NAVIGATIONAL SYSTEMS AND SIMULATORS

MARINE NAVIGATION AND SAFETY OF SEA TRANSPORTATION

EDITED BY
ADAM WEINTRIT

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Faculty of Navigation, Gdynia Maritime University

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Contents

Navigational Systems and Simulators. Introduction

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PREFACE

The contents of the book are partitioned into six parts: global navigation satellite systems (covering the chapters 1 through 5), positioning systems (covering the chapters 6 through 11), navigational simulators (covering the chapters 12 through 20), radar and navigational equipments (covering the chapters 21 through 24), ship handling and ship manoeuvring (covering the chapters 25 through 26), search and rescue operations (covering the chapters 27 through 28).

The first part deals with global navigation satellite systems (GNSS). Certainly, this subject may be seen from different perspectives. The contents of the first part are partitioned into five chapters: A look at the development of GNSS capabilities over the next 10 years, GNSS meteorology, Onboard wave sensing with velocity information GPS, EGNOS performance improvement in Southern latitudes, and An integrated vessel tracking system by using AIS, Inmarsat and China Beidou Navigation Satellite System.

The second part deals with positioning systems. The principles of position, course and velocity determination are treated; radionavigation and terrestrial methods are presented. The contents of the second part are partitioned into six chapters: Recent advances in wide area real-time precise positioning, Assessing the limits of e-Loran positioning accuracy, Fuzzy evidence in terrestrial navigation, Ground-based, hyperbolic radiolocation system with spread spectrum signal – AEGIR, An algorithmic study on positioning and directional system by free gyros, and Compensation of magnetic compass deviation at one any course.

The third part deals with navigational simulators. Different kinds of navigational and manoeuvring simulators and simulating methods are presented. The contents of the third part are partitioned into nine chapters: New level of integrated simulation interfacing ship handling simulator with safety and security trainer (SST), Path following problem for a DP ship simulation model, Simulating method of ship’s turning-basins designing, Capabilities of ship handling simulators to simulate shallow water, bank and canal effects, Development of a costs simulator to assess new maritime trade routes, Analogical manoeuvring simulator with remote pilot control for port design and operation improvement, Simulation model for detecting vessel conflicts within a seaport, Research on ship navigation in numerical simulation of weather and ocean in a bay, and A methodological framework for evaluating maritime simulation.

The fourth part deals with radar and navigational equipments. The contents of the fourth part are partitioned into four chapters: Impact of internal and external interferences on the performance of a FMCW radar, Fusion of data received from AIS and FMCW and pulse radar - results of performance tests conducted using hydrographical vessels “Tukana” and “Zodiak”, Statistical analysis of simulated radar target's movement for the needs of multiple model tracking filter, and The modes of radar presentation of situation in inland navigation.

The fifth part deals with ship handling and ship manoeuvring. The contents of the fifth part are partitioned into two chapters: Multirole population of automated helmsmen in neuroevolutionary ship handling, and Ship's turning in the navigational practice.

The sixth part deals with search and rescue operations. The contents of the sixth part are partitioned into two chapters: Iridium a more effective proposal for the localization, search and rescue in the sea, and Research on the risk assessment of man overboard in the performance of Flag Vessel Fleet (FVF).

This book completes the body of the books series with outlook into the future of navigation and is mainly concerned with the scheduled provision of radio navigation systems, including GNSS in the near and medium-term future.

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Global Navigation Satellite System

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1. A Look at the Development of GNSS Capabilities Over the Next 10 Years

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ABSTRACT: This paper considers what the SNS (Satellite Navigation Systems) as GPS, GLONASS, Galileo and Compass, and SBAS (Satellite Based Navigation Systems) as EGNOS, WAAS, MSAS and GAGAN services might look like 10 years from now. All these systems, called GNSS (Global Satellite Navigation System), are undergoing construction or modernization (new satellites, new frequencies, new signals, new monitoring stations, etc.) and continuous improvement to increase its accuracy, availability, integrity, and resistance to interference. The most significant events in SNS and SBAS in the nearest 10 years are presented also. Additionally three possible scenarios considering these systems (in 2016 and 2021 years), concerning the number of satellites in particular, optimistic, pessimistic and the most probable were taken into account.

