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Advanced Multi-Constellation EGNSS Augmentation and Monitoring Network and its Application in Precision Agriculture

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Abstract:

The European Horizon2020 project "AUDITOR" will focus on an advanced multi-constellation EGNSS augmentation and monitoring network and test corresponding systems in precision agriculture. Deliverable 1.1 sets the basis for the project execution by analysing the state of the art in GNSS receivers, networks and services that will be used as a reference for future development and by analysing the state of the art in precision agriculture with specific reference to location-based services as applicable in areas with poor EGNOS coverage. This document provides comparisons of different GNSS receivers and augmentation solutions and its corresponding applications in precision agriculture that will set the boundaries for the technical tasks by giving a commercial context to the purely technical work.

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Executive Summary

Nowadays, mainly NRTK techniques (but also PPP) solutions are offering multiple specific services to agriculture users. This is an expanding market where providers claim to enable subdecimeter accuracy positioning with reduced convergence time, as precise positioning will play a determinant factor in future autonomous agriculture. Upcoming developments in precision agriculture, like agricultural robots, UAV and smart sensing devices, will require small-sized, accurate, robust and cheap GNSS receivers to enable geo-referencing. Portable receivers, either as handheld devices or smart-antenna products are gaining popularity, while maintaining small form factors integrate more and more sophisticated capabilities and extra external interfaces. The emergence of more affordable, dual-frequency and multi-constellation receivers, as well as evolutions of RTK/PPP solutions, will probably support this upcoming trend. In this context, AUDITOR could benefit from aspects such as portable and accurate receivers together with augmentation systems with larger baselines for a wider reach to allow decimetre accuracy positioning even in areas with poor EGNOS coverage.

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List of Acronyms and Abbreviations

Term	Description
1-PPS	Pulse per Second
ARNS	Aeronautical Radio Navigation Service
ASRC	Automatic Section or Row Control
CAN	Controller Area Network
CDMA	Code division multiple access
DDC	Display Data Channel
DGPS	Differential GPS
EGNOS	European Geostationary Navigation Overlay Service
ESA	European Space Agency
FMIS	Farm Management Information Software
LAAS	Local Area Augmentation System
GBAS	Ground-Based Augmentation System
GEO	Geostationary Earth orbit
GES	Geostationary stations
GLONASS	Global’naya Navigatsionnaya Sputnikovaya System
GMS	Ground Monitoring Stations
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
INLUS	Indian Land Uplink Station
INMCC	Indian Master Control Center
INRES	Indian Reference Stations
JTAG	Joint Test Action Group
LNA	Low-noise amplifier
MCC	Mission Control Centers
MCS	Master Control Station
MEO	Medium Earth orbit
MRS	Monitor and Ranging Station
NLES	Navigation Land Earth Stations
OEM	Original Equipment Manufacturer

PA	Precision Agriculture
PPS	Precise Positioning Service
RIMS	Ranging & Integrity Monitoring Stations
RNSS	Radio Navigation Satellite Systems
RTCM	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematic
SPI	Serial Peripheral Interface Bus
TT&C	Tracking Control (stations)
VRA	Variable Rate Applications
WAAS	Wide Area Augmentation System
WM	WAAS Master Station
WRS	Wide Area Reference Stations

1. Introduction

The European Horizon2020 project "AUDITOR" will focus on an advanced multi-constellation EGNSS augmentation and monitoring network and test corresponding systems in precision agriculture. The objective of AUDITOR is to develop an improved GNSS ground-based augmentation system and secondly to deliver services in precision agriculture based on the new augmentation system. The GNSS augmentation system will implement novel precise positioning techniques with modern and proven algorithms in highly configurable, cost-effective receivers. These new receivers will enable cost-effective precision agriculture services to farmers, especially those with small and medium-sized businesses in areas of Europe where EGNOS coverage is poor.

Deliverable 1.1 sets the basis for the project execution by analysing the state of the art in GNSS receivers, networks and services that will be used as a reference for future development and by analysing the state of the art in precision agriculture with specific reference to location-based services as applicable in areas with poor EGNOS coverage.

This document provides comparisons of different GNSS receivers and augmentation solutions and its corresponding applications in precision agriculture that will set the boundaries for the technical tasks by giving a commercial context to the purely technical work. This deliverable will also be used as input for work package 8 ("Demonstration and field trials").

2. State of the art in GNSS receivers (ACORDE)

2.1 GNSS market overview

2.1.1 GNSS Systems

Currently there are two operational GNSS systems, GPS and GLONASS and two in-development Galileo and BeiDou that is expanding its coverage from regional coverage to global both expected to be fully functional in 2020. A brief summary of these different GNSS systems [2]-[9] is presented in Table 2.1.

Table 2.1: Main GNSS systems

System	**GPS**	**GLONASS**	**Galileo**	**BeiDou**
Owner	United States	Russian Federation	European Union	People's Republic of China
Site	www.gps.gov	www.glonass-iac.ru	www.gsa.europa.eu	en.beidou.gov.cn
Type	Military	Military	Civilian Commercial	Military Commercial
Coding	CDMA	FDMA	CDMA	CDMA
Orbital altitude	20,180 km	19,130 km	23,222 km	21,150 km
Precision	5 m	5 – 10 m	1 m 0.01 m encrypted	10 m 0.1 m encrypted
Period	11.97 h	11.26 h	14.08 h	12.63 h
Nº satellites	**31** (at least 24 by design)	**28** (at least 24 by design),including:24 operational **2** under check by the satellite prime contractor **2** in flight tests phase	**4** in-orbit validation satellites + **8** full operation capable satellites in orbit **22** operational satellites budgeted	**5** geostationary orbit (GEO) satellites **30** medium Earth orbit (MEO) satellites
Status	Operational **1995**	Operational **2015**	In development **2020**	Operational (*regionally* **2012**) In development (global **2020**)

Already operational systems (GPS/GLONAS) provide less location precision than future solutions expect to achieve and they were deploy to support military applications. Although they are currently also used in civilian solutions, it is subject to operational restrictions.

Galileo system is the only one created for civilian applications and will provide the best public precision (1 m) and encrypted (1 cm subject to fees).

A summary of the GNSS systems with global coverage is shown in Figure 2.1 they are all located in the 1151 - 1610 MHz range.

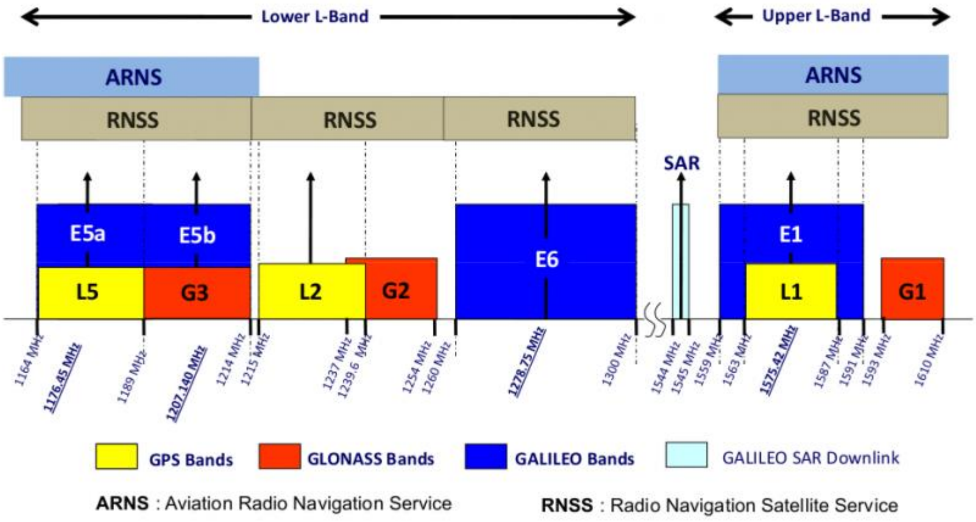

Figure 2.1: GNSS systems and bands ([1])

They are divided into two services related band:

- ARNS (1151 - 1214MHz, 1559 - 1610 MHz): Aeronautical Radio Navigation Service, oriented to Safety-of-Life applications.
    - Bands: **L1**, **L5** (GPS); **E1**,**E5** (Galileo); **G1**, **G3** (GLONASS)
- RNSS (1215.6 - 1350 MHz): Radio Navigation Satellite Systems, related to ground radars more vulnerable to interferences.
    - Bands: **L2** (GPS); **E6** (Galileo), **G2** (GLONASS)

2.1.2 Main augmentation systems

Augmentation systems improve location accuracy or integrity by adding external information to the GNSS system. Depending on the source of the augmentation and coverage information these systems can be divided into:

- Ground-Based Augmentation System (GBAS): additional information provided by ground infrastructure at a local augmentation (airport area).
    - The initial implementation was developed by United States Local Area Augmentation System (LAAS) and is currently available in several international airports (Bremen and Frankfurt, Germany; Sydney, Australia; Malaga, Spain; Zurich, Switzerland; and 15 Russian locations).
- Satellite-based Augmentation Systems (SBAS): additional information provided by geostationary satellites at global (wide area).
    - Multiple SBAS systems [2]-[9] currently coexist which are detailed in Table 2.2.
    - Satellite signals are the main information source but ground segment infrastructure is also required to measure, process and broadcast augmentation data.
    - EGNOS is the only one augmentation solution targeting the Galileo system and targets wider markets.
    - Multiple solutions combine GPS/GLONASS signals to provide augmentation data.
    - Most of augmentation solutions are provided by the countries/regions that support their GNSS infrastructure.

Table 2.2: Main augmentation systems

System	WAAS	EGNOS	MSAS	QZSS	SDCM	GAGAN	StarFire
Full Name	Wide Area Augmentation System	European Geostationary Navigation Overlay Service	Multi-functional Satellite Augmentation System	Quasi-Zenith Satellite System	System for Differential Corrections and Monitoring	GPS Aided GEO Augmented Navigation	StarFire™
Site	www.nstb.tc.faa.gov	www.egnos-portal.eu	global.jaxa.jp	qzss.go.jp global.jaxa.jp	www.sdcm.ru	www.isro.gov.in	www.navcomtech.com
Owner	United States	ESA, UE, Eurocontrol	Japan	Japan	Russian Federation	India	John Deere Co.
GNSS System	GPS	GPS, Galileo	GPS	GPS	GPS, GLONNAS	GPS	GPS, GLONNAS
Ground Segment	WRS: Wide Area Reference Stations WMS: WAAS Master Station GES: Geostationary stations	RIMS: Ranging & Integrity Monitoring Stations MCC: Mission Control Centers NLES - Navigation Land Earth Stations	MCS: 4 Master Control Station GMS: 2 Ground Monitoring Stations MRS: 2 Monitor and Ranging Station	MCS: Master Control Station TT&C: Tracking control stations Monitoring stations	19 + 5 Reference stations Central processing facilities and uplink stations and terrestrial broadcast means.	INRES: 15 Indian Reference Stations INMCC: 2 Indian Master Control Center INLUS: Indian Land Uplink Station	40 GNSS reference stations 2 Redundant processing centers and uplink channels
Enhance Accuracy	7 m	3 m horizontal 4 m vertical	2.2 m	1 m	4 – 7 m horizontal 10 – 15 m vertical	3 m	5 cm
Main Markets	Aviation	Aviation, Road, Agriculture, Mapping, Maritime, Location Based	Aviation, Location-Based	Mobile Applications		Aviation	Road, Agriculture
Main Benefits	Accuracy for precision approach. Increase of availability. Integrity.	Accuracy, Integrity (GPS satellite orbits, Clock errors, Estimate errors due to Earth's ionosphere) Synchronization wit UTC	Accuracy, Integrity, Availability	Fully GPS integration High Accuracy (cm) Stable positioning even in urban or mountainous regions Supports safety and security from space via two message services.	Accuracy, Integrity monitoring (on-line, a posteriori) Error due to ionospheric/ tropospheric effects, ephemeris, clock-and-frequency corrections	Enhance reliability and accuracy for air traffic: Improved efficiency, Increased fuel savings, Direct routes, Reduced work load of flight crew and air traffic controllers, Improved safety, Ease of search and rescue operation	High Accuracy (cm), Reliability (99.999% uptime) Single provider of both GSBAS signal service and GNSS products. Global subscription service (no region limitation)

2.1.3 GNSS Features and Functionalities

Current GNSS receivers integrate multiple features and functionalities that users must evaluated for their specific area of application:

- GNSS system: support for one or more of the GNSS of section 2.1.1 and band support: GPS (L1,L2,L5) , GLONASS (G1, G2, G3) , Galileo (E1,E2,E5a,E5b, E6), BeiDou (B1, B2, B3), IRNSS (L5, S5),
- SBAS Augmentation: methods for improving or "augmenting" navigation system performance, such as integrity, accuracy, availability. Can be a custom proprietary technology or a implementation of one or more of section 2.1.2
- Positioning Rate: location update rate, common values are 1-100Hz.
- Precision/Accuracy: sub-meter, 1-10 meters, 10-100 meters
- Form Factor & Enclosure: depending on the GNSS receiver it can be provided as a single chip/module (also known as OEM) or as a full standalone product. In this case either a compact/small handheld case, rugged or rack station 1U/2U enclosure is usually available.
- GPS channels: The number of hardware channels to scan satellite messages simultaneously common values are 12, 16, 32…88,100+
- Multiband antenna: capability to establish multiple links in different frequency, common values dual or triple bands.
- Differential GPS (DGPS) enabled: enhances location accuracy in GPS from 15m to ~10cm by using a fixed a fixed network of ground-based reference stations.
- Real Time Kinematics (RTK) enabled: enhances precision of positioning by using measurements of the phase of the signal's carrier.
- Multipath mitigation: efficiently mitigate multipath effects. Common methods are narrow correlator, the strobe correlator, the Multipath Estimating Delay Lock Loop (MEDLL), Multipath Elimination Technology (MET), the Multipath Mitigation Technology (MMT), and the Vision Correlator (VC)
- Receiver Autonomous Integrity Monitoring (RAIM): eliminate faulty satellites by monitoring GNSS signals or integrity parameters of SBAS.
- Interference mitigation: embed subsystems to implement anti-jamming solutions.
- Code Differential Rover: receives code differential corrections in RTCM 2.x format from up to five base stations simultaneously.
- Code differential Base: transmits code differential corrections in RTCM 2.x format. It is also called DGPS when referring to GPS only.
- External interfaces: multiple wired interfaces to allow external management and data analysis are provided, commonly a subset of: RS232, RS422, USB 2.0, CAN, GPIO, I2C, SPI, JTAG, Ethernet, DDC (I2C)
- Data output: low level data interfaces that can output 1-PPS, IRIG timecode or raw samples.
- Other Features: active antenna, additional LNA, Geoid/Magnetic variation model, Datums support, data logging capabilities, programmable (user FLASH memory), sensitivity improvements (noise levels), long autonomy (integrated batteries), deployment efforts.

2.1.4 GNSS receivers manufacturers

Multiple manufacturers provide either GNSS receiver modules and/or full closed solutions; the following list enumerated the main providers for these elements and the location of the specific products sections:

- Ashtech/Trimble http://www.trimble.com/mappingGIS/GNSS-Receivers.aspx
- Leica/Novatel http://www.novatel.com/products/gnss-receivers/
- Topcon/Sokki http://us.sokkia.com/es/productos/receptores-gnss
- Hemisphere GNSS https://hemispheregnss.com/Products
- JAVAD GNSS https://www.javad.com/jgnss/
- Septentrio http://www.septentrio.com/products/gnss-receivers
- Navcom Technology http://www.navcomtech.com/navcom_en_US/
- Furuno http://www.furuno.com/en/products/gnss-module/
- GMV http://www.gmv.com/en/space/Satellite_navigation_systems/
- Ublox https://www.u-blox.com/en/position-time
- Tallysman http://www.tallysman.com/index.php/gnss/products/

2.2 GNSS receivers

In this section a detailed list of the main commercial GNSS receivers from the manufacturers presented in section 2.1.4 are presented.

