to the navigation message, allowing the reconstruction of the accurate values in the receiver.

PPP-RTK

PPP-RTK solutions constitute an extension to the PPP concept by providing single-receiver users with information enabling integer ambiguity resolution, thereby reducing convergence times as compared to that of standard PPP. Thus, alongside the precise satellite clocks, orbits and phase bias, PPP-RTK makes use of local/regional/national RTK networks to provide users with ionospheric and tropospheric delay corrections, allowing them to perform integer resolution of ambiguities and achieve centimeter-level accuracy in significantly reduced time. This is typically in the range of 1-10 minutes, but in certain configurations it can even be done within seconds[20]. An additional advantage as compared to RTK-only, is that of sending fully computed corrections to the "rover" and eliminating certain local errors that appear on the local reference stations (e.g. multipath). Several PPP-RTK solutions[21] are currently under deployment building on different methods[22], thus underlining the market potential for this approach. However, PPP-RTK method diminish the main advantage of standalone PPP namely that there is no need to deploy the highly-dense network of GNSS base stations.

DGNSS

Differential-GNSS services encompass techniques used to enhance accuracy, reliability and availability of GNSS information through a network of ground-based reference

19 Note that some RTK providers already deploy L1/L5 solutions.
20 See for example Wübbena 2016
21 See for example Odijk 2016 for the case of Australia.
22 For a review see for example Teunissen 2014.

stations. As with RTK, which is essentially an advanced DGNSS solution based on the use of carrier measurements, the corrections calculated at a reference station of known-location are transmitted via communication channels to the users. DGNSS technology has been developed and deployed worldwide and is able to support multiple GNSS systems such as GPS, GLONASS and Galileo. Commercial DGNSS solutions are widely available and provided by several vendors including OmniSTAR, VERIPOS, etc.

However, with SBAS-solutions becoming more widely available, RTK fees decreasing and PPP solutions emerging the future of DGNSS seems cloudy.

SBAS

For applications where the cost of a differential GNSS system is not justified, or if the rover stations are spread over too large an area, a Satellite Based Augmentation System (SBAS) such as the European Geostationary Navigation Overlay Service (EGNOS) may be more appropriate for enhancing position accuracy. SBAS improves the accuracy and reliability of information by correcting signal measurement errors and by providing information about the accuracy, integrity, continuity and availability of its signals.

SBAS uses GNSS measurements taken by accurately located reference stations deployed across an entire continent. All measured GNSS errors are transferred to a central computing centre, where differential corrections and integrity messages are calculated. These calculations are then broadcasted over the covered area using geostationary satellites that serve as an augmentation, or overlay, to the original GNSS message.

Existing SBAS

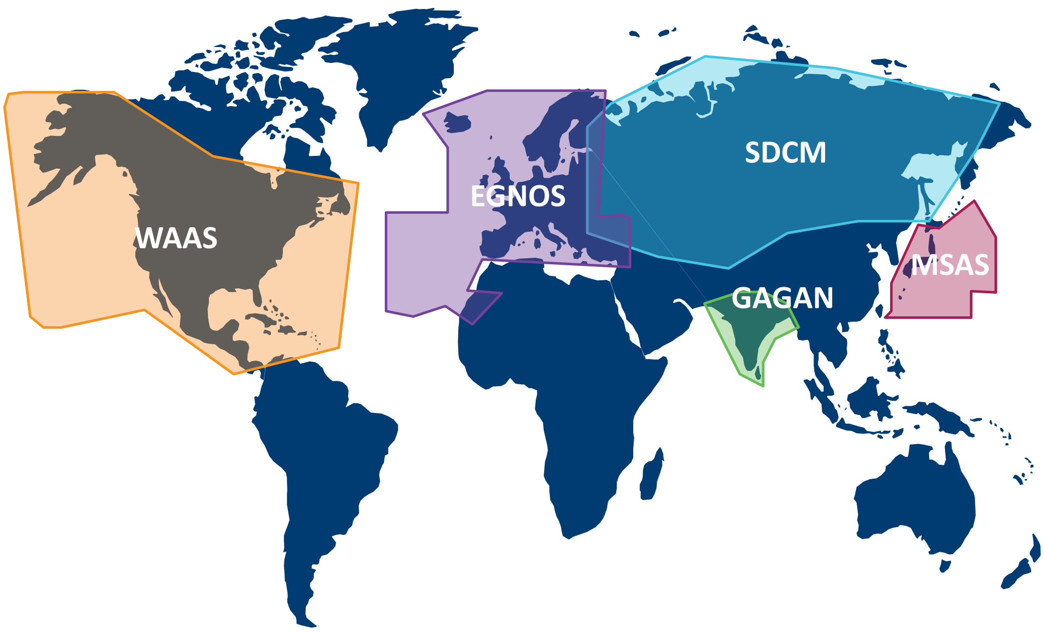
Several countries have implemented their own Satellite-based Augmentation System. For example, in Europe EGNOS covers the majority of the European Union (EU), along with some neighbouring countries and regions. Other national SBASs include:

- USA: Wide Area Augmentation System (WAAS)
- Japan: Multi-functional Satellite Augmentation System (MSAS) and Quasi-Zenith Satellite System (QZSS)[23]
- India: GPS and GEO Augmented Navigation (GAGAN)
- China: Satellite Navigation Augmentation System (SNAS) (In development)
- Korea: KASS (In development)
- Russia: System for Differential Corrections and Monitoring (SDCM)
- South America: SACCSA (Feasibility Study)
- Australia and New Zealand: Australasian SBAS (in development)[24]

2019 update

All of these systems comply with a common global standard and are therefore:

- Compatible: they do not interfere with each other;
- Interoperable: a user with a standard receiver can benefit from the same level of service and performance, regardless of what coverage area they are located in.



23 QZSS started initial operations in November 2018. The SBAS signal that is made by MSAS is planned to be transmitted from QZSS on a GEO using the QZSS SBAS transmission service from around 2020.

24 https://www.linz.govt.nz/data/geodetic-services/australasian-sbas-trial

In Europe today EGNOS is increasingly used for GNSS-based real time mapping solutions by providing free accuracy over Europe for applications where meter accuracy is adequate. Typical examples include GIS and thematic mapping for small and medium municipalities, forestry and park management as well as surveying of utility infrastructures. Most of GNSS receivers used for mapping are now EGNOS ready and the EGNOS signal is free of charge.

STANDALONE / UNCORRECTED GNSS

The dawn of the multi-constellation era, coupled with advancements in GNSS signal structure and the increased availability of multi-frequency options, contributes in increased accuracy and availability of GNSS signals worldwide. More specifically, surveying actors demanding high-accuracy solutions will continue to benefit by the emergence of cost-effective and mass-market multi-frequency receivers. This trend is well exemplified by the upcoming grant for the development of multi-frequency, multi-purpose antennas for Galileo under the EUSPA's Fundamental Elements Programme (FE). Similarly expected R&D in high-end receivers' core advancements and CS User Terminals under FE should yield promise for high-accuracy professional applications, too.

SURVEYING ACTORS DEMANDING HIGH-ACCURACY SOLUTIONS WILL CONTINUE TO BENEFIT BY THE EMERGENCE OF COST-EFFECTIVE AND MASS-MARKET MULTI-FREQUENCY RECEIVERS.

RELATIVE ADVANTAGES BETWEEN STATIC AND DYNAMIC METHODS

The advantages of (real-time) dynamic surveys over static ones include the speed of data collection, the assurance of reliable data in real-time (when using RTK) and the enabling of specific cases of surveying (aerial and hydrographic) where there are mobile targets involved. On the other hand, dynamic surveys are less applicable in urban environments due to the need for better satellite visibility, and tend to be less accurate due to the lack of redundancy in the determination of positions. Depending on the different technology/ technique deployed, the positional accuracy ranges from metre to sub-centimetre levels. In terms of ease of use, static surveys are the most labour, equipment and skills intensive, whereas PPP solutions are the easiest to deploy. Finally, and as a general rule, real-time techniques are simpler to perform compared to the post-processed ones.

Overall, the advantages of using GNSS in surveying include **technical aspects** (e.g. production of 3D surveys in a common reference system, rapid data processing with quality control, high-precision), **operational aspects** (e.g. weather independent, no need for site inter-visibility, day/night operation) and **economic aspects** (e.g. less labour intensive, less skill-demanding, cost-effective). However, it is important to note that in most cases GNSS is used in combination with and adding value to other technologies (e.g. optical instruments, laser scanners, LIDAR, total stations, etc.).

Taking this into account, the following sections will provide a brief overview of the various GNSS-enabled or supported (i.e. combined with other technologies) applications across different surveying and mapping sectors. This will be followed by an analysis of the regulatory framework that strongly influences performance requirements, and a description of the technological trends driven by user requirements but also shaping the evolution thereof.

5.1.4. REAL-TIME DATA TRANSMISSION FORMATS

2019 update

Two major approaches for generation of real-time GNSS corrections are available: observation-state representation (OSR) and space-state representation (SSR)[25]. The OSR is typically used in real-time relative positioning and provides station-related information, as well as geometric and ionospheric correction data in distinct or combined messages. It is the basis of the single or network-based RTK method. The SSR approach, which is the basis of the PPP method, rather than providing combined corrections in observation space, employs decomposed corrections to remove individual GNSS error sources. Both approaches are utilized for real-time data transmission via either open or proprietary protocols.

OPEN PROTOCOLS

2019 update

Network-based RTK corrections utilize the observation-state approach via the RTCM SC-104 standard, which offers a harmonized framework for transmitting such corrections to the user independent of the underlying network architecture[26]. Since RTCM version 3.1 it supports observation and correction data for Galileo, and since version 3.2 - for BeiDou. In addition to network RTK, the RTCM standard provides specific messages, dedicated for PPP correction data. A future adoption of the RTCM format by the Galileo HAS is expected to have a positive impact on the whole value chain of the surveying and mapping segment.

25 http://www.geopp.de/technology/state-space-representation/
26 https://link.springer.com/content/pdf/bbm%3A978-3-319-42928-1%2F1.pdf

PROPRIETARY PROTOCOLS

2019 update

Specific class of network-RTK messages comprises the Network-RTK Residual Error messages. These are used to implement concepts such as VRS (virtual base stations) or MAC (Master-auxiliary concept), which improve the RTK service for specific users via proprietary patented techniques. On the other hand, the state-space representation (SSR) represents a new concept for the provision of correction data in real-time kinematic precise point positioning (PPP-RTK) applications[27]. Currently several CORS networks in France, Germany, Japan and elsewhere offer users with proprietary PPP-RTK services.

Table 4. Comparison of common representation techniques[28]

2019 update

	OSR Observation State Representation				SSR Space State Representation		
	RTK	Network RTK			Phase-based PPP	Code-based PPP	PPP-RTK
	RS	VRS	MAC	VRS/PRS			
Service classification[(1)]	OSR-CS2	OSR-CS2			SSR-CQ2	SSR-DS1	SSR-CS2
Broadcast possible	√	√	√	X	√	√	√
Accuracy	~ cm	~ cm	~ cm	~ cm	< 3 dm	~ 3 dm	< cm
Time required	< 5 s	< 5 s	< 5 s	< 5 s	~ 20 min	< 1 s	< 5 s – 1 min[(3)]
Service area	local	regional			global	global/ regional	global/ regional
Single frequency	X	X	X	X	X	√	X
Required bandwidth	medium	medium	high	medium	low	low	low-medium

(1) CQ2 – Centimeter accuracy in ¼ hours using 2 frequencies
DS1 – Decimeter accuracy in seconds using 1 frequency
CS2 – Centimeter accuracy in seconds using 2 frequencies

(2) no multipath

(3) depends on update rate

27 http://www.geopp.de/technology/state-space-representation/
28 http://www.geopp.de/wp-content/uploads/SSR_Flyer_v3_S2.jpg

5.2 LAND SURVEYING APPLICATIONS

Land surveying is the discipline concerned with the precise measurement and mapping of terrestrial or three-dimensional positions of points and the distances and angles between them. Utilising a range of technologies enabling such precise measurements and data gathering on the field, land surveyors support a wide range of activities from the planning and design of land subdivisions through to the final construction of roads, utilities and landscaping. The methods deployed for different surveying tasks take into account a host of parameters including accuracy and quality requirements, availability of control, equipment constraints, personnel and logistic limitations and, of course, costs.

Land surveyors set out to determine the boundaries of land parcels, draw the work sites for future buildings or produce 3D topographical area models, through a three-stage process that includes research (going through land deeds and topographical maps), field operations (gathering horizontal and vertical data, establishing control marks and monuments) and drafting (drawing property boundaries and features, writing a legal description). GNSS is used to perform three different types of field operations. More specifically it is used to **(i)** form the coordinate framework of a project (**control surveys**) and **(ii)** to accurately map points and features within the confines of the control survey (**detail surveys**). In addition, **(iii)** simple **GNSS positioning** can be used to survey features at metre level for inputs into a computer-aided drawing package or in GIS tools.

> CONTROL SURVEYS REQUIRE SUB-CENTIMETRE ACCURACY ACHIEVED THROUGH SEVERAL REDUNDANT OBSERVATIONS.

The most demanding of those three types in terms of accuracy are control surveys; they require sub-centimetre accuracy achieved through several redundant observations deploying dual-frequency static (for lines of less than 100km) methods. **High- and low-order control surveys**, follow a number of best practices to achieve the required accuracy levels. These are related to the number of independent sessions performed, the number of control points established, the configuration of the antennas, the duration of the sessions, etc. A detailed account is provided in [RD3] (see p.51).

Conventional surveying essentially involves **(i)** the establishment or use of control points, **(ii)** the traverse from one control point to the next, **(iii)** tying physical objects together and "monumenting" of natural/artificial objects and corners. Once a traverse around the property has been drawn the surveyor is able to clearly mark the boundary lines. In this context, GNSS is used to complement and enhance conventional methods, offering significant advantages especially under specific conditions (i.e. good satellite view and operating environment). Thus, contrary to conventional surveying methods that rely on establishing a traverse around the property, GNSS surveying involves putting the GNSS vectors into strong interlocking networks that allow multiple measurements to each of the surveyed points. This enables the identification of vectors that contain significant errors. In the absence of such significant errors, the residual random errors are adjusted using the least-square method, allowing to attain the most accurate positions possible (static surveying). Therefore, a well-designed network is considered critical when performing a GNSS survey, as it enables redundancy in the measurements. There are different ways of designing strong networks[29] - or tapping into existing ones - but the bottom-line remains the same: **accuracy in GNSS surveys is achieved through redundancy of the measurements,** ensured by strong networks (i.e. good geometry), through longer occupation of control points (and re-occupation), or via the use of multi-frequency/multi-constellation receivers.

More details on GNSS surveying applications across three sectors (cadastral, construction and mine) are provided in the next sections.

5.2.1 CADASTRAL SURVEYING AND GEODESY

Cadastral surveying is the sub-field of land surveying that involves the determination of the legal boundaries of land properties. Thus, in order to establish or re-establish the property boundaries, land surveyors proceed with the three steps described previously, i.e. research, field operations and (legal) drafting. Once the appropriate evidence found in land deeds, cadastral registers, recorded past surveys, subdivision plats, topographic maps, etc. has been analysed, the surveyors set out into the field to gather horizontal (and potentially vertical) data of physical objects on the property in question and those adjacent to it, for comparison to the research (historic) data.