1 INTRODUCTION

Nowadays (January 2011) the American GPS Satellite Navigation System (SNS) is fully operational with 31 satellites. Since few years the Russian GLONASS system was being revamped and undergoing an extensive modernization effort, therefore today this system with 21 satellites can be used for fix position also. Galileo system (Europa) and Compass system (China) are under construction, must likely these systems will be operating at the earliest in 2016 and 2021 adequately.

The Satellite Based Augmentation Systems (SBAS) that enhance the integrity, accuracy, and operation of two SNS – GPS and GLONASS. Today the SBAS as Wide Area Augmentation System (WAAS), Multi-functional Transport Satellite Based Augmentation System (MSAS) and European Geostationary Navigation Overlay System (EGNOS) are accessible in USA and Canada, Japan and Europe and North Africa adequately. While WAAS and MSAS are fully operational since few years, EGNOS officially entered into operational phase with the provision of the Open Service as of only October 1, 2009. Additionally the Department of Defense of the United States is cooperating with India to develop new system over Indian space. This is the GAGAN (GPS and Geo Augmented Navigation), new SBAS, actually under construction. Other SBAS will enhance GLONASS and GPS systems, called SDCM (System for Differential Correction and Monitoring), is under construction in Russia. All these SNS and SBAS create Global Navigation Satellite System (GNSS). System Compass was nottaken into account in this paper, because about this system little information is available still.

2 SATELLITE NAVIGATION SYSTEMS CONSTELLATION

Actually (January 2011) GPS spatial segment consists of 32 satellites, 11 the oldest block IIa, 12 block IIR, 8 block IIR–M and 1 block IIF (Table 1) [www.navcen.uscg.gov]. Additionally in this table we can find the information about active life of each satellite in years and months. The value of this life depends on the system and satellite block. The mean values of these satellites life of block IIA, IIR and IIR–M are equal 16.3, 8.9 and 3.2 years adequately. It means that the active life of all satellites of block IIA is greater than nominal value 10 years, considerably. The satellites IIA and IIR transmit one frequency (L1) for civil users only, IIR–M two frequencies (L1, L2), IIF and the future III three (L1, L2, L5). Information about integrity will provide the satellites block III only [Gleason S., Gebre-Egziabher D. 2009] and [Hofmann-Wellenhof B. et all. 2008].

The GLONASS spatial segment consists of 21 satellites, all block M (Table 2), which transmit two frequencies for civil users (L1, L2), but without information about integrity [www.glonass-ianc.rsa.ru]. This information and the third frequency will be provided by the satellites next generation K. The Galileo spatial segment consists of 2 satellites only, 27 operational and 3 active spheres in the future. The satellites will transmit four frequencies.

The accuracy of the user's position obtained from the SNS depends on a number of satellites (ls) visible above masking angle. That's why the total number of satellites, fully operational especially, is very interesting for the users. There is no direct relation between the number ls and the position error M, but for all SNS in the case of position fix in restricted area we can say the following "when ls greater, M is less" and inversely "when ls is less, M is greater" [Januszewski J. 2008].

3 THE MOST SIGNIFICANT EVENTS IN THE GNSS IN THE NEAREST 10 YEARS

The most significant events in the SNS and SBAS waited in optimistic scenario into 10 nearest years (2012–2021) with the consequences for the civil users are presented in Table 3. One of the parameters mentioned in this table is the number of frequencies transmitted by the satellites of each SNS. Because of two or three frequencies make possible the calculation of ionosphere correction, the user's position accuracy increases. Unlike actual generation of GPS and GLONASS systems next generation of these systems, GPS III and GLONASS K, and new system Galileo will provide integrity information. Integrity can be defined as a reliability indicator of the quality of positioning, user's position obtained from SNS also [Januszewski J. 2009].

EGNOS has claimed that they will eventually transmit integrity information for users of GPS and GLONASS systems as well as for Galileo system.

Between 2008 and 2013, the FAA (Federal Aviation Administration) will make the necessary changes in the ground equipment of WAAS to handle the L5 signal from GPS. Having two frequencies for ionospheric corrections will eliminate loss of vertical guidance caused by ionospheric storms.

Japan has had a plan to display a new regional system called the Quasi–Zenith Satellite System (QZSS), which services include enhanced accuracy GPS signals, communications and broadcasting.

