Global Navigation Satellite Systems (GNSS): The Utmost Interdisciplinary Integrator

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ABSTRACT

Currently four global satellite navigation systems are under modernization and development: The US American GPS III, the Russian GLONASS, the European Galileo and Chinese BeiDou systems.

In the paper the interdisciplinary contributions of different scientific areas to GNSS are assessed. It is outlined that GNSS is not only a technical system but also a basic element of mobile computing high-tech market. At the same time a GNSS has the role of a force enabler in security related applications. Technology, market and security policies are interdependent and are sometimes in a relationship of tension.

The goal of the paper is to describe the overall systemics of GNSS from a holistic point of view. The paper also addresses the human factor side of GNSS. The requirements on human resources in GNSS are at least two-fold: On the one hand very specialized engineers are needed; on the other hand the generalists are necessary who are able to understand the system aspects. Decision makers in institutions and industry need special knowledge in technologies, economics and political strategies. Is the current university system able to educate and prepare such generalists? Are specialized master courses for GNSS needed? Are external training courses necessary?

Keywords: Global Navigation Satellite Systems, GNSS, Interdisciplinary Nature, Systemics of GNSS, GNSS in the Information World, GNSS in the Academic Education System

1. INTRODUCTION

GPS receivers have penetrated our daily life. More or less all high-tech multi-media devices like mobile phones, mobile computing devices, automotive devices and many consumer products are equipped with a GPS chip. More over all-classical navigation applications like aircraft navigation and landing, navigation of ships in harbors and the open sea but also the location of near-earth satellites, e.g. imaging satellites are based on GPS. The US Global Positioning System or more general the Global Navigation Satellite Systems (GNSS) provide a unique source for position determination and timing for various users and are in general free of charge. Highly integrated GNSS silicon chips became very cheap over the years. They look as small technical marvels. But they became only possible by the mastering of very complex technology areas and implementation of infrastructures.

The roots of satellite navigation go back to the beginning of the space age. Only five years after the flight of Sputnik I in 1957 the space was already utilized for telecommunication [1] (Communications Satellite Act of President J.F. Kennedy, 1962) and the built-up of the Doppler navigation system TRANSIT in the US. Similar developments were put into place in Russia. In 1973 the GPS NAVSTAR program [2] was launched in the USA and only a few years later the Russians started to develop GLONASS. Clearly this big initial effort to implement in the 70ties such complex systems was driven by the cold war and the competition between the western and eastern hemispheres. GPS and GLONASS were initially purely military systems. After the Korean Airlines (KAL 007) disaster in 1983 GPS (and later GLONASS) was made available for the civil world. Thus, the early satellite navigation systems mutated to dual use systems what they are still today. Dual use systems have the standalone feature that the same system can be used for civil use and to support military applications. In the early 1960s Europe made first steps to built-up and organize its own space sector (European Space Agency ESA was founded in 1975). Satellite navigation was not on the agenda in these days. At that time China was at the end of the so-called Cultural Revolution. First activities in space were also visible in China (the first earth-orbiting satellite was launched in 1970). A quarter of a century later the situation changed in Europe and China because the benefits of satellite navigation got more and more visible in the US: Dessert Storm in 1991 was a clear break-through for GPS in military applications. At the same time civil market was already present for surveying GPS sets, maritime receivers and the first land vehicle devices. Thus, rather lately it was discovered that satellite navigation is on the one hand strategic technology and on the other hand it is a market enabler for basically all civil PNT (Positioning Navigation and Timing) issues. The developments of Galileo in Europe [3], [4] and BeiDou in China were started. Many other activities in the so-called Space Based Augmentation Systems (SBAS) and regional systems (QZSS, Japan) were kicked-off.

2. INTERDISCIPLINARY NATURE OF GNSS

GNSS is an interdisciplinary field par excellence. The reason is on the one hand that several key technology areas are involved. On the other hand these key technology areas don not belong to a unique academic faculty or a single profession.

Key Technology Areas

Satellite navigation like we know it today became only possible over the last 50 years by the integration of several key technology areas: First, we need the ability to build robust satellite platforms with a life-time of 12-15 years. And we need access to space i.e. we need adequate launchers and space transportation systems to reach the MEO (20.000 km) orbit.