This step involves the utilisation of different technological solutions allowing for the desired accuracy and confidence, amongst which GNSS holds a predominant position. In fact, it is estimated that **surveyors are "dependent" on GNSS equipment** for field work[30][31] (including augmentation systems and associated technological innovations), and that private companies and public administrations engaged in cadastral surveying would suffer by unavailability of [GNSS] signals. Even more, the key role of GNSS in cadastral surveying is driving the growth of GNSS devices in the overall surveying sector. According to the recent (2017) GSA GNSS Market Report [RD1] **GNSS surveying equipment for cadastral applications is expected to account for around half of the 500,000 shipments per annum by 2023**.

Classically geodesy[32] is defined as the science concerned with the shape, size, and the gravity field of the Earth. However, geodesy today goes beyond that, being the geoscience that deals with:

- monitoring the solid Earth (displacement, subsidence or deformation of the ground and structures due to tectonic, volcanic and other natural phenomena as well as human activity);
- monitoring variations in the liquid Earth (sea-level rise, ice sheets, mesoscale surface topography features, mass transport);
- monitoring variations in the Earth's rotation (polar motion, the length of the day);
- monitoring the atmosphere with satellite geodetic techniques (ionosphere and troposphere composition and physical state);
- monitoring the temporal variations in the Earth's gravity field;
- determining satellite orbits (including Earth observation and navigation satellites);
- determining positions - and their changes with time - of points on or above the surface of the Earth with the utmost accuracy.

Regardless of the specific GNSS surveying technique (i.e. static, rapid static, dynamic, RTK, etc.) a number of best practices have been developed to allow for the unfolding of the fully-fledged advantages of using GNSS in cadastral surveying **and** to ensure compliance with national legislation. While a more detailed overview will be provided in section 8.2, some key points are summarised below:

- **Dual frequency receivers** use is highly recommended given that it allows better and faster ambiguity resolution
- **Control surveys** should be carried out using static or rapid static (even if RTK can achieve same accuracy under ideal conditions), whereas dynamic techniques allowing maximum productivity for rapid pick up of points are recommended for **detail surveys**
- A **minimum of three horizontal and four vertical control points** ensures the needed redundancy
- **At least two independent observations (baselines)** should be carried out

29 Guidelines on network design are provided in essentially every GNSS Guideline document - see for example RD3
30 "GNSS and real-time network: The surveyor's best friend", GPS World, May 2016 (link to online article)
31 "The day GPS went away", GPS world, September 2017 (link to online article)
32 "What is Geodesy", GIM, (https://www.gim-international.com/content/article/what-is-geodesy).

- The **position of control points** is critical; ensuring a good view of the sky and no obstructions above 15° elevation.
- **Satellite number and geometry:** The multi-constellation era ensures adequate number of satellites in view but Geometric Dilution of Precision (GDOP) predictions are encouraged especially for real-time kinematic surveys.
- **Operating environment:** Minimising multipath effects as well as avoiding placing the control points near cell towers, radio stations, under tree canopy, etc.
- **Independent elevation measurements**, that is either independent antenna height checks and/or use of other technologies is needed to achieve required vertical accuracy with confidence

Even when these guidelines are followed there are limitations in the use of GNSS in cadastral surveying (see also section 5.6). This applies specifically in dense urban areas but also for baseline measurements under 100m, where the use of GNSS is not accepted[33]. However, advances in the availability of signals and frequencies, as well the performance of GNSS receivers may well enable the alleviation or partial tackling of such limitations in the foreseeable future. Galileo is expected to have strong added value in that direction, thanks to its signal strength and bandwidth, and owing to the new emerging services (i.e. Galileo High Accuracy Services). Especially the authentication feature of Galileo High Accuracy Service may prove to fill a gap in surveying; currently no generally accepted technology exists able to authenticate the position of the surveyor.

The main GNSS user requirements are: [RD3] [RD4] [RD29] [RD30] [RD31] [RD32] [RD33] [RD34]

- Accuracy
  - Horizontal: mm- to cm-level mostly, depending on country and cadastral application
  - Vertical: cm- to m-level depending on country and cadastral application
- Availability
  - Availability in urban canyons, under canopy:
    - Better than 95%: mostly medium to high
    - Better than 99%: mostly low to medium; high required by cadastral survey, land survey and real-time topographic
- Robustness
  - Mostly low
- Integrity and reliability
  - Low
- Fixing and convergence time
  - TTFaF: varies from a few seconds to a few min depending on the specific application
- Coverage service area
  - Mostly regional
- GNSS contribution to the PNT solution
  - High

Comparing Table 4 with the performance typically achieved by the different surveying methods in Section 5.5, we conclude that the most of user requirements are currently met by the GNSS-based solutions and therefore the GNSS contribution to all the PNT solutions needed by the all the cadastral applications is "high". However the need of medium to high availability under tree canopy and canyons (urban or natural) is only partially met.

5.2.2 CONSTRUCTION SURVEYING

Construction activities are a key driver for growth especially in emerging markets investing in large infrastructure projects. The increasing availability of more affordable and better performing GNSS-based solutions and especially the proliferation of RTK networks and complementary technologies has provided significant impetus in the growth of the construction sector. GNSS is thus widely used in construction surveying especially for the horizontal accuracy and is increasingly driving the rapid growth of machine control solutions in the construction sector.

Construction surveying involves the staking out of reference points and markers that will guide the execution of the construction project (e.g. road, buildings, etc.). This includes establishing basic lines, grade control and principal points, positioning for corners, delineating the working areas, determining ground profiles and the placement of utilities, and preparing large-scale topographic maps for drainage and site design. Staking also serves as a base for verification of location and quantities of completed work. GNSS-RTK solutions are the preferred solution for several construction activities (e.g., road construction, topographic measurements and surveying of the construction sites, etc.) as they allow for significant cost savings, whilst maintain the desirable level of accuracy in the horizontal dimension. This is due to faster survey times, reduced field expenses in setting out marks, reduced labour cost (often even only one field surveyor suffices for most operations), and optimised use of machines (reduction in wear and tear, fewer errors, less fuel consumption).

One the other hand a number of potential limitations affecting the performance of GNSS-RTK in construction sites must be taken into account. This includes satellite availability due to site obstructions (trees, nearby buildings), multipath errors due to nearby surfaces and positioning latency, i.e.

33 See for example the Surveying and Spatial Information Regulation 2012) on the use of GNSS methods to undertake cadastral surveys in New South Wales (Australia)

the time needed to transmit the reference data to the rover station. The advent of RTK networks[34], including regional or nationwide CORS operated commercially or maintained by institutions, has allowed to mitigate these effects, whilst also alleviating the reference-to-range distance limitations and providing consistent coordinates. In addition, where such networks exist, the costs related to setting up of base stations on the specific construction site are eliminated.

Today, RTK network solutions enable horizontal accuracy of 1-2 cm and vertical accuracy of 2-5 cm, thus giving rise to a number of applications related to construction surveying (excluding those for which vertical accuracy is not enough.). This includes[35]:

- Staking out of road marks, footings, pipelines, utilities, landscapes, fences etc.
- Determining elevation during the installation of utilities (pipelines, cables, power lines, etc.)
- Mapping and site exploration for new projects
- Comparing the "as-built" against the designs

When less than one centimetre horizontal accuracy is necessary, other complementary techniques are synergistically engaged (e.g., sensors, traditional methods, drones).

- At the same time and even if it doesn't fall under the surveying segment *per se*, machine control applications in construction sites have greatly benefited from GNSS solutions. In fact, the recent GSA GNSS Market Report [RD1] has highlighted the role of machine control as a driver for the uptake of GNSS solutions, as reflected by the expected increase in GNSS shipments from 35,000 units in 2013 to 155,000 in 2023. Taking these considerations into account, a short overview of GNSS-enabled machine control applications in construction sites is provided on page 33.

34 A comprehensive overview of RTK Network benefits is provided in *RTK Networks competitive advantage in Machine Control and Site Positioning, Keenan et al (2010)* [RD10]

35 See *Surveying with GPS for Construction Works Using the National RTK Reference Network and Precise Geoid Models, Ahmed El-Mowafy (2014)* [RD9]

Table 5: Main GNSS user requirements of Cadastral surveying

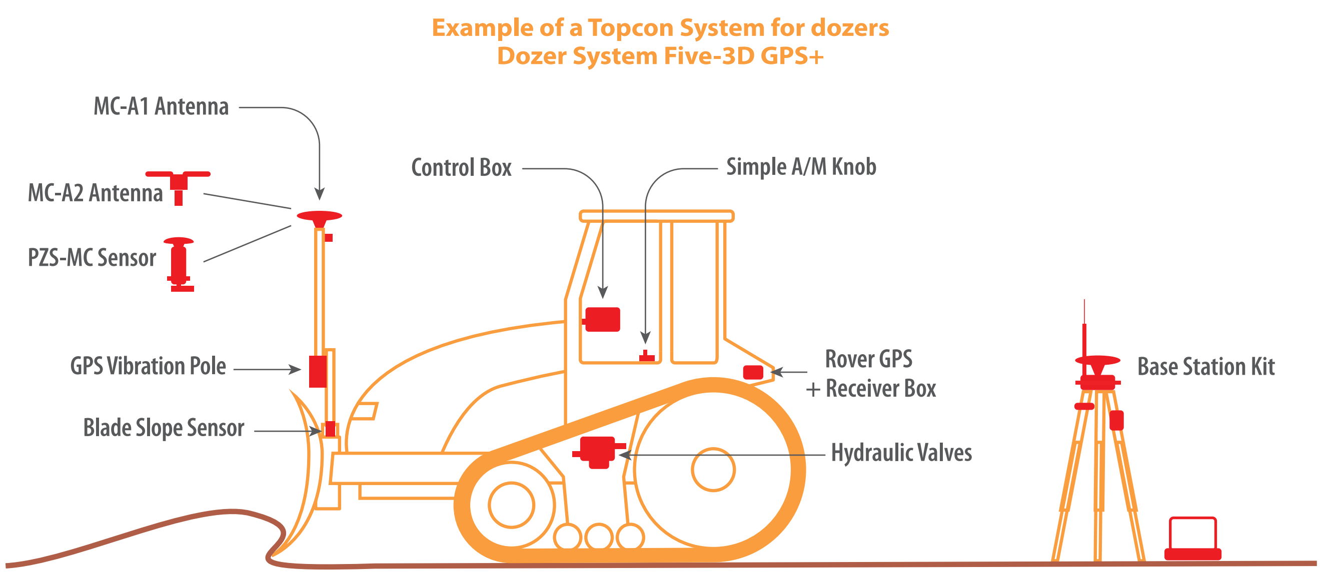
List of Specific Applications in Cadastral Surveying and Geodesy	Accuracy		Availability			Robustness	Integrity and eliability	TTFaF	Coverage service Area	GNSS contribu-tion to the PNT solution
	Horizontal	Vertical	Urban Canyon, Canopy	Better than 95%	Better than 99%					
	mm-level cm-level dm-level m-level	mm-level cm-level dm-level m-level	Yes/No	Low Medium High	Low Medium High	Low Medium High	Low Medium High	a few seconds a few min >20min	Global Regional Local	Low Medium High
National/ international networks and reference frame survey	mm-level	cm-level	No	Medium	Low	Low	Low	>20min	Global	High
Geodetic surveys	mm-level	cm-level	Yes	Medium	Medium	Low	Low	>20min	Regional	High
High-order control surveys	mm-level	cm-level	No	Medium	Low	Low	Low	>20min	Regional	High
Low-order control surveys	cm-level	cm-level	Yes	Medium	Low	Low	Low	>20min	Regional	High
DGNSS or RTK reference station positioning	cm-level	cm-level	No	Medium	Medium	Low	Low	>20min	Regional	High
High-order detail surveys and positioning	cm-level	cm-level	Yes	Medium	Medium	Low	Low	a few seconds	Regional	High
Cadastral surveys	cm-level	N/A[36] or cm-level	Yes	High	High	Medium	Low	a few seconds	Regional	High
Land seismic, dimensional control and source positioning	cm-level	N/A[36] or cm-level	Yes	Medium	Medium	Low	Low	a few min	Regional	High
Land Survey, real time topographic detailing and profiling	cm-level	cm-level	Yes	High	High	Low	Low	a few seconds	Regional	High
Low-order detail surveys and positioning	m-level	m-level	Yes	Medium	Medium	Low	Low	a few seconds	Regional	High
Temporary DGNSS reference for monitor station positioning	m-level	m-level	Yes	Medium	Medium	Low	Low	a few min	Regional	High

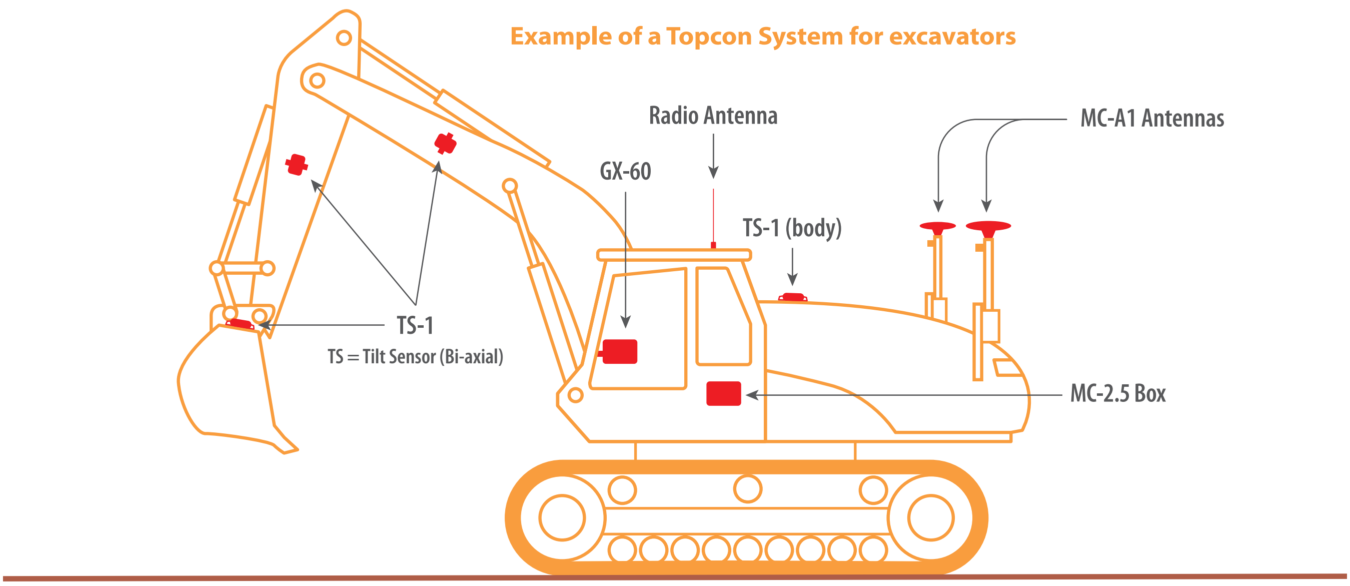
36 The applicability and value of the vertical accuracy required by cadastral surveys depends on each country's legislation.

MACHINE CONTROL

GNSS machine control refers to the control and semi-automatic guidance of vehicles; in the case of construction sites this entails mainly earth-moving machines, i.e. dozers, diggers, graders. Using RTK corrections machine operations can be undertaken at centimetre level accuracy, with increased productivity (fewer passes needed to achieve grade specifications) and at significantly less cost (reduced labour, fuel and maintenance). For example, it is estimated that large-scale projects such as mines, earthworks and transportation may account for up to 50% of total operational costs.