The GPS and GLONASS systems are undergoing uninterrupted modernization (new satellites, new frequencies, new signals, new codes, new monitoring stations, etc.) and continuous improvement to increase its accuracy (position in particular), availability, integrity, and resistance to interference, while at same time maintaining at least the performance it enjoys today with existing already user's receivers [Januszewski J. 2010] and [Springer T., Dach R. 2010]. In the case of the GPS system the plans of the control segment modernization are well known. The next Generation GPS Control Segment (OCX) will provide significant benefits to all users around the world, as well as to GPS operators, mainters, and analysts. Two major upgrades are in development; the Legacy Accuracy Improvement Initiative (L-AII) and the Architecture Evolution Plan (AEP). The L-AII upgrade adds up to 14, actually 11 only, National Geospatial Intelligence Agency (NGA) monitor stations [Kaplan E.D., Hegarty C.J. 2006], [Gower A. 2008].

United States Air Force officials are moving to reconfigure the GPS constellation to create as soon as possible a 27 satellites geometry that will improve the availability and accuracy of positioning, navigation, and timing capabilities, in particular for U.S. military forces [Roper E. 2010].

A third civil signal at the GLONASS L3 frequency will be on newer GLONASS K satellites, probably starting in 2011 (Table 3).

The first two in–orbit validation (IOV) Galileo satellites are scheduled for launch 2011, followed by two more in next year.

4 THE POSSIBLE SCENARIOS AFFECTING THE DEVELOPMENT OF GNSS

Three possible scenarios considering three SNS, the GPS, GLONASS and Galileo, and SBAS in 2016 and 2021 years, optimistic, pessimistic and the most probable were taken into account [Lavrakas J.W. 2007]. The projected total number of satellites, number of satellites transmitting signals for civil users on two and three frequencies and information about integrity for GPS, GLONASS and Galileo for each mentioned above scenario are presented in the author's Table 4.

4.1 *Optimistic scenario*

In this scenario every project meets its projected dates. In the case of GPS system the following assumptions are made for 2016 year:

- all 12 Block IIF and 4 Block III satellites were launched,
- as in 2011 the satellites IIA launched in 1992 or earlier are fully operational still, we can expect that in 2016 years the vitality of all satellites on orbit will be also 20 years.

In this situation we have in GPS satellites:

- 12 Block IIFs ranging from 0 to 6 years old,
- 8 Block IIR–Ms ranging from 7 to 11 years old,
- 12 Block IIRs ranging from 12 to 18 years old,
- 4 Block IIAs ranging from 19 to 20 years old,
- 4 Block IIIs ranging from 0 to 2 years old.

It means that the GPS spatial segment will consist of 40 satellites. As this number is greater than 32 (nominal value), 8 oldest satellites will be able to be not used. In 2016 year two other SNS the GLONASS and Galileo systems are operational with

24 satellites M and few satellites K, and at least 18 satellites adequately.

In this scenario for 2021 year all three systems GPS, GLONASS and Galileo are fully operational, all satellites of these systems transmit at least three frequencies accessible for civil users and the signals contain the integrity information. The GPS spatial segment will consist of at least 24 satellites of Block III, 12 satellites of Block IIF and perhaps all satellites of Block IIR–M and few of Block IIR. The spatial segments of GLONASS and Galileo will consist of 30 satellites of new Block K and 30 adequately.

In this optimistic scenario, already in 2016 year, all present-day SBAS, and GAGAN and QZSS also, will be fully operational, and perhaps in 2021 year other new systems (e.g. in Africa and in South America) additionally.

4.2 *Pessimistic scenario*

In this scenario no project is not realized according to earlier plan. In the case of GPS system the following assumptions are made for 2016 year:

- 8 Block IIF satellites were launched only,
- the block III did not begin,
- the vitality of all satellites on orbit are at most equal nominal. It means that the satellites of Block IIR and earlier are out of service.

In this situation we have in satellites: 8 Block IIFs ranging from 0 to 6 years old and 8 Block IIR–Ms ranging from 7 to 11 years old, that is to say 16 satellites only. It means that user's position cannot be obtained at any point on Earth and at any moment.

In 2016 year the number of Galileo satellites fully operational is less than planned 18, therefore this system is still under construction. The number of GLONASS satellites, all kind M, is less than 24 again. The works over the next satellite generation K continually last.