The different currently available GNSS solutions are listed and categorized following manufacturers taxonomies:

- Products: full products ready for end-users that could provide complete GNSS systems with multiple receivers and extended capabilities.
- Receivers: receiver modules for end-users usually provided in small-factor to ease mobility
- OEM receivers: system-on-chip for integrators that provided complete GNSS receivers.
- Ref. receivers: receivers used as reference measurement equipment's to assist in system integrators
- Boards: hardware development kits for integrators

For each manufacturer their products are listed, specifying the type of solution, number and the list of commercial names. Some manufacturers included product comparison resources for their own solutions that are also listed here:

- Ashtech/Trimble:
  - **Products** (**6**): R2 GNSS receiver, Pro 6H receiver, Pro 6T receiver, GPS Pathfinder ProXRT receiver, R1 GNSS receiver
  - **Comparison**: http://www.trimble.com/mappingGIS/media/product_comparison/GNSS%20Receivers.html
- Leica/Novatel:
  - **OEM6 Receivers (6):** Scalable positioning options and low latency positioning with high data rates, GPS, GLONASS, Galileo and BeiDou
  - **OEMStar Receivers (1):** Low Cost, L1 GPS+GLONASS Receiver Enhances Satellite Availability & Positioning, GPS, GLONASS,

- Topcon/Sokkia:
    - **Products (5):** Receptor GCX2, Smartphone GHX2 RTK, Receptor GRX2, Station SATELLINE-EASy Pro, Reference Receptor GNR5
- Hemisphere GNSS:
    - **Products (6):** S321 GNSS Survey Smart Antenna, AtlasLink GNSS Smart Antenna, A101 Smart Antenna, A325 GNSS Smart Antenna, R330 GNSS Receivers, S320 GNSS Survey Receiver
    - **OEM (6):** Crescent P102/P103, Crescent P206/P207, Eclipse P306/P307
- JAVAD GNSS:
    - **OEM (14):** TRH-G2, TR-G2,TR-G2T, TR-G3, TR-G3T, TRE-G2T, TRE-G3T, TRE-G3TAJT, TRE-3, TRE-3N, DUO-G2, DUO-G2D, DUO-G3D, QUATTRO-G3D
    - **Receivers (13):** TRIUMPH-LS, TRIUMPH-2, DELTA-3, TRIUMPH-VS, TRIUMPH-1M, TRIUMPH-1, TRIUMPH-4X, Alpha 2, Alpha, Delta, Sigma, TyrAnt, GISmore
- Septentrio:
    - **OEM (8):** AsteRx4 OEM, AsteRx-m OEM, AsteRx-m UAS, AsteRxi OEM, AsteRx2e OEM, AsteRx2e OEM, AsteRx2eL OEM, AsteRx3 OEM, AsteRx2eH OEM
    - **Receivers (8):** AsteRx-U, AsteRx-U MARINE, AsteRx2eL HDC, AsteRx3 HDC, AsteRx2eH PRO, AsteRx-i HDC, APS-U
    - **Smart Antennas (4):** APS-3L, APS-3G, Altus NR2, Altus GeoPod
    - **Ref Receivers (4):** PolaRx5, PolaRx4, PlaRx4TR, PolaRxS
- Navcom Technology:
    - **Services (3):** StartFire, RTK Extend, Ultra RTK
    - **Boards (1):** Sapphire
    - **Receivers (2):** SF-3040, SF-3050
- Furuno:
    - **Receivers (8):** GN-87, GN-86, GN-8241, GV-87, GT-87, GT-86, GN-8736, GT-8536
- EOS:
    - **Products (3):** Arrow Lite, Arrow 100, Arrow 200
    - **Comparison**: http://www.eos-gnss.com/comparison-charts/
- GMV:
    - **Receivers (4):** srx-10, srx-10i, srx-20g, nusar
- Ublox:
    - **Receivers (13):** MAX-M8C/Q/W, NEO-M8Q/M, NEO-M8N, LEA-M8S, EVA-M8M, CAM-M8, MAX-7, NEO-7, PAM-7Q, EVA-7M,
- Tallysman:
    - **Receivers (2):** TW5340, TW5341

A summary of this product survey is shown in Table 2.3 related to the type of GNSS products and GNSS/SBAS systems offered from the previous manufacturers.

Table 2.3: Product Survey

Manufacturer	OEM Boards	Handheld Products	Antenna Products	Reference Equipment	Multi-Frequency	Multi-Constellation	SBAS enabled	Submeter Accuracy	Support Software
Trimble		X	X		X	GPS GLONASS	WAAS EGNOS MSAS GAGAN	X	X
Novatel	X	X		X	X	GPS GLONASS Galileo BeiDou	SBAS	X	
Sokkia		X	X	X	X	GPS GLONASS	SBAS		
Hemisphere GNSS	X		X		X	GPS GLONASS Galileo BeiDou	SBAS	X	X
JAVAD GNSS	X	X	X		X	GPS GLONNASS Galileo BeiDou	WAAS EGNOS	X	X
Septentrio	X	X	X	X	X	GPS GLONNAS Galileo COMPASS	TerraStar	X	
Navcom	X	X	X	X	X	GPS GLONNAS	WAAS EGNOS MSAS GAGAN StarFire	X	X
Furuno	X		X		X	GPS GLONNAS	QZSS, SBAS		
EOS		X			X	GPS GLONASS BeiDou Galileo	SBAS	X	
GMV	X			X		GPS Galileo	SBAS		X
Ublox	X					GPS GLONASS BeiDou Galileo		X	
Tallysman			X	X	X	GPS GLONASS			

2.3 Future trends identification

GNSS evolutions are expected in the coming years:

- GNSS multi-frequency operations (already dual, triple bands).
- GNSS multiple-constellation operations (e.g. GPS, GLONNASS, Galileo, BeiDou).
- EGNOS and MSAS reference network expansion.
- SDCM and GAGAN become fully operational.
- Galileo become fully operational.
- GNSS coverage and reliability is expected to be improving due to the increase of orbital satellites.
- Increase of potential markets for smartphone, road, surveying and agriculture applications and grow of precise positioning mass market [11].

SBAS future trends are targeting the two main areas:

- Interoperability between existing SBAS systems: crossing SBAS service areas, geo selection of system, geo ranging…
- Interoperability for future SBAS:
    - SBAS increase of multi-constellation solutions (e.g., GPS and GLONNAS).
    - SBAS increase of multi-frequency solutions (L1, L5, L1/L5).
    - Potential evolution towards a combination of SBAS and RAIM techniques.
    - Increase of global networks and services (e.g. Starfire, Trimble)

According to the Interoperability Working Group (IWG) of when these evolutions are completed the global SBAS coverage is expected to increase from the actual 7.54% at 99% (only WAAS, EGNOS and MSAS) to 92.65%, considering the use of multiple-constellation (GPS and Galileo) [12].

GNSS solutions are evolving increasing their computing power, GNSS channels and reducing their size and consumption. These allow providing increase mobility and integrating better augmentation technologies reducing setup times and improving location update rates.

3. State of the art in precise GNSS positioning (UPC)

Professional users with the need to run precise applications cannot rely on the performance of the GPS Standard Positioning Service (SPS). As outlined in Li 2016 [24], these are applications such as atmospheric water vapor sensing, earthquake and tsunami monitoring), ocean-tide measurement, precision agriculture, lane identification as well as many other remote sensing applications.

Precise positioning in GNSS usually refers to decimetre and sub-decimetre positioning accuracy. In order to allow for such a precision, it is necessary to work with GNSS carrier-phase measurements to benefit from their low noise at the level of few millimetres ($\sigma_{\epsilon L} \cong 2\ mm$). Because carrier-phase measurements are derived from the integrated Doppler (i.e. the number of cycles of Doppler shift that have occurred from the receiver's phase lock), an ambiguity term is given. For precise positioning, it is necessary to constrain (fixing if possible to its real value) the ambiguity term. Its estimation (ambiguity resolution, AR; see section 3.8) is carried out in the navigation filter together with the modelling of multiple sources of errors affecting GNSS signals (see the following section 3.1).

Nowadays, several approaches are considered for precise positioning. In this context, two main general concepts can be distinguished: Real Time Kinematic (RTK) and Precise Point Positioning (PPP). These are based on using GNSS carrier-phase measurements and working on differential or undifferenced GNSS positioning, respectively.

In particular, the Wide Area Real Time Kinematic (WARTK) and the Fast Precise Point Positioning (FPPP) will be covered in more detail in sections 3.4.3 and 3.5.2, respectively.

3.1 Main sources of errors and useful information

In order to allow for precise positioning, the GNSS carrier-phase measurements modelling should take into account various terms commonly accounted for within the pre-processing stage. The main generic terms are the following ones:

- Ionosphere delay: for (1) large temporal and spatial scale ionosphere, and (2) for irregularities: source of error for single-frequency users, and mostly useful information for multi-frequency ones
- Satellite orbits
- Satellite and receiver clocks
- Tropospheric delay
- Cycle slips
- Multipath
- Relativistic clock error
- Wind-up
- Thermal noise

These sources of errors should be cancelled out whenever possible (such as by applying double differences) or mitigated as much as possible by an appropriate modelling to facilitate high accuracy GNSS positioning.

It is also important to remark that carrier-phase GNSS measurements are much more precise than pseudorange measurements. Nonetheless, in case of using phase observables, it is necessary to cope with an ambiguity term that should be constrained (see section 3.8 for details), among the phase wind-up (very precisely known in advance for a static antenna, but not for a moving one).

In the concept adopted in AUDITOR, some of these errors will be cancelled out and others will be estimated using a network of GNSS tracking stations at a Central Processing Facility (CPF) and transmitted to users in the form of correction messages. Some of the sources of errors are briefly described below.

Ionospheric delay

As the GNSS signals propagate through the ionosphere, the signals are affected by the free electrons in terms of a code delay and phase advance. The density of the free electrons, and therefore the delay through its integral, varies with location, time-of-day, angle of transmission through the ionosphere, and solar activity (please refer to section 3.2 for further details).

Satellite orbits

The coarse orbital parameters, together with the coarse models of satellite clocks errors, are transmitted in the navigation message in order to derive the satellite position at the transmission time. The precise predicted orbits can be downloaded several hours in advance from International GNSS Servers (*ultrarapid* orbits).

Satellite and receiver clocks

The estimation of satellite and receiver clock errors are of key relevance due to the clock synchronism errors referring to GPS time scale. On the one hand, the offset of the satellite clocks can be roughly calculated in the short term using a polynomial expression from the clock parameters transmitted in the navigation message (clock bias, drift and drift rate). The precise positioning requires prompt (real-time) satellite clock error estimates, to be provided to the user by the CPF, unless a double-difference approach (Wide Area RTK) is considered (where the clock errors are cancelled out). On the other hand, the offset of the receiver clock shall be estimated as an extra unknown in the navigation filter.

Tropospheric delay

The troposphere delays GNSS signals for both code and phase measurements. This delay is dependent on temperature, humidity, atmospheric pressure, and the angle of transmission through the atmosphere. The most part of tropospheric delay (hidrostatic component, typically greater than 90%) is predictable: i.e. the corresponding Zenith Tropospheric Delay component ZTD and then by mapping the ZTD to lower elevation angles by scaling with a mapping function. The Zenith wet delay component must be estimated simultaneously, though the corresponding mapping function (typically a slow varying random walk) as an additional unknown in the user filter.

Relativistic clock correction

This term corresponds to the relativistic effect on the satellite clock. The correction can be calculated from the parameters in the broadcast satellite navigation message or from the satellite positions and velocities as given in ICD-GPS-200C.

Phase Windup Correction

GNSS carrier phase wind-up is a continuous varying bias introduced into carrier-phase measurements by the rotation of a GPS receiver's antenna. There is also a contribution from the rotation of a GNSS satellite's antenna as it orbits about the Earth. It is fully predictable for static receivers and should be estimated for roving users, unless a differential positioning is considered.

Inter-frequency Delay Code Bias

The Interfrequency Delay Code Bias (IDCB) due to the lack of synchronism of the channels associated to each frequency (or kind of signal) in the satellite and receiver hardware is also known as the L1-L2 instrumental bias. The value of satellite interfrequency code phase bias P1-P2 (group delay) is broadcast in the navigation message and in the header (jointly with receiver DCBs) of the IGS Global Ionospheric Maps (GIMs) provided in IONEX format. IGS products users need to apply P1-C1 and P1-P2 DCB parameters as part of the clock estimation procedure. The Astronomy Institute of the University of Bern (AIUB) calculates GPS P1-C1 and P1-P2 DCB monthly corrections and makes the values available at the beginning of each month.

Cycle slips

The observed carrier phase, as integrated Doppler effect in length units, is affected by an ambiguity, also called phase bias, which approximately corresponds to minus the pseudorange at the locking time. The phase ambiguity consists on the sum of a non-integer component (depending on the addition of the receiver and transmitter components) and an integer number of cycles. The potential causes of cycle slips include in particular the obstruction of satellite signal, a low SNR, atmospheric scintillation and receiver software failure.

Multipath

The multipath error is the measurement impact of the combination of a satellite emitted signal arriving at the receiver antenna via more than one path, and therefore with slightly different delays. It is mainly caused by reflecting surfaces near the receiver antenna. The received signals have relative offsets that quickly drift on time, following the line-of-sight geometry changes. The maximum effect of multipath on phase measurements is a quarter of cycle. Lau and Cross (2007) [106] have shown that appropriate use of a number of stochastic models and ray tracing can result in residual error significantly less than 10 mm.

Thermal noise

This term corresponds to the measurements noise, which can be estimated as 1% of the wavelength for the carrier phase (or chip length for the code). In the case of the pseudorange, the sigma of the noise can reach up to 3 meters for the civilian C/A code and 30 cm for the protected P codes. In the case of the carrier-phase measurements, the sigma of the noise accounts for about 2 mm.

3.2 The Ionospheric delay

3.2.1 Introduction

The GNSS signals are affected by an additional delay due to the presence of free electrons (pulled out from atoms mainly by Extreme ultraviolet (EUV) and X radiation from the Sun), as they travel through the ionosphere. Indeed, the free electrons oscillate due to the GPS electromagnetic signal, becoming a sort of transmitting antenna, which new associated electromagnetic wave overimposes with the original one, changing the properties of the overall GPS signal propagation. The main result is an advance in phase, and a delay in code, proportional to the number of encountered free electrons along the transmitter-receiver path (a.k.a. Line-Of-Sight, LOS) and inversely proportional to the squared frequency (approximation typically valid at least up to 99.9%). Then, in order to correct the single-frequency GPS signals, it is necessary to estimate the so-called ionospheric electron density (i.e. the number density of electrons, N_e) along the LOS, namely the Total Electron Content (TEC) in the slant direction; or, alternatively, to make differences of measurements considering both frequencies, weighted with the inverse of the squared frequency, in order to cancel-out the +99.9% of the effect.

In this context, the most commonly used observable is the so-called ionospheric combination of carrier phases on one hand, and of pseudoranges on the other hand, since these observables are directly related with the Slant Total Electron Content (STEC) plus additional terms as follows:

$$L_I = \alpha_I \cdot STEC + b_I + w_I + m_{L_I} + \epsilon_{L_I} \qquad (1)$$

$$P_I = \alpha_I \cdot STEC + D_I + D'_I + M_{P_I} + \epsilon_{P_I}$$

where $L_I = L_1 - L_2$ and $P_I = P_2 - P_1$ are the ionospheric combination of simultaneous dual-frequency GNSS carrier phases and pseudoranges in length units, $\alpha_I = 0.105 \frac{m_{L_I}}{TECU}$ ($1\,TECU \equiv 10^{16} e^-/m^2$), and $STEC = \int N_e \cdot ds$, i.e. the electronic content along the LOS from the satellite to the receiver. The other terms stand for the carrier phase ambiguity and wind-up terms b_I and w_I respectively, the multipath effect m_{L_I}, and the error ϵ_{L_I}, due to noise and other negligible terms (their contribution is at the subcentimetre level, see Hernández-Pajares et al. 2009 [95] for more details).

In order to deal in a useful way with the influence of the geometry, the STEC values are usually transformed to vertical TEC ones (VTEC). This is done by considering a certain relationship called Ionospheric mapping function or obliquity factor, $F_{IPP} \equiv \frac{STEC}{TEC}$, which is typically assumed to be dependent on the elevation, although it actually depends on local time and latitude as well (Hernandez-Pajares et al. 2005 [91]).

It must be taken into account that different kinds of ionospheric models are used in order to get the most suitable mapping function, detect and estimate the spatial and temporal gradients of the ionospheric electron content and, as a consequence, a good vertical TEC estimation, and most importantly for precise navigation, an accurate STEC estimation.

3.2.2 TEC modelling

There are two main geometric approaches in order to model the TEC, from the point of view of vertical electron content distribution, including the single layer approach, broadly used in the scientific community, and the multi-layer model.

Thin single layer model

The most common and simple model to describe the effect of the ionosphere is to suppose that all the ionospheric electron content is confined in a thin spherical layer over the Earth's surface. This assumption is quiet reasonable since the maximum electron density is mainly located between 200 km and 500 km within which this thin layer (actually some kilometres above due to the asymmetry of vertical electron density distribution) can be centred.

In fact, the Wide Area Augmentation System (WAAS, the American SBAS) user receives the corrections according to the WAAS Minimum Operational Performance Standards (MOPS 1999 [113]), which specifies that the ionosphere information shall be sent in a main grid of 5 by 5 degrees with the thin shell at a height of 350 km. This model is also used in IGS, although considering a height of 450 km.

The thin mapping function F_{IPP} can be easily derived from Figure 3.1:

$$F_{IPP} = \frac{1}{\cos(\alpha)} = \frac{1}{\sqrt{1 - \left(\frac{R_{Earth}}{R_{Earth} + h_{ion}} \cos(\varepsilon)\right)^2}} \quad (2)$$

where ε is the elevation between the local receiver horizon and satellite LOS, h_{ion} is the height of the thin layer and R_{Earth} is the Earth radius.

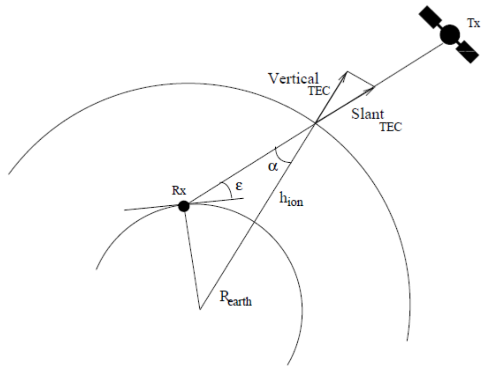

Figure 3.1: Thin layer model scheme where the relation between the STEC and VTEC can be seen graphically. R_X denotes the receiver while T_X denotes the transmitter.

Therefore, the height of the thin layer (h_{ion} or effective height) over the Earth's surface is the parameter that most influences the F_{IPP}. Typically, this height is about 350 to 450 km. But such fixed effective height does not take into account the local time, latitudinal and seasonal variations (Hernández-Pajares et al. 2005 [91]), thus producing a significant mismodelling.