Figure 6: Examples of equipment configuration for machine control [RD11]





GNSS-enabled machine control has two modes: "**indicate**" mode provides visual signs to help the operator in cutting or filling according to the design for the earth-moving project; **"automatic"** mode involves controlling the machine hydraulics to ensure that the blade is always "on grade". In the latter case, accuracy requirements are more stringent and can be typically achieved with an on-site base station. The more advanced systems use two receivers mounted on the machine to allow for its control in a three-dimensional digital design. For example, in dozer or grader type of machines, the first GNSS antenna is installed on the blade interposing vibration damping systems. A second antenna (also on the blade) or slope sensor is used to compute cross slope and orientation of the blade. Other devices such as MEMS and inertial sensors are used to improve the productivity of the system and assist in case of poor satellite visibility. Some illustrative examples are shown in Figure 6.

Apart from boosting the efficiency of machine operators who can control in real-time the execution of the project on their on-board display, **GNSS-enabled telematics solutions enable more efficient construction management**. Thus, by accessing different sets of 3D machine control data coming from the various vehicles on the site, construction managers can better monitor, supervise and coordinate the construction works, identifying bottlenecks, optimising machine utilisation and, eventually, saving costs. Thus, with the increasing spread of GNSS-based machine control systems and the improved integration and visualisation of design and telemetry data the output of construction works is maximised.

The main GNSS user requirements are: [RD3], [RD4], [RD9], [RD10], [RD11], [RD33], [RD34]

- Accuracy
  - Horizontal: mm- to m-level depending on construction application
  - Vertical: mm- to m-level depending on construction application
- Availability
  - Availability in urban canyons, under canopy:
    - Better than 95%: mostly medium, high required by the first application (setting-out/staking, alignment, trajectory, machine control) and second application (vehicle tracking and asset management);
    - Better than 99%: mostly medium; high required by the first application (setting-out/staking, alignment, trajectory, machine control);
- Robustness
  - Mostly low; medium required by the first application (setting-out/staking, alignment, trajectory, machine control);
- Integrity and reliability
  - Low
- Fixing and convergence time
  - TTFaF: typically a few minutes, a few seconds required by the first application (setting-out/staking, alignment, trajectory, machine control) and second application (vehicle tracking and asset management);
- Coverage service area
  - Mostly regional
- GNSS contribution to the PNT solution
  - Typically high, with the exception of the first application (setting-out/staking, alignment, trajectory, machine control) and fifth application (high-order control survey);

Comparing Table 5 with the performance typically achieved by the different surveying methods in Section 5.5, we conclude that:

- the user requirements for four out of six construction surveying specific applications (are currently met by the GNSS-based solutions except machine control and alignment trajectory, setting-out/staking for which currently only partially or not met by the GNSS-based solutions and therefore the GNSS contribution to the PNT solutions needed by the all the construction applications is "medium" or "low". For these specific applications, the main reasons why currently GNSS techniques do not meet the user requirements is because mm-level accuracy (both horizontal and vertical) that cannot be reached by GNSS techniques in dynamic mode.

5.2.3 MINE SURVEYING

According to the International Society for Mine Surveying (ISM), this discipline includes "*all measurements, calculations and mapping which serve the purpose of ascertaining and documenting information at all stages from prospecting to exploitation and utilizing mineral deposits both by surface and underground working*"[37]. In carrying out these activities, the mining sector has been one of the early adopters of geospatial technologies. In this context, augmented GNSS lies at the core of solutions that have emerged and continue to develop with the aim to support greater control over mining processes and to enable the introduction of further automation. The benefits of the use of GNSS solutions are significant in terms of reduced labour costs, reduced fuel costs, improved overall output and profitability. Additional benefits include better safety and improved environmental management at mining sites.

37 http://ism-minesurveying.org/mine-surveying.html

Table 6: Main GNSS user requirements of Construction

Construction Surveying Specific Application	Accuracy		Availability			Robustness	Integrity andreliability	TTFaF	Coverage service Area	GNSS contribution to the PNT solution
	Horizontal	Vertical	Urban Canyon, Canopy	Better than 95%	Better than 99%					
	mm-level cm-level dm-level m-level	mm-level cm-level dm-level m-level	Yes/No	Low Medium High	Low Medium High	Low Medium High	Low Medium High	a few seconds a few min >20min	Global Regional Local	Low Medium High
Setting-out/ staking, alignment, trajectory, Machine control	cm-level	Cm/ mm-level	Yes	High	High	Medium	High	a few seconds	Regional/ Local	Low
Vehicle tracking and asset management	m-level	m-level or N/A	Yes	High	Medium	Low	Low	a few seconds	Regional/ Local	High
Asset positioning at 3m level	m-level	m-level or N/A	Yes	Medium	Medium	Low	Low	a few min	Regional/ Local	High
Low order control survey	cm-level	cm-level	Yes	Medium	Medium	Low	Low	a few min	Regional	High
High-order control survey	mm-level	cm-level	No	Medium	Medium	Low	Low	>20 min	Regional	High
Temporary DGNSS reference for monitor station positioning	cm-level	cm-level	Yes	Medium	Medium	Low	Low	a few min	Regional	High

Both static and dynamic GNSS-based solutions are used for exploration and mine site surveying; for autonomous mining and operations control; for remote control of machines (incl. haul trucks and drillers); for environmental surveying; and for material tracking and loading. Whilst most applications in the mining sector require accuracies at decimetre level, more stringent accuracy demands are found in mine site surveying and mine machinery guidance (especially when autonomous). Furthermore, **a key requirement in the mining sector is improved integrity and reliability, especially for automated machine control and guidance operations.**

Mine site surveying is an integral part of many mining processes and has been prevalent amongst exploration, pit, underground and construction operations throughout the entire project lifecycle. GNSS-based solutions have been adopted for several applications including, but not limited to:

- the coordination of survey control and the development of the basic geodetic base
- the extraction of topographical features for the mine site design
- maintaining and updating maps of the surface layout as the mining operations progress
- conducting progressive ground model surveys during construction to assist in the volumetric surveys[38] for contractor payment
- setting out design and boundaries
- surveying cleared and/or constructed areas

Most mine site activities require an accuracy between 1 and 10 cm and are thus achieved via RTK or DGNSS solutions. The main benefits of the use of GNSS solutions in mine site surveying are once again linked to reduced labour costs and to increased efficiency in supplying real-time positioning at cm level.

38 Volumetric surveys are topographical surveys performed at the same site in a different time to determine the volume of earthworks, stockpiles or landfills. They are executed using ground surveying (i.e. GNSS-enabled means) or aerial surveying. See for example http://www.landair.com.au/our-services/volumetric-surveys

Similar to the description provided earlier on machine control for construction sites, the mining sector is both heavily benefitting but also heavily investing in increased automation and operations control. Here too, the availability of reliable, real-time positioning information at cm level provided by GNSS-RTK or DGNSS (and frequently augmented by additional sensors) is growingly recognised and exploited, especially in open pit mines. Machine guidance in the context of mining operations includes (semi-)automated drilling and excavator control, allowing for cost savings due to reduced passes and machine wear and tear. It also involves the automatic guidance of haulage trucks.

Rio Tinto, one of the world's leading mining groups, has launched the operation of the world's largest driverless fleet of trucks as part of its *Mine of the Future TM* program[39]. Today, 69 autonomous trucks are moving high grade ore in the Pilbara sites in Western Australia. Other companies such as BHP Billiton and Fortescue Metals Group are also launching similar projects. These operations require decimetre level accuracy to support the operation needs and to avoid collisions. They also require integrity and reliability of the signals, both of which will be significantly improved by Galileo.

GIVEN THAT LAND DEFORMATION IS OFTEN OF THE ORDER OF A FEW MILLIMETRES PER YEAR, THE SENSITIVITY OF THE SYSTEM IS CRITICAL.

Apart from a clear trend towards increased automation, GNSS-based solutions are increasingly adopted in mine management systems (incorporating telemetry systems); these allow mine operators to optimise the utilisation of their assets and reduce costs. Another recent development is the introduction of solutions that allow uptake of GNSS-like solutions in deep pit mines. This refers to Leica's Jigsaw Positioning System, powered by Locata (Jps), that has been recently deployed in the deep South Pit mine at Boddington[40]. It entails the deployment of "ground-based satellites", i.e. transmitters that in combination with actual GNSS signals increase the availability of high precision positions in underground mines.

Despite the rapid uptake of GNSS-based solution in the mining sector some constraints remain. Besides accuracy, reliability and integrity requirements mentioned before, incompatibility issues remain inherent in the mining industry. This stems from the lack of existing support infrastructure (i.e. setting up *ad hoc* base stations for every mining site) and the requirement to individually tailor positioning needs for different mine site operations.

5.2.4 MONITORING OF NATURAL PHENOMENA AND RISK PREVENTION

GNSS is being increasingly used as an essential enabling technology to monitor and provide early warnings for natural phenomena[41] such as earthquakes, landslides, volcanoes and flood hazards. In that context, the most established application is GNSS land deformation monitoring. It typically relies on measurements acquired through a CORS network positioned in selected areas (e.g. boundary zones of tectonic plates). The data collected by each of the network's stations are transmitted via GSM or radio modems to a relevant centre. Given that land deformation (especially the one associated with tectonic motions) is often of the order of a few millimetres per year, the sensitivity of the system, i.e. its ability to distinguish land deformation from monumentation deformation (i.e. movement of the station due to other reasons such as temperature excursion, wind, etc.), is critical. Similarly, data processing and analysis techniques must also follow stringent quality standards[42]. The achieved accuracy ranges from centimetre-level for real-time processing to sub-centimetre-level for post-processing. Recent studies[43] have shown experimental mass-market receivers costing a few hundred of euros that can achieve 1-cm accuracies.

In the case of earthquakes, GNSS and accelerometer arrays are being explored as part of fully operational early warning systems (e.g. in California and Japan). GNSS surveying techniques - usually in combination with InSAR from EO satellites - are also deployed for monitoring of volcano ground deformation[44]. Another area where GNSS is deployed is that of water surface monitoring (for tidal effects at sea relevant especially for tsunamis and river flooding monitoring). In such cases, GNSS receivers are placed on floating loosely moored buoys allowing the measurement of water surface levels with accuracies of few centimetres. This is achieved by averaging over a long period of time to remove effects of waves. Such efforts have intensified since the catastrophic tsunami of 2004, with several systems (such as the National Multi-Hazard Early Warning System) being set up.

39 http://www.riotinto.com/ironore/mine-of-the-future-9603.aspx
40 http://www.locata.com/article/boddington-gold-mine/
41 For a comprehensive overview see [RD27]
42 See for example Piras et al. Crustal Deformation Monitoring by GNSS: Network Analysis and Case studies (2009)
43 For example Bellone et al. Real-time monitoring for fast deformations using GNSS low-cost receivers (2016)
44 See USGS GPS Precision Monitoring of Natural Hazards (2016)

The main GNSS user requirements are: [RD3], [RD4], [RD27] [RD29][RD30][RD31][RD33],[RD34]

- Accuracy
  - Horizontal: mm- to cm-level for slope stability, volumetric surveying operations and machine control and m-level for vehicle tracking and asset management
  - Vertical: mm- to cm-level for slope stability, volumetric surveying operations and machine control and m-level for vehicle tracking and asset management
- Availability
  - Availability in urban canyons, under canopy:
    - Better than 95%: high
    - Better than 99%: high
- Robustness
  - Mostly low; medium required by machine control
- Integrity and reliability
  - Mostly low; high required by machine control
- Fixing and convergence time
  - TTFaF: typically a few seconds, a few minutes required by the slope stability and volumetric surveys
- Coverage service area
  - Regional/local
- GNSS contribution to the PNT solution
  - Medium to high;

Comparing the table 6 below with the performance typically achieved by the different surveying methods in Section 5.5, we conclude that:

- the user requirements for the two out of three mining applications (volumetric surveys, machine control and vehicle tracking and asset management) are currently met by the GNSS-based solutions and therefore the GNSS contribution to the PNT solutions needed by the these mining applications is "high".
- the user requirements for one out of three mining applications (slope stability) are currently only partially met by the GNSS-based solutions and therefore the GNSS contribution to the PNT solutions needed by the all the construction applications is "medium". For these specific applications, the main reasons why currently GNSS techniques do not meet the user requirements are the mm-level accuracy that cannot be reached by GNSS techniques and the lack of visibility of the GNSS satellites in deep-pit mines.

5.3 MAPPING/GIS APPLICATIONS

Governmental institutions and enterprises across a host of industrial and economic sectors have been greatly benefitting by the advent of Geographic Information System (GIS) technologies. GIS capture, store, analyse, manage and visualise data linked to specific locations, allowing to better understand relationships, patterns and trends. A very wide range of data is collected and plotted onto GIS environments, supporting the mapping of attributes that are relevant for insurance companies, fleet managers, urban planners, utility companies and cadastral agencies, within the wide spectrum of users. The importance of GIS solutions is exemplified by the rapid growth of the sector. According to recent market studies[45], the GIS sector will grow at CAGR of around 11% during 2016-2020. This is primarily attributed to the increasing urbanisation and the growth of enterprise GIS in developing countries.

Table 7: Main GNSS user requirements of Mining

Specific Application	Accuracy		Availability			Robustness	Integrity and reliability	TTFaF	Coverage service Area	GNSS contribution to the PNT solution
	Horizontal	Vertical	Urban Canyon, Canopy	Better than 95%	Better than 99%					
	mm-level cm-level dm-level m-level	mm-level cm-level dm-level m-level	Yes/No	Low Medium High	Low Medium High	Low Medium High	Low Medium High	a few seconds a few min >20min	Global Regional Local	Low Medium High
Slope stability, volumetric surveys	cm/ mm-level	mm-level	Yes	High	High	Low	Low	a few min	Regional/ Local	Medium
Machine Control	cm-level	cm-level	Yes	High	High	Medium	High	a few seconds	Regional/ Local	High
Machine Control	m-level	m-level or N/A	Yes	High	High	Low	Low	a few seconds	Regional/ Local	High

45 See for example P&S Market Forecast or Research&Markets forecast

Whether, scanning paper maps and survey plans, or processing information captured through photogrammetry, remote sensing or GNSS-enabled field-work, GIS technologies enable the digitisation and visualisation of spatial and attribute data. Indeed, by combining different layers of raster images or vector data, GIS applications generate different types of maps (e.g. thematic, contour, change, etc.) carrying a wealth of information. In recent years, GNSS has been increasingly used in combination with and in support of GIS solutions. This includes:

- Collecting vector spatial data (points, lines and polygons)
- Adding the temporal dimension
- Navigating to or verifying of locations or specific features
- Validating the accuracy of existing data
- Establishing ground control and validation for photogrammetry and satellite imagery

Several applications making the best use of both worlds (GNSS and GIS) have arisen. Indicatively:

- **Asset and fleet management**: Location-enabled GIS platforms allow real-time monitoring of the position and activities carried out by different assets. Thanks to that, fleet managers (e.g. buses, trucks, railways, etc.), farm managers and construction site managers can continuously monitor their vehicles or machinery, plan efficient routes and optimise their overall utilisation.
- **Cadastre**: Cadastral surveys and topographic maps carried out by field surveyors using GNSS receivers can be plotted and visualised onto GIS platforms. Apart from the cases described in section 3.2, this can be relevant for green cadastre applications related to identifying, monitoring and planning of urban greenery.
- **Agriculture:** GIS software tools are used to process, analyse and project soil data, yield-related information and terrain features that have been geo-referenced using GNSS in prescription maps. By "reading" these prescription maps and using a GNSS receiver determining the exact position of the machinery in the field, Variable Rate Applications enable the controllers to apply inputs according to site-specific needs.
- **Photogrammetry:** Photogrammetric mapping involves the recording, measuring, and interpreting of aerial photographic images in order to extract reliable geographic and dimensional information about physical objects and their environments. It is used in various fields including topographic mapping and direct geo-referencing of remotely sensed data. GNSS may be integrated together with inertial sensors, optical imaging sensors, scanning lasers, LIDAR and synthetic aperture radar to effectively and accurately complete photogrammetric mapping projects.
- **g-Governance:** g-governance is an emerging practice entailing GIS/GNSS applications in support e-governance. In practice, using GIS platforms to visualise geo-referenced information, authorities can make informed decisions with regards to land development, resource utilisation, etc.