Secondly, we need the ability to build precise atomic clocks (Rubidium, Cesium, H – Maser, optical clocks in future) and operate them in the satellite orbit for many years. GPS was the first system where spread-spectrum digital signal processing based on BPSK (Binary Phase Shift Keying) was implemented. Thus, thirdly we need the digital technology on hardware and software level to generate the baseband signals and to modulate these finally on one or more carrier frequencies. This includes the design of electronic and digital payload components. In the design and production of GNSS receivers in the user segment leading-edge semiconductor technology and fast digital signal processing on high – performance micro-processors is a key requirement. Not to forget the ability of high precision orbit determination and prediction (decimeter – accuracy over 24 h) and the modelling and prediction of the deterministic and stochastic drift of atomic clocks. Other important key areas are the propagation of electromagnetic waves on L – band frequencies in the atmosphere of the earth. Corrections for time and frequency based on general and special theory of relativity have to be applied. Last but not least the theory and practice of precise geodetic and astronomical reference frames and time systems is an important element of GNSS.

Disciplines involved

On the technical side of GNSS it is not so difficult to identify the academic and technical disciplines which are involved. However, GNSS has not only a technical dimension but also several non-technical dimensions.

Aerospace engineering: All aspects which are concerned with the satellite platforms, the launcher system the constellation built-up and the space operations belong to aerospace engineering. GNSS is basically not so different from other space systems e.g. like other low-earth orbiting constellations e.g. IRIDIUM, GLOBALSTAR, etc.

Communication engineering: The generation and modulation of digital pseudorandom noise on electromagnetic waves, the transmission of these signals, and the de-modulation in the user receiver by various methods of time-series processing like auto-correlation is basically covered by the field of communications engineering.

Electrical engineering: In the navigation payload of the satellites but also in the GNSS receivers of the user segment various electrical components are used. A very important field for small sized and low – cost GNSS chips is the field of semiconductor materials, design and processes. The field of electromagnetic wave propagation between satellites and users and the reflection of signals on smooth and rough surfaces (multipath) and appropriate propagation channel models belong classically to electrical engineering.

Informatics: In the GNSS space, ground and user segments there are many tasks related to the field of information technology. GNSS are to a large extent driven by software. Therefore software engineering with respect to software standards is an issue. Additionally the development of processing systems making use signal and microprocessors is a challenge. Software quality assurance, coding theory and cryptography should not be forgotten.

Physics: Physicians play an important role in GNSS. A basic task of physicians is to design and built precise atomic clocks for extremely precise time keeping and frequency generation. Precise time and frequency also requires the exact knowledge of A. Einstein’s space time continuum and the derivation of various correction formulae and schemes, because GNSS clocks are in space on different gravity potentials and speed relative to a user on the earth surface. Atmospheric physicians cover the models and processes of the ionosphere and the troposphere.

Mathematics: Mathematics is linked to various aspects in the GNSS. Very obvious is the field of orbit determination and orbital mechanics. Precise mathematical acceleration models and precise numerical integration methods of differential equations are needed. Another topic is the optimal parameter estimation in the orbit determination process by use of linear or non – linear estimation methods. Some overlap to theoretical mechanics exists.

Geodesy: The issues of precise global reference coordinate systems, the geodynamic aspects of the system earth, but also the navigation algorithms and least – squares adjustment down to carrier phase ambiguity resolution in mixed real valued and integer valued estimation problems is covered by geodesy.

Product and service design: Finally, the receivers or products for the end – consumers have to be developed and designed with an up-to date form factor. Engineers from the main transport modes (aviation, maritime, land) are needed to install the GNSS related systems and products in the specific platforms. Standardization, verification and testing, safety analyses is an additional area.

Additionally to the classical technical areas several partly non – technical, more general and soft – skill abilities are necessary:

System engineering: At first people are needed who are by themselves no specialists in the above listed domains but have an overview about the interconnections and the interdependences. These people are often called system engineers.