Two-layer voxel model - TOMION

In order to model more accurately the electron density inside the ionosphere, different kinds of electron density models like Chapman functions (see Nsumei et al. 2012 [114], and references therein) can be used. Nevertheless, it has been shown that those single layer models also produce TEC mismodelling in zones with high electron density variability. This mismodelling was strongly mitigated with a new model of the ionosphere introduced by Hernández-Pajares et al. 1997 [87] and Juan et al. 1997 [101]. In this approach, the ionosphere is divided into two shells of volume elements (see

Figure 3.2) where the electron density is considered constant during a certain time interval. Therefore, the assumption that the effective height is constant is substituted for an estimation of top and bottom electron content, i.e. equivalent to a variable height driven by the data. This model reduces the TEC mismodelling, in particular, when there are high electron density gradients, see Hernandez-Pajares et al. 1999 [88] and 2000 [18] for details.

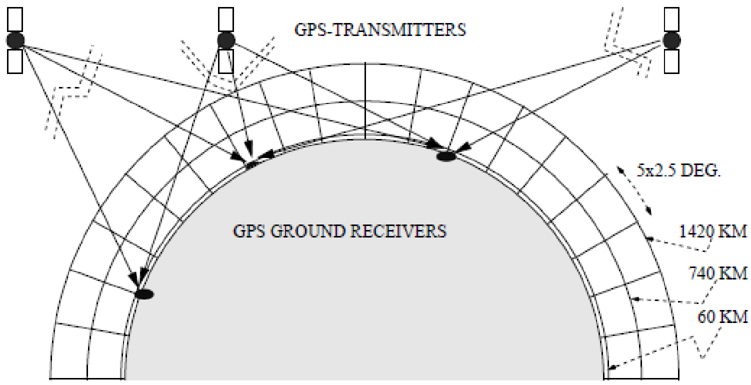

Figure 3.2: Two-layer voxel model used in the computation of TEC at the UPC. From Orús 2005 [116].

The TOMION software, actively developed by the IONSAT-UPC researchers, was initially implemented in the second half of the 1990s (Hernández-Pajares et al., 1997 [87], 1999 [88]). At that time, the main focus was to assess the feasibility of computing better VTEC maps with a coarse tomography algorithm. TOMION has been evolving in newer versions in order to enable processing ground based GNSS ionospheric data, GNSS LEO radio occultation data (Hernández-Pajares et al., 2000b [18]), GNSS geodetic data (Hernández-Pajares et al., 2000 [18]), dual-frequency altimeter data (Orús et al. 2003 [117]) and ionosonde data (García-Fernández et al., 2003 [85]). In real-time processing, it is also possible to provide corrections for precise user positioning by means of Wide Area Real-Time Kinematic (WARTK; see Hernández-Pajares et al., 2002 [90], 2008 [94]). It is also worth mentioning that TOMION has been used since 1998 by the UPC Ionospheric Analysis Centre in the frame of IGS Ionosphere Working Group (IGS Iono-WG; Hernández-Pajares et al., 2009 [95]). Afterwards, an interpolation module using Kriging technique (Orús et al., 2005 [116]) is used to generate improved Global Ionospheric Maps (GIMs) of vertical TEC (see recent performance of an updated version in Gulyaeva et al. 2013 [86]), detection of Solar Flares and indirect Solar EUV flux rate measurement (Hernández-Pajares et al. 2012b [97]), RT global VTEC maps (Caissy et al. 2012 [79]), and finally the Medium Scale Travelling Ionospheric Disturbances detection and propagation characterization (Hernández-Pajares et al. 2012 [19]; see also section 3.3).

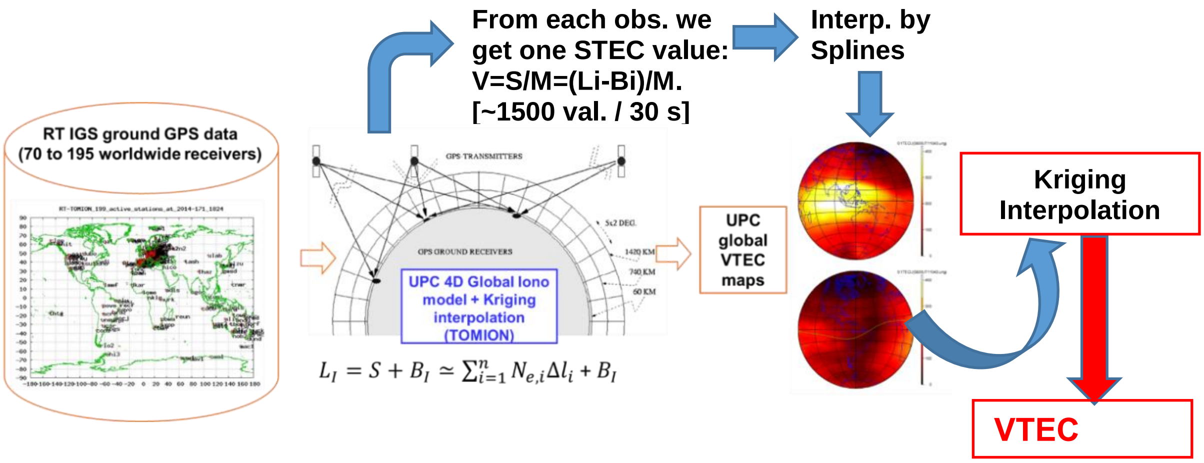

Figure 3.3: Layout summarizing the global VTEC computation from ground GPS data by means of the UPC TOMION software, including the main tomographic model equation (data: ionospheric combination of carrier phases (LI) and length intersection within each voxel (ΔlI); unknowns: its ambiguity (BI), the STEC (S), which includes the mean electron density within each given voxel (Ne,i).

Ionospheric tomography can be considered the key to reduce significantly the modelling error, at any latitude (Hernández-Pajares et al. 1999, see Figure 3.2). This can be understood in terms of its equivalence to a variable effective ionospheric height realistically estimated from the actual balance between top and bottom electron content (see Figure 3.4).

The expected improvement of implementing a dual-layer tomographic model, versus the classical single-layer ionospheric model, can be estimated from the study of Hernández-Pajares et al. 1999 [88], with actual global GPS network geometry and simulated ionospheric delays with a climatic model (IRI), summarized in Figure 3.4. It can be seen a dramatic reduction of the error at low geomagnetic latitudes, between -30 and 30 degrees, up to almost one-order of magnitude in some cases (from more than 20 TECU[1] of daily bias to less than 5 TECU). The improvement is still proportionally very important at mid and high latitude, with a reduction of one order of magnitude as well in some cases, but smaller in absolute terms, in agreement with corresponding milder ionospheric conditions (from 4 TECU to 1 TECU of daily bias reduction at high latitude).

3.3 Medium Scale Travelling Ionospheric Disturbances (MSTIDs)

3.3.1 Introduction

Ionospheric irregularities are a source of error for single-frequency users, and mostly useful information for multi-frequency ones. In particular, the most frequent ionospheric wave signatures, the Medium Scale Travelling Ionospheric Disturbances (MSTIDs), introduce a differential error non-linearly dependent on the baseline distance, affecting then to precise GNSS positioning.

More in detail, the MSTIDs are the most frequent ionospheric signatures of waves, up to few TECUs of amplitude, which propagate through the ionosphere with typical periods ranging from several

[1] 1 TECU = 10^{16} electrons/m^2

minutes to less than one hour, and velocities from 50 to 300 m/s (Hernández-Pajares et al. 2012 [19]).

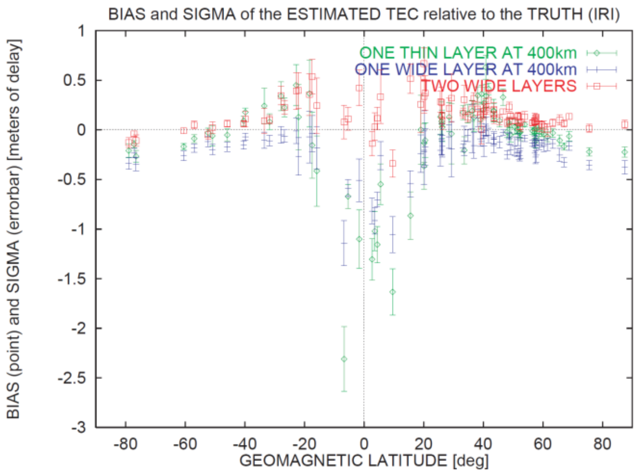

Figure 3.4: The calibrations of the one thin layer GPS model (boundaries at heights of 385 and 415 km, in green), the one wide layer model (boundaries at 60 and 740 km, in blue) and the two-layer model (boundaries at 60, 740 and 1420 km, in blue) are represented. The bias (points) and sigma (error bars) of the deviation between the estimated and the reference TEC (IRI) value are shown for 1st June 1998, as a function of the geomagnetic latitude. The true geometry is used with ionospheric delays (synthetic observations) given by the IRI. Each point represents one single station in a set of 82 IGS selected stations (extracted from Hernández-Pajares et al. 1999 [88]).

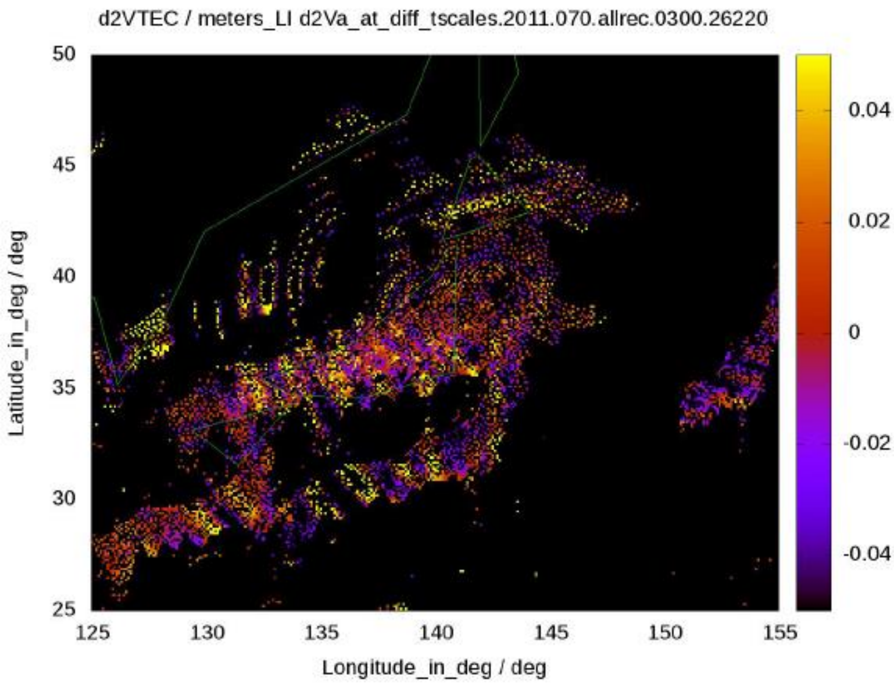

Figure 3.5: Detrended VTEC obtained from GEONET GPS data, coinciding with the Tohoku earthquake and tsunami (GPS second 26220 of day 70, 2011), where the circular ionospheric waves centered at the earthquake epicenter are evident (extracted from Hernández-Pajares 2013 [98]).

3.3.2 Single Receiver Mid-Latitude Medium Scale Travelling Ionospheric Disturbance (SRMTID)

The Single Receiver Mid-Latitude Medium Scale Travelling Ionospheric Disturbance index (SRMTID) was initially introduced in Hernández-Pajares et al. 2006a [86] (Figure 15), in order to easily indicate the Medium Scale TID (MSTID) activity for mid latitude stations, in real-time and without the need of a local network (as it is needed for determining the MSTID propagation parameters, see Hernández-Pajares et al. 2006b [93]). The SRMTID index is defined as the RMS of the STEC rate drift, very precisely deduced from the ionospheric phase for all the satellites in view for a given epoch. It is actually computed as double difference in time, each 300 seconds, to filter out larger periods much larger than those of MSTID (around 1000 seconds).

In detail the algorithm can be summarized in the following way, for each given pair of GNSS satellite-receiver independently:

1) The ionospheric combination, Li, is computed from the L1 and L2 GNSS carrier phases in length units:

$$L_I = L_1 - L_2$$

2) The cycle-slips are hopefully detected and marked, for instance looking for values of double consecutive difference in time of Li, $|d^2Li|$ = |Li(t+dt)-2Li(t)+Li(t-dt)| > d2Li_threshold (for instance d2Li_threshold= 0.10 meters +0.002 meters/sec*(dt/sec))

3) For every time t with measurements, with no cycle slip regarding to the previous and later observations, separated each consecutive pair by <u>dt=30 seconds</u>, d2Li is computed.

4) The RMS of 10 consecutive d2Li values at 30 seconds, i.e. each 300 seconds, is computed, given the SRMTID index:

$$SRMTID[t] = \sqrt{\sum_{j=0}^{9} (d2Li[t - j * 30\,\mathrm{sec}])^2}$$

An example can be seen in Figure 3.6, showing the typical mid-latitude MSTID activity around local winter and noon (see Hernández-Pajares et al. 2006b [93] for a full study). SRMTID can contain, especially at high or low latitude, part of the power due to shorter periods, as scintillation activity.

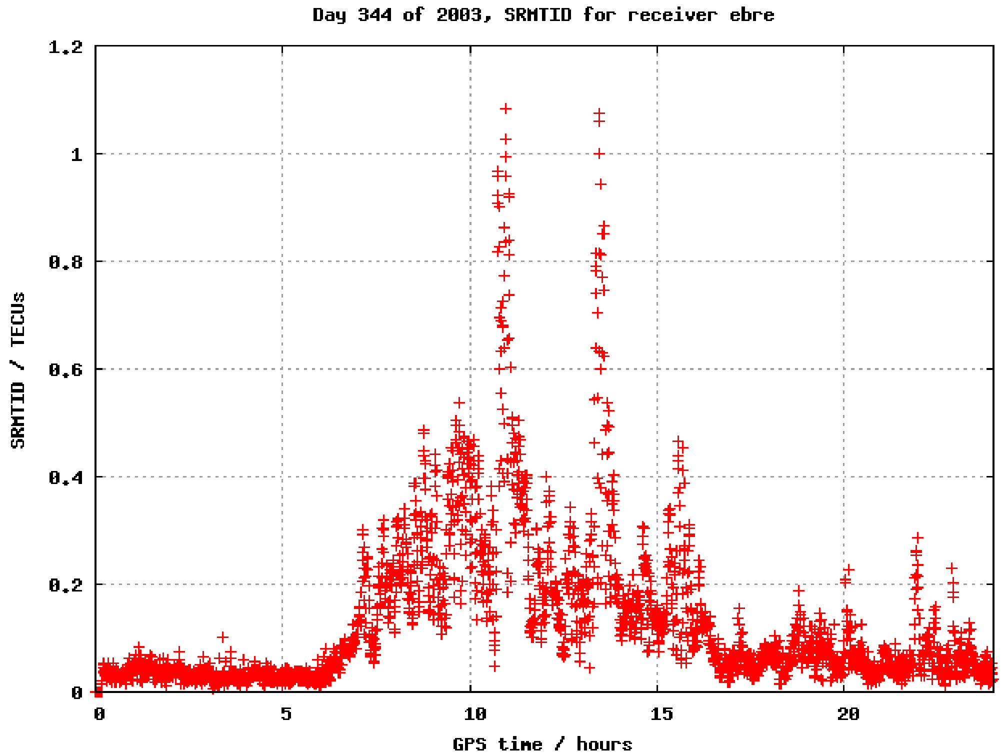

Figure 3.6: Example of SRMTID index corresponding to receiver EBRE during day of year 344 in 2003.

3.4 GNSS precise positioning techniques: Differential GNSS

Differential GNSS (DGNSS) is a GNSS Augmentation System based on improving the accuracy of the user receiver (or rover receiver) by means of differential information/corrections provided by a nearby reference GNSS station or a network of these stations. The application of this concept allows to cancel or mitigate common sources of error between satellites and receivers, thanks to using dual-frequency carrier-phase measurements and applying double-difference processing.

In this section, the main DGNSS techniques with applicability on high-precision navigation/surveying are summarized: the classical DGNSS (or DGPS), the Real Time Kinematics (RTK) and Network RTK (NRTK) and the Wide Area RTK (WARTK; see section 3.4.3).

3.4.1 Classical DGNSS

In DGNSS approach (DGPS in case of using only GPS), we take advantage of knowing an accurate surveyed position of the reference station. In this way, it is possible to derive the deviations between the estimated position and the actual one and thus compute corrections to the GNSS pseudoranges of each satellite. Such corrections are then useful to improve the user receivers positioning.

For instance, the accuracy of DGPS is in the order of 1 meter (1 sigma) when considering baselines between the user receiver and the reference receiver of few tens of kilometres.

3.4.2 Real Time Kinematic (RTK) and Network RTK (NRTK)

The Real Time Kinematic (RTK) positioning system was introduced by Remondi 1985 [28]. It consists on a user receiver that benefits from a base receiver, with well-known coordinates, and a communication link between both to receive and use the common satellites-in-view measurements to perform the corresponding differences, in order to achieve centimetre level positioning accuracy with short convergence time (Landau et al. 2007 [105]). In this approach, it is expected that there are similarities in the GPS receiver-satellite rays that can lead to cancel common errors (see, for instance, Misra and Enge 2001 [112]). In particular, it is assumed that the ionospheric delay is common to both the user and the reference receiver. The main drawback of this technique is that the baseline between the user and the base station is generally limited to less than 20 km and it is assumed that there are no disturbed atmospheric conditions.