Several of these activities have been greatly enhanced by the availability of low-cost mapping-grade GNSS units with decimetre accuracy in real time. In turn, the low-cost data acquisition, updating and in-field mapping processes supported typically by DGNSS solutions have given significant boost in the overall uptake of GIS. In practice, DGNSS with real-time correction or SBAS-enabled receivers allow for immediate attribution and validation in the field, with accurate and efficient recording of the position of features. The collected data can be integrated with or complemented by other technologies (e.g. laser rangefinders) in environments where GNSS availability is hindered. In addition, it can be automatically stored and processed onto a GIS platform in GIS-compatible format.

The use of mapping grade or even consumer-grade mobile devices is currently on the rise. For instance, receiver devices are paired with smartphones or tablets, achieving high-accuracy, but simultaneously cost-effective solutions for Mapping and GIS professionals. A prime example for this is the combined use of *Collector for ArcGIS* on handheld devices coupled via bluetooth with *Trimble R1 GNSS receiver* allowing users to capture GIS data on their smartphones and meeting stringent spatial accuracy requirements[46]. Another innovative example is the software-based GNSS, coupled with Positioning-as-a-Service technique, which provides general mass market devices with scalable high-accuracy positioning capabilities of up to 1-2 cm (95%)[47].

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The main GNSS user requirements are: [RD3][RD4][RD29]][RD30][RD31][RD33][RD34]

- Accuracy
  - Horizontal: m-level to mm-level depending on the GIS application
  - Vertical: m-level to cm-level depending on the GIS application
- Availability
  - Availability in urban canyons, under canopy:
    - Better than 95%: mostly high, medium required by the photogrammetry- related application;
    - Better than 99%: mostly high, medium required by the photogrammetry- related application;

46 http://www.esri.com/esri-news/releases/15-4qtr/esri-and-trimble-offer-the-r1-gnss-receiver-to-enhance-field-gis-workflows
47 https://catalyst.trimble.com/

Table 8: Main GNSS user requirements of Mapping/GIS

Mapping/ GIS Specific Application	Accuracy		Availability			Robust-ness	Integri-ty and reliabil-ity	Size, weight, autonomy		TTFaF	Cov-erage service Area	GNSS contri-bution to the PNT solution
	Horizon-tal	Vertical	Urban Canyon, Canopy	Better than 95%	Better than 99%			Rele-vance	The length of time a device can run			
	mm-level cm-level dm-level m-level	mm-level cm-level dm-level m-level	Yes/No	Low Medium High	Low Medium High	Low Medium High	Low Medium High	Yes/No	>1h >5h a few days	a few seconds a few min >20min	Global Regional Local	Low Medium High
Photogrammetry/ remote sensing high-order ground control	mm-level	cm-level	No	Medium	Medium	Low	Low	No	N/A	>20 min	Regional	High
Photogrammetry, photo control points	cm-level	cm-level	Yes	Medium	Medium	Low	Low	No	N/A	a few min	Regional	High
High-order topographical profiles	cm-level	cm-level	Yes	High	High	Low	Low	Yes	>5h	a few seconds	Regional	High
Automated mapping/facilities management (AM/FM); utilities mapping	m-level	m-level	Yes	High	High	Low	Low	Yes	>5h	a few seconds	Regional/ Local	High
Update of special database, digital mapping	m-level	m-level	Yes	High	High	Low	Low	Yes	>5h	a few seconds	Regional/ Local	High
GIS, assets positioning and attribute collection	m-level	dm-level or m-level	Yes	High	High	Low	Low	Yes	>5h	a few seconds	Regional/ Local	High
GIS - high-precision asset positioning and attribute collection	cm-level	cm-level	Yes	High	High	Low	Low	Yes	>5h	a few seconds	Regional/ Local	High
Topographic mapping	cm-level	cm-level	Yes	High	High	Low	Low	Yes	>5h	a few seconds	Regional/ Local	High
Photogrammetry camera positioning and photo control	cm-level	cm-level	No	Medium	Medium	Low	Low	No	N/A	a few seconds	Regional/ Local	High

- Robustness
  - Low
- Integrity and reliability
  - Low
- Fixing and convergence time
  - TTFF: typically a few seconds, a few minutes required by the second application (Photogrammetry, photo control points) and above 20 minutes by the first application (Photogrammetry/remote sensing high-order ground control)
- Coverage service area
  - Regional/local
- GNSS contribution to the PNT solution
  - High

Comparing Table 7 with the performance typically achieved by the different surveying methods in Section 5.5, we conclude that the user requirements for the nine GIS/mapping applications are currently met by the GNSS-based solutions and therefore the GNSS contribution to the PNT solutions needed by the all the mining applications is "high".

5.4 MARINE SURVEYING APPLICATIONS

Marine surveying encompasses operations performed near or further away from the shore, including marine boundaries determination (marine cadastre), hydrographic surveys and off-shore surveys. Differential GNSS solutions and Precise Point Positioning techniques (PPP) are used for surface positioning of the vessels performing surveys of the seabed, off-shore construction or other marine operations (e.g. pipe and cable lay), as well as bathymetric surveys (in combination with inertial sensors and multi-beam sonars).

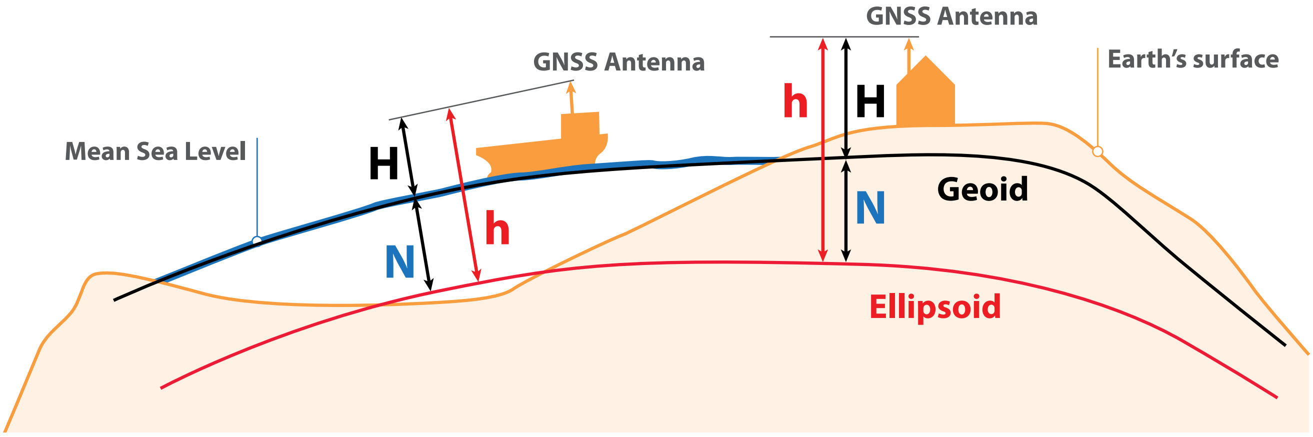
A key consideration in the case of marine operations is the calculation of the vertical position. The absolute height component of the GNSS antenna mounted on a vessel is given in terms of its height (h) above the GNSS reference ellipsoid (e.g. WGS84). The orthometric height (H) however is the height of the antenna above the geoid. This means that, in order to determine the vertical position, geoid models providing the separation between the geoid and ellipsoid (N) at the place of observation must be deployed (see figure 7)

Another important consideration in marine surveying is the availability of differential correction techniques. Whilst RTK is the preferred dynamic solution for several land surveying operations, its utilisation in marine environments is confined to about 10km from the shore. Beyond this distance, the errors at the reference and the rover receivers do not properly cancel out by double differencing, and as a consequence the positioning accuracy deteriorates. Therefore, PPP and DGNSS solutions are most widely used to fix vessels' positions in hydrographic surveys and off-shore operations. Several major vendors offer solutions tailored to the needs of the marine surveyors, including commercial SBAS or DGNSS/PPP networks (see for example the suite of services provided by FUGRO[48]). The sections below provide an overview of the different disciplines falling under marine surveying.

5.4.1 MARINE CADASTRE

In the marine environment, maritime boundaries are implemented to allow the distinction between public use areas, conservation areas and marine parks; to define commercial mining or farming leases; and to clarify the areas falling under the jurisdiction of different entities or the sovereign extent. In this way, the accurate and clear definition of maritime boundaries allows for the unambiguous legal definition, management and security of the interests linked

Figure 7: Absolute vertical height of an antenna on-board a vessel [RD14]



48 http://www.fugro.com/our-expertise/our-services/survey/satellite-positioning

to different areas. Marine cadastre is thus defined as a system enabling the boundaries of maritime rights and interests to be recorded, spatially managed and physically defined in relationship to the boundaries of other neighbouring or underlying rights and interest.

However, contrary to land cadastre where the position of boundaries can be determined by prior evidence or by physical monuments, maritime boundaries exist as virtual objects without visible or tangible demarcation. Thus, to establish the location of the boundaries GNSS-based solutions must be deployed. Differential GNSS methods are typically used to determine maritime boundaries. However, apart from the uncertainties related to GNSS positioning, errors related to the maritime boundary delimitation process are also applicable.

Nowadays marine cadastre is increasingly seen as part of a Spatial Data Infrastructure (SDI) that takes into consideration different layers of information, such as overlapping rights/interests in marine spaces, 3D geometry of the spaces to be managed, the variety of stakeholders involved and different governance principles. Several countries have set forth the establishment of well-defined Marine Cadastre; a prime example is the multipurpose, web-based, publicly accessible U.S. marine cadastre[49], which provides a 3D representation of the seafloor and a 2D visualisation of the relevant rights. Other countries such as Australia, Canada, but also South Africa and Malaysia have completed or launched similar projects. The ongoing integration of different types of cadastres may lead to an increased uptake of GNSS solutions.

5.4.2 HYDROGRAPHIC SURVEYS

Hydrographic surveying entails a number of activities ranging from reconnaissance (e.g. when designing a construction project) to payment of underwater work (e.g. dredging or reclamation). In essence, hydrographic surveying is concerned with the accurate measurement of water depth below a stated datum and the exact position of this measured depth. The collected information is normally projected onto a bathymetric contour map, which presents the sea bed in a way that allows the identification of areas of equal depth (isobaths). Hydrographic surveying is also concerned with the determination of the sea bottom type and the positioning of "intertidal" and shoreline features above a stated datum.

Depth measurements are conducted using multibeam echo-sounders (MBES), which use hundreds of very narrow adjacent beams arranged in a fan-like swath of typically 90 to 170 degrees across. In practice, MBES transmit a sound pulse from the surface and record the returning signal as it bounces back from the seabed. Similarly, LIDAR technologies, usually mounted on aircrafts, measure the time it takes for light to return after bouncing of the bottom. MBES are the instrument of choice for today's hydrographic surveying applications.

However in order to achieve higher precision, the measurements must take into account the movement of the instruments (mounted under a vessel) on the surface of the water. Hence for each vertical depth recording a horizontal position fix is required. This is achieved by using integrated DGNSS

49 http://marinecadastre.gov/viewers/

receivers and inertial sensors (IMUs). The IMUs need to be as close as possible to the transducer (MBES) to minimise errors stemming from an offset between them.

Depending on the type of area, i.e. related to how critical under-keel clearance is and what is the depth in that area, different accuracy standards apply. Four classes are defined by the IHO[50] in terms of decreasing horizontal and vertical accuracy (special, 1a, 1b and 2). Only recently[51], the Barcelona port authority carried out a test to assess the compliance of EGNOS performance in bathymetric surveys against the IHO standards. The findings showed that EGNOS complied with 1a, 1b and 2 classes' standards.

5.4.3 OFF-SHORE SURVEYS

Off-shore surveying is primarily used by vessels performing seabed exploration (in the oil and gas industry for example) and operations in deep water (pipe and cable lay, oil production related operations). This includes, for example, Anchor Handling Tug Supply (AHTS) vessels that handle anchors for oil rigs, tow them to location and anchor them up. Whilst accuracy requirements are not very stringent (i.e. decimetre level suffices), redundancy, reliability and integrity are particularly relevant for off-shore exploration and operation activities. Seismic and bathymetric surveys contributing to the overall geophysical assessment of existing and potential hydrocarbon deposits, are the main types of exploration activities concerned.

During off-shore surveying and exploration activities, GNSS is typically used for the determination of the positions and heights of the survey equipment and the sensors used to record the survey data (e.g. seismic source and receiver locations in seismic surveys, MBES on bathymetric surveys). It is also used to determine the positions of certain points of interest such as the drill centre position (during a rig move). Precise point positioning (PPP) is typically enabled using DGNSS solutions supplied by private vendors (e.g. Fugro Seastar) via satellite communications or terrestrial radio broadcast to support 24/7 reliability, integrity and full redundancy. Even if commercial DGNSS is the predominant solution, there still exists a small reliance on RTK for important shore crossing / transition zones for pipe connectivity.

The importance of integrity and reliability of the navigation and positioning surveys in off-shore exploration is highlighted by a case study presented in [RD13]. Woodside, a leading oil and gas company, commissions annually approximately $100 million worth of exploration surveys. The costs of lost production total millions in lost revenue of operational cost (e.g. a typical survey vessel will be charged around 700k per day in production). As GNSS technologies advance - enabling specifically better vertical measurements - greater uptake should be expected.

The main GNSS user requirements are: [RD3][RD4][RD29][RD30][RD31] [RD33],[RD34]

Table 9: Main GNSS user requirements of Marine surveying

Marine Surveying Specific Application	Accuracy		Availability			Robustness	Integrity and reliability	TTFaF	Coverage service Area	GNSS contribution to the PNT solution
	Horizontal	Vertical	Urban Canyon, Canopy	Better than 95%	Better than 99%					
	mm-level cm-level dm-level m-level	mm-level cm-level dm-level m-level	Yes/No	Low Medium High	Low Medium High	Low Medium High	Low Medium High	a few seconds a few min >20min	Global Regional Local	Low Medium High
Marine Cadastre	m-level	m-level	Yes, if applicable	Medium	Medium	Low	Low	a few min	Global	High
Real-time tidal monitoring	cm-level	cm-level	No	High	Medium	Low	Low	a few seconds	Global	High
Vessel positioning - docking	cm-level	cm-level	No	High	High	Medium	High	a few seconds	Global	High
Hydrographic survey and vessel navigation	m-level	m-level	Yes	High	High	Medium	High	a few seconds	Global	Medium/ High
Off-shore exploration	m-level	m-level	No	High	High	Medium	High	a few seconds	Global	High

50 https://www.iho.int/iho_pubs/standard/S-44_5E.pdf
51 See EGNOS Bulletin Q4-2015

- Accuracy:
  - o Horizontal: typically m-level, cm-level required by vessel positioning and tidal monitoring
  - o Vertical: typically m-level, cm-level required by vessel positioning and tidal monitoring
- Availability:
  - o Availability in urban canyons, under canopy (mostly N/A)
  - o These requirements are understood as availability in open sky conditions
    - ▪ Better than 95%: mostly high, medium required by marine cadastre
    - ▪ Better than 99%: mostly high, medium required by marine cadastre and tidal monitoring
- Robustness
  - o Low to medium, depending on the application
- Integrity and reliability
  - o Mostly high, low required for marine cadastre and tidal monitoring
- Fixing and convergence time
  - o TTFaF: typically a few seconds, a few minutes required for marine cadastre
- Coverage service area
  - o Global
- GNSS contribution to the PNT solution
  - o High

Comparing Table 8 with the performance typically achieved by the different surveying methods in Section 5.5, we conclude that most of the user requirements for the five marine cadastre applications are currently met by the GNSS-based solutions and therefore the GNSS contribution to the PNT solutions needed by the all the mining applications is "high".