Project management, contracts and commercial issues: Because the built – up of the space and ground infrastructures in a GNSS (the same holds for the sub-systems) are large projects for several 1000 M $ project managers are needed who are able to keep control of the complex work package structures and the time schedules. They are supported by controllers who have a commercial background. Because various contracts have to be signed in the development of the space, control and user segments also specialized lawyers are involved.

Finally people are needed who are pioneering services and put them to practice.

Additional Complexity Issues

The description of key technologies shows already that GNSS has various elements of knowledge areas. However, even in a specific knowledge domain GNSS is introducing higher complexity issues. Reasons are the following: GNSS does not consist of a single satellite, but a constellation of about 30 satellites per system. Very accurate metric distance measurements are necessary. This poses extremely high precision requirements on time and frequency generation. The dual use system issue introduces an interface between civil and military space flight. The user requirements (maritime, land, air, space) are very heterogeneous and difficult to harmonize. The usable frequency spectrum in L – Band is scarce. Because GNSS is always a strategic element of security policies governmental agencies are involved. This is also because the public implementation and operational costs are high (> 7 B$ US per 10 fiscal years plus 500 M$/year for operations). Last but not least the value chain, i.e. the cycle from infrastructure to products is very complex and difficult to understand.

3. ROLE OF GNSS IN THE INFORMATION WORLD

The GNSS development is in some aspects similar to the history of the internet. In the 1960's the US Department of Defense awarded some contracts to develop packet network systems. The ARPANET became the first network which made use of the internet protocol. After the military initiative university researchers became involved in the internet development and step by step over the years it evolved to the global digital communication layer for multi – media applications. GPS was originally designed as a navigation system to enhance military operations: The early motto of GPS [2] was: "drop five bombs in the same hole and built a cheap set that navigates". Now GNSS is the basic infrastructure for all information technology applications where geo-location is needed. In Europe it is known that 5 – 7% of the social cross product in the European Union depends already on PNT with a growing tendency.

Some examples are: Intelligent high – way and telematics systems including car-to-car communication, driver assistance systems and in future autonomous driving.

The use of GNSS is the simplest way to synchronize computer networks, power distribution networks and base station networks of telecommunication.

Usually a GNSS sensor provides PNT for Location Based Services and gaming applications.

Civil and military security systems e.g. like C^3I (Command, Control, Communications and Intelligence) or network centric warfare (networking of sensors, command, weapon delivery) are using GNSS on the geo-location side.

The space time context in the new field of "Big Data" is introduced by GNSS.

A good example (out of many others) for such a GNSS and communication based information infrastructure is the Automatic Identification System (AIS) of the maritime community [5]:

Since the Safety of Life Convention (SOLAS) of the IMO (International Maritime Organization) is in place Chapter V of SOLAS required all ships with a gross tonnage > 300 grt to be fitted with an AIS (Universal Automatic Identification System) till 12/2004. Universal AIS (or AIS, as it is commonly known) is an emerging ship and shore based broadcast system, operating in the VHF maritime band. Its characteristics and capabilities will provide efficient shipping traffic management. The AIS can be understood as the marine collision avoidance system. It is an outstanding new tool for enhancing the safety of navigation. An AIS station is a VHF radio transceiver capable of sending ship information such as identity, position, course, speed, length, ship type and cargo information etc., to other ships. Information from an operational shipboard AIS unit is transmitted continuously and automatically without any intervention of the ship's staff.

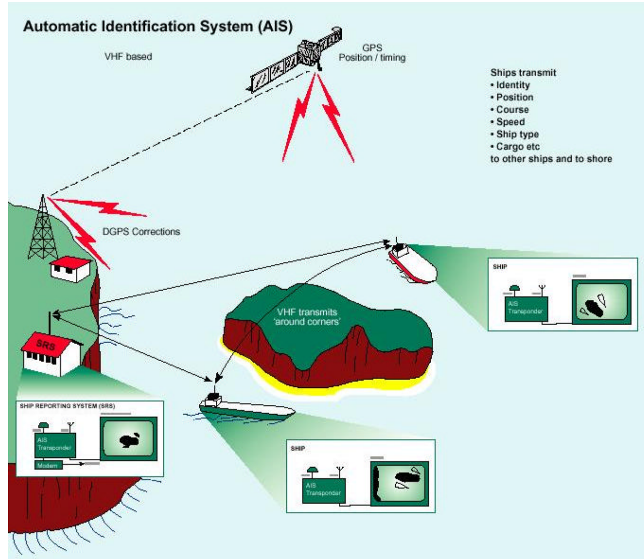

Figure 1: Concept of The Automatic Identification System (AIS) in maritime coastal navigation [5]

