FIG REPORT

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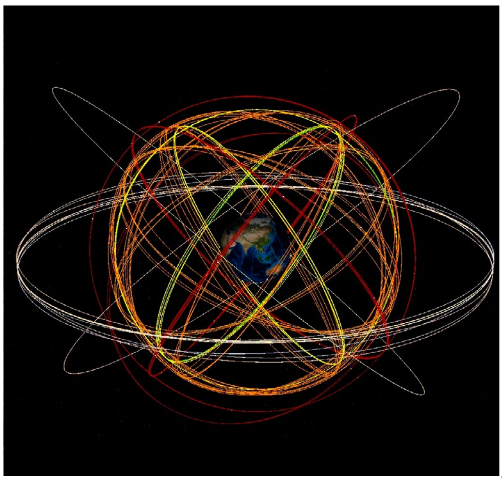
NO 74

Cost Effective Precise Positioning with GNSS



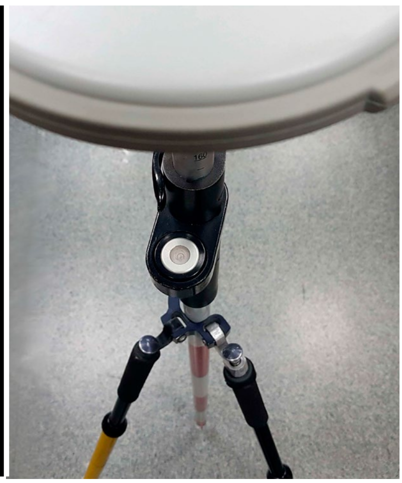


FIG Commission 5

INTERNATIONAL FEDERATION
OF SURVEYORS (FIG)

Cost Effective Precise Positioning with GNSS

FIG Commission 5

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Back cover image: IGS Tracking Network (© IGS).

Editors: Dr. Leonid A. Lipatnikov, Russia and Dr. Stanislav O. Shevchuk, Russia

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FOREWORD

Most surveyors today are aware that data acquisition, management, analysis, presentation and controlling systems are becoming more elaborate and automated. On the other side the results to be provided need to be produced with less cost, so in a cost-effective way.

The International Federation of Surveyors (FIG) Commission 5 – Positioning and Measurement, has been and remains an essential part of the surveying community. During the past three decades, Global Navigation Satellite Systems (GNSS) have and continue to play an increasingly important role in the profession. FIG enhances this development by facilitating GNSS sessions at their conferences, encouraging GNSS research and education, and cooperating with sister organisations such as the International Association of Geodesy (IAG) in the respective domain. Additionally FIG Commission 5 reacts on these developments by establishing Working Groups that deal with GNSS measurement techniques (WG 5.4), the use of GNSS for 3D and vertical reference systems (WG 5.2 and WG 5.3), data fusion in multi sensor systems (WG 5.5) as well as for cost-effective positioning and measurements (WG 5.6).

This Technical Report deals with "Cost Effective Precise Positioning with GNSS" thus focusing on GNSS as well as cost-effectiveness. There is a strong focus on precise positioning and how to reach "geodetic performance" at the least possible cost. As Chair of FIG Commission 5 – Positioning and Measurement, I thank Dr. Leonid A. Lipatnikov, Siberian State University of Geosystems and Technology, Russia and Dr. Stanislav O. Shevchuk, Aerogeophysical surveys CJSC, Russia for their efforts in compiling and creating this very detailed and impressive report.

Volker Schwieger

Chair FIG Commission 5, 2015–2018

March, 2019

The present study is a follow-on to the FIG Report No. 49 *Cost-effective GNSS positioning techniques* edited by Dr. **Neil D. Weston** and Prof. Dr. **Volker Schwieger** initially in 2010. The second updated and enhanced edition of that report by the same editors was published in 2014. That publication considered two possibilities to economize resources. The first one pertained to a reference site or a network of reference stations and the second one was related to the rover or users side.

For the first, the publication was initially focused on Continuously Operating References Station (CORS) networks that provide the reference site(s) data and metadata to the users. For the second, the report proposed to use low-cost (below €150) GNSS receivers instead of high-end geodetic quality receivers. After giving an overview on GNSS and geodetic positioning, both approaches and their opportunities were presented. Finally, several cases on estimating the working costs were developed and analyzed.

LIST OF ABBREVIATIONS

ADAS – advanced driver assistance system
ADC – analog to digital converter
AFREF – African Reference Frame
APREF – Asia-Pacific Reference Frame
AGC – amplifier gain control
ASIC – application specific integrated circuit
B2B – business-to-business
B2C – business-to-customer
BIM – building information model
BKG – Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie)
BNC – BKG NTRIP client
CAD – computer-aided design
CLAS – Centimeter Level Augmentation Service (QZSS)
CODE – Center for Orbit Determination in Europe
CORS – continuously operating reference station(s)
CR – choke ring
CSRS – Canadian Spatial Reference System
DSP – digital signal processor
EGNOS – European Geostationary Navigation Overlay Service
EPN – European Permanent Network
ESA – European Space Agency
EUREF – European Reference Frame
FIG – International Federation of Surveyors (Fédération Internationale des Géomètres)
FKP – Area Correction Parameters (Flächen Korrektur Parameter)
FPGA – Field Programmable Gate Array
GAGAN – GPS Aided Geo Augmented Navigation
GAPS – GPS Analysis and Positioning Software
GATBP – Geoscience Australia (SBAS) Test-Bed Project
GDA94 – Geocentric Datum of Australia 1994
GIS – geographic information system
GNSS – global navigation satellite system(s)
GP – ground plane
GPS – Global Positioning System
GSA – European GNSS Agency
GSAC – Geodesy Seamless Archive Centers (software system)
GSI – Geospatial Information Authority of Japan
GUI – graphical user interface
ICAO – International Civil Aviation Organization
IERS – International Earth Rotation and Reference Systems Service
IF – intermediate frequency
IGS – International GNSS Service
iMAC – Individualized Master-Auxiliary Concept
IMU – inertial measurement unit
IoT – Internet of things
IRNSS – Indian Regional Navigation Satellite System
ITRF – International Terrestrial Reference Frame
JAXA – Japan Aerospace Exploration Agency
JPL – Jet Propulsion Laboratory
KASS – Korean Augmentation Satellite System
LBS – location based services
LEX – L-band Experimental (signal)
LNA – low-noise amplifier
MAC – Master-Auxiliary Concept
MADOCA – Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis
MGEX – Multi-GNSS Experiment
MIT – Massachusetts Institute of Technology
MLBG – Mobile Location Based Gaming
MP – Microprocessor
MSAS – Multi-functional Satellite Augmentation System
NAD83 – North American Datum of 1983
NASA – National Aeronautics and Space Administration (US)

NGS – National Geodetic Survey (US)
NOAA – National Oceanic and Atmospheric Administration (US)
NRCan – Natural Resources Canada
NRTK – network RTK
NSAS – Nigerian Satellite Augmentation System
NTRIP – Networked Transport of RTCM via Internet Protocol
OAF – option authorization file
OEM – original equipment manufacturer
OPUS – Online Positioning User Service
OS – operating system
OSR – observation space representation
PC – personal computer
PND – portable navigation device
PNT – positioning, navigation, and timing
PP – post-processing
PPP – precise point positioning
PRS – pseudo reference station
QZSS – Quasi-Zenith Satellite System
RAM – random access memory
RF – radio frequency
RINEX – Receiver INdependent EXchange (format)
RMS – root-mean-square
ROM – read only memory
RTCM – Radio Technical Commission for Maritime Services
RTK – real time kinematic
SAW – surface acoustic wave
SBAS – satellite based augmentation system(s)
SCOUT – Scripps Coordinate Update Tool
SDC – self-driving car
SDCM – System for Differential Corrections and Monitoring
SDK – software development kit
SDR – software-defined radio
SINEX – Solution INdependent EXchange (format)
SIRGAS – Geocentric Reference System for the Americas (Sistema de Referência Geocêntrico para as Américas)
SIRGAS-CON – SIRGAS Continuously Operating Network
SISNeT – Signal-in-Space through Internet (protocol)
SISRE – signal-in-space ranging error
SOPAC – Scripps Orbit and Permanent Array Center
SPP – single point positioning
SSR – state space representation
UAV – unmanned aerial vehicle
UNAVCO – University NAVSTAR Consortium
UNB – University of New Brunswick
USB – Universal Serial Bus
VRS – virtual reference station
WAAS – Wide Area Augmentation System
WGS84 – World Geodetic System of 1984

1 INTRODUCTION

The Global Navigation Satellite Systems (GNSS) have revolutionized positioning, navigation, and timing (PNT) by bringing unprecedented combination of accuracy and convenience. Adoption of GNSS positioning technology has boosted capabilities of professional and amateur users. Though for both it was an evident breakthrough, accuracy levels available to them were quite different: millimeters versus meters. The two groups of users were clearly divided. Among 5.8 billion GNSS devices used in the world in 2017 only fraction of a percent belonged to a professional segment [1].

Recent events discussed in this publication probably triggered the next revolution which is to make high-precision positioning widely available and enable new applications. Self-driving cars (SDC), self-guided unmanned aerial vehicles (UAV) operating in urban environment, and outdoor augmented reality come true being enabled by that revolution and producing it at the same time. New applications are to increase demand for high precision positioning devices and services. Opportunities for improving cost-efficiency in professional GNSS-related applications emerge as well. The prices for high-end software and hardware decrease. Low-cost high-precision technology gains maturity. Free open source software, free online data processing tools and real-time correction services enable high precision positioning at the lowest cost ever available. Though the major part of the technology is not new, for the first time it becomes widely available to non-professional users.

The progress in technology repeatedly raises questions regarding optimal choice of positioning technology. What are the current options and trends to be taken into account when planning investments in new professional equipment? What are the major opportunities and challenges of developing cost-effective technology? What research and development efforts will be most useful? One may also be curious of what will happen if sub-decimeter accurate positioning becomes available to almost everyone. How can it be implemented? Why has not it happened yet, if low-cost high-precision GNSS positioning technology has been available for more than a decade? Is the situation changing now? The aim of this study is to find the answers or at least the clues leading to them.

Global navigation satellite systems have shown significant progress in recent years. Galileo and BeiDou are now very close to their full operational capabilities. New regional navigation systems, namely Indian Regional Navigation Satellite System (IRNSS or NAVIC) and Japanese Quasi-Zenith Satellite System (QZSS) came into operation. Currently a combined constellation of six global and regional navigation systems GPS, GLONASS, Galileo, BeiDou, IRNSS, and QZSS consists of more than a hundred space vehicles providing dramatic improvement of reliability and accuracy in urban canyons and other GNSS challenged environments if compared to any single system constellation. Apart from expansion satellite systems have been improving in quality. The first new generation GPS III satellite was launched in December 2018. New satellite signals, such as GPS L2C and L5C with new CNAV message, GLONASS L3 CDMA [2], BeiDou B1C, B2a, B2b bring new opportunities for improving GNSS performance for civil users [3], [4]. The accuracy of the navigation message parameters is constantly improving [5], [6]. That reduces the overall error budget in relative and single point positioning. Information about constellations and signals-in-space is available at the official websites of the system maintainers where up-to-date Interface Control Documents versions are published (see appendix A). For general introduction to GNSS one may refer to [7]–[10].

Typically GNSS structure is described as consisting of three parts. Space, control, and user segments are usually named, though it is also logical to mention an independent augmentation segment providing high-precision services. The progress in development of space and ground control segments accumulated over recent years is expressed in: better accessibility and geometry due to a larger number of satellites, better tracking stability, higher precision and faster initialization enabled by new signals, higher accuracy of broadcast ephemerides and clocks. These advantages are offered to all users, while options for improving cost-effectiveness of technology are concentrated within user and augmentation segments which are the focus of the present study.

Previously two editions of FIG report "Cost-effective GNSS positioning techniques" were published by Dr. Neil D. Weston and Prof. Dr. Volker Schwieger in 2010 [11] and in 2014 [7]. The present study is conceived as a follow-on to those publications rather than a revision, though some subjects are common and the structure of appendices is inherited.

Within the scope of the present investigation "high precision" is understood as a level of precision which cannot be achieved in a standard single point positioning (SPP) mode. Thus the present study covers precision (and accuracy) spectrum from sub-meter to sub-centimeter.

2 DEFINING COST-EFFECTIVENESS

In the study high-precision positioning is considered as a class of tasks that can be accomplished by means of available technologies. For every particular task a user choses the most cost-effective technology. It is defined through methods of data acquisition and processing, applied hardware and software within a certain workflow. The cost of accomplishing a task depends on choice of technology. A meaningful estimate of technology cost shall include at least the following constituent parts attributed to different production factors:

- cost of user equipment;
- cost of services enabling high precision;
- cost of qualified labor.

The overall cost-effectiveness is defined by relation between technology performance to the sum of those three constituents. As one may see further all three are important, interdependent, and the cost of all three tends to decrease.

User equipment for high precision positioning including hardware and software has been the most expensive part until now. In many cases its price has been the major factor limiting sphere of high-precision GNSS application. Equipment may be bought, rented, or leased. In some special cases hardware may be assembled from available modules (see paragraph 4.2), software can be obtained for free or developed upon freely available open source code (see chapter 6).

The services enabling or facilitating high-precision positioning include providing raw measurement data from reference stations and/or derivative information products in forms of real-time streams or archives. Also they include user's data processing services. Some services are free of charge, others are available by subscription (see chapters 5 and 7).

Qualified labor is another very important summand of technology cost. According to the estimate [12], in the end of 2018 the median hourly pay for an unskilled laborer in the USA is 14.39 US dollar ($). For professional land surveyor in general it is $19.43. With "GPS skills" median hourly pay increases to $20.42. Thus contribution of general professional qualification to labor cost is $5 per hour, GPS skills worth $1 per hour. Given 261 8-hour working days in a year it is easy to calculate annual input of GPS skill to the total cost of high precision positioning technology. In this case it amounts to $2,088 per year. Applying some low-cost hardware or open source software may require additional IT skills such as Linux administrating or editing scripts which will further increase the cost of labor force. That may be beneficial to an employee with such skills while not necessarily profitable for one's employer.

The three cost summands related to equipment, services, and labor are interdependent and mutually convertible to some extent. For example, using real-time correction service eliminates the need for deploying an own reference station. Thus part of equipment and labor cost is converted to cost of service. Using lower quality equipment is not necessarily cheaper if its malfunctions increase idle time (and labor cost). A certain technological solution may offer higher workflow automation which enables labor cost economy but typically implies higher cost of hard and software.

Convertibility of equipment, service, and labor costs may affect not only the choice of technology made by a customer, but the way the whole industry operates. As it has been shown above, the cost of GNSS user skill in a certain country may exceed $2,000 per year. One may imagine easily how the labor cost will change if a certain satellite based correction service with annual subscription fee of $500 offers highly automated GNSS positioning in a "plug & play" style, which no longer requires special skills from the user. Such services are discussed in chapter 5. This illustrates a very important trend which, apparently, will strongly affect the balance of interests and responsibilities between the conglomerate of equipment suppliers and online service providers on one side and professional GNSS users on another side. This issue is relevant not only to positioning and worth serious discussion, though it is beyond the scope of the present study.

Taking into account all of the mentioned above, three criteria of cost-effectiveness can be formulated in general: high performance, low total cost, ease of use. In further discussion different technological trends and options are considered keeping in mind these three criteria as they help to clarify the influence of every particular development.

3 PRECISE POSITIONING METHODS

3.1 Methods

One of the key elements defining the cost, performance and ease of use of a technological solution is the method of estimating coordinates. The required input dataset and therefore necessity for certain correction services and minimal required equipment capabilities depend upon positioning method. Different methods may offer different levels of data processing automation, labor intensity and user qualification requirements. Two positioning methods typically applied for achieving sub-meter accuracy and precision are considered in the present study. They are phase-based relative positioning and precise point positioning (PPP). Both methods can be implemented in static, kinematic, and stop-and-go modes. They are available in a number of modifications. There are also combinations of the methods known as PPP-RTK or regional network augmented PPP. A brief overview of both methods is provided below to support further discussion of their implementation and improvement.

3.2 Relative Positioning with Phase Measurements

A detailed explanation of GNSS processing algorithms can be found in [8]–[10].

Phase-based relative positioning was the first method that enabled a centimeter-level precision positioning with GNSS. The method requires continuous synchronous phase observations of the same satellites from at least two stations (base and rover). The principle of the method is shown in figure 3.1.

The phase-based relative positioning method relies on single or double difference of carrier phase and code pseudoranges for estimating coordinates of a vector from base to rover. Highly accurate position for the base station is typically known though in some applications it is not necessary. Observation errors are mitigated or excluded

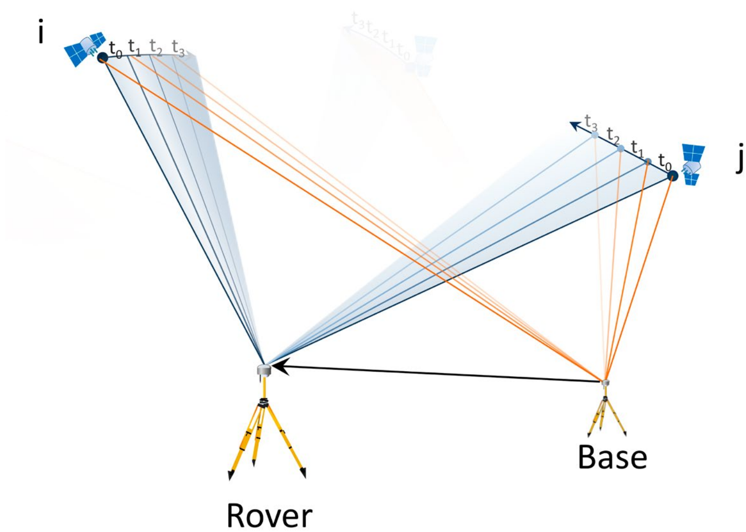


Figure 3.1: *Relative positioning with phase double differences.*

completely in differences. The error mitigation effect is the more significant the shorter the baseline between the base station and the rover. The estimated parameters are coordinates of the baseline vector and phase ambiguities.

In this method estimated ambiguities are integer values. Therefore the ambiguity resolution and fixing is typically applied. I.e. the estimates of ambiguities calculated at the first step (float solution) are replaced with the most probable set of integer values (the second step – ambiguity resolution). On the final step estimation of only three vector coordinates (fixed solution) can be accomplished while integer ambiguities are fixed to presumably errorless integer values and removed. Ambiguity resolution theory can be found in [13].

Smaller number of estimated parameters typically means better conditioning of the problem, and therefore higher accuracy and reliability of the solution. Therefore confidence that ambiguities are resolved to true values and availability of fixed solution are considered as important criterion of quality and reliability of the output coordinate estimates.

An important advantage of the method is that highly accurate and reliable fixed solution on short baselines can be achieved very quickly – within several minutes or even seconds. Another feature of the method is comparatively low minimal hardware requirements: GPS-only single-frequency equipment is typically sufficient to implement high-precision relative positioning on a 10–20 km baseline, depending on application and environment. Only base station observations and coordinates are required apart from the data obtained by the rover directly from navigation satellites.

The method can also be applied for estimation of long and very long baseline vectors. The distance from base to rover can reach several thousand kilometers. In this case long observation sessions are performed, observations on at least two frequencies are needed, and additional corrections are applied. Capability of observing more satellite constellations can help in this case, as well as if positioning is done in complicated environments.

Phase-based relative positioning precision depends on the baseline length, performance of the applied hardware and environmental conditions. Precision of few millimeters is attainable in the best possible conditions. The method is rather simple, reliable and provides high precision fast if the distance between base and rover is short enough.

3.3 Precise Point Positioning

Precise Point Positioning (PPP) was developed in late nineties [14]. It is actively improved nowadays. Its principle is shown in figure 3.2. From user's point of view it may look very similar to single point positioning (SPP) method, which is basic to GNSS. The rover "alone" observes the satellites continuously during the session. High precision is reached due to the following key features of the method:

- highly accurate ephemerides and clock corrections;
- continuous high precision phase measurements together with code pseudoranges;
- sophisticated and highly efficient way of handling different effects (potential error sources), including:

a. exclusion of 1st order ionospheric effect by combinations of observables;

b. calculation of dry tropospheric delay, relativistic effects, phase windup, tidal displacements of a site, etc.;

c. estimation of receiver clock correction, wet zenith troposphere delay, constant phase biases.

More information about PPP algorithms can be found in [15]. For a guide on International GNSS Service (IGS) products used in PPP one may refer to [16]. IGS product tables are provided in appendix C. In static mode PPP coordinate estimates can be accurate to several millimeters in horizontal plane and to centimeter level in vertical direction. In kinematic mode decimeter level accuracy can be achieved.