In order to overcome such limitation, the Network RTK (NRTK) was proposed. NRTK (Wubbena 1996 [128], Wanninger 2004 [125]; Snay and Soler 2008 [122]) applies the RTK concept to a network of base stations (also referred to as Continuously Operating Reference Stations, CORS). This approach allows for taking into account spatial variability nearby the user receiver and thus, improve the user navigation performance. Also, allows for a quality check of the GNSS measurements at network side as well as a better ionospheric estimation (Kashani et al. 2004 [103]).

There are two types, single-base GNSS and Virtual Reference Station (VRS; Wanninger 1999 [126]). In single-base GNSS, a single reference station is given for working in differential mode with the user receiver and estimates from the network on several key error sources are calculated at network level and provided to the user (Edwards 2010 [82]). In VRS, a non-existing station is simulated very close to the user site in order to build the corresponding measurements for improved differential performace.

In general, there are two main RTK drawbacks beyond its high cost of installation and maintenance (passed to the users). On the one hand, its performance is strongly dependent on the adopted baselines and the associated data link to the users becomes critical. On the other hand, the unreliable ambiguity resolution (AR) under degraded observation conditions can affect its performance.

3.4.3 Wide Area RTK (WARTK)

The WARTK technique, introduced 17 years ago and developed by IonSAT members under several ESA-funded projects, can be considered an extension of RTK/Network RTK techniques to enable subdecimeter positioning accuracy with roving receivers hundreds of kilometers away from the reference receiver. In order to enable this, it is necessary to take as basic observation the double differences of carrier phases and use additional specific corrections (namely very precise ionospheric Slant TEC estimations) computed at a Central Processing Facility (CPF) from a permanent network of GNSS receivers (such as the real time International GNSS Service network; see IGS 2013 [21]). In the case of WARTK, it is considered that the permanent receivers are covering a regional/continental scale with a reduced number of them (see Hernández-Pajares et al., 2000 [18]). Beyond an improvement in accuracy for single frequency users, a much faster convergence time can also be achieved for dual-frequency user receivers. In case of using three frequencies as well as Galileo and modernized GPS, by means of the WARTK-3 approach, even single-epoch convergence time could be achieved in real time (see Hernández-Pajares, 2003 [20]).

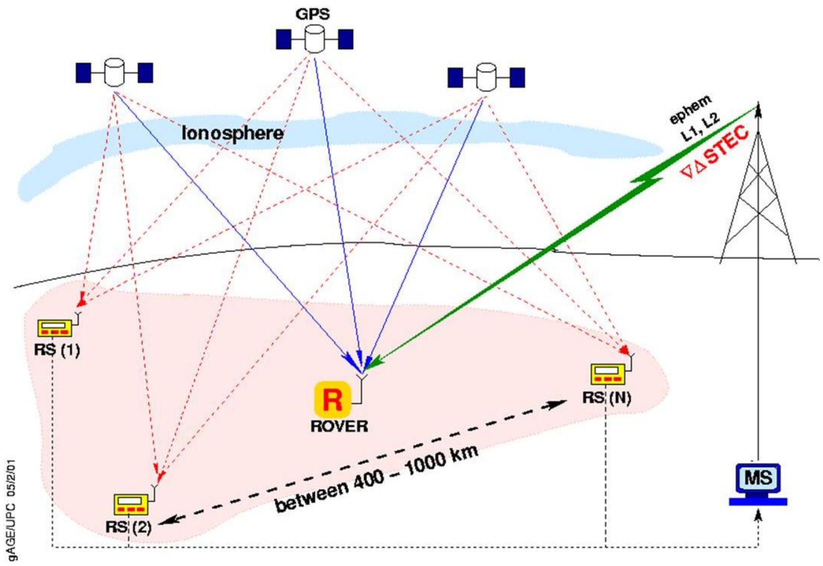

Figure 3.7: Layout representing the main components of the WARTK system: The Central Processing Facility (CPF), continuously running the combined geodetic and ionospheric models, both feed with the measurements of the permanent stations.

WARTK and ionospheric modelling

WARTK solves the baseline problem by introducing a precise real-time ionospheric model to provide accurate ionospheric corrections to users, reproducing the differential ionospheric conditions under baselines of few kilometers (see Hernández-Pajares et al. 1999 [88] and Colombo et al. 1999 [80]).

Unlike the RTK, an ionospheric model is computed in the WARTK CPF, which precisely captures in real-time the linear and large scale electron content variations. The model tomographically maps the ionospheric state as measured by a network of permanent GNSS receivers, each separated up to several hundreds of kilometres, following the same approach as in previous works (see Juan et al. 1997 [101] and Hernández-Pajares et al. 1997 [87]). Using this ionospheric model at CPF level, it is possible to estimate the actual ionospheric delays affecting each satellite-receiver measurement.

Once the ionospheric delays are computed for every satellite in view from the reference receivers, these values are transmitted to the users, which can interpolate them in order to estimate its own ionospheric delays. Applying such ionospheric corrections to the navigation filter equations, even in real-time, the user can quickly constrain the carrier-phase ambiguities, and even fix them when the corrections are confident enough.

With such ionospheric corrections, it is possible to provide a GNSS positioning service with errors below 10 centimeters in a continental scale just with a few dozens of fixed reference GNSS receivers. For instance, the EGNOS RIMS would be enough to ensure a sub-decimeter positioning service at European scale.

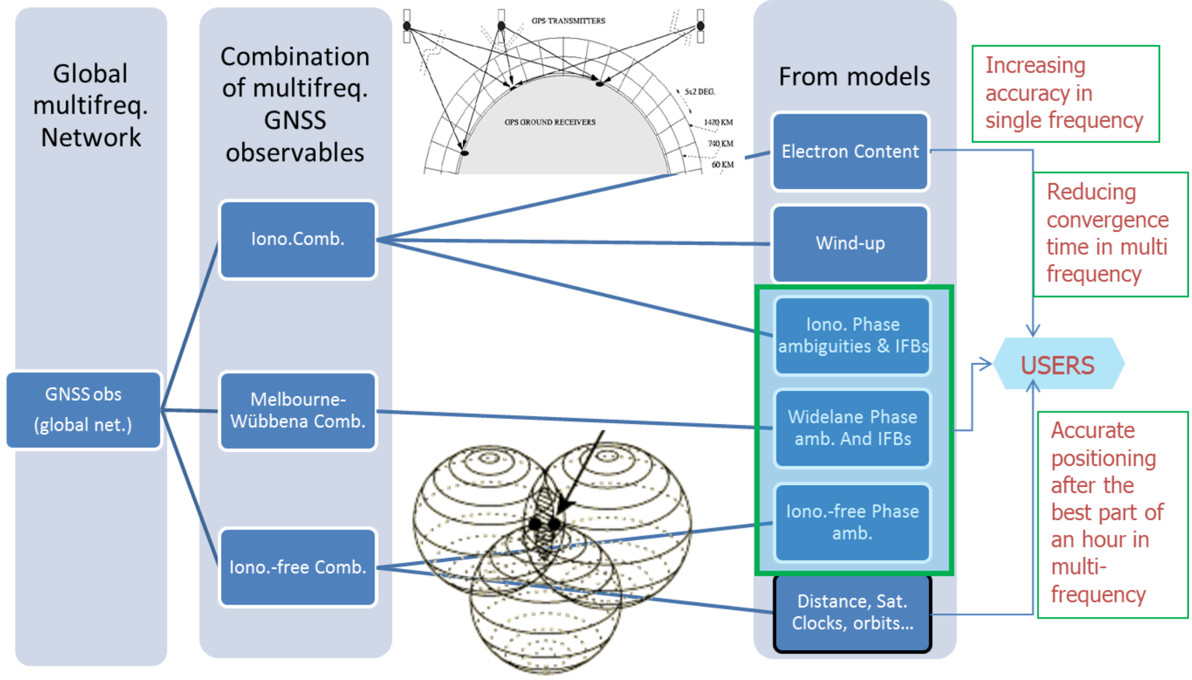

Figure 3.8: Diagram showing the main processing steps of WARTK and FPPP approaches, including phase ambiguity resolution.

For further details, an extensive explanation of the WARTK technique can be found in Hernández-Pajares et al. 2010 [96].

3.4.4 WARTK and MSTIDs

In Hernández-Pajares et al. 2006 [86], it was proven that the applicability of MSTIDs corrections (by means of a simple blind MSTID planar wave model) can improve the performance in positioning range domain. In Figure 3.9, extracted from that manuscript, it is shown the improvement of the WARTK service area under severe MSTID activity on South-West Europe (see Figure 3.10). As reference a daily averaged error given by the threshold of 0.25 TECU is considered (green line). It can be seen that the corresponding baseline distance from the nearest reference site increases from 110 or 180 km (under plain or MSTID downweighted WARTK, respectively) up to about 250 km with the MSTID blind model. This means an increase of about 40% in distance, i.e. almost doubling the service area. This improvement is also significant for shorter baselines (typical of RTK for instance) with an improvement of more than 20% for baselines below 50 km (see the same figure).

The applicability of SRMTID index at the user side aims at improving the performance of WARTK positioning performance beyond that of the MSTID blind model being considered in Hernández-Pajares et al. 2006 [86].

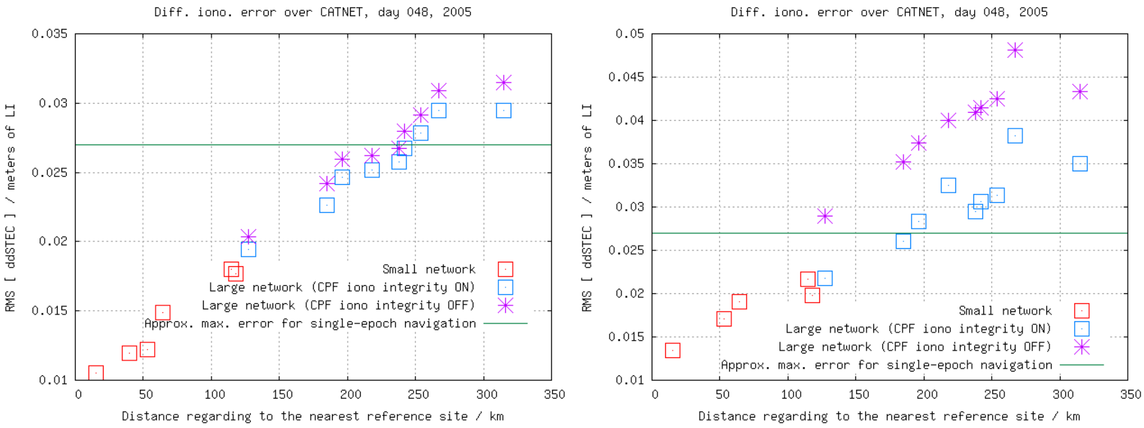

Figure 3.9: Real-time WARTK correction error (in meters) in terms of baseline length (in kilometers) averaged during 24 hours: it can be seen in topside plot using the MSTID planar wave model, with and without downweighting (similar results), and just using the linear interpolation in the bottom side plot, (with and without satellite downweighting in function of its MSTID affection as well). The reference ionospheric error threshold of 2.7 cm (0.25 TECU) is also indicated as a green line, coinciding approximately with the ability of real-time ambiguity fixing for about 2/3 of the observed satellites (1-sigma in an assumed Gaussian distribution).

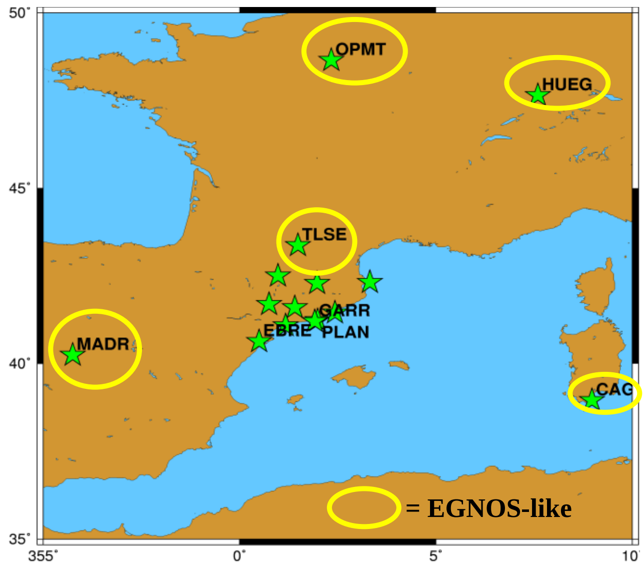

Figure 3.10: Map indicating the reference receivers: highlighted in yellow for the case of a large network, and the remaining labelled ones for the case of a small network; the remaining receivers (not labelled) are treated as roving users.

3.5 GNSS precise positioning techniques: Undifferenced GNSS

Undifferenced GNSS is a GNSS Augmentation System to provide high precision positioning to a user receiver in absolute mode (i.e. without the need of receiving the direct measurements taken from any reference receiver or network of receivers in the nearby (instead of that an estimation of specific corrections for satellite orbits and clocks, and ionospheric corrections, among others, is broadcasted).

As it was the case of DGNSS techniques, it is also based on dual-frequency carrier-phase measurements

The application of this concept allows to cancel or mitigate common sources of error between satellites and receivers, thanks to using dual-frequency carrier-phase measurements and applying double-difference processing.

In this section, the main undifferenced GNSS techniques with applicability on high-precision navigation/surveying are summarized: PPP, Fast PPP (FPPP) and RTK-PPP or regional PPP.

3.5.1 Precise Point Positioning (PPP)

Real time PPP (Heroux and Kouba 1995 [99] and Zumberge et al. 1997 [131]) can be provided in a reliable way by means of using a world-wide sparse reference network in order to compute precise reference satellite orbits and clock products in real-time at a CPF.

Its architecture allows PPP applicability to any user located in a global reference frame without being referred to any local base station or network of stations. In addition, the technique can diminish considerably the impact of certain reference station failures thanks to considering a significant number of permanent receivers in order to derive the precise orbit and clock data.

On the one hand, the main benefits of PPP are the following ones: It is no longer necessary to have base stations in the vicinity of the receivers and thus, this implies a reduction in costs and maintenance2. PPP also enables the provision of service at remote locations where no RTK infrastructure exists but there is GNSS coverage.

On the other hand, the main drawbacks of PPP are the following ones: Its poorer accuracy compared to differential solutions. Its long convergence time of tens of minutes to get to decimeter or subdecimeter level (in static mode) positioning accuracy (Banville et al. 2014 [78]). In addition, it is still not yet possible to reach the accuracy of NRTK (Kouba and Heroux 2001 [104]; Wang et al. 2002 [124]; Rovira-Garcia, 2015 [120]).

The performance of PPP is mainly affected by the accuracy of the satellite clocks and orbits, and inaccurate biases, by the possibility to enable integer ambiguity resolution, as well as by the existing satellites geometry in the sky seen by the user[3].

3.5.2 Fast PPP (FPPP)

FPPP technique is an evolved version of the classic PPP in order to achieve decimeter level positioning and also faster convergence time (for double-frequency user receivers) in undifferenced mode (Juan et al. 2013 [23], Rovira-García, 2015 [120]). This means that the user navigates without the need of a reference receiver (single receiver navigation). As in the case of WARTK, it is based on a combined geodetic and ionospheric model. The FPPP permanent receivers are located world-wide but a higher density of them (average separations between permanent receivers of 800 km or shorter), needed for a sufficiently precise ionospheric model, should be available at regional or continental scale at least, like in WARTK. This allows for a better estimation of orbits and especially clocks, which is necessary because these terms, affecting GNSS travel time between satellite and receiver, are not cancelled out in undifferenced mode of operation.

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[2] This is applicable when comparing to RTK or NRTK. Note that solutions like WARTK can make a reuse of existing infrastructure.

[3] This is important to decorrelate the different unkowns in the navigation Kalman filter.

In Figure 3.11, it can be seen that the centimetre level is reached after a few minutes in the case of FPPP approach, compared to more than one hour for the classical PPP. It is also an example of the fact that the accuracy of FPPP cannot perform as in the WARTK case.

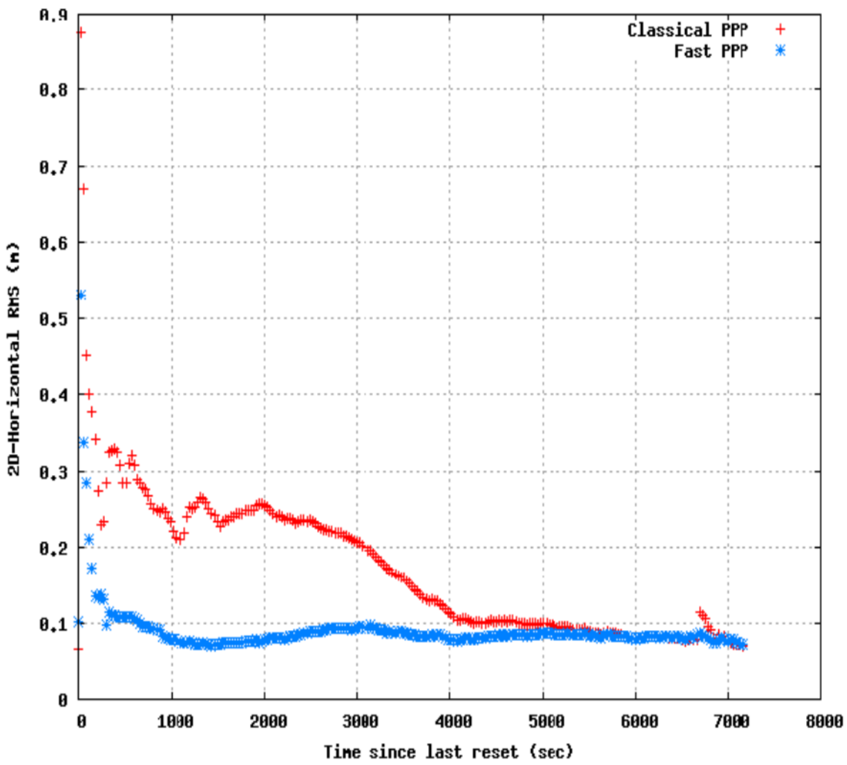

Figure 3.11: Comparison of classical PPP (red) and Fast PPP (blue) convergence of positioning error.