An AIS Station is built-up by one VHF transmitter, two VHF SOTDMA (Self Organizing TDMA) receivers, one VHF DSC (Digital Selective Calling) receiver and marine communication link to ECDIS (Electronic Chart Display). Additionally a GPS receiver for time slot synchronization is used. The AIS station is used on land borne and ship borne. The ship borne AIS component consists of the AIS station, a PC and ECS/ECDIS display and additionally of an external GNSS receiver plus compass and log. A typical range of the AIS at sea is between 20 to 30 nautical miles depending on the antenna height.

4. THE GNSS IMPLEMENTATION AND VALUE CHAIN

To get a complete picture on human resources and academic education requirements it is additional necessary to get aware of the GNSS implementation and value chain. Latter is sometimes not understood by decision makers in governments, institutions and industry.

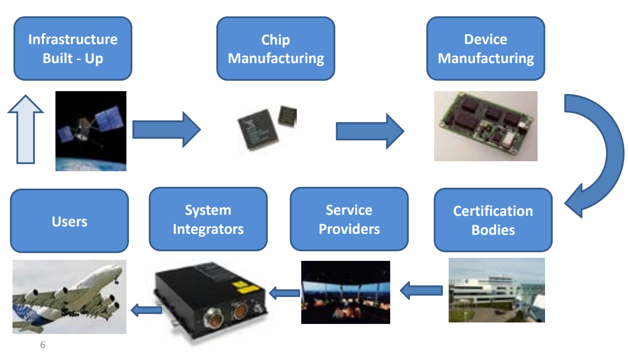

Figure 2: The GNSS value chain

The time scale for the GNSS value chain posed in Figure 2 is of long – term nature and lies between 10 and 15 years. It is a basic problem to have high – quality human resources ready at the different stages of the chain. In the European Galileo development this was not the case. Human resources from other domains were acquired and directed to the European Satellite Navigation programs. These human resources came typically from the telecommunication field, space system domain, and large-scale infrastructure projects in industry and public traffic management. Many staff members and fellow workers at that time were no specialists in satellite navigation. While solving their specific problems they had to build– up their learning – curves. The concept was on the basis "learning – by –doing". Thus it was no surprise that many political, technical and commercial/funding decisions were sub-optimal.

User requirements

In principle the value chain is a closed loop. It starts at the beginning with user requirements. E.g. for aviation GNSS users the so-called required Navigation Performance Parameters (RNPs) are used. In aviation theses requirements formulate the horizontal and vertical accuracy requirements for different phases of flight (en-route, non-precision approach, precision landing), the integrity, availability and continuity requirements.

Infrastructure build – up

The user requirements are mapped to mission, system and sub-system requirements for the satellite navigation system. After this the space and ground infrastructures are developed and produced. Finally the infrastructure and the GNSS have to be validated and verified against the different requirement levels. Typically the process of infrastructure build-up needs several years of time.

Chip manufacturing

The development and manufacturing of GNSS silicon chips starts relatively late in contrary to what might be expected. Usually GNSS chips are developed by public funding, private funding or a mix of both. Because the development of chips and the manufacturing processes for highly integrated semi-conductors is very expensive private companies and investors answer with a certain waiting period or latency on the infrastructure set-up. Private money is only invested if trust is in place for the future of the specific GNSS. Typically, in the case of the Russian GLONASS system in the 1990s western chip manufacturers were very reluctant to invest in combined GPS/GLONASS receivers because of the economic crisis in Russia and the uncertain future of GLONASS. Today the same holds for Galileo in Europe.

Device manufacturing

GNSS chips are integrated on printed circuit boards (PCBs) together with other microprocessors and storage components. The way this integration is performed depends mainly on the specific user groups like aviation receivers, maritime receivers, space receivers and in many different designs for land navigation (car navigation receivers, mobile phones, wearables, etc.).