PPP relies on precise ephemeris and clock products provided by IGS or other correction service. RMS error of final IGS ephemerides for GPS is at 2.5 cm level, RMS error of clock corrections is 75 ps, which is nearly 2 cm in range domain.

Accuracy of broadcast ephemerides and clock corrections has been noticeably improved since the invention of PPP method. RMS Signal-in-Space Ranging Error (SISRE) for GPS decreased from 3.0 m in 2000 (GPS Block II) to 0.4–0.5 m in 2017 (GPS bock IIF). New Galileo constellation demonstrates even better RMS SISRE values of 0.14–0.15 m [5], [6]. Given the apparent similarity between SPP and PPP one may presume that evolution of GNSS will lead to merging this two methods into one – PPP with broadcast (but highly accurate) orbits and clocks, which once may become standard. It is possible, but classical PPP will provide higher accuracy anyway. Navigation message broadcasted by a satellite is a result of forecast while precise product used in PPP is always a result of estimation based on actual observations, whether in real-time (i.e. with delay of some seconds) or in post-processing mode. The most important factor limiting the accuracy of PPP based solely on signals-in-space information is short-term instability of the frequency standards onboard of GNSS satellites, which results in poorly predict-

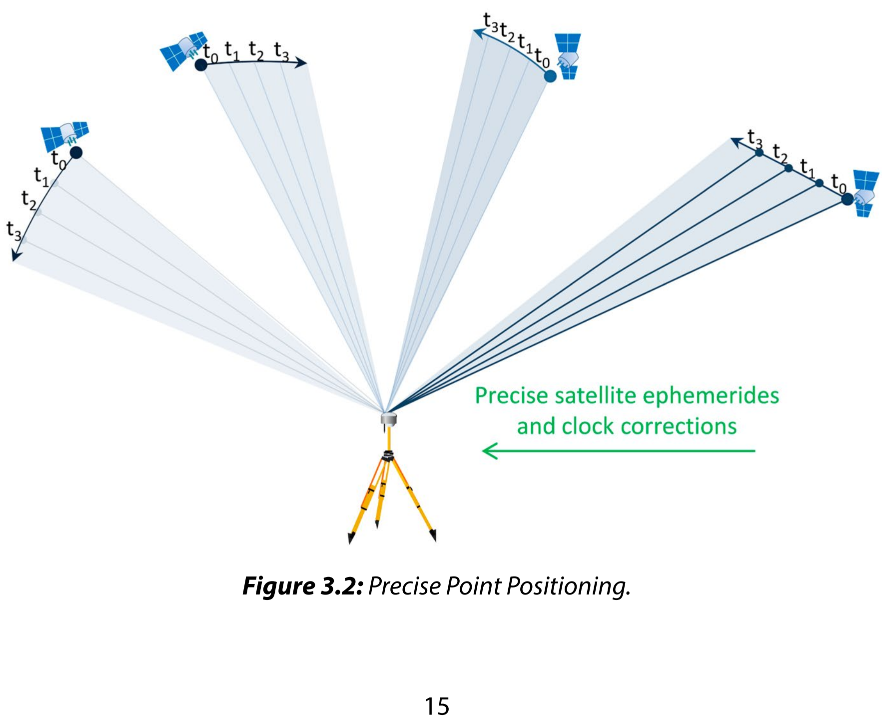


Figure 3.2: *Precise Point Positioning.*

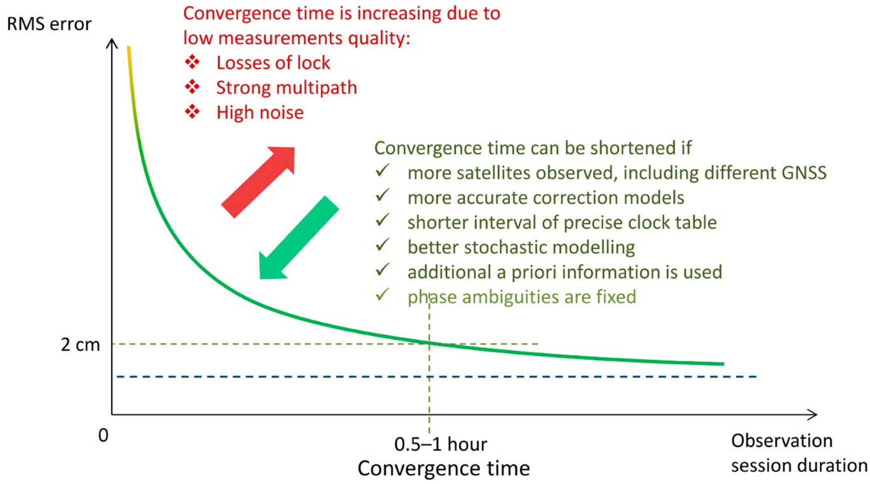


Figure 3.3: *PPP convergence time.*

able behavior of satellite clock. Because of that clock correction cannot be predicted as accurately as it can be estimated. Launch of new satellites with passive hydrogen masers (Galileo) improves the situation, but does not eliminate the issue completely as it can be seen from current estimates of SISRE [6]. Therefore PPP with broadcast orbits and clocks will not match the conventional PPP and phase-based relative positioning in terms of precision in foreseeable future.

The major advantage of PPP is that high positioning accuracy can be achieved without the need for the user to care about availability of a reference station nearby. The information products used in PPP are typically valid throughout the globe and may be generated with only some tens of globally distributed stations. In contrast to it, implementation of phase based relative method providing the same performance requires availability of a reference station within some tens of kilometers from every rover. Therefore it demands a much denser network of base stations, which in global scale would be extremely expensive.

The disadvantage of PPP is a relatively long convergence time, i.e. the duration of continuous observations needed to achieve a certain accuracy level. The convergence time depends on many factors shown in figure 3.3. The convergence time in PPP can be shortened dramatically with increasing number of continuously observed satellites. An experiment described in [17], showed that less than 30 min was needed to achieve accuracy better than 5 cm in every component versus 2 hours for GPS-only solution. The experiment was conducted in 2013 with 23–35 satellites in sight of 4 constellations including GPS, GLONASS, Galileo, and BeiDou.

Convergence time can further be improved by 20–30% for multi-GNSS PPP using a priori information about wet tropospheric zenith delays derived from numerical weather models [18].

Improvement of accuracy and stability of a solution in PPP can be achieved by carrier phase ambiguity fixing. Fixing ambiguities of undifferenced measurements require additional information on fractional phase biases. Techniques of ambiguity fixing in PPP are described in [19], [20].

The problem of long re-convergence after loss of lock can be practically solved by re-fixing ambiguities with predicted ionosphere correction. The method reportedly showed its effectiveness in the test at a van moving in a GPS-adverse environment where satellite number decreases and cycle slips frequently occur and showed improvement of ambiguity fixing rate from 7.7 to 93.6% of all epochs [21].

Triple frequency measurements can be used to significantly improve ambiguity resolution [22], detection, and correction of phase cycle slips [23].

3.4 Combination of Methods

By default PPP implies using dual-frequency measurements. Therefore it cannot be properly implemented with cheap single-frequency receivers as accounting for ionosphere becomes a problem in this case. Global ionosphere models and total electron content estimation are suitable at best for sub-meter accurate positioning [24]. But further improvement of positioning accuracy requires more precise knowledge of local ionosphere parameters. One of potential solution is a PPP with local network augmentation and a concept known as State Space Representation which is implemented in a technology called PPP-RTK [25]. Reportedly it enables cm-level precision positioning with single-frequency equipment. It also enables fast ambiguity resolution on longer distances from CORS to rover if compared to relative positioning. Combining this with lower bandwidth for correction data transmission comparing to RTK this technology seems to be one of the most promising for cost-effective high-precision positioning applications. But one must take into account that using this technology is possible only if a certain infrastructure is deployed in the region.

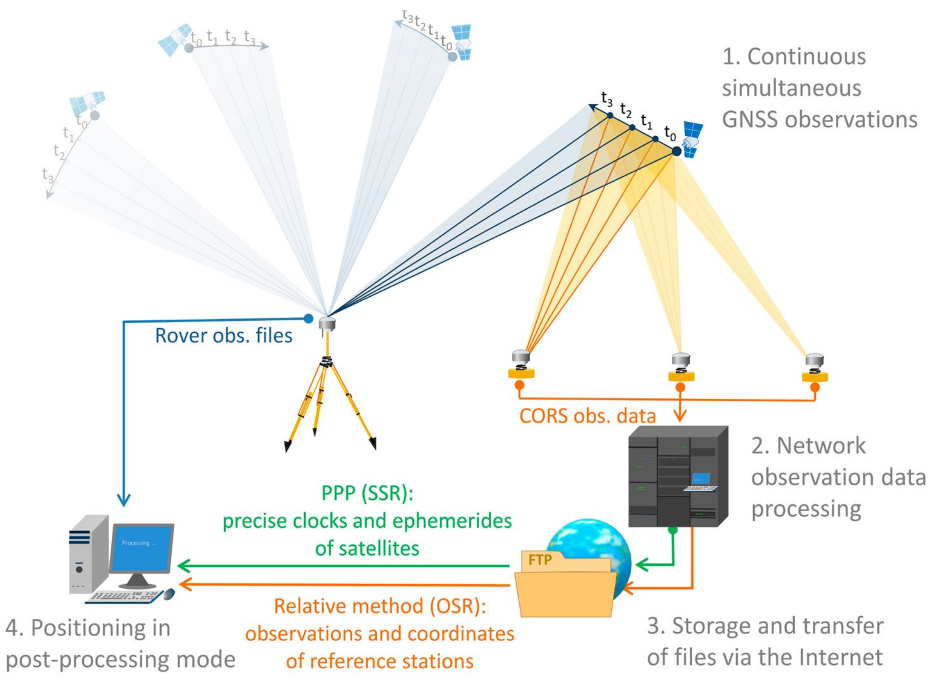


Figure 3.4: *Post-processing using office software.*

Another type of PPP and RTK combination is a technology like Trimble xFill, Leica SmartLink Fill or NovAtel RTK Assist that uses PPP to support RTK solution in case if signal from the local CORS network is lost.

3.5 Post-processing

Post-processing mode is available for both PPP and relative positioning methods. It can be implemented by means of office software (see figure 3.4) or online processing services (discussed in chapter 7). Both relative positioning and PPP can be implemented by using free open source software like RTKLIB described in chapter 6. For PPP precise clock corrections and ephemerides are needed.

Post-processing using office software implies downloading observation data for relative positioning and information products for PPP from archives by the user. Free data sources are discussed in chapter 5.

Using online post-processing services is simpler as it eliminates the need to download data and configure the desktop software. Instead the user uploads one's observation data to the server, typically via convenient website. After some minutes the report with coordinate estimates and result quality assessment is sent to the user by e-mail. Using online processing service not only simplifies post-processing but makes it more reliable as it reduces the scope of possible configuration error. There are several free online-processing services discussed in chapter 7.

3.6 Real-time High-precision Positioning

Using PPP and phase based relative positioning methods in real-time mode enables acquisition of highly accurate results right in the field. The real-time positioning dataflow is shown in figure 3.5.

In real-time mode user equipment receives correction data streams. There are two principle types of correction representation that correspond to the two positioning methods. The Observation Space Representation (OSR), used in relative positioning, means that each correction value is associated with a certain measurement and correct many errors (effects) of that measurement at once. State Space Representation (SSR) is a more advanced, rigorous, and sophisticated approach in which every correction is applied to a certain parameter of a model (ephemerides, clock correction, ionosphere and troposphere corrections, phase biases).

Real-time implementation of relative method is known as Real Time Kinematic (RTK). It has different “network” modifications (Network RTK – NRTK) that take into account additional OSR corrections calculated at a server of reference station network. NRTK technique is superior to RTK as it provides higher positioning accuracy due to more precise accounting for spatially auto-correlated errors in GNSS measurements caused by atmospheric effects, imperfect ephemerides and so on. NRTK corrections can be transmitted in several formats, the most common of which is RTCM. Standard messages in these formats can be used to implement different concepts to account for correction information, for example:

- Virtual Reference Station (VRS) [25], [26];
- Pseudo Reference Station (PRS) [25];

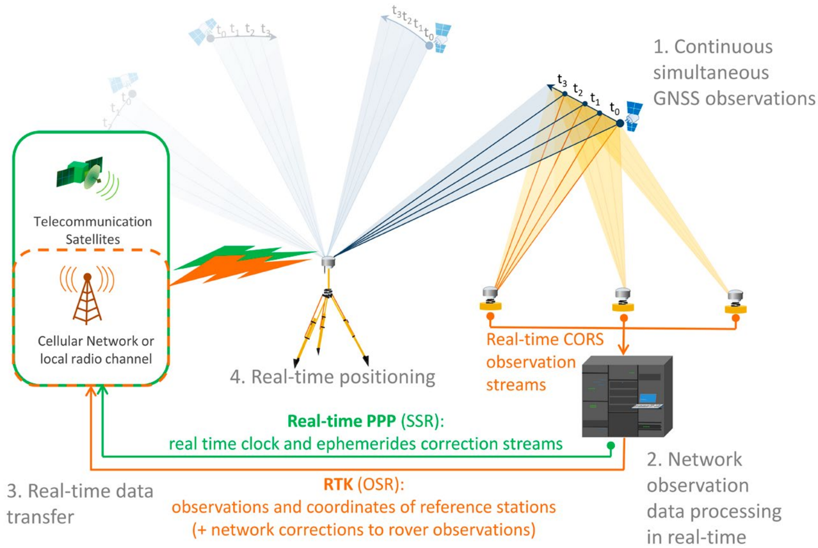


Figure 3.5: *Real-time positioning scheme.*

- Area Correction Parameters (Flächen Korrektur Parameter – FKP) [26], [27];
- Master and Auxiliary Reference Stations (Master-Auxiliary Concept – MAC) [28];
- Individualized Master-Auxiliary Concept (iMAC) [28].

The key difference between the above concepts of the NRTK method is the way network corrections and GNSS measurements from the reference station are represented. Some of the concepts, namely VRS, PRS, iMAC, require two-way communication channel between rover and server. Cellular networks enabling Internet access may be considered as the optimal way for providing OSR correction services for RTK. NTRIP (Networked Transport of RTCM via Internet Protocol) can be used for both OSR and SSR corrections.

SSR correction messages used in PPP can be broadcasted to all users and the required bandwidth is considerably lower than the one with OSR [25]. One-way connection is typically sufficient. It makes PPP the method of choice for providing global high-precision positioning services by means of satellite based augmentation systems, while RTK is preferable in regions where dense CORS and cellular networks are deployed. Real-time correction services are discussed in chapter 5.

3.7 General Remarks

Positioning accuracy depends on the accuracy of an underlying mathematical model including observables, ephemeris, and other elements. More rigorous accounting for all effects influencing measurements obviously enables reduction of overall error budget.

Positioning accuracy also heavily depends on how well equation system is conditioned [29]. In practice it is defined by many circumstances including satellite geometry, plurality of observation types, number and interdependency of estimated parameters. Well-conditioned observation equation system enables efficient use of precise measurement data, while extremely ill conditioned one may not be resolved to a meaningful result.

It is important to mention that the quantity of measurement data itself does not necessarily improve a condition number, but diversity of measurements does. This particularly explains the phenomena of convergence time in PPP which cannot be significantly shorten with a higher observation rate. That would not help because of strong temporal autocorrelation in GNSS measurement error. Therefore more observations do not substantially improve the solution unless they bring truly new information, which happens with change of constellation geometry over time, with more satellites observed simultaneously, or when additional non-GNSS measurements are used.

Reducing the number of estimated parameters in equation systems often enables better resolvability, i.e. more accurate and stable results may be obtained with the same observation data. Therefore fixed solution in relative positioning is normally more accurate and reliable than float solution. This principle is also behind the better stability and accuracy of static positioning if compared to kinematic mode.

With both high-precision methods considered in this study, GNSS positioning may be implemented in static, kinematic and stop-and-go modes, which are different in the way rover position is modeled. In kinematic mode coordinates are estimated epochwise, so the number of estimated coordinate parameters usually equals to number of epochs multiplied by three. In static mode only 3 coordinates are estimated for the whole observation session, which allows improving accuracy and stability of a solution.

Stop-and-go mode is a combination of consecutive static and kinematic sections within one continuous observation session. In this case static and kinematic modes alternate depending on whether the rover is at rest or moving. This approach helps avoiding unwanted increase of estimated parameter number, as the phase ambiguities are kept the same throughout the session, and the satellites are observed without interruptions. The effect of that is a much shorter convergence time during static periods of the session.

In stop-and-go mode a signal indicating the switch between rest and motion may be produced by an operator (e.g. surveyor) or it can be generated automatically. For example, in case of car positioning, odometer data can be used for that. This is probably the simplest example of how external information about whether the object is moving or not can improve GNSS positioning solution. In a more general case any external information can be used. For both PPP, and relative positioning, integration with inertial measurement units (IMU) provides additional information, which can be used for cycle slip detection and significant improvement of kinematic solutions accuracy and stability [30].

External a priori information can be used in the form of additional constraints. For example, in case of positioning of a train one may modify equation system to constrain possible movements in vertical direction and across-track horizontal direction, which will strengthen solution for position along the track. The same principle was particularly applied with vertical constraints in hydrographical survey [31].

As it was mentioned earlier a priori information about different parameters may also improve solution and shorten convergence time. A particular example is using wet tropospheric delay derived from numeric weather models [18].

Thus one of the most important and comprehensive approaches to improving positioning methods consists in rational use of a great variety of available information about the observed system.

4 GNSS USER EQUIPMENT AND ITS COST

4.1 High Precision GNSS Hardware

GNSS equipment of user and augmentation segments have traditionally contributed one of the largest parts of high-precision positioning technology cost to the user. Cost-effectiveness to a large extent is dependent on equipment characteristics.

Detailed description of operation principle and architecture of GNSS receivers can be found in [8]. According to it, a conventional GNSS hardware receiver is basically composed of the analog part, the digital part including the application processor, and the interfaces for input-output. The following building blocks may be identified: single- or multi-frequency L-band antenna plus cable, radio frequency (RF) front-end including the low-noise amplifier (LNA), the oscillator, down converter and mixers, and the bandpass filters, the analog to digital converter (ADC) plus, optionally, an amplifier gain control (AGC). The digital part consists of a baseband integrated circuit containing the correlators, the microprocessor (MP), and the read only memory (ROM) and random access memory (RAM) memory units. The building blocks are shown in figure 4.1 from [8, p. 373].

There are 3 main types of GNSS receiver implementations: software-defined radio based on a general purpose machine, or on a FPGA (Field Programmable Gate Array), hardware-defined radio based on ASIC (Application Specific Integrated Circuit). The key features of these types are shown in table 4.1 [8].

Cost and performance of the three types of equipment architecture differ tremendously. ASIC and FPGA can be considered conventional solutions as they are most often applied. FPGA is an expensive option (> $2,000 procurement cost per bare board). ASIC has the lowest cost per unit if produced in large volumes.

Implementation of software-defined GNSS receiver on general purpose machines provides the lowest efficiency from technical point of view as it can be clearly seen from table 4.1. Nevertheless general purpose machines are applied ubiquitously, produced in huge volumes, and evolving very fast. Therefore, if some years ago software-defined

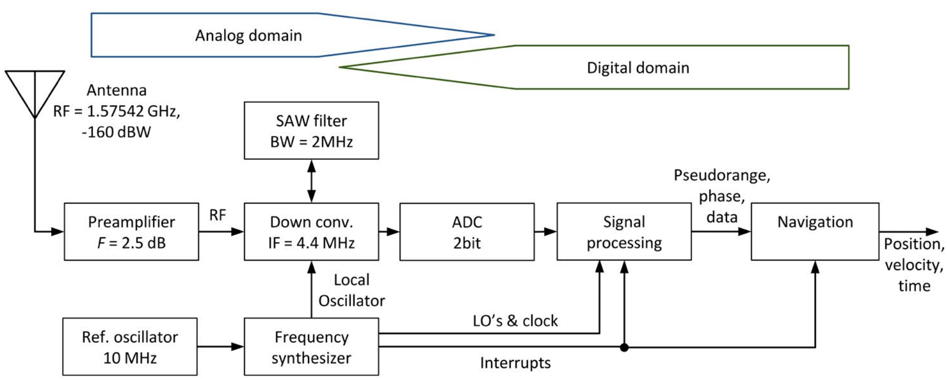


***Figure 4.1:** Example of building blocks for a GPS C/A-code L1 receiver [8, p. 373].*

Table 4.1: *Receiver types [8].*

Receiver type	Platform	Flexibility	Power consumption mW/MOPS	Chip area efficiency, MOPS/mm²
Software-defined	PC or DSP	Programmable	10	1
Software-defined	FPGA	Reconfigurable	0.1	100
Hardware-defined	ASIC	Dedicated	0.001	100,000

receivers on general purpose machines were considered as laboratory concept, nowadays this piece of technology is mature enough for practical application [8]. Wider adoption of this type of receivers is expected to affect high-end GNSS equipment market significantly in future.