5.5 DETAILED ACCURACY REQUIREMENTS PER APPLICATION/ SPECIFIC APPLICATION AND TYPICAL PERFORMANCE ACHIEVED BY GNSS

Table 9[52] provides a comprehensive view of currently achieved performances across the different surveying methods used in the various applications.

In order to better "navigate" within Table 9, the following scheme shows the comparative relevance of different surveying methods across the application categories presented in chapter 3.

Table 10: Typical achieved performance across the different GNSS survey methods

Survey Method	General application sector	Specific application	Typical Achieved Performance
High-Precision Static **(5 - 10 mm)**	Cadastral	National/international networks and reference frame survey Geodetic surveys High-order control surveys	Performed with dual-frequency[1] receivers Horizontal accuracy 5 mm + 1 ppm[2] Vertical accuracy 10 mm + 1 ppm Baseline/Occupation[3]: • 20km for at least 1 hour • 30km for at least 2 hours • 50km for at least 4 hours • 100km for at least 6 hours
	Mapping	Photogrammetry/remote sensing high-order ground control	
	Construction	High-order control surveys	
Medium-Precision Static **(10 - 60 mm)**	Cadastral	Low-order control surveys High-order detail surveys and positioning DGNSS or RTK reference station positioning	Performed with dual-frequency receivers Horizontal accuracy 10 mm + 1 ppm Vertical accuracy 20 mm + 1 ppm Baseline/Occupation • 20km for 20 minutes • 30km for 40 minutes • 40km for 60 minutes
	Mapping	Photogrammetry, photo control points High-order topographical profiles	
	Construction	Low-order control surveys	

52 The contents of the table have been inspired by [RD3]

Survey Method	General application sector	Specific application	Typical Achieved Performance
Low-Precision Static **(1 - 10 m)**	Cadastral	Temporary DGNSS reference for monitor station positioning	Performed with autonomous receiver Horizontal accuracy/occupation: • 10m for 10 minutes • 3m for 3 hours • Metre level reached on day(s) occupation Vertical accuracy: twice the value of Horizontal
	Machine Control	Asset positioning at 3m level	
High-Precision Dynamic **(15 - 50 mm)**	Cadastral	Cadastral surveys; Land seismic surveys High-order detail surveys and positioning	Performed with dual-frequency receivers Horizontal accuracy 10 mm + 2 ppm Vertical accuracy 20 mm + 2 ppm Baseline/Occupation (after initialisation)[4]: • 1km for 5 sec • 15km for 1 min
	Mapping	GIS - high-precision asset positioning and attribute collection Topographic mapping Photogrammetry camera positioning and photo control	
	Construction	Temporary DGNSS reference for monitor station positioning	
Medium/Low - Precision Dynamic **(1 - 5m)** **Note: sub-metre for dual frequency**	Cadastral	Low-order detail surveys	Performed with dual-frequency float/phase smoothed code receivers • H 0.1–0.4m / V 0.2–0.8m • B 20km for 1–15 minute(s) Performed with Single-frequency receivers • H 1–5m / V 2–7m • B 100km for 1 minute
	Mapping	GIS, asset positioning and attribute collection Update of spatial data bases, digital mapping Automated mapping/facilities management (AM/FM), i.e. GIS-enabled digitisation, management and analysis of data related to utilities	
High-Precision Dynamic Real-time **(20 - 80 mm)**	Cadastral	Land survey, real-time topographic detailing and profiling Land seismic, dimensional control[5] and source positioning	Dual-Frequency Receiver performances RTK or NRTK ambiguity fixing time (TTFA) depending on implementations[6] • Horizontal accuracy 10 mm + 1 ppm • Vertical accuracy 20 mm + 1 ppm Special case for network RTK (which depends on the specific network): • Horizontal accuracy 10-20 mm • Vertical accuracy 15-30 mm
	Construction	Setting-out/staking, alignment, trajectory; Machine control	
	Mining	Slope stability, volumetric surveys; Machine Control	
	Marine	Real-time tidal monitoring Vessel navigation - docking	
Medium/Low - precision dynamic Real-time **(1 - 5 m)**	Mapping	GIS, asset positioning and attribute collection	Same as Medium/Low-Precision Dynamic. Network RTK performances are depending on network correction generation methods
	Hydrographic and off-shore	Vessel positioning Hydrographic surveys Off-shore exploration	
	Machine Control	Vehicle tracking and asset management	

1 Only classical dual-frequency resolution techniques are here considered; three-frequency ambiguity resolution techniques are not considered in this table.

2 In Land Surveying, the parts-per million (ppm) convention is used to denote distance measurement accuracy, i.e. one millimetre per kilometre distance. It becomes relevant only when temperature or atmospheric pressure variations apply.

3 The values provided indicate the suggested occupation time needed to compute a baseline of a given length within the given accuracy range.

4 Kinematic Surveying for post-processing ambiguity fixing through and point solutions is here reported; stakeout operations through RTK or Network-RTK can in principle be carried out with a single or a few epochs for RTK averaging once ambiguity fixing has been achieved (High Precision Real-Time Surveying Method)

5 Dimensional control is the technique used to accurately measure 3-D spaces to determine the area between points, creating digitally mapped distances and angles.

6 Occupation time for RTK and NRTK Ambiguity Fixing depends on surveying environmental conditions, baseline from the closest Reference Station and Network implementation methods ; a fixed requirement is not here specified, considering 30s -3 min a occupation time in case of baselines less than 10 Km and number of satellites greater than 7 in good geometric configuration (e.g. PDOP < 4) a nominal case

Note that amongst dynamic solutions only real-time are presented in Table 10.

In the following, some additional elements are provided on the specific performance requirements in the different application sectors together with some notes on the "qualitative" aspects.

5.6 ADDITIONAL USER REQUIREMENT CONSIDERATIONS

5.6.1 LAND SURVEYING

As shown in the preceding tables, land surveying applications present some of the most demanding requirements both in terms of accuracy, where for instance control surveys typically require sub-centimetre accuracy, but also in terms of availability and reliability. On top of the quantitative requirements presented across the different surveying methods (table 1), surveyors seek a number of other important aspects:

- **Interoperability and software flexibility:** In most land surveying operations, GNSS is used together with other technologies (e.g. total stations) and thus interoperability and integration-ability of the GNSS equipment with other technologies is considered critical. In that respect, most manufacturers of GNSS-enabled devices actually advertise these features[53]. Integrated solutions are sought, so that surveyors can use the most appropriate tool (e.g. GNSS, total station) for certain operations (e.g. topographic surveys and stakeout especially in large construction sites), under the given operating environment conditions, without having to switch between field software applications.
- **Real-time and post-processed capability:** Given that different techniques are best suited for different surveying operations (i.e. static for control, dynamic for detail and asset data capturing), surveyors seek solutions that can support both real-time and post-processed surveying.

5.6.2 MAPPING

As discussed in section 3.3 mapping does not impose equally stringent demands on accuracy. Instead, efficiency in terms of equipment costs and required labour, is highly sought for in mapping applications. It is therefore increasingly a matter of price/performance ratio that defines which solution is preferred, and more often than not, mappers require low-cost, yet reliable, GNSS-enabled devices that can provide metre or sub-metre level accuracy. Other considerations include:

- **Interoperability** is an important aspect; given that data captured/referenced with the aid of GNSS are typically integrated within a GIS environment, file format compatibility is needed. Solutions supporting interoperability with the most widespread GIS technologies (e.g. ArcGIS).
- **Multi-functionality** of handheld devices can prove particularly beneficial for mapping applications, since attribute data (e.g. photos, or via bar code scanner, etc.) can be captured simultaneously with the position of the given assets. As mentioned in section 3.3, the trend of handheld devices coupled with additional receivers is currently on the rise. The requirement for ruggedness and robustness, that off-the-shelf smartphones typically lack, is met by equipping them with protective cases, extended battery life and screen covers.

5.6.3 MARINE SURVEYING

Whilst carrying several similarities to the other sectors (especially land surveying) in terms of performance requirements, marine surveying presents certain specificities that are related with the operating environment and the specific tasks undertaken. Thus, whilst accuracy requirements are typically lower than those for land surveying, strong emphasis is put on the following aspects:

- **Flexibility and compatibility:** Marine surveying is characterised by the constrained availability or RTK in the close proximity of the coastline (typically up to 10km). Therefore, it is critical that GNSS-enabled devices can receive corrections from multiple sources. In addition, compatibility between different manufacturers' equipment is also important.
- **Continuity:** Particularly for off-shore surveying operations downtime due to obscured satellite reception should be minimised. Thus, the main vendors (e.g. Fugro, Veripos, etc.) strive to offer 24/7 DGNSS correction services with global coverage.
- **Antenna ruggedness and performance:** Due to a) the difficulty of placing the antenna in the most favourable locations in the mast (due to other sensors being already there) and b) the intrinsic difficulty of determining its position vis-à-vis the vessel and the objects of interest (especially when dynamics are low), antennas should be particularly performant and rugged (for the weather).
- **Integration with other sensors** is also critical for hydrographic surveys since bathymetry is typically performed by MBES or LIDAR, with GNSS providing the exact position of the (sensor on) the vessel or aircraft respectively.

53 See for example http://trl.trimble.com/docushare/dsweb/Get/Document-239290/022543-133_Integrated_Surveying_WP_0605.pdf

Table 11: Relevance of different surveying methods across the main application sectors

	High-precision Static	Medium/Low precision static	(Network) RTK	SBAS	DGNSS	PPP[1]
Cadastral	√√√	√√	√√√	√	√	√
Construction	√√	√√	√√√	√	√√	√
Mining			√√√	√	√√	√
Mapping	√	√	√	√√√	√√√	√
Marine Cadastre			√	√√	√√√	√√
Hydrographic			√√	√√	√√√	√
Off-shore			√	√√	√√√	√√

1 Referring to standard PPP, characterised by long convergence time and no ambiguity resolution.

On top of the aforementioned aspects, a common requirement across sectors, is the "connected" operation allowing a continuous communication and data stream between the manager's office and the in-field workers and surveyors. Thus, managers of construction and mining sites, supervisors of marine operations and professionals responsible for GNSS/GIS-enabled asset management, require all-in-one solutions, that enable monitoring, planning and decision-making, towards process, productivity and cost-optimisation.

Finally, as underlined by the interviewee from Hexagon Leica [RD26], all competitive GNSS devices provide accuracy performance within the "standard" requirements. It is thus the additional elements such as user friendliness, access to support, quality and interoperability that often counts more amongst end-users.

5.7 PROSPECTIVE USE OF GNSS IN SURVEYING

Surveying is the market segment with the most stringent demands in terms of position accuracy. In addition, reliability, integrity and redundancy are critical for several surveying applications including off-shore surveying, mine site surveying and control surveys for different types of cadastral applications. In this context, the evolution of GNSS-based solutions is driven by the demanding performance requirements, the increasing competition putting strain on the prices and the need for integrated solutions that make the best of different technologies (incl. RPAS, LIDAR, etc.). The main technological trends and prospects for the use of GNSS in surveying are briefly presented below.

EMERGING MULTI-FREQUENCY AND MULTI-CONSTELLATION SOLUTIONS

The advent of the multi-constellation era has brought surveyors across practically all sub-disciplines, several important benefits including increased availability (especially in attenuated environments), faster ambiguity resolution and better coverage (relevant especially for northern latitudes). Indeed, the vast majority (85%) of receivers used in the surveying sector today are equipped with software that can track - at minima - two constellations (whereas 40% can track all four global constellations). At the same time, and recalling that several surveying applications require double-frequency receivers, the introduction of Galileo High Accuracy Service on E6 and GPS L5, will allow surveyors to benefit from triple frequency solutions. These are expected to significantly reduce convergence time for PPP and differential techniques. In this context, particular importance lays on the fact that GPS will not support legacy L1 (C/A) / L2 (P/Y) signals beyond 2020. This means that surveyors will need to progressively migrate to E5/L5 capable equipment to guarantee high-precision performance.

HIGH ACCURACY SERVICE NOVELTIES

Various analyses have shown that the Galileo High Accuracy Service E6-B signal is well suited for transmitting PPP information, allowing an adequate update rate for the achievement of centimetre level accuracy. In addition, as the HAS allows for the transmission of different bits from different satellites, the total bandwidth can be highly increased leading to a better performance that, when combined with other factors may reduce the PPP receiver convergence time. Moreover, HAS will offer triple frequency, enabling faster

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convergence time for surveying applications and accuracy comparable to RTK. Another intriguing future high-accuracy prospect for mapping and surveying are brought through the use of GNSS raw phase measurements of Galileo signals via Android-based devices. Since 2017, a dedicated GSA Task Force was established to share knowledge and expertise on Android raw measurements and its use, including its potential for high accuracy positioning techniques. The Task Force includes GNSS experts, scientists and GNSS market players, and promotes a wider use of these raw measurements[54]. Finally, the signal authentication service (SAS) of Galileo would be particularly interesting in sectors where volumetric surveys take place, i.e. where one measures the work performed by contractors against their contractual arrangements (see also [RD26]).

RTK VS. PPP UPTAKE

The landscape of RTK is changing with:

- The proliferation of RTK GNSS receiver "boards" such as the Trimble BD series, Novatel OEM series, Hemisphere GNSS P series, and Septentrio AsteRx series.[55]
- Massive uptake of RTK solutions in fast-growing markets such as China - which lies in the so-called GNSS hotspot of satellite visibility.
- The development of active and passive reference stations and network RTK reference station networks by several national mapping agencies and commercial vendors
- Significant decrease of the price of RTK GNSS receivers, due to a congested market and the competitive pressure from emerging PPP solutions (described next).

These elements are driving, according to some experts[56], the trends towards the commodisation of high-precision GNSS receivers, in particular low-cost dual frequency (L1/L5) receivers capable of centimetre-level horizontal/vertical precision which should become widely available and thus enable the proliferation of RTK for a given range of surveying applications. In 2018, GNSS RTK receiver prices range from 4.000-20.000 EUR, whilst the trend of decreasing prices continues.