In scenario for 2021 year GPS spatial segment will consist at most of 12 satellites of Block IIF and few satellites of Block III only. As the vitality of all GPS satellites are at most equal nominal, the satellites of Block IIR–M and earlier are already out of service. The GLONASS spatial segment will consist at most of 24 satellites M and few satellites K only. The date of FOC (Full Operational Capability) of Galileo system continually lengthens, the number of satellites is less than nominal 27 still.

In this pessimistic scenario in 2016 and 2021 years EGNOS, WAAS and MSAS are fully operational, but without additional geostationary satellites. GAGAN and QZSS are under construction still.

4.3 *The most probable scenario*

All systems are undergoing modernization or construction, but time-limits are not kept.

The last launch of GPS IIF satellite and the first launch of GPS III satellite will be not in 2014 years, but several years later. The vitality of GPS satellites is continually the same as at present, for the most satellites greater than nominal. In this situation in 2016 year we have in satellites: at most 10 Block IIRs ranging from 12 to 16 years old, 8 Block IIR–Ms ranging 7 to 11 years old and 12 Block IIFs ranging from 0 to 6 years old. The construction of Galileo system became finished, but the number of satellites is 18 only. The spatial segment of the GLONASS system consists of 24 satellites M only.

In this scenario in 2021 year we have in GPS satellites: 12 Block IIIs ranging from 0 to 5 years old, 12 Block IIF ranging from 5 to 11 years old and about 8 Block IIR–Ms ranging from 12 to 16 years old. The Galileo system with the number of satellite between 27 and 30 is fully operational. The GLONASS system will consist of about 30 satellites M and K, in the most of the block M.

In the most probable scenario GAGAN and QZSS systems will be fully operational before 2016 year, but in 2021 year other new SBAS will be under construction or on the stage projects.

5 CONCLUSIONS

- in the case of GPS system the kind of scenario will depend on vitality of his satellites, of Block IIR–M in particular. If this vitality will be equal a dozen or so years, as in earlier blocks, scenario will be optimistic,
- in the case of the GLONASS and Galileo systems the kind of scenario will depend on time-limit of the implementation of all improvements,
- in optimistic scenario in 2021 GPS, GLONASS and Galileo systems offer full service on all 32, 24 and 27 satellites, adequately and information about integrity; five years earlier integrity provides the Galileo system only,
- in pessimistic scenario in 2021 one only SNS, the GLONASS system, offers full service, the number of GPS satellites is less than nominal 24, the Galileo system is under construction still; five years earlier all these three SNSs are not fully operational,
- in the most probable scenario in 2021 all three SNSs are fully operational, but in each system information about integrity can be obtained only from the part of his satellites; five years earlier this information is provided by the part of GPS and Galileo satellites only.

REFERENCES

Gleason S., Gebre-Egziabher D. 2009. GNSS Applications and Methods, Artech House, Boston/London.

Gower A. 2008. The System: The Promise of OCX, GPS World, No 8, vol.19.

Hofmann-Wellenhof B. et all. 2008. GNSS–Global Navigation Satellite Systems GPS, GLONASS, Galileo & more, SpringerWienNewYork, Wien.

Januszewski J. 2010. Visibility and geometry of combined constellations GPS with health in question, GLONASS and Galileo, p. 1082−1094, Institute of Navigation, International Technical Meeting, San Diego (CA).

Januszewski J. 2009. Satellite navigation systems integrity today and in the future, Monograph “Advances in Transport Systems Telematics”, p. 123−132, Edited by Jerzy Mikulski, Wydawnictwa Komunikacji i Łączności, Warszawa.

Januszewski J. 2010. Nawigacyjny system satelitarny GPS dzisiaj i w przyszłości, p. 17–29, Prace Wydziału Nawigacyjnego nr 24, Akademia Morska, Gdynia (in polish).

Kaplan E.D. & Hegarty C.J. 2006. Understanding GPS Principles and Applications, Artech House, Boston/London.

Lavrakas J.W. 2007. A Glimpse into the Future: A Look at GNSS in the Year 2017, p. 210−217, Institute of Navigation, National Technical Meeting, San Diego (CA).

Roper E. 2010. GPS Status and Modernization, Munich Satellite Navigation Summit, Munich.