3.5.3 PPP-RTK, Regional PPP

The possibility to use a regional network of stations (Wübbena et al. 2005 [127]; Zhang et al. 2011 [129]) has been considered to enable PPP solutions without the need of a global infrastructure of receivers and to avoid depending on an external precise orbits and clocks provider. In general, the PPP-RTK concept relies on appropriate ambiguity resolution techniques (Li et al. 2012 [26], Li et al. 2014 [25], Odijk et al. 2016 [27]).

3.6 Commercial GNSS NRTK solutions

There are a number of existing network RTK services made available for commercial purposes (directly commercialized by global providers but also through regional providers). Some of them already target the agriculture industry. As representative solutions we can consider the ones being provided by Trimble (including CenterPoint VRS - Agriculture), TopCon (TopNET+) and Leica (Smartnet). These are briefly described in the next subsections.

It is worth mentioning that these solutions have a significant cost through subscription fees (as summarized in Martin and McGover, 2012 [109] for the specific case of Ireland). In addition, several authors (like in Edwards et al. 2010 [82]) have reported that the provided performance claimed by the service providers may be too optimistic, especially in case of challenging conditions (limited number of satellites, multipath, etc.). Last but not least, it is also reported (Wang et al. 2010 [123]) that the risk of incorrect ambiguity resolution shall be seriously considered, especially in case of the long baselines. Therefore, the ambiguity fixing algorithm plays a key role.

3.6.1 Trimble solutions

Trimble VRS Now^{TM} service (http://www.trimble.com/positioning-services/vrs-now.aspx [75]) claims to provide positioning accuracies below 2 centimeters with an instant convergence time in case of regions with good cellular coverage and appropriate GNSS conditions. More specifically, the CenterPoint VRS – Agriculture service (http://www.trimble.com/Positioning-Services/CenterPoint-VRS.aspx [74]; VRS Now-based correction service), targets the agriculture industry, offers 2.5 centimeters with <1 minute of initialization. Nonetheless, these services are limited to very specific regions within the Unites States, Europe (see Figure 3.12) and Australia.

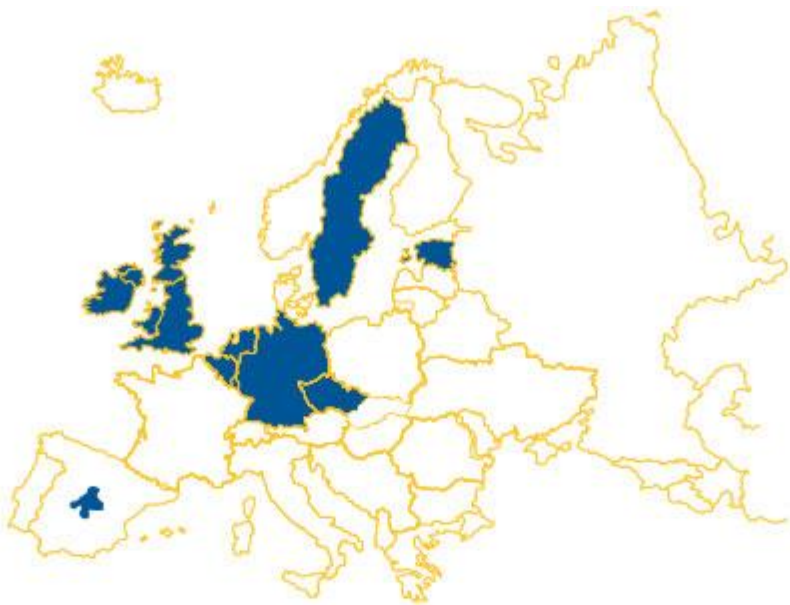

Figure 3.12: Coverage availability (in dark blue) of Trimble's VRS Now and CenterPoint VRS-Agriculture in Europe (from http://www.trimble.com [73]).

Trimble also offers CenterPoint RTX solution to provide <4 cm of accuracy and <5 minutes of initialization time, with world-wide coverage. In this regard, it claims such standard initialization time in case you leave the tractor in the same place as in the previous run (the day before, for instance).

These solutions are based on a network of about 150 permanent reference stations deployed world-wide. Depending on the adopted solution, the associated corrections can be broadcasted to users via satellite, cellular and/or Internet Protocol (IP).

3.6.2 Leica's MAX

The Master Auxiliary Corrections (MAX) method is the network-RTK service of Leica Geosystems relying on SmartNet network of permanent receivers. This method aims at providing few centimeters accuracy to users by means of the Master Auxiliary Concept (MAC; proposed by Leica and Geo++ in Euler et al., 2001 [84]). In MAC the NRTK server sends observations and precise coordinates from a single reference station, called the Master Station. The information on ambiguity and coordinates differences for the auxiliary stations are also transmitted separately. Note that MAC only requires one way communication. In Euler et al. 2002 [83], it was shown that the MAC concept shows advantages in terms of flexibility, homogeneous throughput and frequency of transmission.

Nowadays, Leica also claims that MAX solution is the best NRTK option since it uses internationally recognised standards (including RTCM SC-104), the rover has flexibility to decide on-the-fly how to implement the network corrections and the number of reference stations to be used (especially important to adapt to certain atmospheric conditions). In this way, there is also a certain computational load at the rover end.

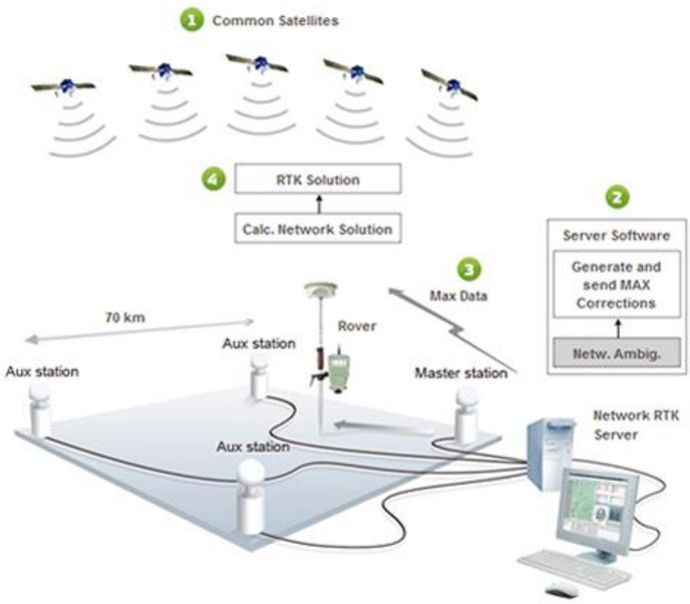

Figure 3.13: MAX network architecture given a rover receiver (from http://uk.smartnet-eu.com/max-corrections_233.htm [68])

It is important to remark that the service coverage depends on the availability of receivers included in the SmartNet networks (in the case of Greece, see Figure 3.14).

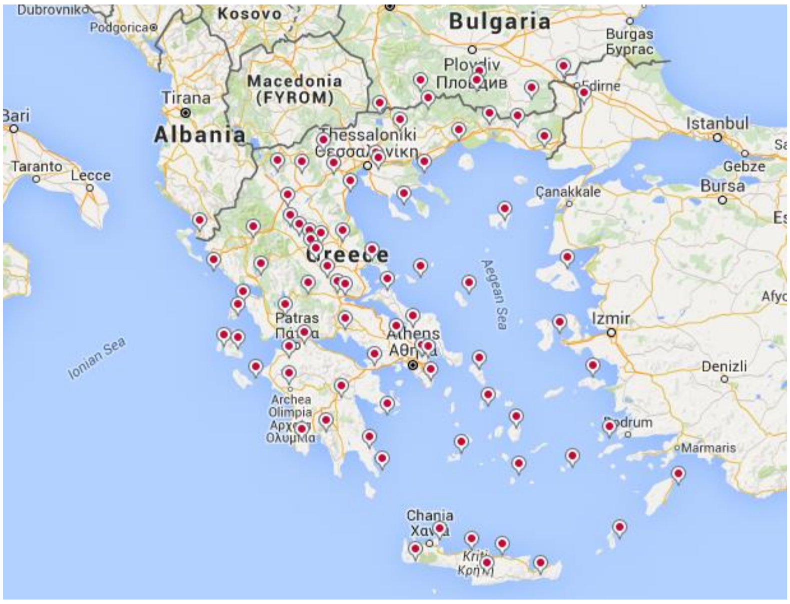

Figure 3.14: Leica's SmartNet receivers deployed in Greece.

3.6.3 TopNET+

It claims to provide solutions with accuracies at the level of several decimetres to few centimeters depending on the user needs (https://www.topconpositioning.com/agriculture/accuracy [77]). Similarily to Leica solutions, it is based on the VRS correction method (by means of a Modelled

Reference Station, MRS), and uses a network of CORS stations. In this case, a dedicated SW shall be used to transmit the user position to a dedicated server (via a GGA NMEA output message) to receive specific corrections (Martin and McGovern, 2012 [109]). TopNET+ also supports all operational GNSS constellations, including BeiDou.

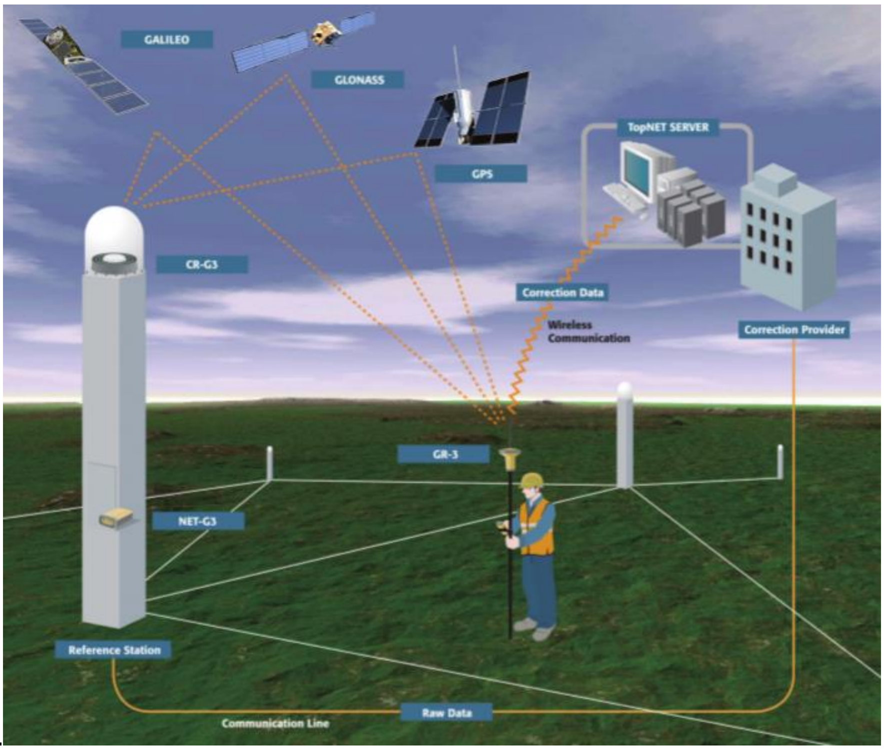

Figure 3.15: Example of surveying using TopNet infrastructure

3.7 Commercial GNSS PPP solutions

There are a number of existing PPP services commercially available. There are few well-known reference SW packages accessible through the Internet that mainly operate as private solutions. In next subsections, details on Automatic Precise Point Positioning (APPS), The Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP), OmniSTAR, Veripos and StarFire, will be provided, as representative solutions available nowadays.

It is also worth mentioning that the International GNSS Service (IGS) has a prototype service called Real-Time Service (RTS) to support users via NTRIP protocol that require real-time IGS products, including orbit and clock corrections to allow for PPP. This service is based on the world-wide network of GNSS receivers and the high-precision GNSS data products provided by the different contributing data centers and analysis centers. For further details, please refer to http://igs.org/rts [67].

3.7.1 Automatic Precise Point Positioning (APPS) of GDGPS

The NASA's Jet Propulsion Laboratory APPS (http://apps.gdgps.net/ [66]) offers the user with precise positioning through the submission of RINEX files using three different input modes: web, email and secure FTP. Moreover, APPS provides the user with four data processing modes, which are a combination of two data processing approaches (static and kinematic) and two latency options (Near Real Time and Most Accurate). At the moment, APPS is based on GIPSY 6.4 for processing the measurements and supports GPS, GLONASS and Beidou (Galileo as well in the near future).

The table below summarizes the expected positioning accuracy of this service (cm, 3D RMS) for a data files spanning 24 hours at 1 Hz.

Table 3.1: Expected Positioning Accuracy using APPS Products (extracted from http://www.gdgps.net/products/auto-positioning.html [71])

User Type	Latency	
	Near Real Time (1 min – 24 hours)	> 1 day
Stationary (dual frequency)	<5 cm	~1 cm
Mobile (dual frequency)	<15 cm	<5 cm
Airborne (dual frequency)	<20 cm	<10 cm
Stationary (single frequency)	~20 cm	~10 cm
Mobile (single frequency)	~50 cm	~25 cm
Airborne (single frequency)	~50 cm	~25 cm

Single frequency users may have in mind that their positioning accuracy will be strongly affected by ionosphere and may obtain higher positioning errors (especially at low latitude or in case of ionospheric storms) than the ones depicted in the table above.

3.7.2 The Canadian Spatial Reference System-Precise Point Positioning (CSRS-PPP)

The Geodetic Survey Division (GSD) of NRCan introduced, in November 2003, the Canadian Spatial Reference System – PPP (CSRS-PPP; http://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php [69]) for improved RTK survey. This is a free on-line post-processing service that allows GPS users in Canada (and abroad) to compute better-accuracy positions from their GPS raw observation data (Mireault, 2008 [111]). To access this service, the user submits RINEX data on-line to receive, via email, its coordinates in either the NAD83 (CSRS) or the ITRF reference system.

Like APPS, CSRS-PPP can process raw GPS data from single or dual-frequency receivers. If static mode is selected, the user receives single position coordinates. If kinematic data is uploaded, then each time epoch will be corrected individually and a time series output is delivered.

Regarding the convergence time, the user coordinates are produced 90 minutes after acquisition/submission (Mireault, 2008 [111]). For improved performance CSRS-PPP recommends to firstly perform RTK work or establish accurate coordinates for two points within the survey area. All in all, it claims providing 5-cm precision level for single epoch positioning and even mm level static positioning over 24h period.

3.7.3 OmniSTAR

OmniSTAR, member of the Fugro Group, is a set of Worldwide Differential & High Performance (HP) GNSS services providing enhancement data via satellite. OmniSTAR uses a network of reference stations (or base stations) to measure the errors induced into the GPS signal by atmospheric, timing and orbital effects. These reference data are gathered at Network Control Centres where they are checked for integrity and reliability and then up-linked to a chain of geo-stationary satellites, which broadcast the data over their coverage area by means of RTCM SC-104 format (http://www.omnistar.com [72]).

OmniSTAR provides four types of services, with different levels of accuracy:

- The VBS service (single frequency DGPS) generally provides a horizontal positioning accuracy at the level of 1 meter for single frequency users. The service is almost provided world-wide.
- The HP service (dual frequency DGPS) usually has a horizontal error of 10 centimetres (2-sigma) and it is said to be especially suitable for agricultural machinery guidance and surveying tasks. The coverage is limited to certain regions and operates in real time.
- The G2 service is similar to HP service but includes GLONASS support to increase the number of available satellites in view aiming to provide horizontal errors below 5 cm in the short term.
- The XP service is capable of providing a horizontal error better than 15 centimetres. This service is actually the only PPP service provided by OmniSTAR and it uses JPL's orbits and clock corrections. It is said to be suitable for Agricultural automatic steering systems.

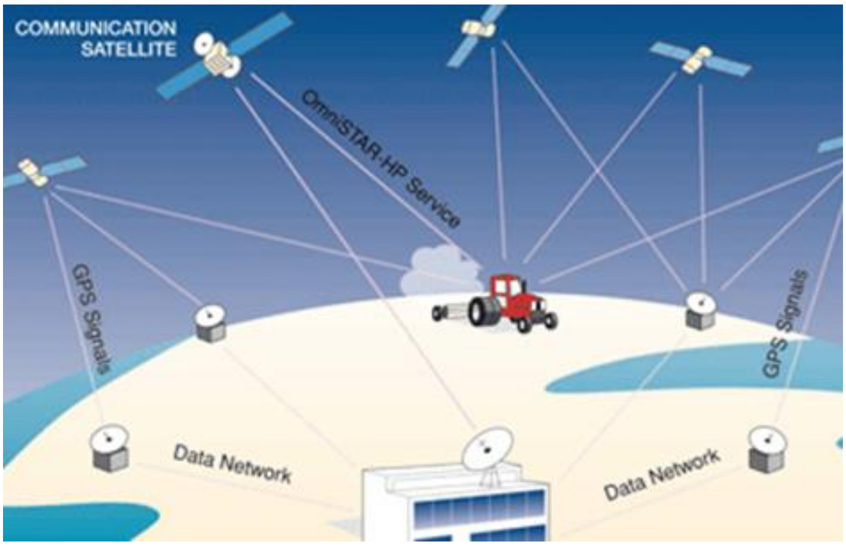

Figure 3.16: Omnistar architecture providing support to precise agriculture

3.7.4 Veripos

Veripos was formed in 1989 to supply GPS augmentation services, in the form of GPS differential corrections, to the offshore oil and gas industry (http://www.veripos.com [76]). The main objective of Veripos is to provide precise navigation and positioning services and solutions by broadcasting GPS correction data. Among the current supplied services, a client can access two main independent PPP services, the Veripos Apex and the Veripos Ultra that provide a global, high accuracy positioning using either a proprietary or a third-party network. Both the Veripos Apex and Veripos Ultra services claim to provide subdecimeter positioning error. There is also the possibility of using multi-constellation (GPS+GLONASS) by means of Veripos Apex2 and Veripos Ultra2 and the newly released Apex5 to operate with GPS, Glonass, Beidou, Galileo and QZSS.