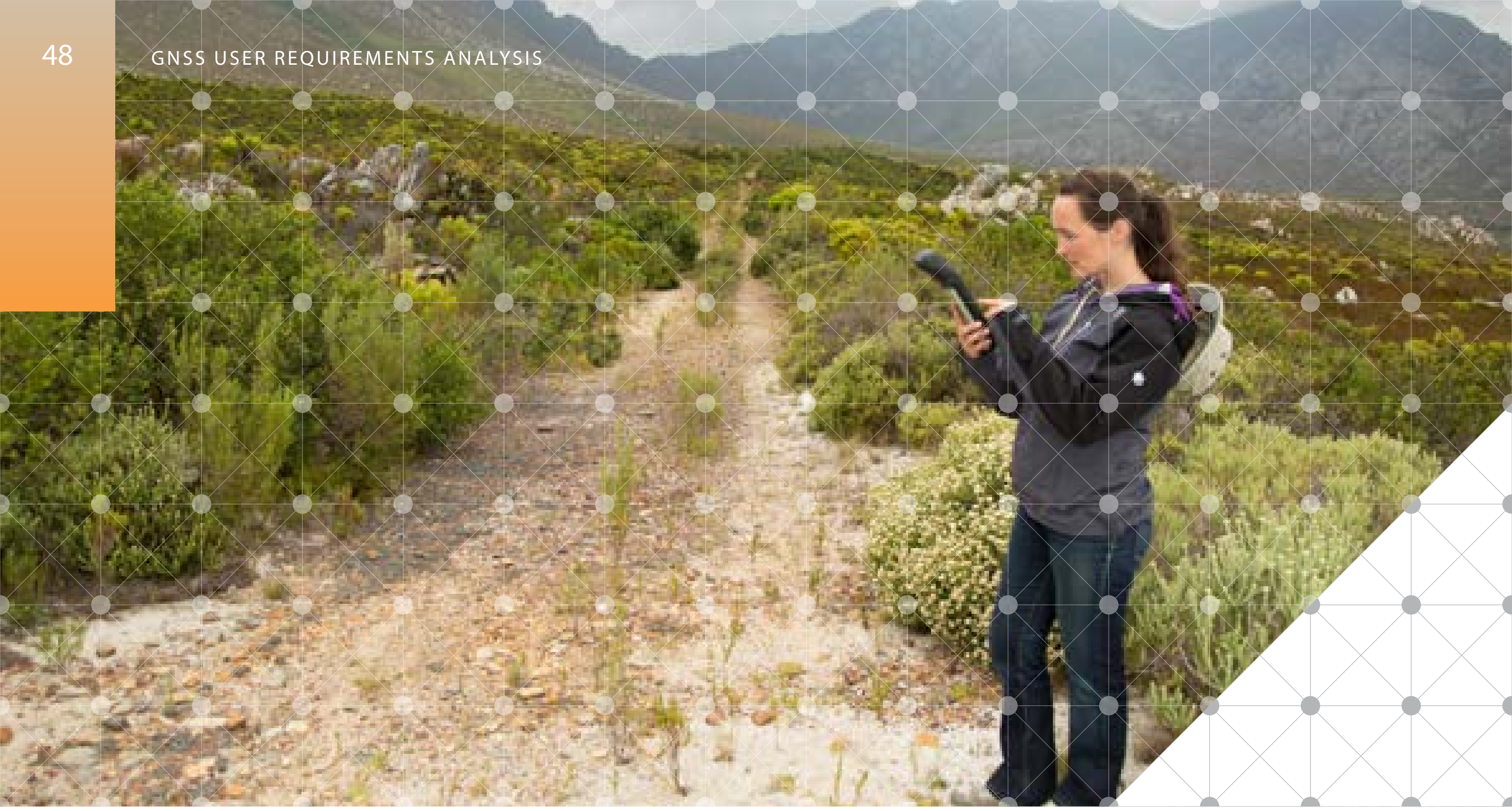
At the same time, and despite the challenges in delivering PPP solutions - especially in a real-time environment, they are currently seen as a viable alternative to DGNSS solutions and are trending amongst users who want good accuracy but at a lesser investment than that required for RTK (or in environments where RTK is not an option, e.g. further from the coast or in countries where such networks are not available). A prime example of well-performing PPP solution is Trimble's CenterPoint RTX which regularly achieves less than 4 cm accuracy for users (but initialisation time less than 15 min). Several other vendors offer PPP solutions including OmniSTAR, VERIPOS, TerraStar, StarFire, etc. Thus, in the context of centimetre accuracy applications, while RTK remains the premium option and offers immediate solution convergence, the minimal equipment needs and global accessibility make PPP an interesting alternative. This view has been strongly highlighted within the interviews performed in the framework of the current study [RD26]. Overall, PPP is expected to become a competitive solution for high-precision applications where very high accuracy requirements do not apply, and differential correction networks are not available.

INTEGRATED SOLUTIONS WITH COMPLEMENTARY TECHNOLOGIES

Driven by rigorous demands, surveying has been traditionally a forward-looking sector, with regards to adopting innovative technologies. In the past few years, several "tools" have been added in arsenal of surveyors, including:

- **3D laser scanners:** By scanning a horizontal and vertical field from a static location they allow the collection of dense clouds of points used to create digital 3D models of buildings or land.
- **Total Stations:** Theodolites used to electronically calculate distances to centimetre accuracy, using a laser or infrared beam along with electronic data logging systems. Robotic versions of total stations are available, allowing surveyors to remotely operate them.
- **LIDAR and photogrammetric cameras:** Usually mounted on-board aircrafts, they are used to measure distances by illuminating different targets and calculating the backscattering of light. Using different wavelengths LIDARs can create elaborate 3D point cloud models of the landscape, with detailed representation of different elevations.
- **RPAS:** Airborne RPAS equipped with different optical or LIDAR sensors are bringing a host of benefits for surveyors, including significant reduction of surveying time, access to areas of complex topography, and increased stream of data at a roughly equivalent accuracy but lesser cost compared to other techniques. In addition, autonomous underwater vehicles (or deep tows) are outfitted with sonar or cameras to accurately map the seabed.
- **Augmented Reality (AR):** AR provides a live view of a physical, real-world environment whose elements are "augmented" by computer-generated input such as geo-related projects and cable information or extracted real-world sensory input such as GNSS data – typically

54 https://www.gsa.europa.eu/sites/default/files/expo/martin_sunkevic_gsa.pdf
55 http://gpsworld.com/rtk-gnss-receivers-a-flooded-market/
56 http://www.apsg.info/Resources/Documents/Presentations/APSG33/Eric_Gakstatter_APSG_Apr_7_2015.pdf



performed in real time and in semantic context with environmental elements.

- **Simultaneous Localisation and Mapping (SLAM):** SLAM techniques enable to construct or update a map in an unknown environment, while keeping track of the location of the operator. Applications include self-driving cars, unmanned aerial vehicles, autonomous underwater vehicles, planetary rovers and newly emerging domestic robots.

GNSS-enabled devices are integrated together with these technologies to provide the coordinates of the sensor performing the measurement - both for the needed initial known point and any further coordinate measurements. This is applicable, for example, to hydrographic surveying (MBES+IMU+GNSS), infrastructure visualisation of oil and gas pipelines (LIDAR+GNSS+IMU), but also cadastral surveying (total stations+GNSS) and geo-referenced laser scanning data collection (terrestrial, airborne, and mobile). To complement the comprehensive overview of laser scanners, LIDAR/photogrammetric cameras and total stations, provided in [RD2], this document gives a more detailed picture of the use of RPAS in surveying (see Annex 2).

5.8 GNSS LIMITATIONS IN THE SURVEYING DOMAIN

GNSS is an integral enabling technology used across the wide range of surveying applications presented previously. However, several limitations apply, which are typically overcome by employing the complementary technologies described in the previous section or by following best practices regarding the type of GNSS equipment used.

OPERATING ENVIRONMENT LIMITATIONS

These are mostly related to constraints related to the environment in which survey operations are carried out. Thus, in dense urban environments, in sites where there are natural (e.g. tree canopy, deep open pit mines) or artificial (e.g. buildings or highly-reflective surfaces in construction sites) obstructions, and in areas with complex topographies, interference and multipath effects as well as limited GNSS signal availability, should be overcome by deploying complementary technologies.

For example, even though GNSS has been proven to work under vegetation cover, there may a significant loss of signal depending on the type and moisture content of the vegetation. In such cases, tertiary or secondary control should be established on the edges of the vegetation, whereas for detail surveys traditional methods should be deployed.

VERTICAL POSITION DETERMINATION

When there is a need for highly accurate vertical position determination (e.g. in control surveys) considerations related to antenna phase centre variations should be taken into account. These are a function of the elevation and azimuth angle between the antenna and a given satellite. For short baselines, and where the same antenna is used (between rover and base), the variations cancel out. But as the baseline length increases, and even more if different antennas are used, the variations pertain and there is a significant deterioration in height determination accuracy. Advanced software methodologies are deployed to model these variations and improve the final outcome. However, it is typically recommended that traditional spirit levelling is deployed to accurately determine the orthometric height of a given site.

DEMANDING DATA POINT COLLECTION

When there is a need of collecting a vast number of data points per second, typically in order to construct 3D models or digital terrain models, laser scanner and LIDAR technologies need to be deployed. In addition, when the access to certain areas is difficult or safety considerations apply, surveying from a distance is ensured with RPAS or aircrafts.

SUSCEPTIBILITY TO INTERFERENCE

Radio interference can be defined as the reception of a mix of multiple signals with one signal being the desired signal to be received and processed and the other signals being undesired. If the undesired signals degrade, obstructs, or repeatedly interrupts the reception of the desired signal it is referred to harmful interference. The origin of the radio interference can be intentional (e.g., GNSS jammers) or unintentional (e.g., malfunctioning equipment in wireless telecom networks creating in-band spurious emissions). GNSS interference is critical for ground CORS infrastructure receivers, as well as RPAS applications. Innovative dedicated mitigation techniques within the receiver chipsets are capable to overall limit its negative effects.

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RTK - TRANSMISSION OF CORRECTIONS FROM BASE STATIONS

The RTK solutions depend on a safe, stable and sufficient transmission of corrections from base stations to calculate a precise position. This transmission is often performed by radio or over the telecommunication network. In the latter case, data transmission is often a lower priority over ordinary telecommunications (especially at peak times), thus reducing GNSS surveying equipment's uptime. Better and more continuous bandwidth for data communication will clearly improve the performance of the measurement equipment.

SENSIBILITY TO AMBIENT HUMIDITY

Additional errors are detected when surveyors perform measurements in extreme conditions and/or with big fluctuations in ambient humidity, such as in Antarctica, or at high altitudes in mountainous areas (e.g., when installing telecom antennas, repeaters) when measurements are taken at points with height difference between the reference station and the rover of orders of 600 m. If such meteorological conditions exist, one practical approach for high-precision surveying is to choose the days for GNSS observations with minimal moisture content (no higher than 12 g/m^3)[57].

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5.9 DRIVERS FOR USER REQUIREMENTS

As already presented in the previous chapters, surveying applications have the most stringent accuracy requirements, ranging from sub-centimetre to metre levels. They also rely heavily on good signal availability, integrity and reliability. The high accuracy required in several surveying applications (e.g. geodetic control surveys) as well as the high cost for the execution of certain surveying operations (e.g. mining and off-shore seabed exploration), call for GNSS-based solutions that provide good redundancy and optimal Time to First Fix (TTFF) and Time-to-Convergence (TTC).

In this context, several organisations representing professional users in different sectors (e.g. hydrography, cadastral surveying, oil & gas, geodesy, marine contractors, etc.), as well as licensing and accreditation bodies, and governmental organisations (e.g. mapping and cadastral agencies), have defined guidelines for the utilisation of GNSS-based solutions in the respective applications, while complying with regulation and/or best practices and standards.

ADDITIONAL ERRORS ARE DETECTED WHEN SURVEYORS PERFORM MEASUREMENTS IN EXTREME CONDITIONS

At the same time, as underlined in chapters 4 and 5, price-dependent technological trends are driving the evolution of GNSS performance requirements in different surveying disciplines. On one side, lie geographical regions (i.e. quickly developing countries such as India and China) and specific sectors (e.g. mapping) that can strongly benefit from the availability of efficient, low-cost GNSS solutions even if these don't meet the most demanding accuracy requirements. On the other side, capital intensive sectors such as mining and oil & gas, are heavily investing in the development of highly-sophisticated solutions that can increase productivity and profitability (e.g. through the deployment of fully autonomous haulage trucks in mining).

Apart from the purely quantitative requirements, some qualitative aspects are central to the greater uptake of GNSS solutions in the surveying sector. This concerns first and foremost interoperability and compatibility between different GNSS-solutions but also with regards to solutions combining GNSS with other technologies and sensors. As discussed in section 5.5, GNSS is often used complementarily with other technologies such as total stations, LIDAR, GIS, RPAS, etc. to perform surveying operations. In addition, in sectors such as mining significant incompatibility issues

57 http://science.lpnu.ua/sites/default/files/journal-paper/2018/jul/13632/180934geodez-30-35.pdf

apply due to the lack of standardised support infrastructure and the tailoring of positioning needs to each specific site[58]. Further sought features are robustness and high-quality of GNSS products including their main sub-components, for instance the antenna phase centre stability and the RMS of code and carrier measurements; as well as the flexibility of receivers for upgrades and re-configuration.

Taking all these aspects into account, the overview of GNSS performance requirements across different application sectors as well as some additional considerations on "qualitative" requirements are provided in Chapter 6. Prior to that and in order to provide a complete picture, policy, regulation and standards-related considerations are presented in the next section.

5.10 POLICY, REGULATION AND STANDARDS

5.10.1 POLICY AND REGULATORY STAKEHOLDERS

INSPIRE IS BASED ON THE SPATIAL INFORMATION INFRASTRUCTURES ESTABLISHED AND OPERATED BY THE 28 EU MEMBER STATES.

At **European Level**, there are several actors to be taken into consideration with respect to the surveying, geodetic and cartographic professions. These include EU policy-makers as well as associations representing the national policy-making entities:

- **The European Commission's Directorate-Generals ENV, Eurostat and Joint Research Centre** are key stakeholders in coordinating the implementation of the INSPIRE Directive;
- **Eurocadastre**[59] **- the Permanent Committee on Cadastre (PCC) in the European Union** is an association of EU Member States' official cadastral institutions;
- **EuroGeographics**[60] is a European association representing European National Mapping, Cadastre and Land Registry Authorities, currently 60 organisations from 46 countries. Its stated purpose is to further the development of the European Spatial Data Infrastructure through collaboration in the area of geographic information and the representation of its members and their capabilities.

At **National Level**, national mapping and cadastral agencies (NMCAs) are generally mandated with assuring and supervising the implementation of laws and regulations that describe state surveying (geodetic) and cadastral activities, which define the scope and requirements of the surveyors' activities in a particular country. For example, they may be responsible for defining the minimum accuracy requirements for cadastral surveys, for maintaining national networks of Continuously Operating GNSS Reference Stations (CORS), for updating and maintaining their countries' national coordinate systems, and for providing supporting INSPIRE implementation.

5.10.2 REGULATION POTENTIALLY IMPACTING GNSS USER REQUIREMENTS

National regulation governing the work of the surveying, geodetic and cartographic professions exists in most EU Member States. It is beyond the scope of this study to examine each in detail (a useful overview can be found at [RD 20]). However, as an illustrative example stemming from the interviews carried out in the process of this study, in Germany "*the law mandates cadastral accuracy of 1-3 cm and the use of open standards and interfaces" (i.e. interoperability of devices) [RD26].*

Considering European regulation, there are a number of directives and policies which potentially affect these industries, such as INSPIRE, the Public Sector Information (PSI) Directive, the Water Framework Directive, the Floods Directive, the Biodiversity Directive and the Habitats Directive, although not necessarily to the extent that GNSS user requirements are generated. The INSPIRE Directive has been examined in more detail since it is considered the most relevant instrument out of those mentioned.