Springer T., Dach R. 2010. GPS, GLONASS, and More Multiple Constellation Processing in the International GNSS Service, GPS World, No 6, vol.21.

www.glonass-ianc.rsa.ru

www.navcen.uscg.gov

Table 1. GPS System, PRN – Pseudorandom noise number, SVN – Space Vehicle Number, launch and input dates, active life and mean active life in years and months of all 32 satellites in January 21, 2011

Block	PRN	SVN	Launch date	Input date	Active life		Mean active life	
					years	months	years	months
IIA–10	32	23	26.11.1990	10.12.1990	16	0.8	16	3.1
IIA–11	24	24	04.07.1991	30.08.1991	19	1.3		
IIA–14	26	26	07.07.1992	23.07.1992	18	5.8		
IIA–15	27	27	09.09.1992	30.09.1992	18	3.2		
IIA–21	9	39	26.06.1993	20.07.1993	17	4.8		
IIA–23	4	34	26.10.1993	22.11.1993	17	2.0		
IIA–24	6	36	10.03.1994	28.03.1994	16	9.0		
IIA–25	3	33	28.03.1996	09.04.1996	14	8.1		
IIA–26	10	40	16.07.1996	15.08.1996	14	4.4		
IIA–27	30	30	12.09.1996	01.10.1996	14	2.8		
IIA–28	08	38	06.11.1997	18.12.1997	13	0.2		
IIR–2	13	43	23.07.1997	31.01.1998	12	11.6	8	11.0
IIR–3	11	46	07.10.1999	03.01.2000	11	0.6		
IIR–4	20	51	11.05.2000	01.06.2000	10	7.5		
IIR–5	28	44	16.07.2000	17.08.2000	10	5.2		
IIR–6	14	41	10.11.2000	10.12.2000	10	1.3		
IIR–7	18	54	30.01.2001	15.02.2001	9	11.1		
IIR–8	16	56	29.01.2003	18.02.2003	7	10.9		
IIR–9	21	45	31.03.2003	12.04.2003	7	7.2		
IIR–10	22	47	21.12.2003	12.01.2004	7	0.3		
IIR–11	19	59	20.03.2004	05.04.2004	6	9.5		
IIR–12	23	60	23.06.2004	09.07.2004	6	6.3		
IIR–13	2	61	06.11.2004	22.11.2004	6	1.9		
IIR–14M	17	53	26.09.2005	13.11.2005	5	1.1	3	1.8
IIR–15M	31	52	25.09.2006	13.10.2006	4	3.3		
IIR–16M	12	58	17.11.2006	13.12.2006	4	1.1		
IIR–17M	15	55	17.10.2007	31.10.2007	3	2.7		
IIR–18M	29	57	20.12.2007	02.01.2008	3	0.6		
IIR–19M	7	48	15.03.2008	24.03.2008	2	9.9		
IIR–20M	1	49	24.03.2009	in commissioning phase				
IIR–21M	5	50	17.08.2009	27.08.2009	1	4.8		
IIF–1	25	62	28.05.2010	27.08.2010	0	4.8	0	4.8

Table 2 GLONASS System, orbit/slot, frequency channel, GLONASS number, launch and input dates, active life and mean active life in years and months of all 21satellites in January 21, 2011

Orbit / slot	Frequency channel	GLONASS number	Launch date	Input date	Life time years	Life time months	Mean life time years	Mean life time months
I / 1	01	730	14.12.2009	30.01.2010	1	1.2		
I / 2	– 4	728	25.12.2008	20.01.2009	2	0.9		
I / 3		satellite 727 in maintenance						
I / 4		without satellite						
I / 5	01	734	14.12.2009	10.01.2010	1	1.2		
I / 6	– 4	733	14.12.2009	24.01.2010	1	1.2		
I / 7	05	712	26.12.2004	07.10.2005	6	0.9		
I / 8	06	729	25.12.2008	12.02.2009	2	0.9		
II / 9	– 2	736	02.09.2010	04.10.2010	0	4.6		
II / 10	– 7	717	25.12.2006	03.04.2007	4	0.9		
II / 11	00	723	25.12.2007	22.01.2008	3	0.9		
II / 12	– 1	737	02.09.2010	04.10.2010	0	4.6	2	2.2
II / 13	– 2	721	25.12.2007	08.02.2008	3	0.9		
II / 14 [x1]	– 7	722	25.12.2007	25.01.2008	3	0.9		
II / 15	00	716	25.12.2006	12.10.2007	4	0.9		
II / 16	– 1	738	02.09.2010	04.10.2010	0	4.6		
III / 17		satellites 714 and 728 in maintenance						
III / 18	–3	724	25.09.2008	26.10.2008	2	3.9		
III / 19	03	720	26.10.2007	25.11.2007	3	2.9		
III / 20	02	719	26.10.2007	27.11.2007	3	2.9		
III / 21	04	725	25.09.2008	05.11.2008	2	3.9		
III / 22 [x2]	-3	731	02.03.2010	28.03.2010	0	10.7		
III / 23	03	732	02.03.2010	28.03.2010	0	10.7		
III / 24	02	735	02.03.2010	28.03.2010	0	10.7		