GNSS equipment is traditionally subdivided into grades according to its purpose, performance, and cost. The present study considers navigation and surveying/geodetic grade devices. The relevant consumer properties of the equipment of a certain grade can be expressed in a variety of characteristics.

Minimal necessary requirements are expressed in standards. There are hundreds of official standards. The recent series of European GNSS Agency (GSA)[1] reports provides a comprehensive overview of the user needs and existing standards:

- Report on Aviation User Needs and Requirements [32];
- Report on Maritime and Inland Waterways User Needs and Requirements [33];
- Report on Location-Based Services User Needs and Requirements [34];
- Report on Agriculture User Needs and Requirements [35];
- Report on Surveying User Needs and Requirements [36];
- Report on Time & Synchronization User Needs and Requirements [37];
- Report on Rail User Needs and Requirements [38];
- Report on Road User Needs and Requirements [39].

Every user defines one's own requirements and priorities regarding the choice of equipment functionality and performance within the frame setup by mandatory official standards for the particular application.

4.2 Technical Aspects of Reducing Costs

4.2.1 Modular Design

The modularity concept is widely accepted in GNSS hard and software development. It enables more flexibility and efficiency in satisfying customer's requirements. Modules with similar functionality, providing the same interfaces and sharing the same form factors (in case of hardware), may be interchangeable. That means that being produced by different companies they will compete on the market. Modular design based on open standards foster competitiveness at the level of components which shall lead to better quality and more opportunities for customization of the final product at lower cost.

1 http://www.gsa.europa.eu.

Modular concept implies unification of some parts of equipment and using standard widely applied elements instead of unique ones, where it is reasonable. One of the examples is the current trend of replacing dedicated field survey controllers with smartphones and tablet computers. Typically a rugged Android device may be several times cheaper than a professional controller while the advantage of the latest is not clear. Therefore minimal set of surveying equipment offered by many suppliers do not include a field controller. Instead receiver configuration and survey software for mobile devices with Android operating system (OS) is often offered. The same considerations are apparently behind the wider use of USB ports and SD-cards in GNSS equipment in recent years.

Modular design allows reducing total cost of equipment by economizing on relatively simple parts, which have limited influence on performance or can be replaced by cheaper analogs (comparing to production of famous brands) without loss of quality. Such elements are: housing, batteries, standard data cables, antenna mount, survey rod, tripod, adapters. In contrast to them, there is a performance-critical part dealing with GNSS signals. Price of this part is predominantly defined by its intellectual component and depends more on performance rather than on per-unit production cost. Development of this part is most complicated, requires large investment of money, time, knowledge and experience. Saving money on it would be a risky decision. Many equipment producers (integrators) decide not to do that part on their own, so they buy it as a ready module from the leading Original Equipment Manufacturer (OEM). Today a large fraction of brand diversity on GNSS hardware market can be explained by availability of OEM modules. The examples of GNSS receivers under different brands based on the same OEM card are provided in table 4.2.

Table 4.2: *Examples of receivers based on Trimble BD970 OEM module.*

Company	Receiver Model	Brand origin
Acnovo	GX9	Mexico
CHCNav	N71, X91	China
EFT	M1, M3, RS1	Russia
FOIF	A30	China
Hi-Target	V30, V60, V100	China
Industrial Geodetic Systems	GR220	Russia
PrinCe	N71, X91	Russia
South	S82T, S82V	China
Stonex	S9 GNSS	Italy

Specifications of some receivers show that those with OEM-cards of different manufacturers may be offered under the same model name. Among the leaders of OEM component producers can be named: Trimble, Novatel, Javad, Hemisphere, Septentrio, ComNav, Swift Navigation etc.

One of the surveying grade equipment set built around BD970 card, mentioned in table 4.2 (multi-frequency, all-constellations receiver with field survey and office post-processing software, rod, power supply, batteries, and case), is available at $3,000. The OEM card itself can be found at a retail price of $2,200, though volume prices are expected to be lower. Thus OEM-board is one of key parts that defines performance and sets the lower price boundary of high-quality professional hardware.

It is important to notice that while practice of building a receiver around an OEM-card does make it easier to offer a high quality product, it does not automatically guarantee that level of quality to the user.

4.2.2 Optional Functionality

As was shown, brand does not necessarily define the technical content of the product. Moreover, two receivers similar in design do not always provide the same functionality. For example, the already mentioned OEM module Trimble BD970 GNSS is available in a variety of configurations from L1 DGPS upwards [40].

A widely used practice among high-precision GNSS hardware manufacturers is to design a versatile product and make some part of its features optional and available for additional fee. Such options can be bought or subscribed to. For example, this can be implemented via Option Authorization File (OAF) to enable the specific options that customer purchases. An OAF allows users to customize and configure hardware according to particular needs, thus only purchasing demanded options [41]. Another mechanism is activating options by uploading license key to the receiver. If a multi-frequency receiver is needed to a customer, one has to pay more than for single frequency, despite the fact that it is exactly the same receiver. This approach is often applied for SBAS, multi-constellation, push-ftp, and high output rate capabilities. Thus not the equipment itself but its functionality is what user pays for.

Such unification allows saving money on development of equipment models in a lower price segment. For a user it provides flexible choice of functionality allowing not paying for the options that are not needed.

The described approach is also interesting in another way. Obviously, a higher price of a device with functionality options activated cannot be explained by the higher production cost, because it is exactly the same device. That suggests a simple conclusion: the variable per-unit production cost is relatively low even for advanced GNSS user equipment. So low that it is still profitable to manufacture and sell high-end receivers even in the cheapest single-frequency configuration. Another possible explanation is that a buyer of an advanced set of options actually pays part of the price for those who choose basic functionality.

As one may see the market price of equipment (and services) may be shaped more by effective demand and marketing strategies, rather than production cost. In other words, the goods are offered and successfully sold at such a price which customers are ready to pay.

4.2.3 Open Programming Interface

Large part of device functionality is defined by embedded software (firmware): RTK base and rover modes, real-time PPP mode, professional software utilities (stake out tool etc.) may cost more than the device without them. Therefore receivers with open programming interface and access to raw data, enabling development of third party software, particularly free open source software, can become a significant factor of decreasing costs for end-users. The examples of receivers based on free Linux operating system (OS) are: Navxperience Open Source Software receiver [42], STONEX RSNET4, South Galaxy series, Swift Navigation Piksi Multi etc. If a user is given sufficient rights on the Linux OS of a receiver, one may find extreme flexibility in customizing the device. Particularly that may enable deployment of free open source software for positioning, data transfer over FTP or NTRIP – right on the receiver. Therefore using free Linux OS is an important factor of cost-effectiveness as it provides greater flexibility in device customization to satisfy the user's needs. What is also noticeable, it can be done at lower or no cost, if compared to purchasing options for receivers with closed programming interface.

4.2.4 Software Defined Radio

The concept of GNSS receiver based on software-defined radio (SDR) consists in using software on a personal computer, embedded device, or cloud service for signal processing, which has traditionally been implemented in hardware elements (mixers, filters, amplifiers, modulator and demodulators etc.). The concept is being developed particularly within the frame of GNSS-SDR project offering an open source implementation of SDR receiver for a wide range of devices form laptops to Raspberry Pi microcomputers [43].

According to [44], a number of commercially successful GNSS receivers were developed combining dedicated system-on-chip architecture and many of the benefits provided by software-defined radio, including Swift Navigation Piksi Multi GNSS Module [45]. Earlier SDR concept was applied in low-cost dual-frequency GPS receiver CASES designed for ionosphere monitoring [46].

The most well-known practical ready-to-use implementation of SDR in GNSS is *Trimble Catalyst* [47]. Surveying grade GNSS antenna module (RF front-end) is connected via USB port to a smartphone or tablet computer with installed software-defined GNSS receiver. This example deserves special attention at least because it is provided by one of the world leading high-precision GNSS equipment manufacturers. That itself may be considered as a proof of maturity of GNSS software-defined receivers. Trimble Catalyst is apparently the first example of successful implementation of GNSS SDR on a smartphone, which may become a game changer in high-precision GNSS technology.

On the Trimble Catalyst website the following system requirements for the smartphone are specified: Android 5.0 or higher, 64-bit CPU, 1.4 GHz processor, Minimum 4x Arm® cores (8x or more Arm cores recommended), 1.4 GB of RAM. The specified minimum requirements correspond to a lower middle price segment. Some smartphone models listed as compatible on the same website can be bought for $150. A number

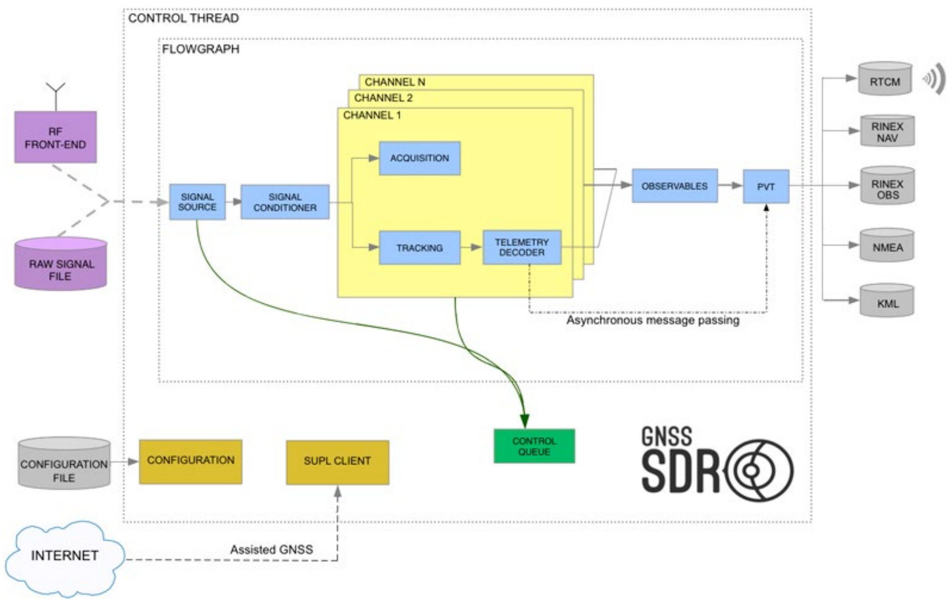


Figure 4.2: *GNSS SDR [43].*

of Android applications are capable of using positions provided by Trimble Catalyst. Using it requires a Catalyst Service application to be installed (available in Google Play). A software development kit (SDK) is available, so more third party software is anticipated in future.

Pricing is another interesting part. Trimble Catalyst hardware cost starts from $350 [48]. That includes DA1 antenna, battery pack, pole mount, USB-C cable, and pouch. But as we have already seen, not the hardware but its functionality is what user pays for. Positioning with Trimble Catalyst is available as a service provided by subscription. Four accuracy options are possible: meter, sub-meter, decimeter, "precision". The top precision option, which works with RTK networks and offers 1 cm – 2 cm accuracy in optimal conditions, may cost over $4,100 per year[2]. Apparently after some years of use it will get more expensive than the best high-end equipment of the same manufacturer.

4.2.5 Low-cost GNSS Equipment

This group includes equipment available at a price considerably lower than minimal price for high-precision positioning kit, which is currently about $3,000 per set sufficient for work. According to [49], the low-cost price segment is 100–500 euro (€). There is also a segment of ultra-low-cost devices (few $10 per unit), which are applied in mobile devices, wearables, tablet computers. Usually these are the devices initially developed for navigation in SPP mode with accuracy of several meters, but providing access to raw phase measurements, which enables high-precision positioning. Some additional functionality like real-time PPP or RTK processing may be embedded by the manufacturer. There are papers demonstrating feasibility of sub-decimeter accuracy level with this kind of equipment [48]–[53].

U-blox, NVS Technologies, Broadcom, SiRF/CSR are among the most well-known producers of low-cost and ultra-low-cost GNSS chips. Using those chips in a high-precision positioning device requires availability of raw phase measurements.

It is possible to achieve high accuracy with low-cost device assembled by the user oneself. One of the examples is a design offered by T. Takasu and A. Yasuda based on U-blox receiver, BeagleBoard open-hardware computer, RTKLIB software. Schemes of assembly and test results are provided in [51]. There is a newer project with Raspberry Pi microcomputer ($41), U-blox M8T receiver (€79), Tallysman antenna (€80) [55]. Research community and GNSS enthusiasts are actively involved in the development and assembly of such devices though in real life this kind of equipment is not often applied because of complexity in accomplishing practical tasks. An overview of RTKLIB-compatible low-cost devices can be found in OpenStreetMap wiki [56].

Although the opportunity to achieve high precision with low-cost equipment has been demonstrated in numerous experiments, such devices have been unable to compete against full-featured mature professional equipment at least in terms of reliability. In a recent experimental study [53] low-cost receivers Swift Piksi Multi ($540, multi-frequency GPS-only), NAVIS NV08C-RTK ($490), Emlid Reach ($399), U-blox NEO-M8P ($235), Skytraq S2525F8 ($200) were tested in different environments (rural, suburban and urban), in different modes with different antennas and compared with high-end (Navcom SF-3050) and mid-range (Hemisphere Eclipse P307) receivers. The results were the following. For static applications, low-cost receivers may be a viable option

2 https://www.esri.com/~/media/Files/Pdfs/partners/hardware/trimble/Catalyst.pdf.

depending on the accuracy and continuity requirements. The low-cost receivers had nominal performance in the rural environment where there was minimal multipath interference. Three of the five low-cost receivers had a horizontal RTK fixed-integer position accuracy of 2.6 cm (95%) or better while the other two had sub-meter accuracy. In the rural environment, the single-frequency receivers had poorer RTK availability and time to first RTK fix compared to the multi-frequency receivers. Regarding the single-frequency low-cost receivers the following conclusions were made:

1. They can achieve centimeter-level accuracy in static applications in rural environments.
2. They perform better when using a high-quality antenna versus a low-quality antenna.
3. They cannot hold an RTK fixed-integer solution for any significant time in dynamic applications.
4. They spend most of their time in an RTK float solution.

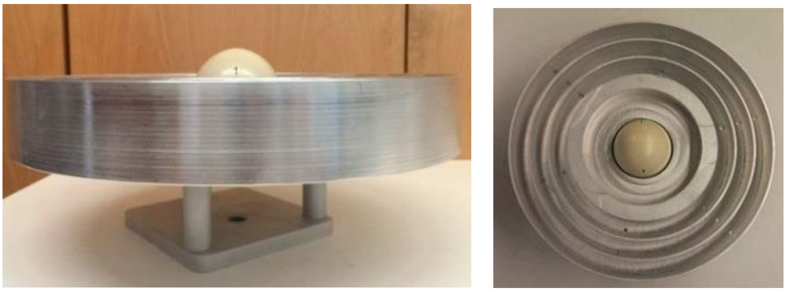
The multi-frequency Swift Piksi performed better than the L1-only, low-cost receivers but displayed the same shortcomings (degraded accuracy, worse availability) in the suburban and urban environments during static testing. It had consistent performance across all metrics during the dynamic testing, having better metrics across the board than the single-frequency receivers. However, it did take longer than the reference receiver and the Eclipse P307 to reacquire an RTK fixed-integer lock after traveling under a bridge.

While low-cost equipment still demonstrates lack of performance it evolves continuously. Though the study described above was published nearly a year ago, the new versions of compared devices are available now. In that study Swift Piksi Multi was the only multi-frequency device. It was tested in GPS-only configuration. But the current version utilizes all four major GNSS constellations and SBAS. Also an enhanced specification with inertial module is available now. The tested NAVIS receiver has evolved to NV08C-RTK-M with double-frequency and multi-constellation capabilities. It is obvious that this type of devices will be further improved as they target very promising emerging markets such as autonomous high-precision navigation for UAVs and cars, which are safety-critical and therefore require high reliability. In a short term one may expect the increase of their price with increasing performance.

As it has been confirmed by the study described above, analog part (RF front end) including antenna sets up a limit for precision and defines a large fraction of equipment cost. The studies [54], [57] show that the quality of GNSS observations depends stronger on the antenna performance rather than on the receiver. A serious disadvantage of low-cost antenna is the absence of effective protection from reflected signals (multipath effect). Nevertheless there are developments that may considerably improve it.

Software-based multipath mitigation techniques are available in [58]–[60]. Another option is defending low-cost GNSS antenna from multipath signals. An L1-optimized choke ring ground plane (CR-GP) was designed at University of Stuttgart to reduce the multipath signal (see figure 4.3).

The tests showed that the introduced low-cost single-frequency GPS receiver-system, which contains the U-blox LEA-6T single-frequency GPS receiver and Trimble Bullet III antenna with a self-constructed L1-optimized CR-GP, can reach standard deviations of 3 mm in east, 5 mm in north and 9 mm in height in the test field that has many reflec-



a) ***b)***

Figure 4.3: *L1-optimized CR-GP with antenna (side view and top view) [61].*

tors. This accuracy is comparable with geodetic dual-frequency GNSS receiver-system. The improvement of the standard deviation of the measurement using the CR-GP is about 50 and 35% compared to the used antenna without shielding and with flat ground plane respectively [61].

Important part of potential for high-precision positioning cost-effectiveness improvement is associated with the recent progress in the development of ultra-low-cost modules for smartphones, tablet PCs, and wearable electronics. Broadcom BCM4775X module is of particular interest as the first dual-frequency multi-GNSS module, apparently of ultra-low-cost category, embedded into smartphone. According to the manufacturer [62], the BCM4775X family includes a dual-processor architecture (ARM CM4+CM0) that ensures high power efficiency. The BCM4775X includes a new RF architecture, enabling the lowest power consumption at any received signal condition. The BCM4775X achieves system-level performance benefits from tightly integrating the sensor and GNSS signals. Measurements from sensors such as accelerometers, gyroscopes, magnetometers, and others are fused with GNSS measurements to provide a highly accurate, cross-calibrated output to applications while lowering system power. Cross-calibration is achieved by using sensor measurements to aid GNSS for small movements and by using GNSS to calibrate sensor measurements, the latter having inherent drift that accumulates over time and larger movements.

The BCM47755 chip supports two frequencies (L1+L5), and as a result, achieves lane-level accuracy outdoors and much higher resistance to multipath and reflected signals in urban scenarios, as well as higher immunity to interference and jamming. The BCM47755 can simultaneously receive the following signals:

- GPS L1 C/A, L5;
- GLONASS L1;
- BeiDou B1;
- Galileo E1, E5a;
- QZSS L1, L5.

First tests of the chip with Starling positioning engine by Swift Navigation have shown sub-meter accuracy: 0.884 m (90%) [63] but the researchers and developers aim at its further improvement.

4.2.6 High Precision Positioning with Smartphone

Providing accuracy and precision with a smartphone or tablet PC without additional hardware is a promising direction of research and development because it offers an access to totally different GNSS market segments, enables new applications that may dramatically increase the number customers interested in high precision and accuracy. One of the major challenges was a performance of patch antenna used in smartphones.

Centimeter level accuracy positioning with smartphone was proven feasible in 2013 by a research team from Texas University at Austin [64] (see figure 4.4).

RTKLIB open source software was ported to smartphone operating system (OS) Android, initially without opportunity to use internal GNSS antenna of a smartphone for precise positioning due to OS limitations [65].

Starting from Android version 7.1, operating system and applications got access to raw GNSS measurements data provided by embedded GNSS antenna [66]. The list of smartphones supporting that feature is available at [67]. It was shown that cm-level positioning accuracy is achievable, though there are still problems with noisy code measurements. The open source project is available on GitHub [65]. A detailed study of positioning with Android devices is provided in [68].

Finally in 2018 Xiaomi launched the first dual-frequency GNSS smartphone with a Broadcom BCM47755 chip. Xiaomi Mi 8 is claimed to be the world's first smartphone providing up to decimeter-level accuracy for location-based services and vehicle navigation. Dual frequency in this case means L1+L5 signals transmitted by GPS and Galileo

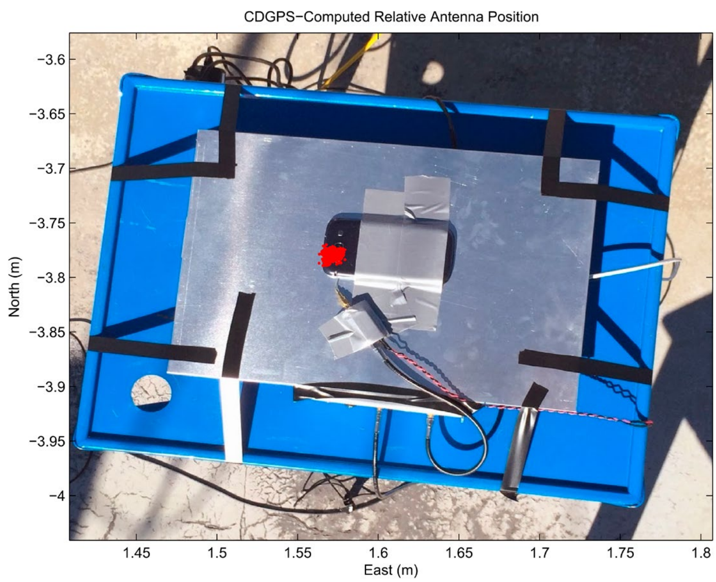


Figure 4.4: *Result of carrier-phase GNSS solution using data collected from the antenna of a smartphone. The cluster of red near the lower left-hand corner of the phone represents 500 solutions over an 8-minute interval, superimposed on the photo and properly scaled [64].*

[69]. In the next paragraph the impact of such developments on the overall cost-effectiveness of high precision GNSS positioning technology is discussed.