To ensure global coverage availability and service redundancy, data is broadcasted using RTCM SC-104 from a suite of 7 L-Band communication satellites that can be received by using either a small omni-directional antenna (High-power (HP) level) or a large stabilised antenna (Low-power (LP) level).

3.7.5 StarFire

The StarFire Global Satellite Based Augmentation System (SBAS) was developed by NavCom (a John Deere Company) to provide a worldwide precise positioning service with decimetre positioning accuracy (https://www.navcomtech.com [4]). This is accomplished by the use of a network of 40 GPS reference stations to compute GPS satellite orbit and clock corrections. Continuous availability of StarFire corrections is ensured by two completely redundant network processing centres with multiple communication uplinks, and three Inmarsat geostationary satellites (L-band) that broadcast the correction data providing near-worldwide coverage (76^{o} North - 76^{o} South latitude range) and enabling precise real-time navigation without the need for local ground base stations.

StarFire service is available on a subscription basis. It is important to remark that end users not only must have a subscription to allow for the expected positioning accuracy of 5 cm world-wide but also their own series of GNSS receivers.

Figure 3.17: StarFire receiver on top of a tractor (from http://www.deere.com [70])

3.8 Integer Ambiguity resolution

Carrier phase ambiguity resolution is the key to high precision positioning with GNSS. Reliable ambiguity resolution is a function of several factors, the main ones being residual measurement errors, geometry and algorithmic formulation. To have a good chance of reliable ambiguity resolution, the overall error budget in the user range is generally required to be at the level of half a cycle with an uncertainty of less than a quarter of a cycle (Sauer, 2003 [121]). There are five ways to achieve this requirement:

- Using single/double differencing to remove common errors
- Using products to mitigate errors (such as satellite orbit and clock)
- Using data from networks to estimate errors (such as UPD)
- Using linear combinations of original measurements
- Combination of methods above (e.g. single differencing and linear combination)

In particular, both WARTK and FPPP allow for the constraining of the ambiguity term (fixing it whenever possible) thanks to a very accurate estimation of the ionosphere (Hernández-Pajares et al. 2000 [18], Hernández-Pajares et al. 2003 [20], Bertiger 2010 [13], Chen 2015 [15]), among other approaches of ambiguity resolution (Collins et al. 2010 [16], Laurichesse and Mercier 2007 [107] , Li et al. 2016 [24]).

3.9 Benefits of multi-GNSS and multi-frequency

The benefits of using multi-GNSS and multi-frequency have been explored by the scientific community to estimate their impact in the above-considered RTK/NRTK and PPP concepts (Li et al. 2015 [108], Paziewski and Wielgosz 2014 [119] and 2015 [118], Odolinski et al. 2015 [115] and Melgard et al. 2013 [110]), and particularly on the ambiguity resolution techniques (e.g. Zhang et al. 2003 [130], Julien et al. 2004 [102], Ji et al. 2007 [100], Deng et al. 2014 [81]). In such an scenario, it is envisaged an extension of the RTK/NRTK baselines (and thus a reduction of costs in infrastructure and maintenance), an abrupt reduction of the convergence time (instantaneous ambiguity fixing such as in the case of WARTK-3; Hernández-Pajares, et al. 2003 [20]), and a significant improvement on the reliability and availability of services (Vollath et al., 2003 [29], Chen, 2004 [14]).

Then, the use of an increasing number of carrier phase and pseudorange and a better distribution of satellites in the sky above the user will also be associated with a better Dilution of Precision (DOP), and thus an improvement on the positioning precision. Note that the navigation Kalman filter could directly work with the multiple equations from the GNSS observables rather than with combinations of them (Odijk 2016 [27], Rovira-Garcia, 2015 [120]).

Beyond the benefits of multi-frequency multi-GNSS, another important advantage, at Central Processing Facility level, of the current and near-future scenario will be the increasing number of NTRIP datastreams by means of tools like BKG's BNC in order to derive precise products to be broadcasted to users.

4. State of the art in precision agriculture (DLO)

4.1 Definition of Precision Agriculture (PA)

Precision agriculture (PA) refers to the application of new agricultural practices aiming to increase or maintain the production rate using less input of any kind (agrochemicals, water, energy, man-hours) improving economic profitability and simultaneously increasing sustainability. As a result, PA is based on recording and reacting technologies in order to respond to inter and intra-field variability in crops and guidance technologies to lower agricultural inputs.

4.2 Typology of PA technologies

4.2.1 Recording technologies

Recording technologies aim to map the spatial variability, since intra and inter-field variability may result from a number of factors. These include climatic conditions, soils, cropping practices, presence/lack of fertilizers, weeds and plant diseases. The data may come from a variety of sensors, which can be divided in three main groups:

1. remote airborne sensing
2. proximal mobile sensing
3. proximal stationary sensing

4.2.2 Reacting technologies

Reacting technologies aim to achieve an optimized use of inputs to generate maximum output. These primarily site specific application of input, better known as variable rate application (VRA), allows farmers "to place a specified amount of input on a particular area of a field". The VRA of inputs is required for savings in time, cost and fuel as well as for the reduced use of resources for a sustainable agriculture.

4.2.3 Guidance technologies

Guidance technologies, such as parallel tracking systems and automated guidance systems, are based on GNSS-positioning technologies and reduce overlaps and time and thus minimizing costs for labour and fuels. Guidance technologies also avoid the over-application of inputs and allow work in darkness.

4.3 Stakeholders in PA and adoption

4.3.1 Stakeholders

An overview of the stakeholders in PA at different scales can be seen in Figure 4.1.

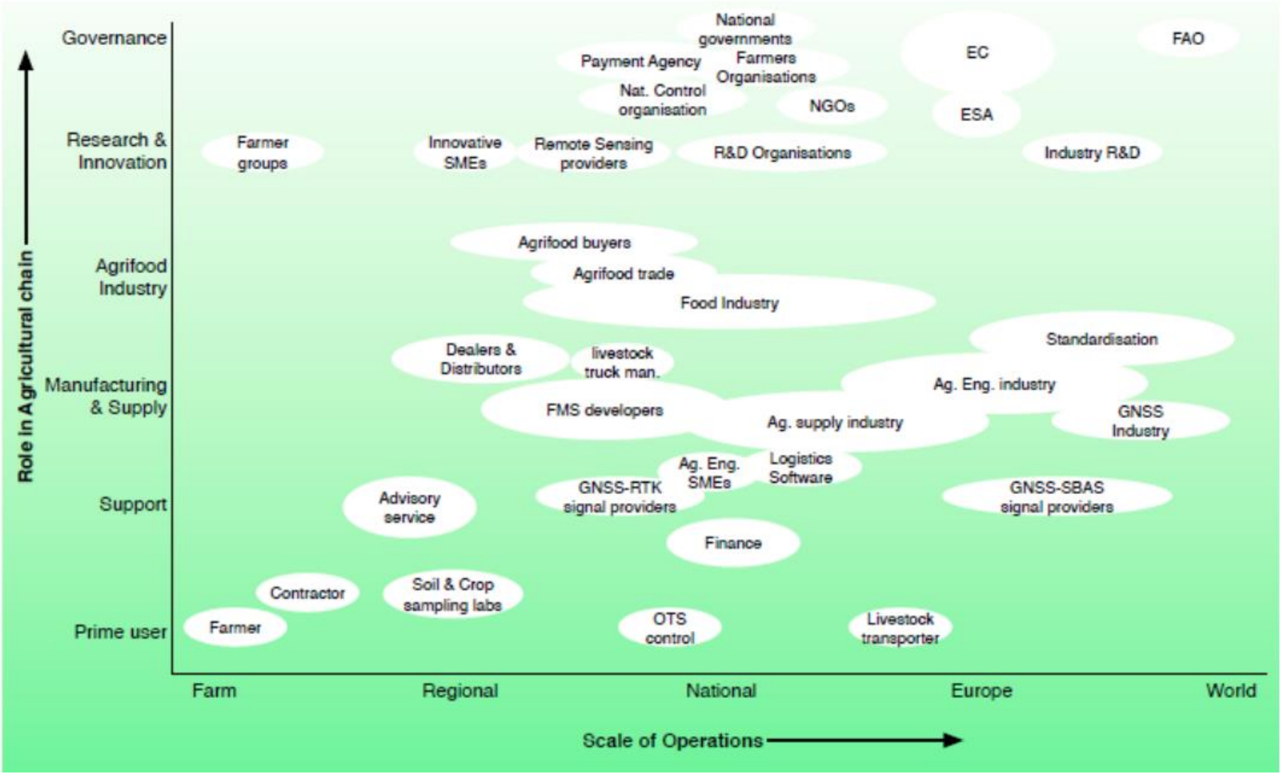

Figure 4.1: An overview of stakeholders in the context of precision agriculture ([30])

4.3.2 PA adoption prerequisites

According to a study among Danish and US farmers regarding the use of PA technologies, the main prerequisites for PA to increase its adoption are (Fountas et al., 2005 [45]):

a) lower cost

b) better understanding of the PA technologies and their benefits from the farmers

c) financial support from the government

d) ease to use the huge amount of data in field level

e) user friendly software.

Before investing heavily in PA tools, interested farmers can evaluate the technology, whilst estimating the degree of variation present in fields and the potential benefits of PA by engaging contractors and consultants with the appropriate tools (Jochinke et al., 2007 [48]). The theory of Rogers (2003) [58] and its five key attributes of innovation adoption (relative advantage, compatibility, complexity, trial ability, and observability) applies on PA adoption.

4.4 Market overview

4.4.1 General GNSS market in PA

In the last 10 years, PA has moved from good science to good practice and now 70-80% of new farm equipment sold has some form of PA component inside. In Europe, there are 4,500 manufacturers with a mix of large multinational companies and numerous SMEs producing 450 different machine types with an annual turnover of €26 billion and employing 135,000 people directly and a further 125,000 in the distribution and service network (Zarco-Tejada et al., 2014 [65]).

Focusing only in the European agriculture segment, this has experienced an increase in the installed base of GNSS devices from 51,000 units in 2006 to 129,000 units in 2013 (Figure 4.2), as per GSA's GNSS Market Report 2015 [42], with almost 90% of the applications for which the units are destined requiring high accuracy and precision (i.e. tractor guidance, automatic steering and variable rate application). These facts lead to estimate a current addressable user base of differential augmentation service of at least 110,000 devices. According to some industry experts, in four to five years GNSS devices will be standard equipment on all farm tractors and combine harvesters.

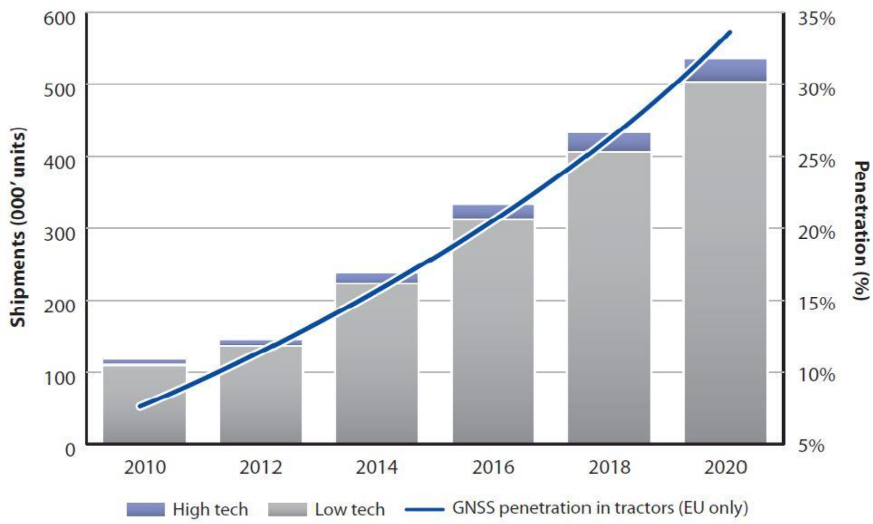

Figure 4.2: Shipments (thousands of units) and penetration (%) of installed GNSS devices worldwide in the agriculture sector ([31])

At the same time, the retrofitting of existing tractors with GNSS receivers involves about 4% of the European fleet. Because tractors have a long lifetime, the retrofitting market is expected to continue to grow for some years, at an estimated rate of 12% per year.

According to a cost and benefits analysis commissioned by the European GNSS Agency (GSA), EGNOS delivered positive benefits starting from less than 20 hectares of cultivation of soft and durum wheat, corn and barley. In Europe, where the average farm size is 16 hectares, EGNOS could therefore represent the best technology for small and medium-sized farms, especially with its low implementation cost.

From 2013 to 2023, annual shipments of GNSS devices are expected to increase more than fivefold, up to almost 1.2 mln units worldwide. Overall, GNSS penetration is foreseen to experience a steady increase over the next decade, reaching 50% by 2023. Increasing competition, bargaining power of end users and economies of scale are all expected to contribute to a progressive decline in the average price of devices, with the effect of technological advancements only partially compensating price erosion (Figure 4.3).

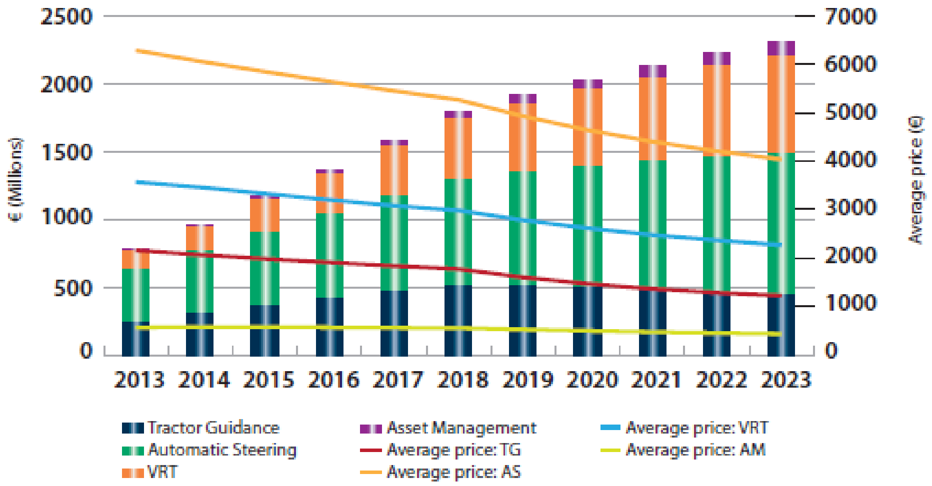

Figure 4.3: Core revenue in GNSS related precision agriculture and estimation of product pricing till 2023 ([32])

However, thanks to the sustained growth in GNSS device shipments, and in particular advanced applications, global revenues are expected to increase in all GNSS-enabled agricultural applications. Variable Rate Technologies (VRT) will progressively gain momentum, with revenues increasing from €135 million in 2013 to €723 million in 2023. Likewise, revenues from Asset Management (AM) will grow from €11 million in 2013 to €102 million in 2023.

Automatic Steering (AS) will generate the largest share of revenues and remain the most expensive application in terms of average price per device. However, it is also expected to experience the fastest price decrease, as high-accuracy applications will become increasingly available worldwide. Overall, revenues associated with Tractor Guidance (TG) are expected to peak in 2018, at which point they will begin to decline as farmers shift towards more advanced solutions.

The integration of GNSS positioning in Farm Management Information Systems (FMIS), together with the use of additional information coming from various sensors, has revolutionised precision farming. Additional sensors can be used to enable remote sensing with additional information being provided by earth observation systems and meteorological stations. The emergence of more affordable, dual-frequency and multi-constellation receivers, as well as evolutions of PPP solutions, will further support precision farming – contributing, for example, to the improvement of GNSS-based machine auto guidance.

4.4.2 Recording PA technologies

4.4.2.1 Soil mapping

Soil mapping can be executed using soil samples from the field under investigation. Another method to map a field regarding its soil properties is the use of on-the-go sensors that have the potential to provide benefits from the increased density of measurements at a relatively low cost. These sensors can be either combined with a GNSS receiver and produce maps of soil properties or they can be used as real-time sensors where the output of the sensor is used immediately for variable rate fertilizer application. There are two types of soil sensors; mobile and stationary sensors. Most mobile sensors are attached to a tractor in order to collect data from the soil of the field, like electrical conductivity (EC), pH and moisture content. As with these sensors soil is loosened, its main application is during winter time. On the other hand, stationary sensors are used during the growing season, but this is spot related, so the data is of low spatial variance.

Adoption of Soil mapping

Soil sampling with GNSS was provided by 57% of the dealerships, with grid and zone soil sampling services following closely at 54% and 35% of businesses, respectively (Lambert et al., 2015 [51]).