[x1] – additional satellite 715 in maintenance, [x2] – additional satellite 726 in maintenance

Table 3. The most significant events in the satellite navigation systems and satellite based augmentation systems in the nearest 10 years and their consequences for users

Year	Event	Consequences for users
2010	three GLONASS M satellites crashed into Pacific Ocean after a failed launch first launch of QZSS spacecraft Michibiki additional launches of Compass satellites	Full Operational Capability of GLONASS system cannot be obtained for the first time in history the signal L1C is transmitted in space new GEO, IGSO and MEO satellites of China's system
2011	24 GLONASS M satellites all GAGAN satellites on geostationary orbit the first launch of GLONASS K satellite	two SNS systems (GLONASS and GPS) fully operational GAGAN – Indian SBAS fully operational the beginning of the new generation of GLONASS satellite the first use of code division multiple access CDMA
2012	third SDCM satellite on geostationary orbit	SDCM – Russian SBAS fully operational
2013	WAAS – two frequencies (L1 and L5) for ionospheric corrections	elimination of vertical guidance caused by ionospheric storms
2014	the first launch of GPS III A satellite	the beginning of the third generation of GPS system
2015	Full Operational Capability of the next Generation GPS Control Segment (OCX) Galileo constellation with 18 satellites (4 IOV and 14 fully operational)	continuous L-band tracking coverage of the GPS constellation additional features and functionality of control segment (CS) for the first time in history, integrity information about SNS for the users of the all the world, Initial Operational Capability (IOC)
2016	24 GPS satellites transmitting L2C	full access to two civil frequencies
2018	24 GPS satellites transmitting L5 Galileo constellation 27–30 satellites	full access to three civil frequencies full access to all signals and services, Full Operational Capability (FOC)
2019	30 GLONASS K satellites	full access to three civil frequencies, integrity information about system
2020	35 Compass satellites fully operational (5 GEO, 27 MEO and 3 IGSO)	full access to all signals and services
2021	24 GPS satellites block III transmitting L1C	full access to new block III, integrity information and new signal L1C

Table 4. The projected total number of satellites, number of satellites transmitting signals for civil users on two and three frequencies and information about integrity for different satellite navigation systems and for different scenarios in 2016 and 2021 years

Year	Scenario	System	Number of satellites			Integrity
			total	with two frequencies	with three frequencies	of the system
2016	optimistic	GPS	40	24	16	non
		GLONASS	at least 24	at least 24	several	non
		Galileo	at least 18	at least 18	at least 18	yes
		Total	at least 82	at least 66	at least 40	–
	pessimistic	GPS	16	8	8	non
		GLONASS	less than 24	less than 24	0	non
		Galileo	less than 18	less than 18	less than 18	non
		Total	less than 58	less than 50	less 26	–
	the most probable	GPS	at most 30	at most 20	12	non
		GLONASS	24	24	0	non
		Galileo	18	18	18	yes
		Total	at most 72	at most 62	30	–
2021	optimistic	GPS	at least 44	at least 44	24	yes
		GLONASS	30	30	30	yes
		Galileo	30	30	30	yes
		Total	at least 104	at least 104	84	–
	pessimistic	GPS	a dozen or so	a dozen or so	a dozen or so	non
		GLONASS	at most twenty several	at most 24	several	non
		Galileo	less than 27	less than 27	less than 27	non
		Total	about 65	about 60	about 45	–
	the most probable	GPS	about 32	about 32	24	non
		GLONASS	about 30	a dozen or so	a dozen or so	non
		Galileo	27 ÷ 30	27 ÷ 30	27 ÷ 30	yes
		Total	about 89 ÷ 92	about 73 ÷ 79	about 63 ÷ 72	–