4.3 Market-related Factors Defining Cost

4.3.1 Market Trends and Forecasts

As a result of different factors the high-precision positioning equipment has been getting cheaper in recent years and that process is likely to continue [1], [70], [71]. The trend is illustrated by a chart from GNSS Market Report 2015 [72] in figure 4.5, which particularly shows the change of average price of professional surveying-grade equipment at retail. The order of forecasted price decrease is few 10% over 10 years.

The trend is explained by increasing competitiveness brought by Chinese companies to professional GNSS equipment market. Also it may be attributed to overall progress in the development of electronics and associated price dynamics which, can be very approximately quantified by Moor's and Grosch's laws.

The forecast is apparently conservative. It nearly corresponds to linear extrapolation of the trend that was observed before the year 2015. A deeper look into the structure of GNSS equipment market three years later allows us to presume the possibility of a far more significant price decrease.

According to the recent GSA GNSS Market reports [1], [72] the GNSS user equipment market is constantly growing. The total installed base, i.e. the number of devices in use, is forecasted to increase from 5.8 billion devices in 2017 to 8 billion by 2025. Until now all high precision equipment has belonged to professional segment of the market, which is currently constitutes only a fraction of a percent of the total installed base.

It is reasonable to presume that the fraction of high-precision instruments of professional devices amount will increase in future, particularly due to fast development of drone applications. Earlier UAV guidance has relied on autopilot mostly in open environment. Thus high positioning accuracy was not necessary for navigation. New appli-

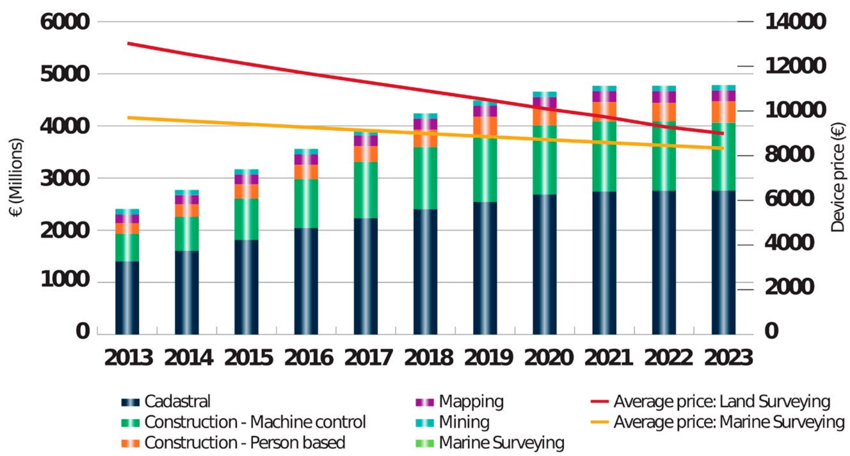


Figure 4.5: *Core revenue of GNSS device sales and services by application [72].*

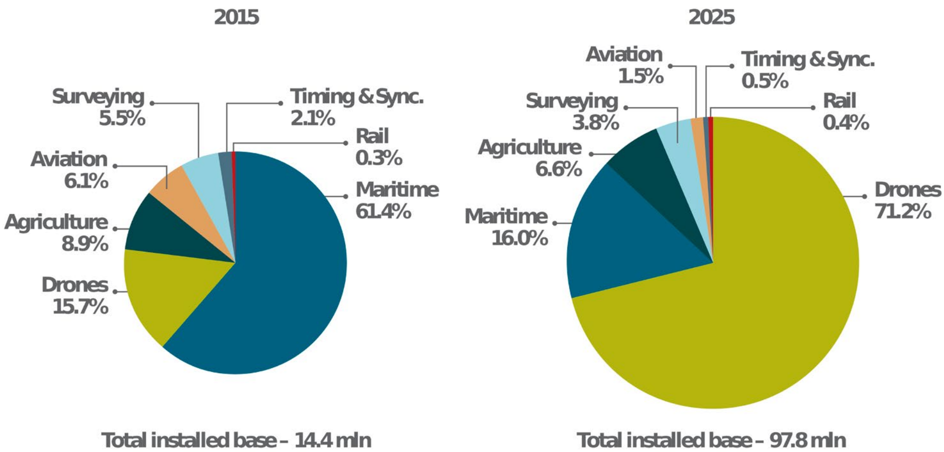


Figure 4.6: *Installed base of "Professional" segments [1].*

cations of drones, such as automated delivery, and penetration of self-guided UAVs into urban environment will require more reliability and safety, particularly in the aspect of collision preventing. Consequently a higher positioning precision will be demanded.

Nevertheless the total installed base is dominated by low-accuracy non-professional devices and this situation is to persist in future (see figure 4.7).

In 2017 the major part (5.4 billion of 5.8 billion) of GNSS devices in the world were intended for mass market Location Based Services (LBS) – smartphones, tablet PCs. Road segment was the second largest (e-call, car navigation) – 0.38 billion devices. Nearly seven-fold growth of installed base in professional segment is anticipated by 2025. Even though, its fraction in the total number of GNSS user devices worldwide is expected to be slightly above 1% by that time.

It means that if at least some part of LBS and road market segments adopts high precision positioning technology that could further increase the high-precision equipment installed base manifold, which is to play a very significant role in decreasing the costs.

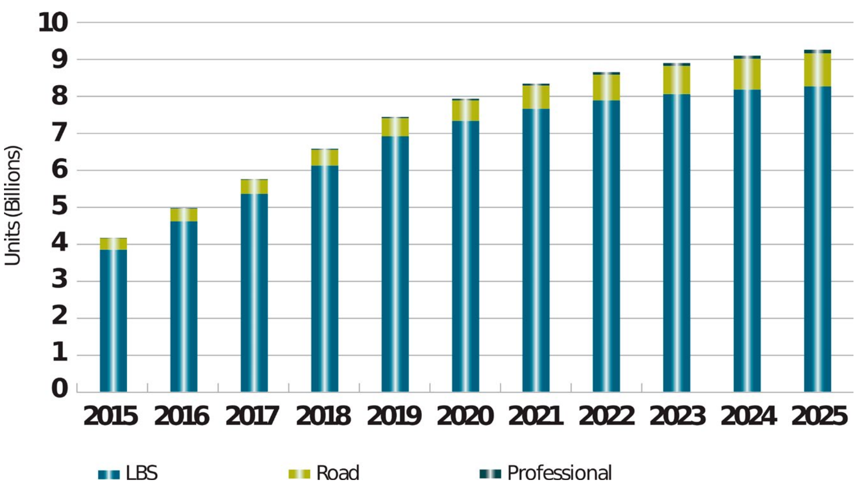


Figure 4.7: *Global installed base by segment [1].*

4.3.2 Effects of Production Scale

There is a widely known dependency between the cost and scale of production. With increase of output quantity the average cost per unit decreases unless it reaches a certain level. That is called economies of scale. Effects of economies of scale on production costs can be summed [73].

First, it reduces the per-unit fixed cost. As a result of increased production, the fixed cost gets spread over more output than before.

Second, it reduces the-per unit variable costs. Economies of scale bring down the per-unit variable costs. This occurs as the expanded scale of production increases the efficiency of the production process.

In case of high-tech products, such as GNSS user's hardware, software or correction services, fixed costs including development are more significant than variable per-unit costs. In special cases variable per-unit cost can be negligible. Examples are software and correction services provided via a satellite based system, as more users do not increase cost of production. In these particular cases one could expect hyperbolic decrease of the cost with increase of the number of customers.

That can be illustrated using GNSS Market report forecasts assuming variable per-unit cost of production negligible. Let us consider a certain high-precision product in 2015 which constitutes 5% of installed base in professional surveying sector (39,600 pcs.) with cost $5,000 per unit. Now let us compare this situation with the year 2025, assuming that the product with the same production cost (also totally fixed) constitutes 5% of surveying and drone navigation segments (3,667,500 pcs.). The volume of installed base in that case increases by factor of 92.6. The cost per unit decreases correspondingly from $5,000 to $54.

Definitely this is a very special example suitable mostly for SDR or correction services. For hardware in general variable costs cannot be considered negligible though they are still apparently smaller than the fixed ones. Even more important conclusion is that production cost is not necessarily the largest part of the price at retail.

4.3.3 Demand Elasticity as the Key Factor

In this chapter we have already discussed some pieces of technology potentially able to shift the balance between achievable positioning accuracy and the cost of solution. They are interesting not only from technological point of view but also because of the way they really affect the user cost of high precision. Let us return to some of them once more.

Trimble Catalyst, which is the newest ground breaking software-defined smartphone-based receiver, unlikely to make any impact on average equipment price in professional high-precision segment if its subscription fee is $4,100 per year. One may argue that Trimble Catalyst is primarily intended for short-term on-demand use and may be cost-effective with a more flexible subscription plan. But traditional professional GNSS hardware can also be rented for a short time. So right now it is difficult to see any advantage in cost-effectiveness in comparison with hardware-defined receivers. To understand why, the reader should probably ask oneself: what would happen with the demand for high-end surveying receivers of the same manufacturer with a price of more than $10,000 if they could be effectively substituted with something worth $350 and a smartphone?

Another point is the widely used practice of designing and manufacturing equipment with maximum capabilities and blocking some of them unless the user pays an additional price. Definitely it provides some benefits reducing the fixed part of production cost due to unification while offering opportunities for customization. The idea that the customer pays for the functionality rather than for the equipment itself sounds rather logical. But it apparently implies that at least one of the following statements is true. First, the real production cost of such equipment is significantly lower than the price of its simplest configuration and therefore the customers are typically overcharged for the full-featured versions, sometimes extremely. Second, a customer purchasing equipment with additional functionality pays part of the price for the buyers of a basic functionality of the same equipment model. Apparently, in both cases the true production cost has very little in common with the price at retail.

The third "finding" is that evolution of low-cost equipment affects its cost. Swift Navigation represents a bright example of how a start-up from Kickstarter went to mass production successfully. At the same time it is also an example of what happens when a device conceived as low-cost one gets capabilities of a higher-grade equipment. The initial project outline described the proposed Piksi as an RTK GPS receiver with open source software that costs one tenth [70] the price of any other available RTK system. Currently the retail price for Swift Piksi Multi receiver (OEM card alone) is $595. A receiver within a rugged enclosure costs $1,895. With inertial module its cost reaches $2,895. Antenna pack costs another $195, accessory pack with cables and connectors – $65 more. As radio communication module is not included by default, the additional radio pack may be purchased for $695 if RTK functionality is needed. The total price for ready-to-use RTK equipment without IMU is $2,850. If the cost of surveying rod and case are added, the total price will be over $3,000, which is surprisingly (or not) matches the lower boundary price of the devices based on a popular Trimble OEM-card (see table 4.2).

The examples above illustrate convergence of the two trends: high-precision equipment gets cheaper if it loses some of its advanced features, low-cost equipment gets more advanced while getting more expensive. The price is clearly shaped according to a stereotype that a better solution must be more expensive, regardless of production cost. Though the price decrease seems more than just feasible, it happens much slower than one could expect from an open and highly competitive market.

The possible reason is inelasticity of demand. As was already mentioned, currently high-precision positioning technology is present only in professional, i.e. business-to-business (B2B) segment of GNSS equipment market. The number of professional users is increasing with ongoing adoption of modern technology in developing countries. According to [1], current level of GNSS technology penetration in hydrographic surveying is 100% globally. In land surveying it is nearly 80% and expected to reach 100% by 2021. Therefore the demand for professional equipment is actually limited. There is no need for suppliers to decrease its price if that does not raise the sales sufficiently. Seemingly it is the main reason why the price of high precision decreases much slower than it could.

Therefore adoption of high-precision positioning technology by non-professional (business-to-customer or B2C) market segments may become especially important for further improvement of its cost-effectiveness. That may not only increase sales manifold enabling economies of scale, but also make use of higher price elasticity of demand which will foster suppliers to decrease prices.

5 CORS NETWORKS AND CORRECTION SERVICES

5.1 CORS Networks

Efficient implementation of high-precision positioning by means of GNSS requires additional ground infrastructure. Continuously Operating Reference Station (CORS) networks are the core of it. A CORS network provides access to a reference frame by means of GNSS observation data, used for high precision relative positioning or for deriving other information products. In the simplest case raw GNSS measurements obtained from CORS may be used to process baselines in a posteriori mode or in RTK. Centralized processing of observation data allows providing additional area correction parameters in case of Observation Space Representation (OSR) or detailed and rigorously modeled corrections in State Space Representation (SSR). In case of phase-based relative positioning CORS networks may be considered as a more efficient alternative to deploying own reference stations. In case of PPP CORS network is always in the back-end of service providing required information products.

Typically CORS network is expected to be a geodetic network in a full sense, i.e. an adjusted geometric build-up implementing a certain self-consistent reference frame. For example IGS tracking network implements IGS14 reference frame and it is part of ITRF2014, as well as older versions of ITRF. EUREF is implemented by means of European Permanent Network. Though consistency is what normally can be expected, one should be careful dealing with station coordinates provided by network operators. Particularly, attention should be paid to their reference epoch and accounting for reference frame temporal evolution. Also it is important to distinguish between networks in geodetic sense and in telecommunication sense. Sometimes CORS stations are grouped together to enable convenient access to information, while they never were an adjusted geodetic network.

In many cases network operator does not possess the stations, but provides a common web interface and acts as a liaison between a station owner and a customer.

CORS networks can be subdivided by scale into global, macro-regional, national, regional/local. There are several vast CORS networks providing data and information products for free. The global networks are: tracking network of International GNSS Service[3] (IGS), SONEL[4], and UNAVCO[5] networks. Macro-regional networks are EPN (Europe)[6], SIRGAS-CON (Central and South Americas), AFREF network[7] (Africa), APREF network[8] (Asia-Pacific). There is also a plan for establishing North East Eurasia Reference Frame NEEREF [74]. The most well-known national network is the USA's National Geodetic Survey CORS Network incorporating nearly 2000 stations. Japan's GSI CORS network including more than 1,300 reference stations [75] is one of the densest in the world.

Currently it is reasonable to expect that nearly every economically developed territory is covered with a certain CORS network or several of them. Even in extremely sparsely populated territories CORS networks may be available, for example in Antarctica (ANET)

3 http://www.igs.org/.
4 http://www.sonel.org/-GPS-.html.
5 https://www.unavco.org/instrumentation/networks/map/map.html#.
6 http://www.epncb.oma.be/.
7 http://afrefdata.org/.
8 http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame.

and Greenland (GNET)[9]. More than 90 networks are listed in appendix B including commercial ones, and the list is very far from being complete.

Although a CORS network may typically be present on a territory, its use may be restricted by national authorities or internal policy of its operator. The fact that the same stations are typically included in the networks of different levels may be helpful, when searching for CORS in a certain region. For example, in Poland there is ASG-EUPOS[10] national network that includes 127 stations, 19 of them belong to macro-regional European Permanent Network (EPN), and only 6 to global IGS tracking network. Higher level networks typically provide easier access to data and their stations satisfy the highest standards of site stability and observation data quality. Global networks are typically used as data sources for estimating SSR parameters used in PPP. Local/regional and national networks are typically denser and therefore provide better RTK coverage.

While the CORS networks described above are operated by authorities of different level and/or scientific institutions, there is a large number of private networks providing access to correction data by subscription. In many cases such networks are deployed by the major GNSS equipment manufacturers to provide comprehensive solutions for high-precision PNT to their customers.

5.2 Correction Services

Every CORS providing real-time observation data can be considered as a correction service enabling RTK positioning. Merging stations into a network allows processing data in a centralized way and transfer the result to the user in the optimal representation, in either observation space (OSR) or state space (SSR). The observation data and information products may be delivered to user in real time or archived for post-processing.

Country-level CORS networks are the backbone for correction services like SAPOS[11] (Germany), SWEPOS[12] (Sweden), PositioNZ[13] (New Zealand), the already mentioned ASG-EUPOS (Poland), and others. Such services provide corrections for RTK, code-based differential positioning. In many cases post-processing services are also available.

International GNSS Service (IGS) provides free access to real-time data streams and archives of observation data and information products. RINEX observations are available from more than 500 globally distributed stations, 191 stations provide real-time data streams. Official IGS information products including GNSS ephemerides and clock corrections are available both in real-time via NTRIP data streams and via FTP archives. Archives also contain estimates of station coordinates, Earth rotation parameters, atmospheric corrections, particularly global total electron content grids and troposphere estimates (see appendix C). IGS solutions for satellite ephemerides, clock corrections and other parameters typically represent the weighted mean of corresponding products provided by the 12 independent analysis centers coordinated by Massachusetts Institute of Technology (MIT) and Geoscience Australia.

IGS is one of four Technique Centers of IERS (International Earth Rotation and Reference Systems Service) responsible for maintaining International Terrestrial Reference

9 https://www.unavco.org/projects/major-projects/polenet/polenet.html.
10 www.asgeupos.pl.
11 www.sapos.de.
12 https://www.lantmateriet.se/swepos/.
13 apps.linz.govt.nz/positionz/.

Frame (ITRF). IGS plays major role in providing wide access to the most precise global terrestrial reference frame ITRF2014 by disseminating GNSS measurements from ITRF sites. All IGS products are represented in IGS14 reference frame, which is a pure GNSS implementation of ITRF. In practice one may consider these two reference frames the same. IGS information products can be considered as the gold standard of accuracy and precision in GNSS.

Official IGS products currently include parameters for GPS and GLONASS only. SSR parameters estimates in real-time and a posteriori modes for Galileo, BeiDou, and QZSS are provided by a smaller number of IGS analysis centers participating in Multi-GNSS Experiment (MGEX)[14]. Information about MGEX products may be found in appendix C. Some MGEX analysis centers provide unique information products with higher spatial and/or temporal resolution.

RTK2go is a community NTRIP Caster SNIP Pro available for free for broadcasting user real-time data streams. Though terms of use do not prohibit commercial application of the service, the data streams disseminated via the caster become freely available to all RTK2go community [76].

The mentioned above online correction services, including those provided by the CORS networks considered in chapter 5, are based on already existing technologies that were developed and tested for a limited number of skilled users. For instance, high-performance NTRIP casters like Professional BKG NTRIP Caster can provide data from more than a hundred base stations for more than 2,000 clients at a moment. New applications such as precise autonomous UAV guidance, location based services, self-driving cars may increase the number of simultaneously served data streams to several hundred thousand. Also the future mass market applications will require a very simple user interface. Another problem is that the majority of existing CORS networks was not designed for safety of life applications. Also new applications are much more sensitive to discontinuities in the coverage area. Therefore development of new real-time correction services enabling highly accurate, seamless, reliable, and easy to use positioning is needed.

Sapcorda Services GmbH[15] was created as a joint venture formed by Bosch, Geo++, Mitsubishi Electric and U-blox. SAPCORDA stands for Safe And Precise CORrection DAta. It is supposed to offer globally available GNSS positioning services via Internet and satellite broadcast and to enable accurate GNSS positioning at centimeter level. The services are designed to serve high volume automotive, industrial and consumer markets. It is claimed by the company that the real-time correction data service will be delivered in a public, open format and is not bound to receiver hardware or systems. The services are intended for automotive new mobility solutions, autonomous airborne systems, LBS, the Internet of things (IoT), and other applications.

Skylark is a cloud-based high-precision GNSS correction service announced by Swift Navigation March 20, 2018. According to a press release of the company, Swift was working with Beta customers for over a year and is now previewing the service to all customers in six major metropolitan markets. Skylark is currently operating in San Francisco Bay Area, Los Angeles, San Diego, Phoenix, Pittsburgh and Detroit – with full contiguous U.S. and global expansion underway. Skylark allows receivers to simply connect to a constantly adapting, cloud-based model to obtain GNSS observations,

14 http://mgex.igs.org/.
15 http://www.sapcorda.com/.

eliminating dependence on base stations in each area of deployment. Skylark works seamlessly with Swift Navigation GNSS receivers – Piksi Multi and Duro. Users can sign up for Skylark online[16] and immediately connect to existing coverage areas. The service is claimed to maintain low bandwidth to save on data costs. It is offered with a free 30-day trial, and flexible pricing plans. Skylark's pricing structure includes a monthly plan for $50 per device and an annual plan for $495 per device.