4.4.2.2 Yield mapping

Yield mapping refers to the process of collecting georeferenced data on crop yield and characteristics, such as moisture content, while the crop is being harvested. Various methods, using a range of sensors combined with GNSS, have been developed for mapping crop yields.

Adoption of yield mapping

According to Cropwatch extension service of the University of Nebraska – Lincoln, yield monitoring equipment was introduced in the early 1990s and is increasingly considered a conventional practice in modern agriculture. The pioneers of precision agriculture already have generated several years of yield history and have examined different ways of interpreting and processing these data. In their study of retail precision agriculture dealerships they found that yield monitoring services were provided by 23% of the businesses surveyed (Holland et al., 2013 [47]).

4.4.2.3 Topographic mapping

Field elevation is crititcal in precision agriculture. Elevation is very useful to understand production response. It influences soil formation, water movement and cropping aspects (Whelan and Taylor, 2013 [63]). It can determine waterlogged areas, erosion risk, drainage restrictions, and often is related to soil type. Using the data from the GNSS receivers, it is possible to produce a Digital Elevation Model (DEM) of a field or a farm. This DEM can be used to identify specific terrain attributes, such as slope, aspect, curvature, solar radiation interception, landscape water flow directions and topographic wetness indices.

Adoption of topographic mapping

We have not been able to find adoption numbers on topographic mapping in PA.

4.4.2.4 Canopy mapping

Canopy mapping involves the accurate mapping and monitoring of agricultural crops and other land cover with GNSS devices.

Adoption of canopy mapping

According to Löwenberg-DeBoer (2011 [52]) USDA data suggests that less than 5% of the crop area in the USA is monitored with data from canopy sensors.

4.4.2.5 UAVs

An unmanned aerial vehicle (UAV), commonly known as a drone and also referred by several other names, is an aircraft without a human pilot aboard. The flight of UAVs may be controlled either autonomously by onboard computers or by the remote control of a pilot on the ground or in another vehicle. Worldwide use of the UAV in agriculture is already well-established for data capture, frost mitigation, herding, inspection, precision agriculture, remote sensing, seeding, spraying, and variable rate dispersal.

Adoption of UAV

The American Association for Unmanned Vehicle Systems International, the trade group that represents producers and users of drones and other robotic equipment, predicts that 80% of the commercial market for drones will eventually be for agricultural uses. The worldwide market of drones for civilian use was $609 million in 2014 and is forecast to reach $4.8 billion in 2021 at a compound annual growth rate (CAGR) of 19%.

One current bottleneck in the agricultural use of UAV's is the strict (inter)national regulations. According to EASA (European Aviation Safety Agency), open use could be for flights within 500 meters and maximum altitude of 150 m. ICAO (International Civil Aviation Organization) is preparing rules for 2018. Once guidelines for commercial use are established, the drone industry said it expects more than 100,000 jobs to be created and nearly half a billion in tax revenue to be generated collectively by 2025, much of it from agriculture. The same survey reported that 33% of precision agriculture dealerships provided satellite/aerial imagery services (Lambert et al., 2015 [51]).

4.4.3 Reacting PA technologies

Reacting technologies comprise variable rate applications and automatic section or row control.

4.4.3.1 Variable rate applications (VRA)

VRA is a method of applying varying rates of inputs in appropriate zones throughout a field. The goals of VRA are to maximize profit to its fullest potential, create efficiencies in input application, and ensure sustainability and environmental safety. Application of VRA in crop production can include:

- Fertilizer (macro and micro nutrients) and Lime
- Pesticides (herbicide, insecticides, and fungicides)
- Manure (litter)
- Seeding
- Tillage (vary depth based on level of compaction)
- Irrigation

Adoption of VRA

Surveys showed that 20% of the Australian grain growers have adopted some form of VRA (varied from 11–35%) (Robertson et al., 2012 [57]).

Yet, current barriers for user adoption are summarized:

- Machinery can become more complex reducing reliability and increasing user frustration
- VRA requires good equipment management, calibration and proper maintenance
- VRA requires good knowledge of machinery
- Need to determine how to develop prescription maps
    - Assess field variability (i.e. soil variability through intensive soil sampling) using either grids or management zones
    - Generate prescription maps
    - Who will perform these activities? Producer, consultant, Co-Op?
- Need to define overall goal for using VRA (i.e. reduce costs, increase yields, improve environmental stewardship, etc.)

The two basic technologies for VRA are: map-based and sensor-based.

4.4.3.1.1 Map-based VRA

Map-based VRA adjusts the application rate based on an electronic map, also called a prescription map. Using the field position from a GNSS receiver and a prescription map of desired rate, the concentration of input is changed as the applicator moves through the field.

Map-based VRA involve the following steps:

- Sampling the field with recording technologies
- Running sample analysis in Farm Management Information Software (FMIS)
- Generating a site specific map of the properties in FMIS
- Using this map to control a variable rate applicator in the field with help of GNSS devices

4.4.3.1.2 Sensor-based VRA

Sensor-based VRA requires sensors on the applicator which measures soil properties or crop characteristics "on the go." Based on this continuous stream of information, a control system calculates the input needs of the soil or plants and transfers the information to a controller, which delivers the input to the location measured by the sensor. GNSS receivers are used to geo-reference the sensor output.

4.4.3.2 Automatic section or row control (ASRC)

ASRC uses GNSS systems to automatically turn off machine sections or individual rows in areas that have been previously been covered (e.g., headlands or point rows) or areas designated as no-go zones (e.g., grassed waterways, terraces, outside a field boundary). ASRC can also automatically turn sections or rows back on when the machine moves into an area that has to be covered (Figure 4.4).

<u>*Adoption of ASRC*</u>

There has been an increase (39 %) in the number of retail dealerships providing GPS-equipped sprayer boom control (CropLife 2011 [44]) and also in the number of producers (27 %) currently using section control technology in Alabama, USA (Winstead et al. 2010 [64]).

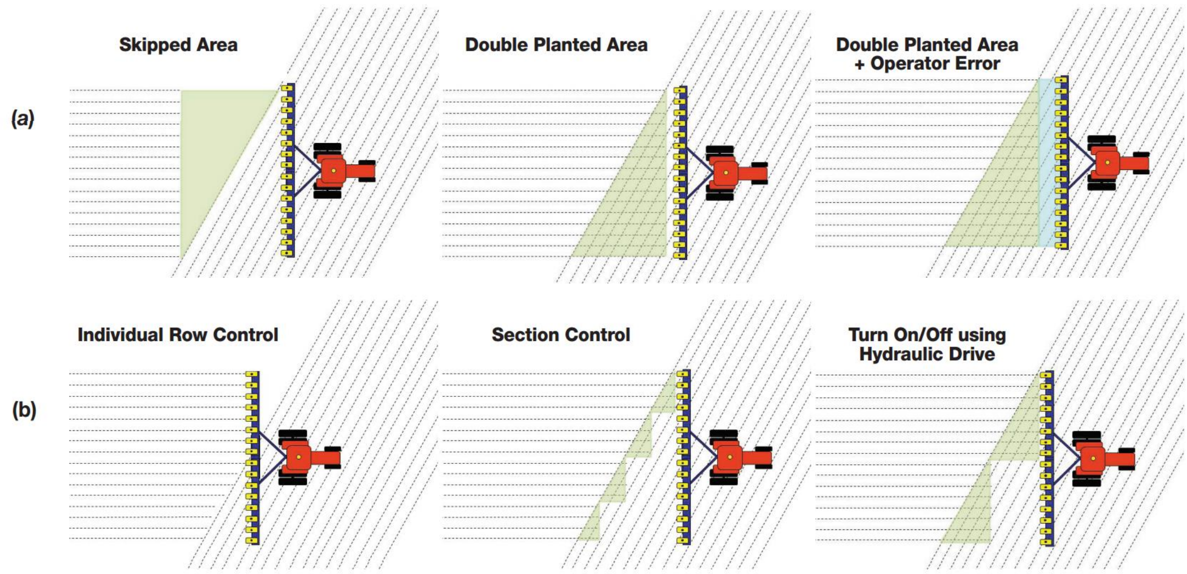

Figure 4.4: A comparison between using a traditional machine setup where the operator must decide to stop planting (a) versus one equipped with automatic section or row control (b) reducing overlap and skipped areas ([33]).

4.4.3.3 Virtual fencing for controlling cattle

Virtual fencing is a method used in livestock farming of controlling animals without ground-based fencing. It uses a GNSS system to define fence boundaries and a specially designed collar that alerts the animal to the fact that it has reached the “fence”. The virtual fence system also enables farmers to continuously monitor the location of their cattle. So moving a fence to accommodate changes in pasture or protect a sensitive environmental area becomes a simple matter of re-drawing lines on a computer instead of a huge and expensive physical task.

Adoption of virtual fencing

According to our literature research there’s not yet a commercial application of virtual fencing (also refer to section 4.5).

4.4.4 Guidance PA Technologies

The largest market in the GNSS PA segment comprise the guidance technologies. Farmers use GNSS for guidance and automatic steering and parallel swathing.

4.4.4.1 Steer help and auto-steer

Both the steer help and auto-steer use a GNSS receiver to identify the tractor’s location in the field. The basic difference between the two systems is that steer help, usually a lightbar, requires the operator to manually adjust steering, while auto-steer technology adjusts the steering automatically, allowing the operator to monitor the field operation of the implement instead of wheel steering. In respect to the GNSS correction systems, 70% used the WAAS correction (free service for the USA only), while 22% used a personal RTK base station, and only 17% had purchased a satellite correction (Beck et al., 2016 [43]).

Adoption of steer help and auto-steer

Purdue University (Holland et al., 2013) pointed out an increasing trend of using auto-steer and a declining trend of light-bar systems (Figure 4.5). According to Pedersen et al. (2015), about 36% of the German farmers replied that they use auto guidance on their farms and only 9% and 1% of the Danish and Finnish farmers.

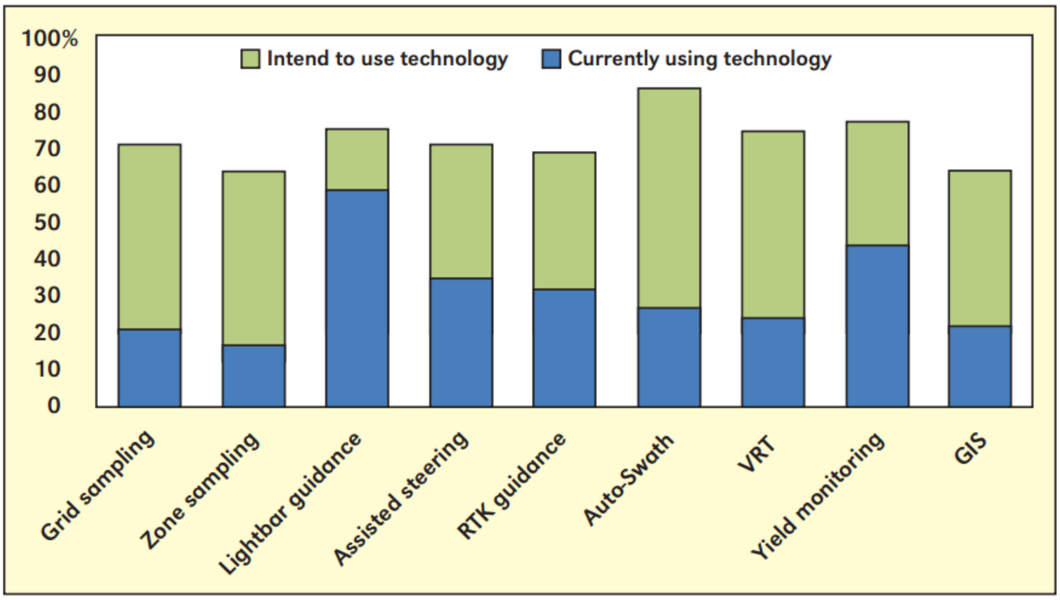

Figure 4.5: Results of 2009-2010 Alabama Precision Ag Adoption Survey ([34])

4.4.4.2 Controlled traffic farming (CTF)

Controlled traffic farming (CTF) is a system which confines all machinery loads to the least possible area of permanent traffic lanes. CTF allows optimised driving patterns with GNSS guidance (reduce of tracking to 15%) and more efficient operations (i.e. reduced overlaps). As all operations are aligned, input applications can be targeted very precisely relatively to the crop rows.

Adoption of CTF

Currently, the adoption of CTF in Europe is limited. Approximately 50,000 ha are known to be under CTF management. Although the benefits of CTF have been demonstrated for Australian and Northern European farming systems large scale adoption has not yet occurred (Beck et al., 2016 [43]).

4.4.4.3 Agricultural robots

Over the last years a strong trend is seen towards more agricultural robots able to perform a wide range of agricultural tasks. These robots are equipped with GNSS and specialized tools and accessories, arms and hands and are summarized in the following classes:

i. robots with autonomous systems for navigation in the fields;
ii. automated harvesting systems;
iii. robots for weed control;
iv. robots for mowing, pruning, seeding, spraying and thinning;
v. robots in nurseries;
vi. robots for row crop, vineyard, and orchard applications;
vii. agricultural robot platforms;

The main function of GNSS in these robots is to support autonomous path or route-planning and a corresponding guidance (auto-steer).

Adoption of Agricultural robots

Current world-wide adoption is estimated less than 100 ag-robots, since most or still under development or in prototype-phase. First sales is started for some market innovators: e.g. Conver Greenbot (Figure 4.6), Bosch Deepfield Robotics and Blue River Technologies.

Figure 4.6: Conver Greenbot – autonomous mowing robot ([35])

4.5 Agricultural companies active in Europe which offer GNSS products/services

	Recording					Reacting			Guidance		
Company name	Soil mapping	Yield mapping	Topographic mapping	Canopy mapping	UAVs	Variable rate applications	Automatic section and row control	Virtual fencing*	Steer help and auto-steer	Controlled traffic farming	AgRobots
Ag Leader Technology		x	x	x		x	x		x		
AGCO Corporation		x				x	x		x	x	
AgEagle					x						
Agjunction Inc.									x		
AirInov					x						
Blue River Technologies											x
Case/New Holland						x	x		x		
Claas		x		x		x	x		x		
Conver Greenbot											x
Cropwatch	x										
Deepfield robotics											x
Delair-tech					x						
Dickey-John Corporation						x	x				
Drone4Agro					x						
eBee Ag					x						
Farmobile									x		
Fritzmeier Isaria				x							
Hexagon Agriculture						x	x		x		
John Deere		x		x		x	x		x	x	
Kverneland IM Farming						x	x				
Leica Geosystems			x								
Precision Hawk					x						
Precision Plant Inc.							x				
Raven Industries Inc.		x			x	x	x		x		
Teejet Technologies							x		x		
Topcon Precision Agriculture		x	x	x		x	x		x		
Trimble Navigation Limited		x	x	x		x	x		x		
Veris Technologies	x										
WeedIT Ag				x							
Yara N-sensor				x							

* No manufacturers found

4.6 Upcoming technological developments (industry trends)

IoT: The Internet of Things (IoT) is a network in which devices and machines are embedded with electronics, software, sensors, and network connectivity, which enables these objects to collect and exchange data.

Big-data: Big data is a term for data sets so large or complex that traditional data processing applications are inadequate. Challenges include analysis, capture, data curation, search, sharing, storage, transfer, visualization, querying and information privacy.

Virtual plant modelling (2D and 3D): This comprises computational models of plant development in 2D or 3D to understand the physical and biological principles that drive the development of plant systems and organs.

Augmented reality: Augmented reality (AR) is a direct or indirect view of a physical, real-world environment whose elements are augmented (or supplemented) by computer-generated sensory input such as sound, video, graphics or GNSS data.

Swarm robotics (more but less heavy machinery): Swarm robotics is a new approach to the coordination of multirobot systems which consist of large numbers of mostly simple physical robots (Figure 4.7). Both miniaturization and cost are key-factors in swarm robotics. These are the constraints in building large groups of robotics; therefore the simplicity of the individual team member should be emphasized. This should motivate a swarm-intelligent approach to achieve meaningful behavior at swarm-level, instead of the individual level.