2. GNSS Meteorology

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ABSTRACT: GNSS meteorology is the remote sensing of the atmosphere (troposphere) using Global Navigation Satellite Systems (GNSS) to derive information about its state. The most interesting information is a delay of the signal propagation due to the water vapor content - the Slant Wet Delay (SWD). The inverse modeling technique being concern here is the tomography. It is the transformation of the slant integrated observation of state of the atmosphere (SWD), to the three dimensional distribution of the water vapor. Over past six years the studies on GNSS tomography were performed in the Wroclaw University of Environmental and Life Sciences on the GNSS tomography. Since 2008 the new national permanent GNSS network ASG-EUPOS (about 130 GNSS reference stations) has been established in Poland (www.asgeupos.pl). This paper presents the issues of the Near Real Time troposphere model construction, characteristic of GNSS and meteorological data and the building of the required IT infrastructure.

1 INTRODUCTION

Global Navigation Satellite System is designed for positioning, navigation, amongst other possible applications it can also be used to derive information about the state of the atmosphere, what is now recognized as GNSS meteorology. Particularly GNSS meteorology is the remote sensing of the atmosphere from satellite platform (GNSS radio occultation meteorology) (Pavelyev et al. 2010) and ground permanent stations (ground based GNSS meteorology) (Bender et al. 2010). Continuous observations from GNSS receivers provide an excellent tool for studying the earth atmosphere. There are many GNSS meteorology applications: climatology, nowcasting and 4D monitoring.

The ground based GNSS meteorology is based on the tropospheric delay, one of the results of GNSS data processing . The tropospheric delay is represented by the Zenith Total Delay *ZTD*. The *ZTD* can be split into hydrostatic *ZHD* and wet *ZWD* component of the delay:

$$ZTD = ZHD + ZWD \tag{1}$$

The wet component of Zenith Tropospheric Delay *ZWD* is the foundation for computing of water vapor content in the atmosphere. The relation between *ZWD* and the water vapor content in atmosphere is expressed by *IWV* (Integrated Water Vapor) and given by the equation (Kleijer 2004):

$$IWV = \frac{ZWD}{10^{-6} \cdot R_w}\left(k_2' + \frac{k_3}{T_M}\right)^{-1} \tag{2}$$

where R_w is the specific gas constant for water vapor, k'_2, k_3 are refraction constants (Boudouris 1963) and T_M is weighted mean water vapor temperature of the atmosphere (Kleijer 2004).

The IPWV (Integrated Precipitable Water Vapor) is computed IPWV according to relation:

$$IPWV = \frac{IWV}{\rho_w} \tag{3}$$

where ρ_w is the water density (Mendes 1999).

The *IPWV* is delivered according to equations (2 and 3) from *ZWD* and gives the information about contents of water vapor (2D model) above GNSS stations. The EUREF Permanent Network (EPN: www.epncb.oma.be) is the base of determination of IPWV in Europe (Vedel and Huang 2004). Since 2005 EPN analysis centres ASI, BKG, GOP and LPT delivers Near Real Time *ZTD* for meteorological applications in the frame of international project E-GVAP (EUMETNET GPS Water Vapour Programme) (Dousa 2010).

The spatial structure and temporal behavior of the water vapor in the troposphere (4D model) can be modeled by using the GNSS tomography method. The input data of GNSS tomography are: the signal Slant Wet Delays SWD, which are the results of the

GNSS data processing, the meteorological observations from synoptic stations and the Numerical Weather Prediction (NWP) models data. The NWP models data are also used for GNSS data verification and calibration of the tomography model (Rohm and Bosy 2010). The STD can be separated like (1) into hydrostatic SHD and wet SWD components and represented by the well known relation:

$$STD = SHD + SWD = m_d(\varepsilon)ZHD + m_w(\varepsilon)ZWD \quad (4)$$

where ε is the satellite elevation angle and $m_d(\varepsilon)$ and $m_w(\varepsilon)$ are the mapping functions (Niell 1996; Boehm et al. 2006).