5.3 Satellite Based Augmentation Systems (SBAS)

Overview of SBAS can be found in [8], [77]. For updates on SBAS constellations in general one may follow MGEX web page [78]. As it is shown in [77], currently satellite based correction/augmentation systems may be subdivided into two types: "aviation-style" and "non-aviation". They are compared in table 5.1.

Table 5.1: *Satellite based augmentation/correction system[17] types according to [77].*

Parameter\System type	**"Aviation-style"**	**"Non-aviation"**
Primary focus	Integrity and reliability	High accuracy
Message structure	RTCA formats	RTCM or proprietary formats
Signal	L1/L5 similar to GPS C/A	No standardization
Ranging codes	Typically transmitted	Typically not transmitted
Cost	Free	Paid (except for QZSS)

Currently there are several "aviation-style" SBAS either operational or in tests:

– European Geostationary Navigation Overlay Service (EGNOS);
– GPS Aided Geo Augmented Navigation (GAGAN);
– Geoscience Australia (SBAS) Test-Bed Project (GATBP) [79];
– Multi-functional Satellite Augmentation System (MSAS);
– Nigerian Satellite Augmentation System (NSAS);
– System for Differential Corrections and Monitoring (SDCM);
– Wide Area Augmentation System (WAAS).

WAAS, MSAS, EGNOS, and GAGAN are certified by International Civil Aviation Organization (ICAO). The status of the currently observable SBAS space vehicles can be tracked via IGS MGEX [78]. Korea has approved and is developing its Korean Augmentation Satellite System (KASS). China, South Africa and South America are currently in the conceptual phases of design for their own systems [77].

Typically "aviation-style" SBAS are free of charge, though they may offer additional services on a commercial basis. "Aviation-style" SBAS corrections can be delivered via Internet using SISNeT (Signal-in-Space through Internet) technology developed by the European Space Agency (ESA) for relaying EGNOS messages.

16 https://skylark.swiftnav.com/.
17 One may see from table 5.1, "non-aviation" systems do not allow ranging. So, unlike "aviation-style" SBAS, they do not augment GNSS constellation in the full sense of the word. Therefore they are further referred to as "satellite based correction systems". The term "SBAS" is only used for systems transmitting ranging codes.

Although "aviation-style" SBAS were designed mostly for GNSS integrity monitoring they can be used typically for sub-meter-accurate positioning in real time [80]–[82]. Some examples of user equipment provide better than 30 cm horizontal RMS error with WAAS, EGNOS, MSAS etc., according to the manufacturers [83], [84].

Wanninger and Hesselbarth investigated applicability of WAAS, EGNOS and MSAS clocks and orbits data for implementing standard double-frequency PPP in 2013. The best result was achieved with WAAS: static estimates with biases below 7 cm and standard deviations below 5 cm in all 3 coordinates over 24 hour intervals were obtained [85]. Thus "aviation-style" SBAS can be used to improve positioning accuracy though it is not their main purpose.

5.4 Precision-oriented Satellite Based Correction Systems

Apart from integrity-oriented "aviation-style" SBAS there are satellite based correction systems intended for improving positioning accuracy and precision. Wide range of commercial systems is available including GDGPS [86], Starfix [87], MarineStar [88], C-NAV [89], StarFire [90], [91], OmniSTAR [92], Trimble RTX [93]–[95], TerraStar [96], [97], Veripos [98], Leica SmartLink [99], Atlas [100], SECORX [101]. Some of these systems rely upon each other. For example, TerraStar corrections are used in Leica SmartLink and Septentrio SECORX. An overview of performance is presented in the following table taken from [77] and updated from service providers' websites. Not all companies list the accuracy confidence level. Some mention a 1-sigma level (corresponding to 68%), others mention a 95% confidence (corresponding to 2-sigma). However, in some cases it seems that 1-sigma is being mixed up with 95% (i.e. a website states 1-sigma, but a brochure states 95%). The accuracy values presented in this table are the accuracies reported by the companies, and do not refer to values resulting from independent research [77].

Commercial systems may rely on proprietary data formats. Due to lack of standardization every commercial satellite based correction service is compatible with a limited number of user equipment models.

Some commercial satellite based services offer support to conventional RTK survey. Trimble xFill, Leica SmartLink Fill and NovAtel RTK ASSIST backup RTK survey by preserving high solution accuracy for some time after loss of RTK correction signal. Such services are much cheaper than their fulltime analogs.

The subscription prices for top precision services typically vary from $1,000 to $2,700. Some of the listed global services are available under different conditions depending on what country user specifies on the online store website. For instance: in Germany $995 per year (over IP only $745 per year), in the USA $1,995 per year, in Russia and China $1,250 per year.

Sub-meter accurate corrections provided by commercial service may cost to user $400 per year or more. One may notice that sub-meter accuracy corrections in many regions are available with free SBAS.

Unlike free integrity-oriented "aviation-style" SBAS, satellite based correction services intended for high-precision positioning are typically commercial. The new QZSS Cen-

Table 5.2: *Services provided by commercial satellite based correction systems.*

Company	Services	Accuracy (horizontal, 95%), cm	Convergence time, min	GNSS[a]	Comment
Trimble	CenterPoint RTX Fast	< 2.5	< 5	G,R,E,C,J	
	CenterPoint RTX Standard	< 2.5	< 15	G,R,E,C,J	
	FieldPoint RTX	< 20	< 15	G,R,E,C,J	
	RangePoint RTX	< 50	< 5	G,R,E,C,J	
	ViewPoint RTX	< 100	< 5	G,R,E,C,J	
Trimble (services provided by Fugro)	OmniSTAR HP	< 10	<45	G	
	OmniSTAR G2	< 10	< 20	G,R	
	OmniSTAR XP	< 10	< 45	G	
	OmniSTAR VBS	< 100	< 1	G	Pseudo-range corrections
Fugro	Starfix.G2+	< 3	No data	G,R	Uses ambiguity resolution
	Starfix.G4	< 10	No data	G,R,E,C	
	Starfix.G2	< 10	No data	G,R	
	Starfix.XP2	< 10	No data	G,R	3rd party corrections
	Starfix.HP	< 10	No data	G	
	Starfix.L1	< 100	No data	G	Single frequency code corrections
NavCom	StarFire SF2	< 10	30–45	G,R	
	StarFire SF3	< 3	30	G,R	
C-Nav	C-NavC²	< 8	No data	G,R	StarFire algorithms
	C-NavC¹	< 15	No data	G	StarFire algorithms
Veripos (Hexagon)	Apex 5	< 5	No data	G,R,E,C,J	Own reference station network and calculation
	Apex 2	< 5	No data	GR	
	Apex	< 5	No data	G	
	Ultra 2	< 10	No data	GR	JPL reference station network and calculation
	Ultra	< 10	No data	G	
	Standard 2	< 100	No data	GR	Pseudo-range corrections
	Standard	< 100	No data	G	
TerraStar (Hexagon)	TerraStar-C PRO	< 3	< 18	G,R,E,C	Uses ambiguity resolution
	TerraStar-C	< 5	30–45	G,R	
	TerraStar-L	< 50	< 5	G,R	Pseudo-range corrections
Leica Geosystems (Hexagon)	Leica SmartLink	< 3	30	No data	TerraStar corrections
Hemisphere	Atlas Basic	< 50	Instant	G,R,C	
	Atlas H100	< 100	1–2	G,R,C	
	Atlas H30	< 30	1–5	G,R,C	
	Atlas H10	< 8	10–40	G,R,C	

a Designations used in the table: G – GPS, R – GLONASS, E – Galileo, C – BeiDou, J – QZSS. Actual GNSS constellations support may depend upon the region.

timeter Level Augmentation Service (CLAS[18]) with MADOCA/LEX[19] corrections is changing this situation. Preliminary tests of the service have shown that in static PPP a 3-dimentional RMS of 0.041 m can be expected after 2 hours or more of convergence. QZSS provides corrections for GPS, GLONASS, and Galileo. For kinematic PPP, a 3-dimentional RMS of 0.200 m can be expected after 90 minutes of convergence and 0.145 m after a few hours [102]. CLAS is expected to become the first free of charge satellite based service designed to provide such a high level of accuracy. Though QZSS coverage area is limited to Asia-Pacific region the recent development most likely will have a global impact because it sets up a new standard of free high-accuracy satellite based augmentations.

5.5 Cost-effective Solutions for GNSS Infrastructure

The quality of equipment used in GNSS CORS networks is critically important. At the same time the cost of high-end equipment may be a serious issue, especially in case of deployment of a dense RTK network on a large territory.

Using high-quality but cheaper GNSS equipment based on OEM modules offered by leading manufacturers may be a cost-effective solution. One of the examples is EFT CORS Network in Russia. The network comprises 365 stations that were deployed within only 3 years. The stations are equipped with four-constellation multi-frequency EFT A-series antennas (available at nearly $900) and EFT RS1 receivers based on Trimble BD970 OEM-modules. Now EFT CORS is one of the fastest growing and the second largest network in the country. Relying on more cost-effective solutions it provides rather attractive terms of use: unlike other major networks in Russia it offers RINEX data to any registered user for free.

Cooperation is another very important aspect of cost-effectiveness. In some regions a large number of permanent base stations may be already deployed by private companies for their own purposes. But those stations may be inaccessible directly because disseminating the data is not necessarily a priority for the owners. Potential users may not even know about them. Services like HIVE[20] bring CORS operators and users together, providing a web interface for accessing archive data and data streams, and acting as a liaison. Currently HIVE provides access to 538 stations, which is the largest set of CORS in Russia. Another example of cooperation being a factor of cost-effectiveness is a free community NTRIP caster RTK2go [76].

Free open source software including BKG NTRIP Caster, BNC, RTKLIB, GSAC provides opportunities for further decreasing cost of infrastructure deployment (see chapter 6). Using virtual cloud services may also offer saving money on initial stage because it eliminates the need to buy and maintain server hardware.

The future of cost-effective high-precision GNSS infrastructure is more evidentially connected with proliferation of PPP and PPP-RTK rather than relative method, because the advantage of lower bandwidth of SSR comparing to OSR will become more important with growing number of users. Also SSR is more suitable for seamless positioning as it does not require high density of a CORS network. The problems of PPP, including longer convergence and re-convergence, are apparently solvable, as it is shown in chapter 3.

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18 http://qzss.go.jp/en/overview/services/sv06_clas.html.
19 https://ssl.tksc.jaxa.jp/madoca/public/public_index_en.html.
20 https://hive.geosystems.aero/?locale=en.

For satellite based correction services the data communication channel is a high cost component. Therefore such systems typically implement one-way communication to the user equipment, so that the same corrections are broadcasted to everyone in the coverage area. A possible alternative option is using telecommunication satellites for accessing the Internet and receiving NTRIP correction streams selected by the user. That requires a two-way satellite communication link, which has always been very expensive. That may be changed with new telecommunication satellite systems to provide global low-cost wide-band internet access corresponding to 5G standards. The overview of new telecommunication systems is given in table 5.3 according to [103]–[105]. Another initiative helping to make the Internet access cheap and ubiquitous is project Loon[21] focused on extending connectivity to underserved areas using stratospheric balloons as telecommunication equipment carriers.

Table 5.3: *Planned new generation telecommunication satellite systems.*

Name	Proposed constellation	Key backing organizations
ONEWEB	720 initial, >2,000 target	Airbus, Virgin, Qualcomm, Intelsat, Bharti
STARLINK	4425 initial, 12,000 target	SpaceX
BOEING	1,400–3,000	Boeing
Sphera/Ephir	640	Russian Space Systems
China's system	54 initial, 12,000 target	China Aerospace Science and Technology Corp.

The first test satellites of STARLINK were launched in 2018, first launch of ONEWEB satellites took place in early 2019. Though the user price of the internet access with such systems is to be determined, their claimed mission is to make the access affordable for everyone in the world.

If the initiatives described above succeed, that will make commercial satellite based correction services compete directly with free NTRIP correction services like IGS-RTS.

One may argue that IGS operates on a volunteer basis and the services are not guaranteed; therefore they cannot be used in performance and safety critical applications. But commercial service providers do not usually offer any guarantee above required by applicable laws. Terms of service typically state that it is provided "as is" and the providers disclaim and exclude all warranties regarding the accuracy, compatibility, merchantability, fitness for purpose, performance, satisfactory quality or use of the services, etc. Recovery is limited to the amounts paid by the user for the service. Also one may find the following statement in the terms of service: "You understand and acknowledge that the Services are not, nor are they intended, to be used for any safety critical or safety related use or application and you shall not use them in that manner" [106]. It is worth mentioning that the commercial service provided under this term is used in advanced driver assistance system [107]. So for a service being commercial does not necessarily mean more responsibility.

Actual reliability of a service is a matter of infrastructure redundancy and strict following high operation standards. Its safety must be proved by open and traceable statistics. Therefore IGS-RTS may become the backbone public infrastructure for mass market oriented precise positioning technology.

21 https://loon.co/.

6 GNSS SOFTWARE

Software is another category of performance-critical and potentially expensive parts of the technology. When choosing certain solution it is necessary to take into account the cost of all software to be used. There may be packages for multiple tasks: field data acquisition, real-time positioning and displacement analysis, raw data manipulation, GNSS signals post-processing, network adjustment, CORS network management, and so on. The complete toolchain for many practical applications may also include computer-aided design (CAD) software and geographic information systems (GIS).

The software implementing general GNSS-related functionality is offered by manufacturers of GNSS equipment. Examples of desktop software allowing GNSS processing and network adjustment are Trimble Business Center[22], Leica Geo Office[23], Leica Infinity, Topcon's Magnet Office Tools, Spectrum Survey Office Pro[24], Javad's Justin and Giodis[25], CHC Geomatics Office[26], etc. The price of such software packages starts from $500 and may exceed $6,000 depending on functionality and brand. Some of the examples feature modular design, so that the user may purchase only the modules needed for specific applications.

Proprietary software is expected to provide the best workflow integrity and compatibility of interfaces if it is used with geodetic sensors of the same manufacturer. That may give an especially important advantage in performing complex tasks, dealing with heterogeneous data from different surveying techniques, e.g. GNSS, laser scanning, geometric leveling, and photogrammetry. Though such native and versatile solutions may be rather expensive, they also may be very cost-effective due to high performance, workflow efficiency, and stability. Nevertheless the user should be careful when choosing a toolchain relying exclusively on proprietary data formats, because in that case one becomes dependent on the solutions of the only provider. Availability of convertors to open formats for every type of generated data is important.

GNSS software may also be developed by a third party. Carlson Software and MicroSurvey provide solutions for accomplishing such tasks as field data acquisition, adjustment and so on. There is also a category of scientific GNSS software that is very comprehensive. It is used for solving the widest spectrum of problems, for instance in geodynamical analysis and estimation of precise ephemerides. Extra expertise is needed to grasp the full power of this software. The examples are GAMIT/GLOBK[27], Bernese GNSS Software[28], GipsyX[29]. In some cases high-end scientific software may be obtained for free for non-commercial use, like GAMIT/GLOBK.

The software may be available on a pay-per-use basis. Some developers offer their software with short-term licenses, e.g. for one week. The renewal may be ordered on demand. Another option is using cloud-based platforms providing software as a service. One example of such platform is GeoCloud[30].

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22 https://geospatial.trimble.com/products-and-solutions/trimble-business-center.
23 https://leica-geosystems.com/products/total-stations/software/leica-geo-office.
24 https://eu.sokkia.com/products/software-field-controllers/office-software/geopro-office.
25 http://javad.com/jgnss/products/software/giodis.html.
26 http://www.chcnav.com/index.php/product/detail?id=57&ctype=1&cid=1.
27 http://geoweb.mit.edu/gg/.
28 http://www.bernese.unibe.ch/.
29 https://www.nasa.gov/press-release/nasa-astronaut-crewmates-return-to-earth-after-197-day-mission-in-space.
30 https://www.geocloud.work.

It is important to find the balance between total cost of the toolchain and performance of the workflow. The cost of a single high-end software package with unique functions may exceed $35,000. But in many cases the whole toolchain may be built from free open source software, which is described below.

RTKLIB is a free open source library and a set of ready to use applications for accomplishing a diverse tasks related to GNSS data exchange and processing. It is offered under BSD 2-clause license[31]. RTKLIB can be considered as the most mature free open source software for GNSS signals processing. Users are permitted to develop, produce or sell their own non-commercial or commercial products utilizing, linking or including RTKLIB as long as they comply with the license. Functionality of the applications is represented in the table below.

Table 6.1: *RTKLIB functionality.*

Function	**Graphic user interface**	**Command line Interface**
AP Launcher	RTKLAUNCH	–
Real-Time Positioning	RTKNAVI	RTKRCV
Communication Server	STRSVR	STR2STR
Post-Processing Analysis	RTKPOST	RNX2RTKP
RINEX Converter	RTKCONV	CONVBIN
Plot Solutions and Observation Data	RTKPLOT	–
Downloader for GNSS Products and Data	RTKGET	–
NTRIP Browser	SRCTBLBROWS	–

Graphical user interface (GUI) of RTKLIB utilities is shown in figure 6.1.

Apart from RTKLIB there are many examples of free software for education, research and development of derivative software products. Among them GPStk [109], [110], gLAB [111], GNSS-SDR [43], GNSS-SDRLIB [112].

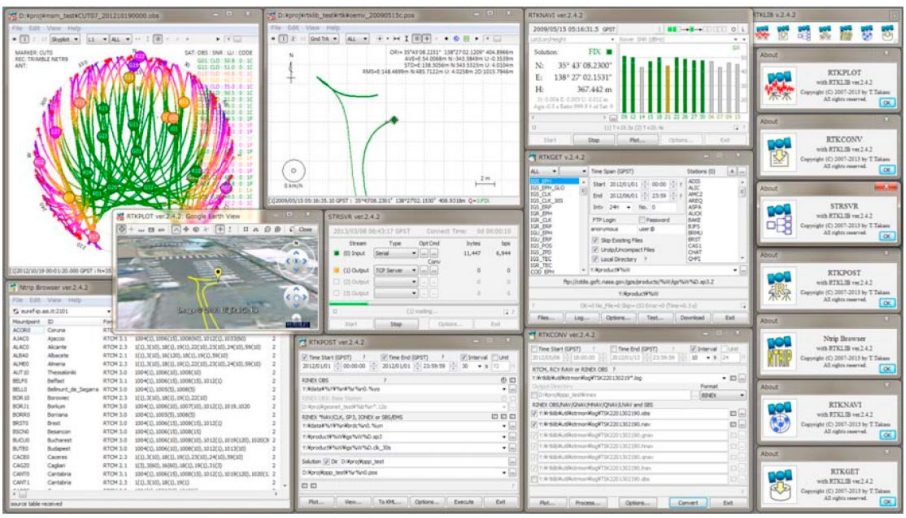

Figure 6.1: *RTKLIB applications graphical user interface [108].*

31 http://opensource.org/licenses/BSD-2-Clause.

TEQC (Translation, Editing and Quality Check software) is a powerful and unified program for solving many pre-processing problems with GPS, GLONASS, Galileo, SBAS, BeiDou, QZSS, and IRNSS data, especially in RINEX or BINEX format. Its primary functions are: translation of binary data in various native binary formats to RINEX and BINEX files, editing (time windowing, file splicing, satellite or other filtering, metadata extraction, editing, and correction of RINEX header metadata or BINEX metadata records), quality check of GPS and GLONASS data [113], [114]. TEQC is provided free of charge but its source code is not available.

ADJUST is a free open source software provided by the USA National Geodetic Survey for geodetic network adjustment. Additional utilities for data format conversion, statistical testing, site clustering are also available [115].

SNAP – Survey Network Adjustment Package is a suite of programs developed by the Land Information New Zealand (LINZ) for adjusting the coordinates of stations in a survey network to best fit the observed data. It can use GPS data (baselines or multistation vector and point data), horizontal angles, zenith distances, slope and horizontal distances, azimuths, projection bearings, leveled height differences, latitude, longitude, and height observations [116]. Source code is available at GitHub under MIT license.

*The BKG NTRIP Client (*BNC) is an open source multi-stream client program designed for a variety of real-time GNSS applications. It was primarily designed for receiving data streams from any NTRIP supporting broadcaster. The program handles the HTTP communication and transfers received GNSS data to a serial or IP port feeding networking software or a DGPS/RTK application. It can compute a real-time PPP solution from RTCM streams. It is also capable of post-processing of RINEX formatted data. During the last years BNC has been enriched with RINEX quality and editing functions. BNC can be run with GUI as well as in batch processing mode [117].