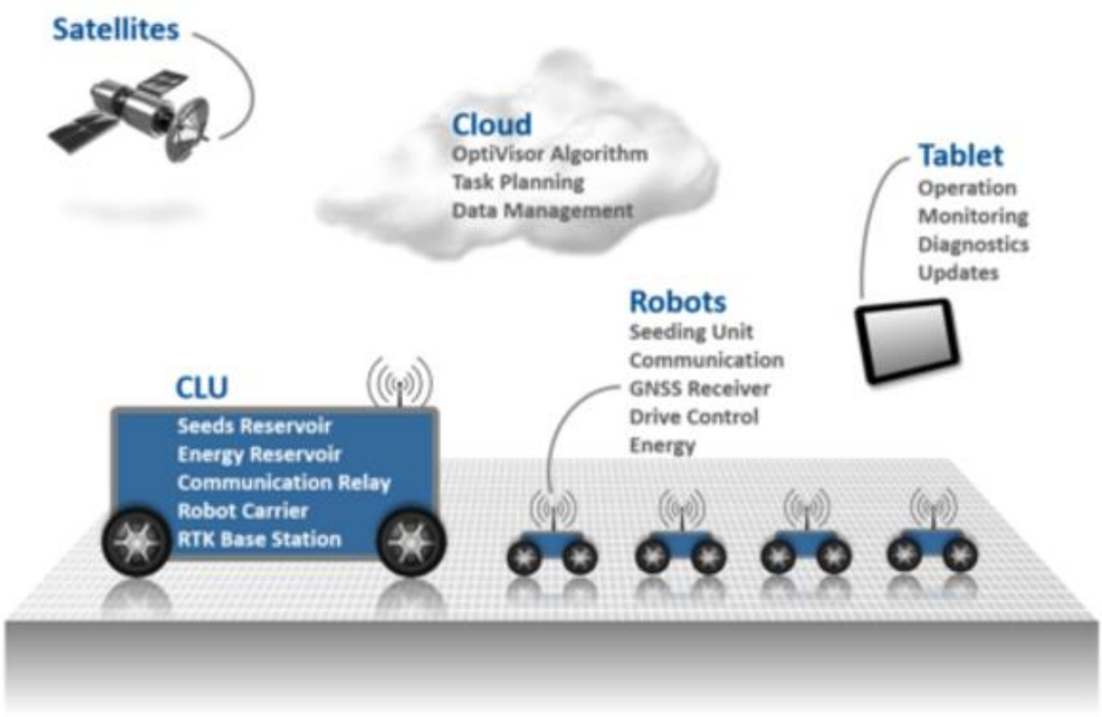

Figure 4.7: Example of Mobile Agricultural Robot Swarms ([36])

Master-slave tractors: With this system two tractors are combined in a single unit by a GNSS navigation system and a wireless connection, so that one of the vehicles can perform the same work as the other, but without driver. The guided tractor, that the one without driver, follows the vehicle guide in the same workflow. On the one hand, this allows very large working widths and, on the other hand, offers very flexible application possibilities. The farmer can adjust his productivity in a more optimal way, because of the increase operating width.

Ambient Awareness (person and obstacle detection): Autonomous vehicles are being increasingly adopted in agriculture to improve productivity and efficiency. Environment perception and interpretation capabilities are fundamental requirements for the safe operation of an autonomous agricultural vehicle,. The obstacles that might be encountered in the field can be separated into four overall categories that should be detected and handled in different ways: positive obstacles, negative obstacles, moving people/animals/obstacles, and difficult terrain.

Advanced sensing (thermal imaging, chlorophyll fluorescence): Chlorophyll fluorescence induction curves can be reliably used for automatic identification of plants, and act as input for an individual plant treatment to reduce input and maximize output. Thermal imaging can be used as measure for plant water stress and leaf evaporation.

4.7 Barriers in PA adoption and gaps in knowledge and technologies

Although precision agriculture is an important tool for feeding a growing planet while minimizing environmental damage, the motivation for farmers is less altruistic. According to Eduardo Barros, Accenture's Global Products Agri-business Lead, data-driven decisions about irrigation, fertilization and harvesting can increase corn farm profitability by $5 to $100 per acre. Barros adds that a 6-month pilot study found precision agriculture improved overall crop productivity by 15%.

It seems like PA is the solution for farmers if not for the nasty implementation details: new sensors and equipment for granular data measurement, data collection, integration with third-party data sources like weather models and satellite imagery, and number-crunching data analysis to produce recommendations. While not insurmountable hurdles for big corporate farms, the technology requirements and expertise are beyond the reach of smaller farmers (Table 4.1), particularly in developing countries.

Table 4.1: Reasons for not using PA techniques in England ([30])

Reason	2012 % of holdings	95% CI
Not cost effective and/or initial setup costs too high	47	± 3
Not suitable or appropriate for type or size of farm	28	± 2
Too complicated to use	27	± 2
Not accurate enough	2	± 1
Other reason	8	± 1

Based on responses from 1454 farms that do not use any precision farming techniques.

Source: from Department for Environment Food and Rural Affairs (2013).

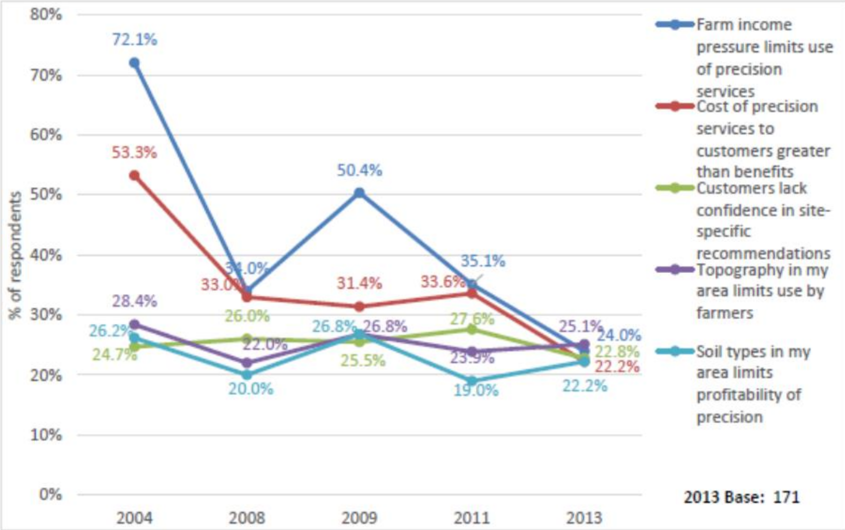

Figure 4.8: Customer regarding issues that create a barrier to expansion/adoption of PA over time ([30])

As reported in Sørensen et al. (2010 [59]), farmers often experience an overload of information (Figure 4.8), which originates from different data sources and is represented in various forms. Information brought to farmers originate from systems installed by third parties such as meteorological stations or specialized infrastructure, e.g. sensors for measuring temperature, humidity and soil moisture (Wang et al., 2006 [61]). Farmers need to combine all these data effortlessly and take precise decisions to produce qualitative products, improve their income and adhere to governmental regulations and principles. Further discussed in McCown (2012 [53]), all this information should also be combined with the ‘‘farmer’s internal system of practical knowing and learning’’, building thus a real cognitive system.

By combining aspects of IoT and big data, precision agriculture has a lot in common with burgeoning analytics applications in many other industries. The need for prodigious data collection, from many sources, associated storage and computational horsepower makes it a great fit for cloud services. Not only do shared services broaden the available market for precision agriculture, but the cloud enables agricultural crowdsourcing, by aggregating data from a wide variety of smaller operations to improve prediction models (Figure 4.9).

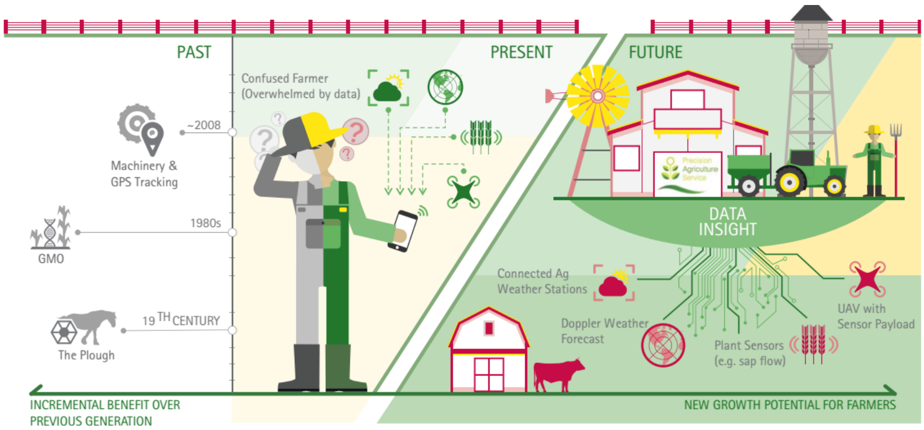

Figure 4.9: Graphical representation of the evolution of PA ([37])

4.8 Market potential

The PA market is estimated to exhibit a high growth potential till 2020. The total market is expected to reach USD 4.9 Billion by 2020 from USD 2.2 Billion in 2015 (Figure 4.10), at a Compound Annual Growth Rate (CAGR) of 11.7% between 2015 and 2020. Cost reduction and advancement in the agricultural industry are acting as the drivers for the market.

Figure 4.10: The US precision agriculture market is set to grow ([38])

Farm management systems and sensing devices are expected as largest growth segment of the PA market (Figure 4.11). The growth can be attributed to the fact that it helps in crop protection, monitoring & auditing, minimizing waste & pollution management, landscape & soil management, and crop nutrition. It assists in better utilization of resources and improves crop quality.

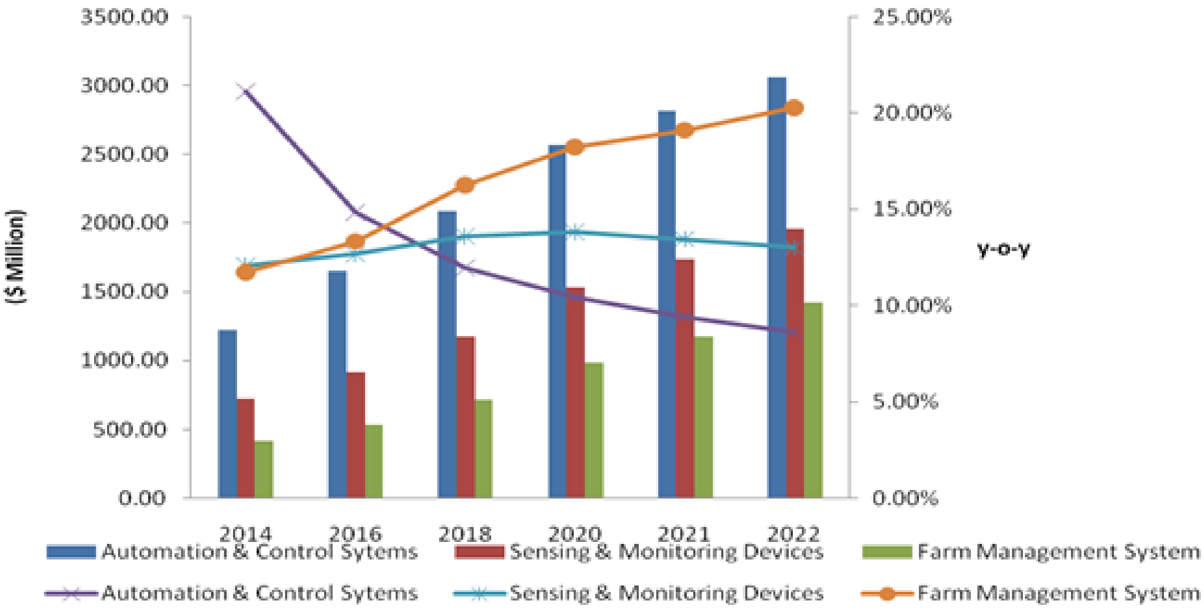

Figure 4.11: Global precision agriculture market analysis forecast 2015-2022 ([39])

According to a new report from Tractica, annual shipments of agricultural robots will reach 992,000 worldwide by 2024, up from just 33,000 in 2015 (Figure 4.12). The market intelligence firm forecasts that some of the largest application segments will include unmanned aerial vehicles (UAVs) for agricultural purposes, soil management robots, materials management robots, driverless tractors, and dairy management robots.

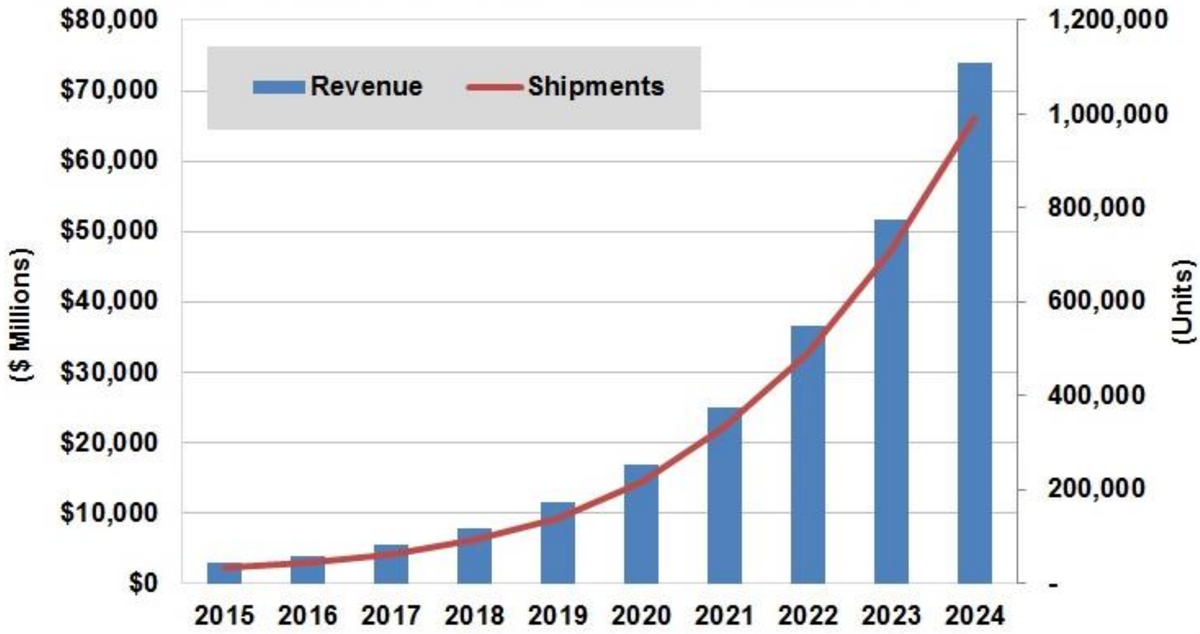

Figure 4.12: Agricultural robot revenue and shipments forecast 2015-2024 ([40])

A widely-cited drone report [41] released by the Association for Unmanned Vehicle Systems International predicts that the legalization of commercial drones will create more than $80 billion in economic impact (such as revenue, job creation) between 2015 and 2025 (Figure 4.13), and that precision agriculture will provide the biggest piece of that growth.

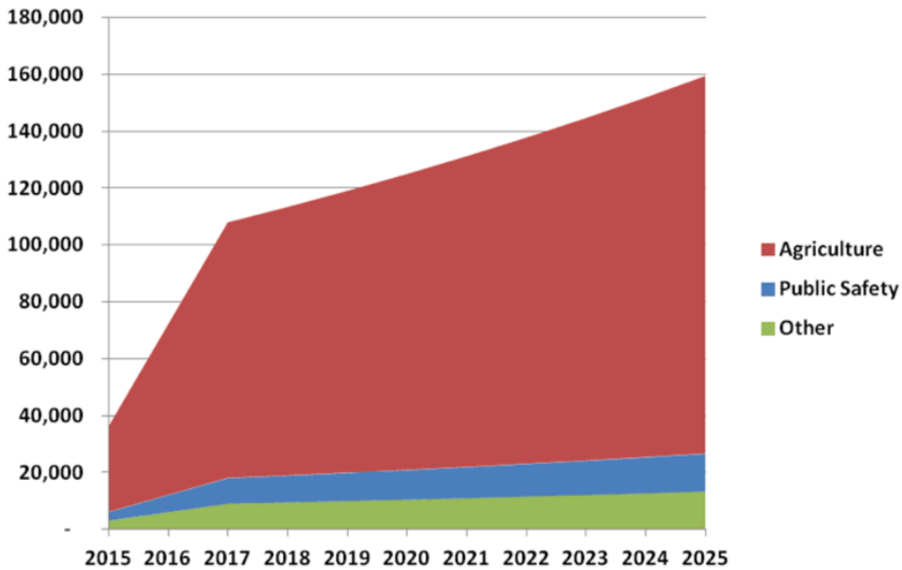

Figure 4.13: Annual UAV sales for Agriculture, Public Safety and Other Markets ([41])

5. Conclusion

There are multiple GNSS systems supported by different countries which are currently providing different levels of functionality and expanding their coverage and performance parameters. These GNSS systems are “augmented” via an increasing number of SBAS systems that improve their location accuracy, coverage or resilience.

GNSS receiver commercial features that in past years were presented as optional, e.g. multi-constellation or multi-frequency, are now mandatory to ensure deep market penetration. Moreover GNSS receivers are not only multi-system capable but also combine this multi GNSS/SBAS data with proprietary algorithms to offer better solutions.

The increment in GNSS receivers processing capabilities allow to integrate more complex algorithms that improve acquisition times, position accuracy, update date, hardware channels and provide a rich set of external interfaces and raw data outputs. GNSS receiver’s adaptability and extensibility are key factors for future products that will allow providing rich full location services in future multi GNSS/SBAS scenarios via advance dynamic merging algorithms.

Nowadays, mainly NRTK techniques (but also PPP) solutions are offering multiple specific services to agriculture users. This is an expanding market where providers claim to enable subdecimeter accuracy positioning with reduced convergence time. Nonetheless, these still require large networks of permanent receivers with short baselines, significant subscription fees and/or appropriate operational conditions. In this context, AUDITOR could benefit from aspects such as larger baselines between network stations (WARTK), one of the best existing ionospheric models world-wide (TOMION) and reduced costs at multiple levels.

The largest growth segment in the precision agriculture market is expected to be the segment of farm management systems and sensing devices. Especially the latter supports crop protection, monitoring and assists in a better utilization of agricultural inputs. Together with the expanding UAV market and new technology developments in agricultural robots and big data processing will surely support rise of this market segment. It is expected that this will require small-sized, accurate, robust and cheap GNSS receivers to enable geo-referencing for the sensing devices. The emergence of more affordable, dual-frequency and multi-constellation receivers, as well as evolutions of RTK/PPP solutions, will probably support this upcoming trend. The use of one or multiple augmented systems is a prime factor to increase the limited accuracy of current GNSS systems. Precise positioning will play a determinant factor in future autonomous agriculture and road scenarios. Portable receivers, either as handheld devices or smart-antenna products are gaining popularity, while maintaining small form factors integrate more and more sophisticated capabilities and extra external interfaces.

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