In the GNSS tomography *SWD* extracted from (4) is linked with the wet refractivity N_w by the given equation:

$$SWD = A \cdot N_w \quad (5)$$

where *A* is the design matrix.

Currently several methods exist to solve the GNSS tomography model. The first is to add horizontal and vertical constraints into the system of equations (5) and then solve it (Hirahara 2000), the second is to use a Kalman filter with the same equation system (Flores et al. 2000), the third is to find the solution directly from the GNSS phase measurement equation (Nilsson and Gradinarsky 2006) and another is Algebraic Reconstruction Technique (ART) developed by Kaczmarz (Bender et al. 2009). The method presented in this paper uses the minimum constraint conditions imposed on the system of observation equations (5) (Rohm and Bosy 2009; Rohm and Bosy 2010).

The wet refractivity N_w is estimated from equation (5) and finally the water vapour distribution in the troposphere (4D) represented by the water vapour partial pressure *e* and the temperature *T* is extracted from the formula:

$$N_w = \left(k_2' \frac{e}{T} + k_3 \frac{e}{T^2}\right) Z_v^{-1} \quad (6)$$

where Z_v^{-1} is an inverse empirical compressibility factor (Owens 1967).

The new Polish national permanent GNSS network (Ground Base Augmentation System) ASG-EUPOS has been established since 2008. 17 Polish stations equipped with GNSS receivers and uniform meteorological sensors work currently in the frame of the European Permanent Network (Bosy et al. 2007; Bosy et al. 2008). The ASG-EUPOS network consists (including foreign stations) of about 130 GNSS reference stations located evenly on the country area and build network of greater density than EPN network. This guarantees that the 4D troposphere delay and water vapor models will be more representative for the territory of Poland.

Since 2010 the idea of integrated researches based on the GNSS and meteorological observations from ASG-EUPOS stations is realized in the frame of research project entitled *Near Real Time atmosphere model based on the GNSS and the meteorological data from the ASG-EUPOS reference stations on the territory of Poland*. The paper presents in the second section the methodology of NRT atmosphere models construction procedures. The second section encloses proposal of the method of water vapor distribution in space and time (4DWVD) using GNSS tomography technique. The third section includes the ASGEUPOS system description and sources of GNSS and meteorological data, localization and accuracies. The fourth section contains the specification of IT infrastructure for NRT data streaming and processing. The paper is closed in fifth section with conclusions.

2 NEAR REAL TIME ATMOSPHERE MODEL

The GNSS and meteorological observations form ASG-EUPOS stations are the base of near real time models of tropospheric delay and water vapor (NRT ZTD and NRT ZWD) in atmosphere. Figure 1 shows the diagram of NRT ZTD and NRT ZWD models construction (Bosy et al. 2010).

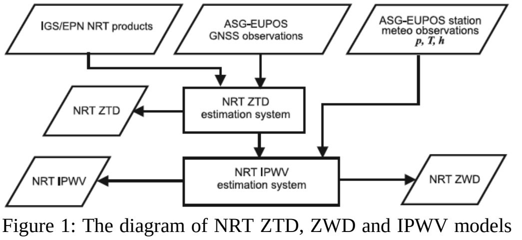

Figure 1: The diagram of NRT ZTD, ZWD and IPWV models construction on the base of GNSS and meteorological data from ASG-EUPOS reference stations

The NRT ZTD will be obtained from the NRT solution of ASG-EUPOS stations network. The strategy of NRT solution will be realized according to standards used for global IGS and regional EPN permanent GNSS networks and NRT solution strategy created in the frame of COST Action 716 (European Cooperation in the field of Scientific Technical Research-exploitation of ground-based GPS for climate and numerical weather prediction applications, 1998-2004), TOUGH (Targeting Optimal Use of GPS Humidity Data in Meteorology, *http://tough.dmi.dk/*, 2003-2006) and E-GVAP (The EUMETNET GPS Water Vapour Programme, *http://egvap.dmi.dk*, 2004-2008) projects (Dousa 2004; Dousa 2010). The ZHD for all ASG-EUPOS stations will be estimated in NRT mode on the base of meteorological observation of Polish EPN stations equipped with meteorological sensors. Next according to relation (1) the values of ZWD will be computed. The IWV and IPWV values above all