Simple NTRIP Caster – SNIP is an NTRIP Caster. The basic version NTRIP Lite is available for free with a number of base stations limited to 3 and reduced functionality.

Back40precision NTRIP Caster basic version is available free of charge with a limit of 10 base stations and 100 users allowed to be active at any given time. It is claimed that this version of software will not expire.

GSAC is UNAVCO's Geodesy Seamless Archive Centers software system, which powers geodesy data repositories with a web services enabled application programming interface. It is intended to provide simple, consistent web services at geodetic-focused data centers in order to facilitate discovery, sharing, and access to data. The GSAC data model assumes data are collected at instrument sites such as GNSS or VLBI station. Ancillary site-based data and information such as meteorological observations, or a streaming data endpoint, can also be presented through GSAC. GSAC supports queries for metadata about geodesy sites and instruments, and provides access to instrumental data files. The GSAC software includes a web GUI that leverages the GSAC web services for web-based search and access [118]. GSAC is a part of a larger Dataworks project which provides subsystems as open source software modules that can be employed by regional GNSS managers for small networks (e.g. tens of stations). Subsystems and modules include GNSS downloading from the receiver and subsequent data management, metadata management using a streamlined database, data and metadata distribution [119].

Together with other open source tools including coordinate conversion software (Concord[32]), geographic information systems like (QGIS[33], GRASS GIS[34], etc.) computer aided design software like (FreeCAD[35], BRL-CAD[36] etc.) the GNSS software discussed above can be sufficient to organize workflows based completely on free software. Apart from saving money using free software provides complete dataflow traceability and great opportunities for customization and automation of data processing for a skillful user.

32 https://www.linz.govt.nz/data/geodetic-services/download-geodetic-software/snap-concord-downloads.
33 https://www.qgis.org/ru/site/.
34 https://grass.osgeo.org/.
35 https://www.freecadweb.org/.
36 https://brlcad.org/.

7 FREE ONLINE POST-PROCESSING SERVICES

7.1 Overview

GNSS post-processing may be done with online services instead of using desktop software. Nowadays most of web-based GNSS prost-processing services are free of charge.

Web-based GNSS prost-processing services implement relative or PPP GNSS positioning method. Some services provide both of the methods.

Table 7.1 considers the list of web-based GNSS prost-processing with their specifications and web-links. The specifications are taken from the service's websites. Also information about the services is taken from overviews [120]–[123].

AUSPOS is the Australian worldwide GPS post-processing service based on relative positioning method. AUSPOS uses the Bernese GNSS software for processing baselines, IGS orbits and IGS network station data. Dual-frequency observations in RINEX or compact RINEX files need to be at least 1-hour long; 6-hour files are recommended. An AUSPOS reports sent to user by email contain coordinates in Geocentric Datum of Australia 1994 (GDA94) and International Terrestrial Reference Frame (ITRF).

OPUS solutions are the most common in the United States. The service provides two processing modes: OPUS-Static (available worldwide, requires 2-hour observation session or longer) and OPUS-Rapid Static (available with sufficient nearby CORS stations, requires at least 15 minutes observation session data). OPUS uses at least three NGS CORS stations for processing if the observation file is collected from U.S. territory. If data to be uploaded is from somewhere outside the U.S., OPUS uses three IGS network stations as reference stations.

SCOUT requires minimum 1-hour observation data for processing and uses GAMIT scientific processing software. Computation is performed using data from the nearest IGS reference stations listed by SOPAC. Three reference stations are used at minimum. They are chosen automatically or by the user. The coordinates are referred to ITRF2005 and World Geodetic System 1984 (WGS84) with observation epochs on analysis solution report.

Trimble CenterPoint RTX Post Processing is a free service offered by Trimble. Users are required to register every year to get unlimited use of the service. It is based on a proprietary Trimble 100+ worldwide CORS network. The claimed accuracy is 2 cm for 1-hour observation data. The reported output frames include ITRF2008 at current epoch and a user selectable frame like NAD83/2011 at 2010.0. RTX is one of the few services that directly exports NAD83 framed results. A single page PDF and a XML result file are returned by RTX. RTX supports a limited number of receivers (Trimble) and a relatively small subset of IGS modeled antennas. Supported input file formats are RINEX and Trimble receiver formats. Observations longer than 24 hours are not accepted.

APPS uses real-time predicted, rapid and final GPS orbit and clock products from JPL's GDGPS System. Real-time solutions are typically available with a 5 second delay. The users may also enable accounting site displacement effects (solid Earth tides and ocean tidal loading) in processing if they prefer. The software used in APPS is JPL's GIPSY-OASIS. APPS supports input in RINEX 2, RINEX 2.11 input files, GIPSY TDP files.

Table 7.1: *Free online GNSS post-processing services.*

Online services	**Specifications**							
	Service long name	Company/ agency	Processing method, data source	GNSS supported	Reference frame; geoid model	Input data format	Observations mode	Submittal page
AUSPOS	Australian Online GPS Processing Service	Geoscience Australia	Relative (IGS stations and data, AFN, ARGN)	GPS	ITRF, GDA 94/2020; AUSGeoid 98/09/2020	L1, L1+L2 RINEX	Static	http://www.ga.gov.au/bin/gps.pl
OPUS	Online Positioning User Service	NOAA National Geodetic Survey (NGS)	Relative (NGS CORS, IGS)	GPS	IGS08, NAD83(2011); NAVD88, GEOID12A	L1, L1+L2 RINEX	Static	https://www.ngs.noaa.gov/OPUS/index.jsp
SCOUT	Scripps Coordinate Update Tool	Scripps Orbit and Permanent Array Center (SOPAC), University of California	Relative (IGS stations)	(no data)	ITFR08, WGS84	RINEX, Hatanaka	Static	http://sopac.ucsd.edu/scout.shtml
Trimble CenterPoint RTX	Trimble CenterPoint RTX Post Processing	Trimble Inc.	PPP (Trimble CORS network)	GPS GLONASS Galileo BeiDou	ITRF1988..2014, NAD83 (+mods), ETRS89..2000-R05, GDA94,SIGRAS etc.	L1+L2 RINEX, Trimble formats	Static	https://www.trimblertx.com
APPS	Automatic Precise Positioning Service	NASA – Jet Propulsion Laboratory (JPL)	PPP (JPL)	GPS	ITRF08, ITRF14	L1+L2 RINEX, Hatanaka, GIPSY *.tdp	Static, kinematic (members only)	http://apps.gdgps.net
CSRS-PPP	Canadian Spatial Reference System – Precise Point Positioning	Natural Resources Canada (NRCan)	PPP (IGS, NRCan)	GPS GLONASS	ITRF08 , IGB08/ NAD83; CGDV28/2013	L1, L1+L2 RINEX, Hatanaka	Static, kinematic	https://webapp.geod.nrcan.gc.ca/geod/tools-outild/ppp.php
GAPS	GPS Analysis and Positioning Software	University of New Brunswick (UNB)	PPP (IGS MGEX, NRCan)	GPS BeiDou Galileo	IGB08, ITRF2000	L1+L2 RINEX, some receiver formats	Static, kinematic	http://gaps.gge.unb.ca
MagicGNSS/ PPP	MagicPPP – Precise Point Positioning Solution	GMV Innovating Solutions	PPP (IGS, GMV)	GPS GLONASS Galileo	ETRS, ITRF08	L1+L2 RINEX, Hatanaka	Static, kinematic	http://magicgnss.gmv.com/ppp

CSRS-PPP uses precise GPS and GLONASS orbit and clock products provided by IGS and Natural Resources Canada (NRCan), and estimates single station positions in static and kinematic modes. Input data supported in RINEX formats include Compact RINEX/Hatanaka and ZIP-compressed files. Output results are returned in a set of files including positions (NAD83 and ITRF + UTM coordinates), PDF graphical analysis reports, errors analysis etc.

GAPS is an ongoing project at University of New Brunswick and was developed by the Department of Geodesy and Geomatics Engineering. The service processes GPS data only (GLONASS is not used in processing) using IGS rapid and final clock and orbit products. GAPS instruments also allow estimating ionospheric delays, code biases, satellite clock errors and code multipath.

MagicGNSS/PPP is a free service based on software developed by Spanish Company GMV. It allows processing static and kinematic GPS, GLONASS, and Galileo data in RINEX format and in real-time mode. Only dual-frequency PPP is supported. Real-time GPS and GLONASS orbits and clocks needed by PPP are generated internally. Also the service uses IGS rapid and final information products for post-processing. The service output data include PDF report, SINEX, receiver clock bias files, tropospheric delay, KML trajectory and RINEX CLK clock bias files.

The main advantages of using online post-processing services are:

- high automation makes post-processing more convenient, fast, and reliable;
- user does not need one's own base station;
- user does not need to buy GNSS post-processing software.

The disadvantage is typically lower flexibility in processing configuration, including limited number of supported reference frames. The majority of post-processing services do not support stop-and-go mode and event markers. As the user of a web-based processing service has limited or no influence on settings and processing data flow, the quality of positioning solution is independent on one's skills and is expected to be stable. Therefore it can be subject to meaningful evaluation. Results of different experimental studies on positioning accuracy and precision are provided below.

7.2 Static Tests

There is a lot of scientific publications devoted to online services precision and accuracy testing in different modes and in different signal-receiving conditions (with or without obstacles and reflectors).

Static tests of GNSS post-processing services described in articles [120], [124]–[127] show almost similar level of accuracy for services of the same category (PPP or relative positioning). The level of positioning errors is few centimeters for 24-hour measurement sessions both for relative positioning and PPP services. In a study published in [120] 32 daily GPS-only observation sessions data recorded with 30-second interval on SGU1 station in St. George, UT USA were used. The comparison of average solutions obtained with different services is shown in table 7.2.

Table 7.2: *Average solution difference from OPUS [120].*

UTM coordinate and ellipsoidal height differences	RTX	AUSPOS	CACS	mag-icGNSS	JPL APPS	GAPS
$x-x_{OPUS,}$ m	0.003	0.003	0.004	0.015	0.006	0.003
$y-y_{OPUS}$, m	−0.003	0.000	−0.008	−0.005	−0.004	0.004
$H-H_{OPUS,}$ m	0.003	0.003	0.005	−0.002	0.006	0.007

Tests with shorter static observation sessions (1 to 12 hours) are described in [124]. The mean errors are given in table 7.3 rounded to cm.

Table 7.3: *Online positioning error with observation session duration from 1 to 12 hours [124].*

Service	Mean differences between processed and known coordinates, m									
	1 hour		2 hour		4 hours		6 hours		12 hours	
	Plan	Height	Plan	Height	Plan	Height	Plan	Height	Plan	Height
CSRS-PPP	0.03	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.00	0.00
Magic GNSS	0.33	0.50	0.05	−0.03	0.04	−0.03	0.04	−0.03	−0.03	−0.03
APPS	0.03	0.00	0.02	0.01	0.02	0.00	0.02	0.00	0.00	0.00
Timble RTX	0.02	0.00	0.02	0.01	0.02	0.00	0.02	0.00	0.00	0.00
AUSPOS	0.05	0.00	0.02	0.02	0.02	0.00	0.02	0.00	0.00	0.00
OPUS	N/A	N/A	N/A	N/A	0.02	0.01	0.02	0.01	0.01	0.01

Figure 7.1 taken from the article illustrates accuracies of PPP and phase-based relative positioning services.

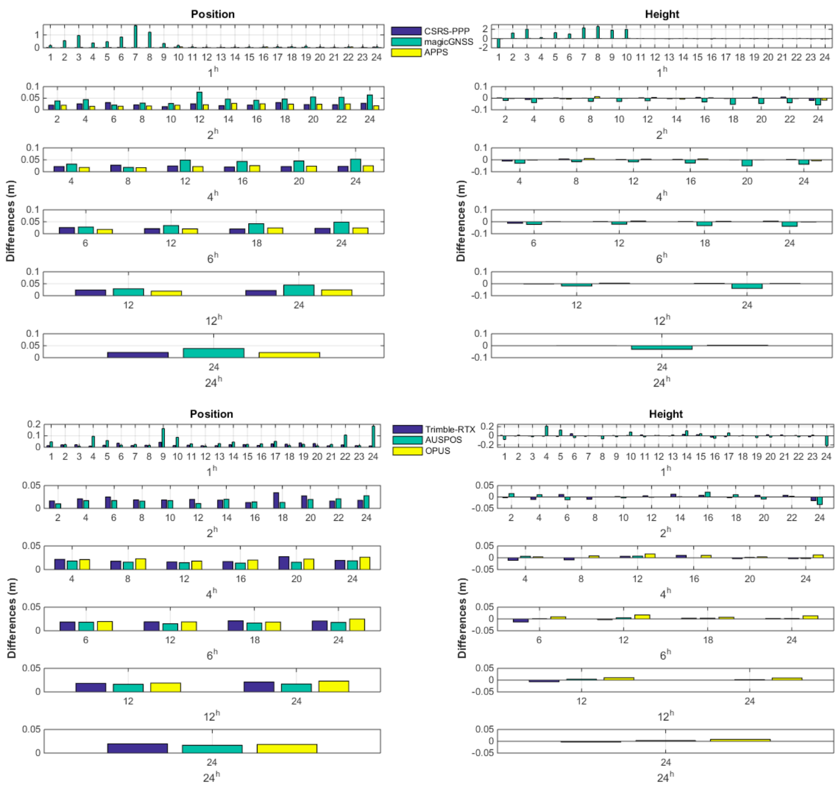

Figure 7.1: *Web services errors estimation for 1 to 12 hour observation sessions [124]*

Table 7.4: *Analysis of static sessions taken in different signal-receiving conditions processed by online services [121].*

Service	Differences to coordinates processed with Bernese 5.2								
	Open radio-horizon			The forest border			Inside the forest		
	N, m	E, m	U, m	N, m	E, m	U, m	N, m	E, m	U, m
Differences between coordinates									
AUSPOS	0.001	0.011	–0.009	–0.006	0.005	0.004	–0.089	–0.519	0.882
OPUS	0.009	0.013	0.024	–0.001	0.012	0.010	1.188	0.580	2.922
CSRS-PPP	–0.009	0.004	0.142	0.029	0.039	0.016	0.216	–0.289	0.708
APPS	–0.001	0.006	0.103	0.000	0.007	0.075	0.071	–0.075	–0.223
GAPS	–0.008	0.000	–0.007	0.013	0.019	0.043	0.071	0.109	0.117
Trimble RTX	–0.013	0.005	–0.015	–0.004	0.014	0.005	N/A	N/A	N/A
Standard deviations									
AUSPOS	0.021	0.008	0.008	0.033	0.012	0.030	1.576	0.927	1.573
OPUS	0.010	0.014	0.010	0.019	0.026	0.021	6.635	6.645	6.157
CSRS-PPP	0.023	0.009	0.021	0.062	0.060	0.057	0.436	0.354	0.401
APPS	0.006	0.005	0.006	0.009	0.007	0.009	0.117	0.138	0.116
GAPS	0.006	0.007	0.006	0.009	0.009	0.009	0.115	0.138	0.113
Trimble RTX	0.012	0.012	0.012	0.016	0.016	0.016	N/A	N/A	N/A

In [121] static tests of online post-processing services with data acquired in complicated environment are given. The observation points were situated near the forest edge and in the forest. Data from 6-hour sessions were processed and analyzed. The authors provided analysis of PPP results with the ultra-rapid, rapid and final orbits and satellite clock products. In table 7.4 the differences between Bernese 5.2 processed coordinates and solutions of the online services are shown.

7.3 Kinematic Tests

Most of PPP online services are capable of processing data in kinematic mode. Accuracy tests of kinematic PPP are often based on comparison of processing results with etalon trajectory estimated using phase-based relative positioning method implemented in desktop post-processing software.

The articles [128]–[130] describe tests of PPP services in kinematic mode with data collected in different environmental conditions.

An experiment with CSRS-PPP, GAPS, APPS, and MagicGNSS on a 12-hour kinematic trajectory with 5-second data record interval is described in [130]. The authors obtained the solutions with final information products by the PPP services and relative processing from the nearest EPN station and calculated differences shown in figure 7.2 for two kinematic sessions (day 261 and 268). In the experiment ITRF2008 reference frame was used.

The estimated errors (absolute deviations and standard deviations) are given in table 7.5. Most of services reached the similar level of accuracy (except GAPS on the first day) – a few centimeters.

Another kinematic test was performed and analyzed by the authors of [129]. A GNSS receiver was located on a car that was moving along different trajectories at speed of

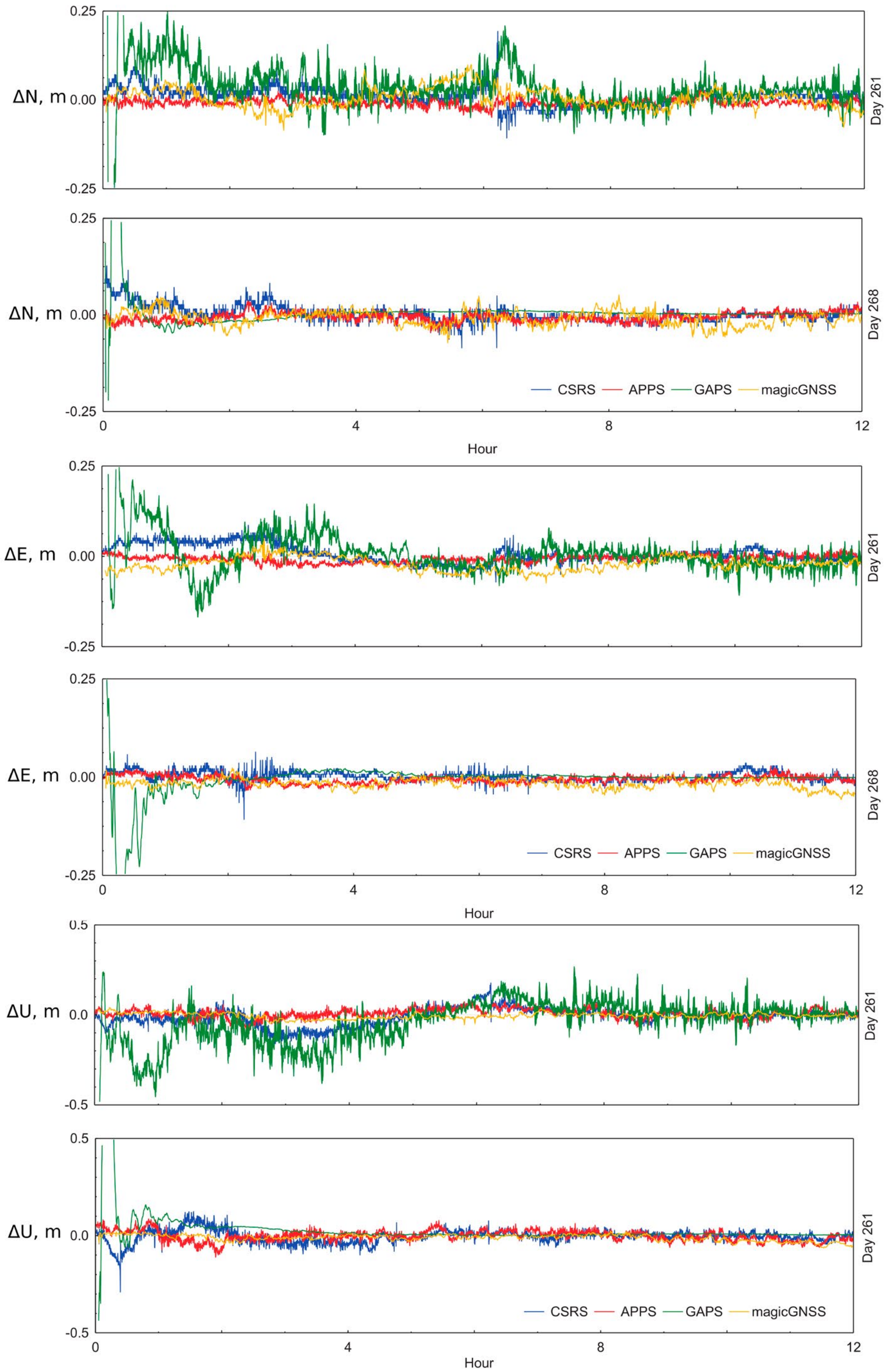

Figure 7.2: *Web services solution differences for 12-hour kinematic sessions [130].*

Table 7.5: *Mean absolute coordinate deviations and standard deviations [130].*

Day of year	Service	Absolute deviations	Standard deviations				
		ΔN, m	ΔE, m	ΔU, m	σN, m	σE, m	σU, m
261	CSRS-PPP	0.016	0.020	0.016	0.020	0.033	0.036
	APPS	0.007	0.010	0.007	0.009	0.016	0.022
	GAPS	0.131	0.062	0.078	0.043	0.133	0.095
	MagicGNSS	0.018	0.022	0.015	0.024	0.009	0.013
268	CSRS-PPP	0.015	0.015	0.008	0.009	0.023	0.024
	APPS	0.007	0.010	0.007	0.009	0.017	0.021
	GAPS	0.094	0.021	0.071	0.019	0.130	0.038
	MagicGNSS	0.013	0.017	0.011	0.017	0.013	0.015

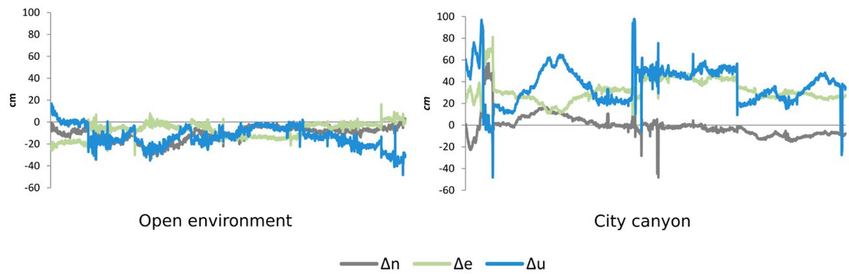

Figure 7.3: *CSRS-PPP track deviations from the relative solution [129]*

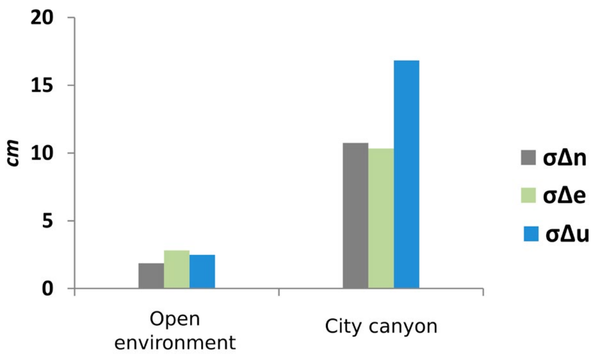

Figure 7.4: *CSRS-PPP standard deviations from the relative solution [129]*

30–40 km/h. The resulted trajectories estimated with CSRS-PPP service were compared to Leica Geo Office relative solution in ITRF2008 taken as a reference.