INSPIRE

The European Union has undertaken to create a harmonised and standardised European spatial data infrastructure, primarily for the sharing of environmental spatial information among public sector organisations and in order to better facilitate public access to spatial information across Europe. This is being realised through Directive 2007/2/EC on establishing an Infrastructure for Spatial Information in the European Community (INSPIRE), based on the following principles:

- Data should be collected only once and kept where it can be maintained most effectively;
- It should be possible to combine seamless spatial information from different sources across Europe and share it with many users and applications;
- It should be possible for information collected at one level/scale to be shared with all levels/scales; detailed for thorough investigations, general for strategic purposes;

58 See RD13 for more information
59 http://www.eurocadastre.org/
60 http://www.eurogeographics.org/

- Geographic information needed for good governance at all levels should be readily and transparently available;
- Easy to find what geographic information is available, how it can be used to meet a particular need, and under which conditions it can be acquired and used.

The INSPIRE directive lays down a general framework for a Spatial Data Infrastructure (SDI) for the purposes of EU environmental policies. INSPIRE is based on the spatial information infrastructures established and operated by the 28 EU Member States, and addresses 34 spatial data themes needed for environmental applications. To ensure that the spatial data infrastructures of the Member States are compatible and usable in an EU and trans-boundary context, the INSPIRE Directive requires additional legislation or common Implementing Rules (IR) to be adopted for a number of specific areas, such as:

- Metadata;
- Interoperability of spatial data sets and services;
- Network services, e.g. data discovery and viewing services;
- Data specifications and data and service sharing; and
- Monitoring and reporting services.

These rules must be followed by all entities and professionals involved in creating geo-spatial information for public sector purposes. Thus, this encompasses as well mobile collection of geo-referenced spatial data using GNSS-enabled devices. INSPIRE also stipulates, that the ETRS89 coordinate system shall be used for the referencing of spatial data sets, and mandates the use of the European Vertical Reference System (EVRS) for expressing gravity-related vertical heights.

5.10.3 NON-REGULATORY SOURCES

Several of the key professional bodies of the industry, listed and described in Chapter 4.3, publish codes of conduct for their professionals, as well as issuing best practice documents and guidelines for the execution of specific tasks. The latter class of documents, although they are non-regulatory and non-binding on the professionals in question, tend to be respected in practice by the professionals in their respective fields. Furthermore, given that in the majority of EU countries, (land) surveyors are held liable for the work they perform complying with such guidelines is considered essential. Such guideline documents can therefore be seen as a potential source of user requirements, as they often supply detailed technical specifications for specific activities, imposing, for example, performance requirements for equipment such as GNSS receivers.

- **CLGE's Code of Conduct for European Surveyors** aims at reinforcing and clarifying the highest standard of professional behaviour among European Surveyors. European Surveyors are bound to respect this Code of Conduct wherever they provide their services either temporarily or permanently, regardless of their professional status. The code specifies that "European Surveyors and their employees respect and comply with all European and national laws, regulations, technical rules, accepted standards, norms and codes of practice appropriate to and required by their profession, and in relation to the services which they undertake to perform".

The following are examples of guidelines which affect the work of surveyors in various industries:

- **The RICS Black Book** is a suite of guidance notes that define good technical standards for quantity surveying and construction professionals;
- **The RICS Red Book** contains mandatory rules, best practice guidance and related commentary for RICS members undertaking asset valuations;
- **IMCA and IOGP's Guidelines for GNSS positioning in the oil and gas industry** (e.g. IOGP's Surveying and Positioning Guidance Note 4: *Use of the International Terrestrial Reference Frame as the reference geodetic system for surveying and real-time positioning*).
- **IHO Standards for Hydrographic Surveys** provides a comprehensive overview of standards for the execution of hydrographic surveys yielding data for navigational charts and marine environment protection.

5.10.4 REFERENCE SYSTEMS AND STANDARDS

The surveying, cartographic and geodetic professions rely on a number of standards, frameworks and reference systems. GNSS technologies contribute to the maintenance and update of these systems, and they are therefore included as potential sources of user requirements.

The geodetic infrastructure for precise geo-referencing (e.g. three-dimensional and time dependent positioning, geodynamics, precise navigation, geo-information) is referred to as the European Reference Frame. The definition, realisation and maintenance of the systems comprising this infrastructure is carried out by **EUREF, a sub-commission of the IAG (Reference Frame Sub-Commission for Europe of the International Association of Geodesy).** Its aim is to provide a unique and homogeneous pan-European reference system for activities related to precise geo-referencing and navigation, Earth Sciences research and multidisciplinary applications.

The two main geodetic reference systems for Europe are:

- The **European Terrestrial Reference System (ETRS89):** the single pan-Europe standard coordinate reference system, adopted by the European Commission as the recommended frame of reference for geodata for Europe;

- **The European Vertical Reference System (EVRS)**: a zero-tidal gravity-related kinematical height reference system. The latest version is EVRS2007.

These systems are supported by the following projects and activities:

- **The EUREF Permanent Network (EPN)** is a network of continuously operating GNSS reference stations covering the European continent, provided voluntarily by over 100 self-funding agencies, universities, and research institutions in more than 30 European countries;

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- **European Vertical Reference Network (EUVN)** – an integrated network of GNSS, levelling and tide gauge observations as a static height reference, which supports the periodical update of EVRS realizations (the latest one is EVRF2007)[61];
- **The European Combined Geodetic Network (ECGN),** a research project aimed at high accuracy geoid determination. The purpose of ECGN is to connect the height systems obtained via geometric positioning by GNSS with gravity-referenced heights with centimetre-level accuracy. ECGN is considered a European contribution to the **IAG's Global Geodetic Observation System (GGOS)**;
- **EUPOS (European Position Determination System)** is a European partnership of public administrations and institutes working in the field of geographic information, land surveying and geodetic surveying, aiming to establish a uniform network of DGNSS (Differential Global Navigation Satellite System) reference station systems and services

In this context, a knowledge exchange network (POSKEN) comprising of CLGE, EUPOS, EUREF and EuroGeographics has been set up in 2014 with the aim of:

- Providing a networking platform for experts
- Providing inputs for service and policy developments
- Supporting the creation of standards, guidelines and recommendations
- Assisting harmonisation issues for GNSS network operators and users
- Advertising the use of ETRS89 in Europe.

Finally, a number of standardisation organisations produce standards related to geographic information, which include requirements related to positioning, such as the **Centre for European Standardisation (CEN) and the International Standards Organisation (ISO);** the ISO/DIS 6420 standard on "Hydrometry - Position fixing equipment for hydrometric boats" is an example. FIG, IAG and ISPRS are all registered as liaison bodies for the purposes of relevant ISO activities.

5.11 CONCLUSIONS

The surveying market grows steadily driven by increased urbanisation in emerging countries, heavy investments by leading companies in capital-intensive sectors (construction, mining, oil & gas), and due to the increased availability of low-cost yet highly-performant handheld devices in mapping.

The stringent accuracy demands across the various surveying applications, have been traditionally tackled by adopting cutting-edge technological solutions. In that context, **GNSS holds a predominant place in the surveyor's toolbox**, enabling highly-accurate solutions that can be integrated with complementary technologies (e.g. total stations, laser scanners, LIDAR) and significantly support in reducing operational costs (labour, fuel, machine maintenance).

Different GNSS-based techniques are deployed for the various surveying operations (i.e. control, detail, positioning) carried out in the different disciplines (cadastral, construction, mining, mapping, hydrographic and offshore). Static GNSS techniques enable the highest precision possible, whilst real-time dynamic techniques provide very accurate solutions and improved flexibility for in-field surveyors and site managers alike. **The accuracy, reliability, availability and TTFF/TTC of GNSS-enabled solutions has been enhanced in recent years thanks to the advent of the multi-constellation and multi-frequency era, the proliferation of differential correction networks/services, and the increased affordability of high-accuracy receivers.**

Thus, GNSS-based solutions are deployed by surveyors today across a wide range of activities including, but not limited to, measuring the boundaries of land parcels, performing topographic mapping, managing a number of construction or mining vehicles (machine control) or executing off-shore seabed exploration campaigns. Taking into account the technical and economic specificities and priorities of the different surveying disciplines, **this report has provided an overview of the state-of-the art GNSS-based solutions, shed light on the current market, technology and R&D trends and outlined the key user requirements for GNSS**.

61 https://evrs.bkg.bund.de/Subsites/EVRS/EN/Projects/EUVN/euvn_cont.html

The adoption of GNSS-enabled surveying solutions is a function of the extent to which quantitative and qualitative requirements are met. In that context, improving E-GNSS positioning will require appropriate system evolution, identification and marketing of the unique proposition, as well as actions to stimulate wider acceptance by, and applicability to, the different professional users and their customised needs.

The validation of GNSS user requirements falling under both categories (quantitative/qualitative) has been pursued through targeted interviews [RD26] with representatives of key stakeholder groups and should be further enhanced in the future (first and foremost professional user groups, but also mining and oil & gas companies). Additional emphasis should be placed on users' expectations vis-à-vis the EGNSS proposition, especially in relation to the new opportunities opening by Galileo HAS and SAS, dual frequency receivers (or even multi-frequency in the wake of PPP). This, coupled with related market development activities, would allow the realisation of the full potential of E-GNSS in the technology-driven, performance-sensitive reality of the surveying sector and its evolution.

06

USER REQUIREMENTS ON THE PNT SOLUTION

In light of the considerations presented in the preceding chapter 5 regarding user requirements gathered for each application including the specificities, limitations, drivers pertaining the use of GNSS in surveying, and UCP consultation and validation with the industry ([RD33],[RD34]) this section presents a combined picture of the performance requirements on the PNT solutions across the different applications in the surveying domain.

6.1 TABLE WITH USER REQUIREMENTS ON THE PNT[62] SOLUTION[63]

Table 12: PNT requirements for surveying

Id	Description[1]	Application	Specific Application	Type	Source
GSA-MKD-USR-REQ-SURV-0010	The PNT solution shall enable the performance of static surveys with a horizontal accuracy of: 5-10mm	Cadastral and Geodesy	• National/international networks and reference frame surveys • Geodetic surveys • High-order control surveys	Performance (Accuracy)	[RD3]: RICS Guidelines [RD4]: Surveyor's General Guidelines
		Mapping	• Photogrammetry/remote sensing high-order ground control		
		Construction	• High-order control surveys		
	10-60mm	Cadastral and Geodesy	• Low-order control surveys • High-order detail surveys and positioning • DGNSS or RTK reference station positioning		
		Mapping	• Photogrammetry, photo control points • High-order topographical profiles		
		Construction	• Low-order control surveys		
	1-10m	Cadastral and Geodesy	• Temporary DGNSS reference for monitor station positioning		
		Machine Control	• Asset positioning at 3m level		
GSA-MKD-USR-REQ-SURV-0020	The PNT solution shall enable the performance of dynamic surveys with a horizontal accuracy of: 15-50mm	Cadastral and Geodesy	• Cadastral surveys; Land seismic surveys • High-order detail surveys and positioning	Performance (Accuracy)	[RD3]: RICS Guidelines [RD4]: Surveyor's General Guidelines
		Mapping	• GIS - high-precision asset positioning and attribute collection • Topographic mapping • Photogrammetry camera positioning and photo control		
		Construction	• Temporary DGNSS reference for monitor station positioning		
	1-5m	Cadastral and Geodesy	• Low-order detail surveys		
		Mapping	• GIS, asset positioning and attribute collection • Update of spatial data bases, digital mapping • Automated mapping/facilities management (AM/FM), i.e. GIS-enabled digitisation, management and analysis of data related to utilities		

62 PNT stands for Position, Navigation and Time.

63 The applicability of these requirements to the different high-level application sectors (i.e. Land Surveying, Marine Surveying, Mapping) and their individual applications (e.g. cadastral, mining, hydrographic, etc.) can be seen in Table 9.

Id	Description[1]	Application	Specific Application	Type	Source
GSA-MKD-USR-REQ-SURV-0030	The PNT solution shall enable the performance of dynamic, real-time surveys with a horizontal accuracy of: 20-80mm	Cadastral and Geodesy	• Land survey, real-time topographic detailing and profiling • Land seismic, dimensional control[2] and source positioning	Performance (Accuracy)	[RD3]: RICS Guidelines [RD4]: Surveyor's General Guidelines
		Construction	• Setting-out/staking, alignment, trajectory; • Machine control		
		Mining	• Slope stability, volumetric surveys; • Machine Control		
		Marine	• Real-time tidal monitoring • Vessel navigation - docking		
	1-5m	Mapping	• GIS, asset positioning and attribute collection		
		Hydrographic and off-shore	• Vessel positioning • Hydrographic surveys • Off-shore exploration		
		Machine Control	• Vehicle tracking and asset management		
GSA-MKD-USR-REQ-SURV-0040	The availability of the location information provided by the PNT solution fulfilling its performance requirements shall be high (>95%), including in harsh environments	All	• All	Performance (Availability)	[RD3]: RICS Guidelines [RD4]: Surveyor's General Guidelines
GSA-MKD-USR-REQ-SURV-0050	The ability of the PNT solution to provide timely warnings to the user when data provided by the system should not be used shall be Very High.	Construction	• Machine Control	Performance (Integrity)	[RD3]: RICS Guidelines [RD4]: Surveyor's General Guidelines
		Mining	• Machine Control		
		Marine Surveying	• Vessel positioning and navigation		
GSA-MKD-USR-REQ-SURV-0060	The PNT solution shall enable convergence times (time to first accurate fix) targeting a value of 30 seconds.	All	• e.g. Cadastral survey, Machine Control, Topographic Mapping, GIS mapping	Performance (Signal Quality; signal processing)	[RD29], [RD30], [RD31] 2019 update
GSA-MKD-USR-REQ-SURV-0070	The PNT solution shall provide satellite clock corrections with an update rate of 30s or better (i.e. less than 30 seconds).	Marine Surveying	• Marine cadastre • Vessel positioning • Hydrographic surveys and vessel navigation • Off-shore exploration	Performance (Satellite Clock Corrections Update Rate)	[RD22]: Rizos et al. [RD28]: Chen et al.
GSA-MKD-USR-REQ-SURV-0080	The PNT information shall be transmitted in two or more bands (E1, E5, E6) thus enabling dual or triple frequency RTK and PPP solutions.	All	All	Function (Multiple Frequencies)	[RD24]: Galileo CS GNSS High Accuracy and Authentication
GSA-MKD-USR-REQ-SURV-0090	The solution shall provide PNT information that is trustable[4]	Cadastral surveying and geodesy	• Cadastral surveys	Function (Authentication)	[RD24]: Galileo CS GNSS High Accuracy and Authentication 2019 update
		Construction surveying	• Machine control		
		Mining	• Machine control		
		Marine application	• Vessel positioning and navigation		

Id	Description[1]	Application	Specific Application	Type	Source
GSA-MKD-USR-REQ-SURV-0100	The PNT solution should provide real-time mm-level accuracy, both horizontal and vertical	Construction	• Setting-out/staking alignment • Machine Control	Accuracy	[RD33], [RD34]
GSA-MKD-USR-REQ-SURV-0130	Galileo precise orbit and clock corrections shall be available in a similar way as GPS/GLONASS are provided in the IGS Real Time Service	All	All	Functional	[RD34]
GSA-MKD-USR-REQ-SURV-0140	EGNOS Open Service should provide same level of coverage over EU member states (e.g., improve over Romania).	Mapping/GIS	All	Coverage	[RD33]
GSA-MKD-USR-REQ-SURV-0150	Documentation related to reference systems, needed data for the compliance to the INSPIRE directive (transformation from GTRF to ETRF2000) shall be available at the GSC portal.	All	All	Functional	[RD34]

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1 For more details on the different survey methods please consult Table 9.
2 Dimensional control is the technique used to accurately measure 3-D spaces to determine the area between points, creating digitally mapped distances and angles.
3 This requirement is essential for the utilisation of PPP in precise applications (cm-level).
4 The ability of the system to guarantee to the users that they are utilising navigation data that has not been modified and comes from the Galileo satellites and not from any other source.