Certification bodies

In some specific user segments which belong to safety critical navigation the GNSS receivers have to be compatible with many certification standards. Usually governmental institutions like the Federal Aviation Administration (FAA) in the US or the EASA (European Aviation Safety Agency) are necessary to develop all the standards, processes and test procedures to certify e.g. aviation receivers.

Service providers

In some application cases service providers will be involved in the implementation chain. Such service providers build-up their own infrastructure to support GNSS operations. We may think here e.g. on fleet-management centers or differential correction services (DGPS) to enhance the positioning accuracy.

System Integrators

System integrators are necessary to integrate GNSS receivers in avionics systems, bridge equipment of large ships or in car navigation systems together e.g. with electronic maps, dead reckoning sensors, etc.

Users

Last but not least the user comes into play. He is performing his navigation mission by making use of the GNSS infrastructure and the GNSS based navigation systems. This is closing the loop of the value chain. The problem is that since the GNSS development started off with the user requirements usually more than a decade of time has passed. Because of the everlasting innovation cycles the user requirements may have changed after such a long time. This leads to the demand by the users that the user requirements have to be changed or up-dated. Because satellite-life time is on the order of 12 to 15 years it is not instantaneously possible to up-date the space and ground infrastructures. The standard approach to cope with changing user requirements is to work with satellite blocks, e.g. GPS Block I, II/IIA/IIR, III which are modernized from batch to batch.

5. HUMAN RESOURCES AND EDUCATION

The requirements on human resources in GNSS are at least two-fold: On the one hand very specialized engineers are needed; On the other hand the generalists are necessary who are able to understand the system aspects. Decision makers in institutions and industry need special knowledge in technologies, economics and political strategies. Is the current university system able to educate and prepare such generalists? Are specialized master courses for GNSS needed? Are external training courses necessary?

Status of the current GNSS academic education system

Although GPS development started in the 1970s in military programs academic research in GPS is visible since the early 1980s. A pioneering role was taken over by geodesists because they got aware of the high precision potential of the GPS carrier-phase observable. They discovered that centimeter level accuracy may be obtained by processing the recovered carrier-wavelength of 0.2 m. The US National Geodetic Survey (NGS) in Rockville, MD was among the first surveying institutions to assess the use of GPS for precise point positioning. Many European professors joined the NGS for a sabbatical year in the 80s. When coming back to their home universities they were among the first to establish GPS in research and teaching in the European university system. The same happened in continental US, Canada, Japan and Australia. Thus, geodesy and surveying somehow was the first academic discipline which integrated GPS elements in the study courses. Later when aviation, land and maritime aspect came into the scope of GPS other faculties from aerospace engineering and electrical engineering joined this very compact science community. The roots of the early days in GPS in academic GPS research are still visible: Among others the sustained players on university level in the PNT community are Stanford University, Ohio State University, Ohio University, University of Colorado, University of Calgary, University of Nottingham, Technical University Delft, Technical University Graz, University of New South Wales and my own university. These historical core players have been joined by a lot of new university institutes during the last decade. In general the situation at these universities is that teaching in GNSS is integrated in the more classical study courses like e.g. aerospace engineering. GNSS is usually one special teaching area among many others like aircraft design, space systems technology, structural mechanics, etc. As pointed out earlier GNSS has basically an interdisciplinary nature comprising many key technology areas. This leads to the fact that GNSS research and teaching is distributed among all the different faculties involved. Somehow this is a proliferated situation which is not fulfilling the demands on human resources in institutions and industry. Let us take a brief look to the space sector:

In the space sector down-stream market GNSS is with 35% revenue very important (satellite based communication direct broad casting services is 64% and earth-observation 2%). Considering these numbers it is very surprising that some study courses in aerospace engineering completely neglect satellite navigation.