Figure 7.3 shows deviations of trajectories measured in open environment and inside city canyon. Calculated standard deviation charts are shown in figure 7.4.

Standard deviations for open radio-horizon conditions were about 3 cm for each axis. In city canyon conditions the accuracy diluted because of satellite blockings and multipath. Standard deviations were of 15–20 cm.

8 COST-EFFECTIVE SOLUTIONS BY APPLICATION

8.1 Surveying

Surveying has been one of typical application spheres of high-precision positioning technology. User needs and requirements in this application are summed in [36]. Surveying may require different level of positioning accuracy depending on the purpose of a survey. Nearly all aspects cost-effectiveness considered in this study are relevant for this application type, including:

- smartphones and tablet computers as field controllers;
- software-defined GNSS receivers;
- free post-processing services;
- free CORS networks (correction services) like IGS, EPN, SIRGAS;
- high-precision SBAS for PPP survey and RTK support;
- sub-meter accurate positionig for GIS applications with "aviation-style" SBAS;
- low-cost and mid-range equipment providing high precision (if it offers optimal balance between the cost and workflow performance).

Additional opportunities are connected with combination of positioning methods. Particularly in remote areas where GNSS infrastructure is not available a surveyor may use one's own base station with coordinates defined in PPP while the survey is done using relative positioning method.

Geodetic monitoring is one of the most performance demanding geodetic applications of GNSS. Precision and reliability are the key requirements. Nevertheless implementation of affordable monitoring systems became one of the first applications of high-precision low-cost solutions. In 1996 it was proposed to combine high-end geodetic-grade receivers and cheap single-frequency receivers for observing short baselines in a network for geodynamic monitoring [131]. Since than the concept has been applied in other projects [132], [133].

Another aspect of designing a low-cost system for high-precision monitoring is communication. An automatic low-cost GPS monitoring system using WLAN communication was developed. The mesh network, which is self-organized and self-healed, is to provide a higher reliability and redundancy [134].

Free open source software for observation data processing is another opportunity for making geodetic monitoring affordable. Particularly RTKLIB software was used in different monitoring projects, including tsunami forecasting [135], landslides monitoring [136]. GOCA Software developed at Karlsruhe University of Applied Sciences uses RTKLIB for GNSS measurements processing [137]. Examples of real life projects on geodetic monitoring with GOCA are available at the official website[37].

There is a number of developments that may help fighting disadvantages of low-cost equipment, suitable for static applications, such as multipath hemispherical map [60] and other tools for multipath mitigation [58], [59], [61]. New opportunities of cloud-based GNSS signals processing [138], with 5G networks enabling cheap transfer of

37 http://goca.info/.

large amounts of data, and with fit-for-purpose low-cost GNSS equipment may noticeably widen the application sphere of geodetic monitoring. Earlier only dangerous natural objects such as volcanoes, landslides, faults, or unique engineering structures (TV towers, dams, bridges) were monitored using GNSS. Taking into account the trends mentioned above, monitoring of nearly every engineering structure of interest may become affordable. Massive deployment of such systems will increase the amount of geodetic information by several orders. One may imagine a city with nearly every building monitored, which is a particular case of Internet of Things concept implementation. Apparently, interpretation of monitoring data will be the major problem, because displacements of certain points of a building alone do not say much about its overall technical condition. Meaningful evaluation will require detailed information about its structure. Therefore mass introduction of cheap geodetic monitoring systems will strongly depend on the progress in introduction of Building Information Models (BIM). Higher level automation of monitoring results analysis and decision making, particularly enabled by machine learning algorithms, is required.

The future of cost-effective surveying techniques in general is likely to be defined by the progress in the development and adoption of high-precision positioning technology intended for amateur users (LBS). When (not if) centimeter level positioning becomes available to any user of a smartphone, probably with a cheap attachment, that will completely change the professional surveying to an extent we currently may only try to guess.

8.2 Automated Guidance

8.2.1 Road Vehicles

Advanced driver assistance systems (ADAS) *and self-driving cars (SDC)* are to become one of the major applications on a mass market of high precision positioning solutions. Most likely their development will play an important role in decreasing the cost for high-quality GNSS measurement systems. The key required components are high precision correction services enabling seamless and reliable positioning along every road and highly accurate hardware.

The high precision GNSS leaders develop their own applications for automotive industry. Trimble RTX corrections are applied in General Motors' Super Cruise™ hands-free highway driving system [107].

NovAtel demonstrated precise positioning with the Teseo APP (Automotive Precise Positioning) automotive GNSS chipsets from STMicroelectronics. The Teseo APP features built-in integrity checking for use in safety-critical systems. NovAtel's positioning engine combines the GNSS measurements from these chipsets with Inertial Measurement Unit (IMU) data and Hexagon PPP correction services on the demonstration platform to deliver centimeter-level PPP positioning solutions in real-time.

One of the examples is provided by Swift Navigation: The Voyage company deploying self-driving taxi equipped with Piksi Multi receiver ($595 per unit) became one of the first clients of the new generation Skylark correction service [139]. One of the roles of GNSS in SDC navigation is in identification of the road lane at which the car is moving. Lane-level accuracy navigation solutions with low-cost equipment are described in [140].

Apart from GNSS high-definition maps, cameras, radar, lidar and inertial sensors are typically used in automatic guidance systems.

8.2.2 Industrial Machines

Machines with automated guidance relying on GNSS are applied in construction and agriculture. There are examples from other industries, like a solution for alpine snow management offered by Leica[38].

Steering automation is one of the basic functions of a machine control system. Apart from it, there are unique functions for every machine type. An example is grade control function adjusting attitude of the dozer blade. Dedicated control systems are available for excavators, graders, dozers, scrappers, rollers, drillers, pilers, pavers, cold planers, etc. A wide range of solutions for agricultural of machinery is available as well. Complete automation of some jobs is already achievable. There are ready to use examples of autonomous tractors [141] with a large variety of attached automated equipment or specialized robots [142], [143]. An overview of robotics in agriculture can be found in [144].

The specific purpose of a machine and the level of process automation define the required level of positioning accuracy: from sub-meter to centimeter. In some cases not the high accuracy of positioning but high precision or pass-to-pass repeatability is required.

The speed of motion is typically lower for industrial machines in comparison to road vehicles. Industrial machine control systems have proved to work safely and efficiently with already existing correction services though in future they can benefit from the new generation correction services with easier interface and seamless coverage.

Application of GPS for spatially variable rate treatments in agriculture have been reported at least since early nineties [145]. Nevertheless, according to GSA [1], in 2018 the proportion of all high-powered tractors that is equipped with GNSS is still around 20%. The penetration level is expected to reach 50% by 2025. Given that advanced automatic control systems may in some cases replace operators, this technology is expected to generate significant benefits and therefore it is generally a cost-effective solution.

Among the possible ways of further improving cost-effectiveness of such systems free "aviation-style" SBAS, QZSS CLAS, CORS networks, free NTRIP correction services for PPP can be considered taking into account the existing limitations. There are examples proving that automation may be done effectively by the framer oneself using drone parts and open source software [146].

8.2.3 Unmanned Aerial Vehicles

Drones are another type of automatically guided vehicles that will expand the demand for high-precision positioning solutions. It is expected that in near future drones will find mass applications in such spheres as delivery of goods. Some very ambitious plans for that are being implemented. The examples are Amazon PrimeAir[39], Project Wing[40], Matternet[41], Zipline[42], Flytrey[43]. Though there are obstacles for mass UAV introduction conjugated with safety issues, noise pollution and legislative regulation [147], drone-related applications are expected to dominate professional segment of GNSS equipment market by 2025 [1].

38 https://leica-geosystems.com/products/machine-control-systems/leica-icon-alpine.
39 https://www.amazon.com/Amazon-Prime-Air/b?ie=UTF8&node=8037720011.
40 https://x.company/projects/wing/.
41 https://mttr.net/.
42 https://www.flirtey.com/.
43 http://flirtey.com/.

Until recent time drones have not normally required precise positioning technology. High precision was necessary mostly in case of aerial surveys. Post-processing was an option. Professional surveying-grade GNSS equipment onboard of a UAV could cost more than the vehicle itself. Even if such equipment was installed in many cases it was not used for navigation of the drone. Instead low-cost low-precision modules were used. Autopilot was typically applied in open environments while in a complicated situation the drone was guided remotely by the operator. Massive application of drones, especially in urban environment, will definitely require a complete independence for autopilot. Requirements for precision and reliability of positioning will become very strict.

Currently a number of low-cost RTK modules for drones are available [148]–[152]. One of the solutions is an application of several light-weight low-cost GNSS receivers on one UAV, which enables attitude determination at the same time providing opportunities for multipath mitigation and improving reliability of coordinate estimates [153]. The authors of the article report 99.9% availability of fixed solution in urban environment.

8.3 High Accuracy Location Based Services

A new class of high-precision location based services (HPLBS) implemented with smartphones and tablet computers is being shaped nowadays. The extent of its future adoption by the market is not yet clear. But most likely it will define the pace of cost decrease for high precision positioning technology. User needs and requirements for LBS are analyzed in the dedicated European GNSS Market report [34]. Here are some of the services described in the report which require high positioning accuracy.

Mobile Location Based Gaming (MLBG) is a growing trend among LBS. MLBG integrates elements of traditional open-air field games (e.g. Hide-and-seek, Paper Chase) with new technologies available on mobile devices including positioning technologies (such as GNSS receivers), wireless fast speed internet/permanent internet connection, image recognition, maps and augmented reality among others.

Fraud management services create another level of security during a credit card transaction by checking the customer's location through one's smartphone.

Billing services may offer payment processing based on location or activity duration for public transport, gyms, theme parks, parking.

M-health: navigation for visually disabled.

Smart parking applications provide real-time parking availability to drivers. GNSS is then used to guide a driver to the best available space with turn-by-turn instructions. The GNSS user requirements in this application are the same as those of route planning and turn-by-turn navigation applications, except for the horizontal accuracy which should be higher in order to enable the parking assistance feature. Common devices enabling this application are smartphones, portable navigation devices (PNDs) and in-vehicle navigation systems.

Insurance telematics is another way how precise positioning of a car can be helpful. Black boxes rely on GNSS data to increase the fairness of motor insurance for both insurers and subscribers. Supported by an increasing popularity amongst insurers and users in markets such as Italy, UK and United States, Insurance Telematics witnessed a vigorous growth (compound annual growth rate of 54%) between 2012 and 2016, reaching 9 million units in 2016 [1].

Personal navigation, non-professional mapping are also mentioned among applications requiring high positioning accuracy [34].

Success of future high-precision LBS depends upon progress in development and adoption of some other technologies which are to be merged with GNSS positioning, namely augmented reality and high-precision in-door navigation. Introduction of HPLBS will also require the development of a new generation of correction services to provide accurate, seamless, reliable, and easy positioning. These characteristics are targeted by developers of SAPCORDA and Skylark [139] services.

9 CONCLUSION

In the present study different ways of improving cost-effectiveness of high-precision positioning technology have been discussed. Some of them are free and easily accessible by any user.

Equipment providing high precision positioning at lower costs was discussed. The two converging trends were highlighted: high-precision equipment gets cheaper in basic configurations; low-cost equipment gets more advanced while getting more expensive. It was shown that in the professional equipment B2B market segment the price is shaped more according to a stereotype that better solution must be more expensive, rather than by production cost. A dramatic improvement of cost-effectiveness may be expected when high-precision positioning technology is adopted by non-professional B2C market segments because of economies of scale and higher price elasticity of demand.

Technical opportunities for further efficiency improvement were considered. Next generation of space telecommunication networks (OneWeb, StarLink, etc.) may soon make internet access ubiquitous at low cost, forcing commercial satellite based correction services to compete against free high-class IGS Real Time Service. New initiatives focused on development of new open standards for correction services are to enable seamless positioning in a "plug & play" style for mass market. With low-cost double-frequency GNSS chips, Android OS enabling raw GNSS data access, and software-defined GNSS receivers implementation of high-precision positioning on smartphones and other general purpose devices is already feasible. However, it remains to be seen how these opportunities will play out in markets and in practical terms.

The present study considered practical ways of improving cost-effectiveness of precise positioning technology and identified, to authors' knowledge, the most important trends in its development. Though it is practically impossible to give a comprehensive guide on selecting the most cost-effective technology for every particular case, the following general algorithm can be proposed.

1. *Formulating the task*. It is necessary to clearly define the major types of job to be done, expected periodicity, and the term while the matter is not going to change.
2. *Modeling a solution*. Products of the leading companies can be used as the base. They should be analyzed to learn the structure and major elements, i. e. workflow, equipment, services, data sources, processing methods.
3. *Searching for alternatives.* It is offered to look for possible replacement or modification of the base solution, starting from entire toolchains and going down to element scale. Different technical aspects of cost-effectiveness described in chapters 4–8 may be helpful at this step. As a result several most promising configurations worth a more detailed analysis should be identified.
4. *Selecting the most effective option,* taking into account available resources: money, time, and expertise.
5. *Making a decision* whether the selected solution is reasonable. If the best solution is not appropriate then the task should be reformulated.
6. *Verifying the decision.* It is better to test and run in the technology before major investments. A free trial period for service, software, and hardware is often an option.

As one may notice, the proposed algorithm is not rigorous. The success is strongly dependent on theoretical knowledge, experience, and intuition of the decision maker. When searching for the most effective solution, it is extremely important to have a wide vision of opportunities. That vision should be based not only on commercial proposals, but also on independent sources of information, such as case studies and comparative tests, which can be found in professional journals, conference proceedings, reports of non-profit organizations, etc. There are many free fit-for-purpose solutions, but their developers unlikely have an advertising budget comparable to the one of a commercial company. Finally, the high efficiency of decisions made and technologies applied is possible, if only the alternatives are clear and the customer understands what one is paying for.

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APPENDIX A – ADDITIONAL INFORMATION AND RESOURCES

Data Formats and Protocols

1. IGS formats page: RINEX (2.10-3.04), clock RINEX, Hatanaka compact RINEX, clock RINEX, SINEX, Tropo SINEX, sp3, erp, RINEX, IONEX, site log.
   https://kb.igs.org/hc/en-us/articles/201096516-IGS-Formats
2. BIAS SINEX
   http://www.biasws2012.unibe.ch/docs/sinex_bias_0.01-2.txt
3. SINEX: Solution (Software/technique) Independent Exchange Format
   https://www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex_cont.html
4. NTRIP
   http://rtcm-ntrip.org/home.html

GNSS Interface Control Documents

1. GPS
   https://www.gps.gov/technical/icwg/
2. GLONASS
   http://russianspacesystems.ru/bussines/navigation/glonass/interfeysnyy-kontrolnyy-dokument/
3. BeiDou
   http://en.beidou.gov.cn/SYSTEMS/ICD/
4. Galileo
   https://www.gsc-europa.eu/electronic-library/programme-reference-documents
5. QZSS
   http://qzss.go.jp/en/technical/ps-is-qzss/ps-is-qzss.html
6. NAVIC/IRNSS
   https://www.isro.gov.in/irnss-programme

Relevant Organizations and Information Sources

1. International Earth Rotation and Reference Systems Service
   https://www.iers.org
2. International GNSS Service (IGS)
   http://www.igs.org/
3. IGS Real Time Service
   http://www.igs.org/rts/access
4. IGS Multi-GNSS Experiment (MGEX)
   http://mgex.igs.org/
5. European GNSS Service Centre
   https://www.gsc-europa.eu

6. Crustal Dynamics Data Information System (CDDIS)
https://cddis.nasa.gov/

7. Information and Analysis Center for Positioning, Navigation and Timing
https://www.glonass-iac.ru/en/

8. BKG GNSS Data Center – NTRIP
https://igs.bkg.bund.de/

9. Navipedia
https://gssc.esa.int/navipedia

Free Software

1. NGS Geodetic Tool Kit
www.ngs.noaa.gov/TOOLS/index.shtml

2. Open Geospatial Consortium
www.opengeospatial.org/

3. UNAVCO
www.unavco.org/software/software.html

4. GPSTk Software
www.gpstk.org/bin/view/Documentation/WebHome

5. NTRIP software overview by BKG
igs.bkg.bund.de/ntrip/download

6. RTKLIB Software
www.rtklib.com

7. Geoscience Australia
https://github.com/GeoscienceAustralia

8. Land Information New Zealand
https://www.linz.govt.nz/land/landonline/system-support-and-software-downloads/software-downloads
https://github.com/linz

9. GNSS-SDR
https://gnss-sdr.org/

10. gLab Software
http://www.gage.upc.edu/gLAB

11. GNSS tools on Navipedia
https://gssc.esa.int/navipedia/index.php/GNSS:Tools

APPENDIX B – GLOBAL AND REGIONAL REFERENCE STATION NETWORKS

Global

1. IGS Tracking Network
   http://www.igs.org/network
2. Hexagon tracking network
   https://hxgnsmartnet.com
3. Trimble Stations
   https://www.trimble.com/trs/findtrs.asp
4. TopnetLive
   http://www.topnetlive.com/
5. UNAVCO Network
   https://www.unavco.org/instrumentation/networks/status/all
6. SONEL
   http://www.sonel.org/-GPS-.html

North America

1. The National CORS Network – United States
   https://www.ngs.noaa.gov/CORS/
2. Plate Boundary Observatory – Western United States
   http://www.unavco.org/projects/major-projects/pbo/pbo.html
3. The Southern California Integrated GPS Network
   http://www.scign.org/
4. Canadian Active Control System (CACS)
   https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php?locale=en
5. Bay Area Deformation Array – USGS/UC Berkeley
   http://seismo.berkeley.edu/bard/
6. Eastern Basin-Range and Yellowstone Hotspot GPS Network
   https://www.uusatrg.utah.edu/RBSMITH/public_html/RESEARCH/UUGPS.html
7. Pacific Northwest Geodetic Array
   http://www.panga.cwu.edu/
8. Parkfield, California Crustal Deformation Measurements
   https://earthquake.usgs.gov/monitoring/gps/Parkfield