07 ANNEXES

ANNEX 1: THE USE OF RPAS IN SURVEYING

In recent years, surveyors have been apt in recognising benefits from the use of Remotely Piloted Aircraft Systems (RPAS)[64] across a wide range of surveying activities. The use of RPAS is generally seen as a low-cost, high-yield solution that brings a number of benefits[65], including:

- **Significant reduction of surveying time**
  RPAS gather raster data from the sky - in the form of geo-referenced digital aerial images taken from different angles. When equipped with survey-grade GNSS RTK receivers, RPAS are effectively flying rovers receiving corrections from the base station, and collecting vast amounts of highly-accurate data in a very short time-frame (as compared to conventional ground methods).[66]

- **Collection of vast numbers of data**
  RPAS can collect in a short time frame millions of data points with a resolution as sharp as 1.5 cm per pixel. On top of that, RPAS-mounted cameras can produce continuous filming footage. The collected data can be issued electronically within a few hours of the survey, or if required, downloaded onto a USB while still on site.

- **Reduced health and safety risks**
  In sites such as mines, construction areas, unstable slopes or transport routes, reduced time for the execution of high-accuracy surveys and increased access (from the air), translates into minimised health and safety risks.

- **Increased access to areas hardly reached by other means**
  Areas of complex topographical features can be accurately mapped using RPAS with LIDAR or other optical sensors.

Thanks to these benefits[67], RPAS are increasingly used in a number of applications, including:

- Surveying and measurements of objects and areas to create point clouds, digital terrain modelling (DTM), digital elevation modelling (DEM) and volumetric analysis Land cover classification and mapping
- Surveying and mapping of land and infrastructure environment, including site plans, status plans and documentation of construction progress
- RPAS-based GIS applications
- Surveying and mapping of mines, gravel pits, construction sites and remote working.
- Surveying and mapping for cartography, orthophotography, topography, cadastral surveys and urban and regional development
- Inspection and survey of embankments, dams and retaining walls
- Archaeological surveys and excavation monitoring

Despite the important benefits brought on by RPAS, significant limitations related to regulation, harmonisation thereof pertain. In addition, lack of education can also be considered a significant barrier for adoption (see [RD26]). However, this trend of RPAS utilisation is definitely on the rise.

With regards to E-GNSS value proposition, and beside the relevant elements described in earlier parts of the report (i.e. increased accuracy, better availability/continuity), the integrity provided by EGNOS is of significance for the safe execution of RPAS operations. In addition, the increased accuracy and authentication features of Galileo High Accuracy Service and Signal Authentication Service could become relevant for beyond-the-line-of-sight operations.

64 Other common terms are UAV, UAS and drones.
65 https://www.sensefly.com/applications/surveying.html
66 See for instance a dedicated article comparing ground survey to drone-based survey results at http://publications.aols.org/OPS-Magazine/2015Summer/files/19.html
67 http://www.rics.org/be/news/news-insight/comment/drones-the-benefits-for-surveyors/

ANNEX 2: ANALYSIS OF PAST AND ON-GOING PROJECTS

This chapter presents an analysis of the most relevant EU-funded projects and initiatives which are either (1) focused on the technological development of specific GNSS solutions in the context of surveying, geodetics and cartography, or (2) which pave the way for the broader adoption of such solutions, potentially providing inputs for the generation of new user requirements. Thus, a significant number of projects has been developing solutions addressing GNSS performance in difficult environments (e.g. in areas with strong ionospheric disturbances); other projects have focussed on the development of software or robust components for High-Precision receivers, taking into account the unique features of Galileo signals (e.g. MBOC/AltBOC) but also multi-constellation developments. Table 12 takes stock of some of the most important projects in that context.

ANNEX 3: DEFINITION OF KEY GNSS PERFORMANCE PARAMETERS

This Annex provides a definition of the most commonly used GNSS performance parameters, coming from [RD32] and is not specifically focusing on the Surveying community.

Availability: the percentage of time the position, navigation or timing solution can be computed by the user. Values vary greatly according to the specific application and services used, but typically range from 95-99.9%. There are two classes of availability:

- System: the percentage of time the system allows the user to compute a position – this is what GNSS Interface Control Documents (ICDs) refer to
- Overall: takes into account the receiver performance and the user's environment (for example if they are subject to shadowing).

Table 13: Projects which could potentially be supported by GNSS

Technologies used	Project Acronym	Funding	Key Objective(s)	Applied GNSS Solution
GNSS	PARADISE	H2020 (GSA)	Develop a solution that makes survey-grade GNSS-based positioning available in situations where to date GNSS could not be adopted due to prohibitively bad signal conditions, such as indoors, urban canyons, forests etc.	Improved GNSS signal processing together with an adapted and highly performing precise-point-positioning (PPP) algorithm
GNSS, EO	COREGAL	H2020 (GSA)	Development of an innovative Galileo-based positioning platform enabling low-cost, high-accuracy and unprecedented use of airborne GNSS-Reflectometry (GNSS-R) for biomass retrieval.	Combination of Earth Observation (EO) data (e.g. satellite imagery), regional data (e.g. airborne imagery and GNSS-based remote sensing data) and, when available, local data (in situ measurements) to improve current biomass estimation algorithms
GNSS	ADVANSYS	EU FP7	Develop a prototype of an affordable high-sensitivity high-resilience hybrid receiver concept comprising antenna, GNSS receiver and dead-reckoning sensors.	Multi-antenna beamforming technology and multi-sensor fusion
GNSS, LIDAR	ATENEA	EU FP7	Integrate GNSS/INS receiver architectures and LIDAR techniques to provide an advanced navigation solution for a wide range of surveying applications in difficult environments.	Integrated GNSS/INS/LIDAR navigation filter, EGNOS ephemeris for hybridisation applications.

Technologies used	Project Acronym	Funding	Key Objective(s)	Applied GNSS Solution
GNSS	SIGMA	EU FP7	(1) The development of a simulation and testing platform providing the means to develop and validate new GNSS (multi-constellation) algorithms; (2) Development, implementation and test of high-accuracy algorithms based on Precise Point Positioning techniques (PPP) for multiconstellation environments; (3) Implementation of innovative mitigation techniques for multipath and interference; (4) Development and implementation of advanced integrity techniques based on multiconstellation scenarios (Advanced RAIM).	Integration of GNSS and GPS
GNSS	PRECISIO	EU FP7	Development of a software-based satellite navigation receiver capable of receiving and processing signals from multiple existing and future GNSS (GPS, GLONASS, Galileo, Compass).	Development of a Software Defined Radio (SDR) GNSS receiver
GNSS	mapKITE	H2020 (GSA)	Develop a mature EGNSS-enabled prototype of a novel tandem terrestrial-aerial mapping system based on a terrestrial vehicle (TV) and on an unmanned aircraft (UA), both equipped with remote sensing payloads.	Leverages EGNOS and the unique features of the Galileo signals, such as E5 AltBOC
GNSS	ENCORE	EU FP7	Develop a high-precision and low-cost land management (urban and rural cadastre as well as geo-referencing) application based on Galileo signals, using novel Galileo signal characteristics.	Utilisation of MBOC/AltBOC signals
GNSS	CALIBRA	EU FP7 (GSA)	Develop and implement algorithms tailored for high precision carrier phase GNSS based applications in order to tackle the effects of ionospheric disturbances.	Mitigation of ionospheric disturbances
GNSS	I2GPS	EU FP7	Developing a novel, integrated approach to the use of synthetic aperture radar interferometry (InSAR) and GNSS for use in the monitoring of subsidence, tectonic changes or other environmental hazards, which can only be identified by millimetre-precision surveying techniques	Integrating the antenna of a GNSS receiver with a Compact Active Transponder antenna to ensure millimetric co-registration and assure a coherent cross reference between the two precision surveying techniques
GNSS	CIGALA	EU FP7	Develop and test ionospheric scintillation mitigation approaches to be implemented in professional multi-frequency GNSS receivers.	Receiver-level counter-measures for GPS and Galileo signals (E1, E5a, E5b, E5 AltBOC)

Technologies used	Project Acronym	Funding	Key Objective(s)	Applied GNSS Solution
GNSS	SX5	EU FP7	Develop a software application for precise positioning based on an E5 Galileo receiver primarily targeting scientific users.	Use of Galileo E5 signal for combined "code-and-carrier positioning" for higher accuracy
GNSS	GAL	EU FP7	Develop a methodology to determine precise and high-resolution gravity field models through Kinematic Airborne Gravimetry (KAG), with the joint use of EGNOS, GPS, Galileo and strapdown Inertial Measurement Units (IMUs), and its further integration with GOCE global models.	KAG-GNSS/INS uses the IMU as a gravimeter and the GNSS receiver to determine the geometric accelerations.
GNSS	HANDHELD	EU FP7	Develop a portable standalone system to harvest the possibilities of precise positioning offered by Galileo, including the development of an innovative GNSS antenna with electronically adjustable matching, controlled by the receiver, and strong filtering to avoid auto-interference from the Bluetooth and WLAN transceivers in the PDA.	Galileo for precise positioning, replicating classical survey equipment (high-end antenna, pole, receiver and controller), in one portable device.
RPAS, DGNSS	PUMPED	EU EASME	Provision of a low-cost real-time precise navigation solution based on GNSS for RPAS. The accuracy offered by PUMPED will lie between 10cm and 50cm.	Precise navigation by applying DGNSS techniques with low profile GNSS chipsets (often used in RPAS platforms)
GNSS, DGNSS, EG-NOS	MONITOR	EU FP6	Demonstrate, via pilot projects, the use of GNSS for environmental and civil engineering monitoring	EGNOS and GPS/Galileo for monitoring buildings in landslide areas, bridges and construction workers and machines.
GNSS, GIS, Augmented Reality	LARA	H2020	Promote innovation based on the use of Galileo and EGNOS, sensor technologies and LBS monitor, document and manage utility infrastructures' data with an intuitive 3D augmented visualisation and navigation/positioning technology	EGNOS and GPS/Galileo for guiding utility field workers by helping them 'see' beneath the ground, rendering the complexity of the 3D models of the underground grid such as water, gas and electricity.

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 centimeters 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. For safety-of-life-critical applications such as passenger transportation, the "integrity concept" is generally mature, and integrity can be described by a set of precisely defined and measurable parameters. This is particularly true for civil aviation. For less critical or emerging applications, however, the situation is different, with an acknowledged need of integrity but no unified way of quantifying or satisfying it. 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.

Robustness to spoofing and jamming: robustness is a qualitative, rather than quantitative, parameter that depends on the type of attack or interference the receiver is capable of mitigating. It can include authentication information to ensure users that the signal comes from a valid source (enabling sensitive applications).

Note: 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 or spoofing.

Indoor penetration: ability of a signal to penetrate inside buildings (e.g. through windows). Indoor penetration does not have an agreed or typical means for expression. In GNSS, this parameter is dictated by the sensitivity of the receiver, whereas for other positioning technologies there are vastly different factors that determine performance (for example, availability of Wi-Fi base stations for Wi-Fi-based positioning).

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:

- Cold start: the receiver has no knowledge of the current situation and thus has to systematically search for and identify signals before processing them – a process that typically takes 15 minutes.
- Warm start: the receiver has estimates of the current situation – typically taking 45 seconds.
- Hot start: the receiver knows what the current situation is – typically taking 20 seconds.

Latency: the difference between the time the receiver estimates the position and the presentation of the position solution to the end user (i.e. the time taken to process a solution). Latency is usually not considered in positioning, as many applications operate in, effectively, real time. However, it is an important driver in the development of receivers. This is typically accounted for in a receiver, but is a potential problem for integration (fusion) of multiple positioning solutions or for high dynamics mobiles.

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. For example, GPS chips will use more power when scanning to identify signals (cold start) than when computing position. Typical values are in the order of tens of mW (for smartphone chipsets).

ANNEX 4: SYNTHESIS OF SURVEYING USER REQUIREMENTS

The detailed and overall synthesis of Surveying User Requirements is provided in joint MS Excel workbook.

Content text updated in 2019

ANNEX 5: LIST OF ACRONYMS

AHTS	Anchor Handling Tug Supply
AltBOC	Alternative Binary Offset Carrier
AUTH	Authentication – referring to Galileo Signal Authentication Service
CAGR	Compound Annual Growth Rate
CEN	Centre for European Standardisation
CLGE	Council of European Geodetic Surveyors
CORS	Continuously Operating Reference Stations
CS-HA	Commercial Service High Accuracy
DEM	Digital Elevation Modelling
DGNSS	Differential GNSS
DTM	Digital Terrain Modelling
EASME	Executive Agency for Small and Medium-sized Enterprises
ECGN	European Combined Geodetic Network
EGNOS	European Geostationary Navigation Overlay Service
EGNSS	European GNSS
ENV	Refers to European Commission's DG Environment
EPN	EUREF Permanent Network
EUPOS	European Position Determination System
EUROGI	European umbrella organisation for Geographic Information
EVRS	European Vertical Reference System
FIG	International Federation of Surveyors
GDOP	Geometric Dilution of Precision
GDP	Gross Domestic Product
GGOS	IAG's Global Geodetic Observation System
GIS	Geographic Information System
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GSA	European GNSS Agency
IAG	International Association of Geodesy
ICES	Chartered Institution of Civil Engineering Surveyors
ICSU	International Council for Science
IFHS	International Federation of Hydrographic Societies
IGS	International GNSS Service
IHO	International Hydrographic Organisation
IMCA	International Marine Contractors Association
IMU	Inertial Measurement Unit

INS	Inertial Navigation System
INSPIRE	Infrastructure for Spatial Information in the European Community
IOGP	International Association of Oil & Gas Producers
ISM	International Society for Mine Surveying
ISO	International Standards Organisation
ISPRS	International Society for Photogrammetry and Remote Sensing
IUGG	International Association of Geodesy and Geophysics
KAG	Kinematic Airborne Gravimetry
LBS	Location-Based Service
LIDAR	Light Detection And Ranging
MBES	Multibeam echo-sounders
MBOC	Multiplexed Binary Offset Carrier
MEMS	Microelectromechanical systems
OEM	Original Equipment Manufacturer
PARLS	Publicly Appointed and Regulated Liberal Surveyors
PCC	Permanent Committee on Cadastre (under Eurocadastre)
PDA	Personal Digital Assistant
POSKEN	Positioning Knowledge Exchange Network
PPP	Precise Point Positioning
PSI	Public Sector Information (Directive)
RAIM	Receiver autonomous integrity monitoring
RICS	Royal Institution of Chartered Surveyors
RMS	Root Mean Square
RPAS	Remotely Piloted Aircraft System
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematic
SAPOS	Satelliten Positionierungsdienst
SBAS	Satellite-based augmentation system
SDI	Spatial Data Infrastructure
SDR	Software Defined Radio
TTC	Time-to-Convergence
TTFF	Time to First Fix
UCP	User Consultation Platform
USB	Universal Serial Bus
VBS	Virtual Base Station
WGS84	World Geodetic System 1984
WLAN	Wireless Local Area Network

ANNEX 6: UPDATES FOLLOWING THE USER CONSULTATION PLATFORM 2018

As per EUSPA document reference GSA-MKD-MS-UREQ-250284 available here.

ANNEX 7: UPDATES FOLLOWING THE USER CONSULTATION PLATFORM 2020

As per GSA document reference EUSPA-MKD-MS-UREQ-250284 available here.

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