Future looking options in academic training for GNSS

On the human resources side of GNSS a new professional academic is needed: This specialist could be called “GNSS engineer”. Typically after a B.Sc. in one of the key technology areas he should have an interdisciplinary academic training. He should be able to work on the level of system engineering but if it is required also in a special technical field of satellite navigation. As outlined in chapter 2 it is quite straight-forward for insider professors to define a study course and the respective curriculum. The level of such a study course would be a M.Sc. in “Satellite Navigation”. Thus, it could be asked: Where is the problem? Many new master courses are and were established in the classical academic faculties.

Integration of GNSS engineering master course into classical faculties: This concept would be the most direct approach. It would be important to integrate such a satellite navigation master in one of the larger engineering faculties like information technology or electrical engineering. For instance a faculty of geodesy would be too small. The financial issue for such a master course is solved because it would be fully integrated into the university infrastructure. However, the problem could be the awareness of the faculty members on the importance of GNSS. Usually the larger faculties try to cope with highest priority with some megatrends in their discipline like e.g. green energy. A decision process is necessary to appoint specialist professors and the supporting staff for a satellite navigation master. The minimum number of students in such master should be about 30 first-semester students. Although currently there is a high demand on satellite navigation engineers in Europe in none of the big German universities an implementation of such a M.Sc. happened up-to now because believe is that the area of satellite navigation is too special.

Integration of GNSS engineering in classical faculties as an executive master course: A first alternative approach would be to implement a so-called executive master. This master is only partly integrated into a faculty mainly with respect to the curriculum side. The students in this case have already an employment contract in agencies or industry. The executive master consists of presence stages at the university and idle phases where the students are doing their job in industry or agencies. The employer will pay a certain amount of fee to the university to support for the budgetary issue. These fees from employers could be augmented by various ways of sponsoring. The disadvantage for this approach is that the organizational and contractual effort for all parties involved is very high.

Implementation of GNSS international master courses: This concept starts from the assumption that no university on a national level would be able or willing to establish a specialized master course on GNSS by its own. The idea is then to group a certain number of leading professors from different international universities together. An organizing university is providing the infrastructure (curriculum issues, lecturing rooms, board and lodging). The various financial issues like travel expenses for the lecturers have to be solved. This approach requires a contract between the universities involved which is not easy to obtain in the administrations. Alternatively an external funding layer could be used. In Europe an international master [6] was established at ENAC (L'Ecole Nationale de l'Aviation Civile) in Toulouse by funding of the European GNSS Agency (GSA).

External GNSS training courses: This possibility is more or less a standard. The concept is that employees are taking part in timely limited training courses (1 to 3 days) besides their jobs. On worldwide basis a lot of public and private providers offer such courses in the GNSS field. Mentioned should be the ESA Summer School on GNSS.

6. CONCLUSIONS

The importance of GNSS for the modern digital infrastructure is outlined by the following facts: 6-7 % of the European gross product depends on PNT (Positioning Navigation Timing), 5 billion mass market GNSS chips are fielded in civil mobile communication and navigation devices. The number of military GPS receivers in comparison is below 0.5 million units in US plus NATO. The GNSS core market is about 80 billion $ US per year. This is accompanied by an enabled market of 200 billion $ per year (the market which indirectly is using GNSS technology for derived products and services).

The availability of GNSS is taken by the information industry and many service providers as granted: However, several key technology areas had to be mastered since 1950. Launcher systems, satellites and payloads, precise atomic clocks in space including relativistic corrections, precise orbital mechanics, estimation theory and filtering and coordinates reference frames, propagation of electromagnetic waves in the earth atmosphere, very large scale integrated semiconductors, fast signal processing algorithms, powerful signal and microprocessors. For building up the space and ground infrastructures the ability of project management and system engineering is necessary, but also the pioneering of applications and the development of markets and business opportunities.

Thus, a full operational GNSS might be seen as an integral of many interdisciplinary fields: Fundamental sciences (physics, mathematics), engineering sciences (space engineering, electrical engineering, semiconductor development, and computer engineering and software development, geodesy, communication and product engineering), socio economic strategies and evaluation methods.

Unfortunately the implementation of GNSS engineering and related fields in the academic world is not optimal. GNSS does not clearly belong to one of the big technical faculties. Several options for a GNSS related education, e.g. a GNSS M. Sc. are discussed. The best and realistic way to implement a high – quality academic education in GNSS is not easy to see.

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