Central and South America

1. SIRGAS Continuously Operating Stations
   http://www.sirgas.org/en/sirgas-con-network/stations/

2. Red Geodesica Nacional Activa – Mexico
http://www.inegi.org.mx/inegi/default.aspx?s=geo

3. COCONet – Continuously operating Caribbean GPS Observational Network
http://coconet.unavco.org/

4. TLALOCNet – Mexico
https://www.unavco.org/projects/major-projects/tlalocnet/tlalocnet.html

5. RBMC – Brazil
https://ww2.ibge.gov.br/home/geociencias/geodesia/rbmc/rbmc_est.php

6. Estaciones GNSS Permanentes – Argentina
http://www.copa.org.ar/Eljalon/estaciones.htm

Europe

1. EUREF Permanent Network – Europe
http://www.epncb.oma.be/

2. SAPOS ® – German National Survey Satellite Positioning Service
https://www.sapos.de/

3. SWEPOS – Swedish Network of Permanent Reference Stations for GNSS
https://swepos.lantmateriet.se/

4. Geodetic Data Archiving Facility – Italy
http://geodaf.mt.asi.it/

5. Reseau GPS Permanent – France
http://rgp.ign.fr/

6. Switzerland's automated GNSS network (AGNES)
http://pnac.swisstopo.admin.ch/

7. CZEPOS – Czech Republic
http://czepos.cuzk.cz/

8. ESTPOS – Estonia
https://www.maaamet.ee

9. GNSSNET.HU – Hungary
https://www.gnssnet.hu/

10. LATPOS – Latvia
https://latpos.lgia.gov.lv

11. LITPOS – Lithuania
https://www.geoportal.lt/geoportal/web/litpos-paslauga

12. ASG-EUPOS – Poland
http://www.asgeupos.pl

13. ROMPOS – Romania
http://www.rompos.ro

14. AGROS – Serbia
http://www.agros.rgz.gov.rs/

15. SKPOS – Slovak Republic
http://www.skpos.gku.sk
16. SIGNAL – Slovenia
http://www.gu-signal.si/
17. MOLDPOS – Moldavia
http://moldpos.md/
18. FAGN – Russian Federal Astro-Geodetic Network
http://new.rgs-centre.ru/map
19. HIVE – Russia
https://hive.geosystems.aero/
20. EFT CORS – Russia
https://eft-cors.ru/
21. SmartNet Russia
http://smartnet-ru.com/
22. GSI Network – Russia
http://topnet.gsi.ru
23. UGT Holding – Russia
http://ugt-holding.com/reference_stations_ugt-holding
24. PRINNET – Russia
http://www.prin.ru/seti_referencnyh_stancij/prinnet/
25. RTKNET – Russia
http://rtknet.ru
26. Rostechinventarizatsya – Russia
http://гнсс.рф
27. CORS network of Tumen Region – Russia
http://ggs72.ru
28. CORS network of Novosibirsk region – Russia
http://cngt.nso.ru/page/25
29. CORS network of Bashkortostan Republic – Russia
http://www.tncrb.ru/WebSPTN/#
30. Elravis network, Grozny – Russia
http://elravis.ru/bazovye-stancii-gps/
31. Geospider, St. Petersburg and Leningrad region – Russia
http://geospider.ru/
32. CORS network of St. Petersburg – Russia
https://ref.kgainfo.spb.ru/
33. CORS network of Buryat Republic – Russia
http://geo-baikal.ru/spiderweb/frmIndex.aspx
34. CORS network of Krasnoyarsk region – Russia
https://krastehcentr.ru/

35. CORS network of Volga region – Russia
http://ooogradient.ru/stancii-povoljiya/

36. CORS network of Perm Region – Russia
http://ctipk.ru/sstp_access

37. CORS network of Kursk Region – Russia
https://rcny.ru/2/

38. CORS network of Tomsk – Russia
http://www.admin.tomsk.ru/pgs/2rp

39. CORS network of Yamal-Nenets Autonomous Area – Russia
https://tbd.ru/osvtp/osvtp_index.php

40. CORS network of Komi Republic – Russia
http://gis.rkomi.ru/Catalog/ResourceDescription/-104

41. CORS network of Kaluga Region – Russia
http://www.giskaluga.ru/projects/ripd/RSKVGO/

42. CORS network of Kirov Region – Russia
http://www.kirovgiprozem.ru/ftp/

43. CORS network of Chuvash Republic – Russia
http://rs.cap.ru/login.aspx

44. CORS network of Khanty-Mansi Autonomous Area – Russia
https://cio-hmao.ru/референцные-станции/

45. System.Net – Ukraine
https://systemnet.com.ua/

46. MAO GNSS – Ukraine
http://gnss.mao.kiev.ua/

47. TNT-TPI GNSS Network – Ukraine
https://net.tnt-tpi.com/page/bss

48. ZAKPOS – Ukraine
http://zakpos.zakgeo.com.ua/

49. NGCNET – Ukraine
http://www.ngcnet.com.ua

50. GNSS Network for Precise Positioning – Belarus
http://geo.by/ru/for-organizations/precise-positioning-service

Africa

1. African Geodetic Reference Frame (AFREF) Network of GNSS Reference stations
http://afrefdata.org/

2. CORS Map – Africa's GNSS CORS
https://corsmap.com/

3. NIGNET (NIGerian GNSS Reference NETwork)
http://segal.ubi.pt/GNSS/NIGNET/intro.html

4. TrigNet CORS – South Africa
http://www.trignet.co.za/

5. Rwanda Natural Resources Authority
http://197.243.38.46/spiderweb/frmIndex.aspx

6. Algerian permanent GPS network
http://www.inct.mdn.dz/site%20anglais/web_inct_sim/gps.php

Asia-Pacific

1. Australian Regional GPS Network
http://www.ga.gov.au/geodesy/argn/

2. GeoNet – New Zealand
https://www.geonet.org.nz/

3. PositioNZ – New Zealand
https://www.linz.govt.nz/data/geodetic-services/positionz

4. Crustal Movement Observation Network of China (CMONOC)
http://202.127.29.4/shao_gnss_ac/

5. JLCORS – China
http://chj.jl.gov.cn

6. SZCORS – China
http://www.szpl.gov.cn

7. MOMRA Geodetic Networks – Saudi Arabia
https://www.gcs.gov.sa/En/ProductsAndServices/Products/GeodesyandLand-Survey/pages/cors.aspx
http://www.momracors.com/portal/en/

8. Asia-Pacific Reference Frame (APREF)
http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame#heading-5

9. Turkish National Permanent GNSS Network (TNPGN)
https://www.harita.gov.tr/english/u-11-turkish-national-permanent-gnss-network--tnpgn-.html

10. Geographical Survey Institute – Japan
http://www.gsi.go.jp/ENGLISH/page_e30030.html

11. Indian Seismic and GNSS Network, ESSO – India
http://www.isgn.gov.in/ISGN/

12. MyRTKnet – Malaysia
http://www.rtknet3.gov.my

13. InaCORS – Indonesia
http://nrtk.big.go.id/sbc

14. Ground Infrastructure for High Precision Satellite Navigation – Kazakhstan
http://svsn.kz/index.html

15. Kyrgyzstan GPS/GNSS Network
http://old.gosreg.kg/index.php?option=com_content&view=article&id=452

Arctic and Antarctica

1. POLENET – Arctic and Antarctica
https://www.unavco.org/projects/major-projects/polenet/polenet.html

2. LARsen Ice Shelf System, Antarctica (LARISSA)
https://www.hamilton.edu/larissa
https://www.unavco.org/projects/major-projects/larissa/larissa.html

APPENDIX C – IGS PRODUCTS

IGS Official Orbit and Clock Products

Table C.1: *IGS GPS Orbits.*

Type	Accuracy	Latency	Updates	Interval
Broadcast	~100 cm	real time	N/A	daily
Ultra-Rapid (p)	~5 cm	real time	4 per day	15 min
Ultra-Rapid (o)	~3 cm	3–9 hours	4 per day	15 min
Rapid	~2.5 cm	17–41 hours	Daily	15 min
Final	~2.5 cm	12–18 days	Weekly	15 min

Table C.2: *IGS GPS Satellite Clocks.*

Type	Accuracy	Latency	Updates	Interval
Broadcast	~5 ns	real time	N/A	daily
Ultra-Rapid (p)	~3 ns	real time	4 per day	15 min
Ultra-Rapid (o)	~150 ps	3–9 hours	4 per day	15 min
Rapid	~75 ps	17–41 hours	Daily	5 min
Final	~75 ps	12–18 days	Weekly	30s

Table C.3: *IGS GLONASS Satellite Ephemerides.*

Type	Accuracy	Latency	Updates	Interval
Final	~3 cm	12–18 days	Weekly	15 min

p – predicted half
o – observed half

Orbit accuracies are 1D mean RMS values over the three XYZ geocentric components. IGS accuracy limits, except for predicted orbits, are based on comparisons with independent laser ranging results and discontinuities between consecutive days. The precision is better.

Table C.4: *Geocentric Coordinates of IGS Tracking Stations.*

<table>
<tr><th colspan="2">Type</th><th>Accuracy</th><th>Latency</th><th>Updates</th><th>Sample Interval</th></tr>
<tr><td rowspan="2">Final positions</td><td>horizontal</td><td>3 mm</td><td rowspan="2">11–17 days</td><td rowspan="2">weekly</td><td rowspan="2">weekly</td></tr>
<tr><td>vertical</td><td>6 mm</td></tr>
<tr><td rowspan="2">Final velocities</td><td>horizontal</td><td>2 mm/yr</td><td rowspan="2">11–17 days</td><td rowspan="2">weekly</td><td rowspan="2">weekly</td></tr>
<tr><td>vertical</td><td>3 mm/yr</td></tr>
</table>

IGS Real-Time Service Products

Table C.5: *IGS Real Time Service Correction Streams.*

Stream Name	Description	Ref Point	RTCM Messages	Provider / Solution ID	Bandwidth kbits	Software
IGS01	Orbit/Clock Correction, Single-Epoch Combination	APC	1059 (5),1060 (5)	258 / 1	1.8/sec	ESA/ESOC
IGC01	Orbit/Clock Correction, Single-Epoch Combination	CoM	1059 (5),1060 (5)	258 / 9	1.8/sec	ESA/ESOC
IGS02	Orbit/Clock Correction, Kalman Filter Combination	APC	1057 (60), 1058 (10), 1059 (10)	258 / 2	0.6/sec	BKG
IGS03	Orbit/Clock Correction, Kalman Filter Combination	APC	1057(60), 1058(10), 1059(10), 1063(60), 1064(10), 1065(10)	258 / 3	0.8/sec	BKG

APC: Antenna Phase Center CoM: Center of Mass, (not compliant with current RTCM-SSR standard). The figures in brackets next to each RTCM message ID denote the message sample interval in seconds. Additional analysis center product streams may be available through the IGS casters.

Table C.6: *GNSS Broadcast Ephemerides Streams by IGS.*

Stream Name	Description	RTCM Messages	Supported GNSS	Bandwidth kbits	Software
RTCM3EPH	Broadcast Ephemeris	1019(5), 1020(5), 1045(5)	GPS, GLONASS, Galileo	6.0/sec	BKG/BNC
RTCM3EPH01	Broadcast Ephemeris	1019(5)	GPS	4.0/sec	DLR/RETICLE

Table C.7: *RTCM Messages.*

RTCM	v3 Message Types
1019	GPS Broadcast Ephemeris
1020	GLONASS Broadcast Ephemeris
1045	Galileo Broadcast Ephemeris
1057	GPS orbit corrections to Broadcast Ephemeris
1058	GPS clock corrections to Broadcast Ephemeris
1059	GPS code biases
1060	Combined orbit and clock corrections to GPS Broadcast Ephemeris
1061	GPS User Range Accuracy
1062	High-rate GPS clock corrections to Broadcast Ephemeris
1063	GLONASS orbit corrections to Broadcast Ephemeris
1064	GLONASS clock corrections to Broadcast Ephemeris
1065	GLONASS code biases
1066	Combined orbit and clock corrections to GLONASS Broadcast Ephemeris
1067	GLONASS User Range Accuracy
1068	High-rate GLONASS clock corrections to Broadcast Ephemeris

IGS Earth System Parameters Estimates

Table C.8: *IGS Earth Rotation Parameters.*

Type		Accuracy	Latency	Updates	Sample Interval
Ultra-Rapid (p)	PM	~200 µas	real time	4 times/ day	daily integrations at 00, 06 12, 18 UTC
	PM rate	~300 µas/day			
	LOD	~50 µs			
Ultra-Rapid (o)	PM	~50 µas	3–9 hours	4 times/ day	daily integrations at 00, 06, 12, 18 UTC
	PM rate	~250 µas/day			
	LOD	~10 µs			
Rapid	PM	~40 µas	17–41 hours	Daily	daily integrations at 12 UTC
	PM rate	~200 µas/day			
	LOD	~10 µs			
Final	PM	~30 µas	11–17 days	Weekly	daily integrations at 12 UTC
	PM rate	~150 µas/day			
	LOD	~10 µs			

Polar Motion (PM) Polar Motion Rates (PM rate) Length-of-day (LOD)

Note 1: 100 µas = 3.1 mm of equatorial rotation; 10 µs = 4.6 mm of equatorial rotation.

Note 2**:** The IGS uses VLBI results from IERS Bulletin A to partially calibrate for LOD biases over 21-day sliding window, but residual time-correlated LOD errors remain.

Table C.9: *IGS Atmospheric parameters.*

Type	Accuracy	Latency	Updates	Sample Interval
Final tropospheric zenith path delay with N, E gradients	4 mm (ZPD)	< 4 weeks	daily	5 minutes
Final ionospheric TEC grid	2–8 TECU	~11 days	weekly	2 hours; 5 deg (lon) x 2.5 deg (lat)
Rapid ionospheric TEC grid	2–9 TECU	<24 hours	daily	2 hours; 5 deg (lon) x 2.5 deg (lat)

IGS Tracking Network

http://www.igs.org/network

IGS Multi-GNSS Experiment (MGEX) Products

Table C.10: *MGEX Products.*

Institution	Constellations	Products	References
CNES/ CLS	GPS+GLO+GAL	Satellite orbits and clocks (15 min; *.sp3) Satellite and station clocks (30 s; *.clk) Site coordinates and ERPs (*.snx)	[154]
CODE	GPS+GLO+GAL+BDS+QZS	Satellite orbits and clocks (15 min; *.sp3) Satellite and station clocks (5 min; *.clk) Earth orientation parameters (12 h; *.erp) Biases (1 d; *.bia)	[155], [156]
CODE	GPS+GLO+GAL+BDS+QZS	Satellite orbits and clocks (5 min; *.SP3) Satellite and station clocks (30 s/5 min; *.CLK) Earth orientation parameters (12 h; *.ERP) Biases (1 d; *.BIA)	
GFZ	GPS+GLO+GAL+BDS+QZS	Satellite orbits and clocks (15 min; *.sp3) Satellite and station clocks (30 s/5 min; *.clk) Earth orientation parameters (1 d; *.erp) Biases (1 d; *.bias)	[157], [158]
JAXA	GPS+QZS	Satellite orbits and clocks (5 min; SP3)	
JAXA	GPS+GLO+QZS	Satellite orbits and clocks (5 min; SP3) Satellite and station clocks (30 s; *.CLK) Site coordinates and ERPs (*.SNX)	
SHAO	GPS+GLO+GAL+BDS	Satellite orbits and clocks (15 min; SP3) Satellite and station clocks (5 min; *.CLK)	
TUM	GAL+QZS	Satellite orbits and clocks (5 min; SP3)	[159]
Wuhan Univ.	GPS+GLO+GAL+BDS+QZS	Satellite orbits and clocks (15 min; *.sp3) Satellite and station clocks (5 min; *.clk) Earth orientation parameters (1 d; *.erp)	[160]

Broadcast Ephemerides

Table C.11: *Combined multi-GNSS broadcast ephemeris files.*

Institution	Constellations	Notes
BKG	GPS+GLO+GAL+BDS	Converted from stream RTCM3EPH on http://mgex.igs-ip.net
IGS	GPS+GLO+GAL+BDS +QZSS+SBAS	Merged from receiver-generated RINEX navigation files
TUM/DLR	GPS+GLO+GAL+BDS +QZSS+IRNSS+SBAS	Merged from streams of about 35 stations

Table C.12: *Differential Code Biases.*

Institution	Constellations and Signals	Notes
CAS	GPS(C1C,C1W,C2L/S/X,C2W,C5Q/X) GLO(C1C,C1P,C2C,C2P) GAL(C1C/X,C5Q/X,C7Q/X,C8Q/X) BDS(C2I,C6I,C7I)	[161]
DLR	GPS(C1C,C1W,C2L/S/X,C2W,C5Q/X) GLO(C1C,C1P,C2C,C2P) GAL(C1C/X,C5Q/X,C7Q/X,C8Q/X) GAL(C6C) since Q2/2017 BDS(C2I,C6I,C7I) QZS(C1C/X,C2L/S/X C5Q/X) since Q3/2017	[162]

Details are available at http://mgex.igs.org/IGS_MGEX_Products.php

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FIG PUBLICATIONS

The FIG publications are divided into four categories. This should assist members and other users to identify the profile and purpose of the various publications.

FIG Policy Statements

FIG Policy Statements include political declarations and recommendations endorsed by the FIG General Assembly. They are prepared to explain FIG policies on important topics to politicians, government agencies and other decision makers, as well as surveyors and other professionals.

FIG Guides

FIG Guides are technical or managerial guidelines endorsed by the Council and recorded by the General Assembly. They are prepared to deal with topical professional issues and provide guidance for the surveying profession and relevant partners.

FIG Reports

FIG Reports are technical reports representing the outcomes from scientific meetings and Commission working groups. The reports are approved by the Council and include valuable information on specific topics of relevance to the profession, members and individual surveyors.

FIG Regulations

FIG Regulations include statutes, internal rules and work plans adopted by the FIG organisation.

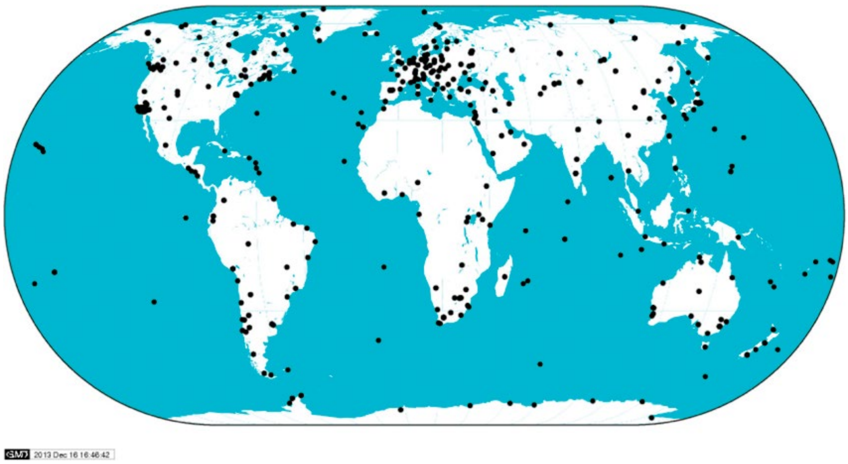
List of FIG publications

For an up-to-date list of publications, please visit
www.fig.net/pub/figpub

ABOUT FIG

International Federation of Surveyors is the premier international organization representing the interests of surveyors worldwide. It is a federation of the national member associations and covers the whole range of professional fields within the global surveying community. It provides an international forum for discussion and development aiming to promote professional practice and standards.

FIG was founded in 1878 in Paris and was first known as the Fédération Internationale des Géomètres (FIG). This has become anglicized to the International Federation of Surveyors (FIG). It is a United Nations and World Bank Group recognized non-government organization (NGO), representing a membership from 120 plus countries throughout the world, and its aim is to ensure that the disciplines of surveying and all who practise them meet the needs of the markets and communities that they serve.



Most surveyors today are aware that data acquisition, management, analysis, presentation and controlling systems are becoming more elaborate and automated. On the other side the results to be provided need to be produced with less cost, so in a cost-effective way.

The International Federation of Surveyors (FIG) Commission 5 – Positioning and Measurement, has been and remains an essential part of the surveying community. During the past three decades, Global Navigation Satellite Systems (GNSS) have and continue to play an increasingly important role in the profession. FIG enhances this development by facilitating GNSS sessions at their conferences, encouraging GNSS research and education, and cooperating with sister organisations such as the International Association of Geodesy (IAG) in the respective domain. Additionally FIG Commission 5 reacts on these developments by establishing Working Groups that deal with GNSS measurement techniques (WG 5.4), the use of GNSS for 3D and vertical reference systems (WG 5.2 and WG 5.3), data fusion in multi sensor systems (WG 5.5) as well as for cost-effective positioning and measurements (WG 5.6).

Additionally, FIG is also trying to integrate GNSS surveying as a base and a starting point for land administration as well as cadastral registration, especially in developing countries regarding property evidence. This is one of the major reasons why FIG is looking at cost-effective technologies and techniques for enabling surveyors in developing countries to use the best equipment at a reasonable price. Reducing costs of high precision positioning is also strongly connected with the progress in new promising R&D directions such as high precision location based services for mass market and precise autonomous guidance for self-driving cars, unmanned aerial vehicles, and industrial machines.

This Technical Report focuses on the cost-effective use of precise GNSS positioning. It was prepared within the framework of Working Group 5.6"Cost-Effective Positioning". If you wish to contribute to the activities of any working group please feel free to contact the authors, current WG or Commission 5 Chair (see fig.net/commission5/).

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