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Nominal and Real Accuracy of the GPS Position Indicated by Different Maritime Receivers in Different Modes

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ABSTRACT: Nowadays on the ship's bridge two or even more GPS receivers are installed. As in the major cases the coordinates of the position obtained from these receivers differ the following questions can be posed – what is the cause of this divergence, which receiver in the first must be taken into account etc. Based on information published in annual GPS and GNSS receiver survey it was estimated the percentage of GPS receivers designed for marine and/or navigation users. The measurements of GPS position based on the four different stationary GPS receivers were realized in the laboratory of Gdynia Maritime University in Poland in the summer 2012. The coordinates of the position of all these receivers were registered at the same time. The measurements in mode 3D were made for different input data, the same for all receivers. The distances between the individual unit's antenna were considered also. Next measurements in mode 3D also were realized on two ships in different European ports. Additional measurements were made in mode 2D with three receivers for different their's antenna heights. The results showed that the GPS position accuracy depends on the type of the receiver and its technical parameters particularly.

1 INTRODUCTION

An uninterrupted information about the ship's position is one of the most important elements of the safety of navigation in the sea transport in restricted and coastal areas, recommended by International Maritime Organization – IMO (imo.org). The information about user's position is obtained generally from specialized electronic position–fixing systems, in particular, satellite navigation systems (SNS) as the American GPS system (Januszewski J. 2010, Hofmann-Wellenhof B. et al. 2008, Kaplan, E.D. & Hegarty, C.J. 2006). Nowadays (March 2014) this system is fully operational with very robust constellation 31 satellites (www.gpsworld.com).

For marine and navigation users GPS position fix can be obtained in 2D or 3D mode, that includes only horizontal coordinates (no GPS elevation) or horizontal coordinates plus elevation and requires a minimum at three or four visible satellites, respectively. In mode 2D the user must manually introduce the real value of antenna height (above geoide – sea level).

Information on several hundred GPS receivers designed for marine and/or navigation users and position accuracy which can be obtained can be found in annual receiver survey published in GPS World.

On each ship's bridge one GPS stationary receiver is installed at least but on many ships there are two or even more GPS receivers. As in the major cases the coordinates of the position obtained from these receivers differ the following questions can be posed:
- what is the cause of this divergence ?

- which receiver in the first must be taken into account and why ?
- which input data has the biggest influence on position's accuracy ?

2 GPS RECEIVER SURVEY

The most known and at the same time the most comprehensive GPS and GNSS receiver survey is published each January in GPS World monthly (gpsworld.com). The survey 2014 provides the information on 380 receivers from 47 manufacturers. These receivers are designed for 15 different kinds of user environment and applications. In the table 1 it was showed the number of receivers for marine, navigation and both marine and navigation. More than 80% of these receivers can be used in marine or/and navigation applications.

About each receiver the reader can find information on 19 parameters, among them information concerning position:

- autonomous (code),
- real-time differential (code),
- real-time kinematic,
- post-processed, or
- note: na – not applicable (in the case of some models of Hemisphere, Rockwell Collins and Trimble manufacturers), or
- lack of information, e.g. all models Furuno manufacturer, or
- note: data available upon request (e.g. Interstate Electronics Corporation).

Table 1. The number of GPS receivers designed for marine and navigation user environment and applications.

User	Number of receivers	Percentage
Marine	10	2.6
Navigation	53	13.9
Marine and navigation	246	64.7
Total	309	81.2

Depending on the manufacturer and the receiver it can be given the first value among mentioned above, the first two, three or the most frequently cases the first four.

For marine and land navigation users with the receivers L1, C/A, the most important is the first magnitude, position accuracy, and in the case of DGPS receiver second also. The first magnitude is given always in meters, as precise value (e.g. 2.5), as value bracket (e.g. 2 –3) or as approximated value (e.g. ≈ 5).

Some manufacturers add information about given values, e.g. CEP (Circular Error Probable), RMS (Root Mean Square) or confidence level in percentage, e.g. 95%, but most receivers is without. In all these cases we must suppose that given meters concern horizontal accuracy with 95% confidence level. The greatest (1.2 m) and the smallest (10 m) accuracy provide the models OEM (NovAtel manufacturer) and the models SIRP (CSR manufacturer), respectively. Position autonomous (code) information about accuracy for several dozen selected receivers designed for marine and/or navigation users is showed in the table 2 (gpsworld.com).

3 GPS POSITION IN DIFFERENT MODES

The GPS position fix can be obtained in mode 2D or 3D, the choice made by the user was possible first of all in the case of professional GPS receivers produced in 1990s when the number of fully operational satellites was 24 sometimes one or two more. With then constellation the damage or failure of two and sometimes one satellite only can signify the increase of DOP coefficient value considerable. At that time the solution was the choice of mode 2D.

The current values of HDOP, VDOP (in mode 3D only) coefficients were indicated by almost all receivers, PDOP or GDOP coefficients rarely.

As nowadays the number of GPS satellites is 30 or 31 always the number of satellites visible by receiver's antenna above masking angle $H_{min} = 5^{O}$ or even 10^{O} is at any moment and at any point on the Earth greater than minimal number 4 considerably. Therefore the currently produced GPS receivers (e.g. MX 512 Simrad) determine position in 3D mode only.

In the case of some receivers, as Furuno GP33, if the number of satellites which can be used for position determination is for any reason equal 3, position is obtained in mode 2D automatically, but the user cannot introduce the real value of antenna height. These receivers indicate DOP value which can be recognized as PDOP or HDOP if the position was determined in mode 3D or 2D respectively.

4 GPS POSITION ACCURACY

The accuracy of the user's position solution determined by SNS is ultimately expressed as the product of a geometry factor and a pseudorange error factor (Kaplan, E.D. & Hegarty, C.J. 2006):

(error in SNS solution) = (geometry factor) x
(pseudorange error factor) (1)

As the error solution can be expressed by M – the standard deviation of the positioning accuracy, geometry factor by the dilution of precision (DOP) coefficient and pseudorange error factor by σ_{UERE} (UERE – User Equivalent Range Error), these rela-tion can be defined as:

$$M = DOP \cdot \sigma_{UERE} \qquad (2)$$

If we can obtain all four coordinates of the observer's position (latitude, longitude, altitude above given ellipsoid, time – φ,λ,h,t), factor DOP is expressed by GDOP (Geometric Dilution of Precision) coefficient, if we want obtain horizontal coordina-tes, only, geometry factor DOP is expressed by HDOP (Horizontal Dilution of Precision) coefficient. In this situation the horizontal accuracy with 95% confidence level $M_{\varphi,\lambda}^{95\%}$ can be approximated by:

$$M^{95\%}_{\varphi,\lambda} \approx 2 \cdot \mathrm{HDOP} \cdot \sigma_{UERE} \qquad (3)$$

Specializing the equation giving the functional relationship between the errors in the pseudorange values and the induced errors in the computed position and time bias for the vertical dimension we can say that the 95% point for the distribution of the horizontal error (2 б) can be estimated by the doubled product of HDOP coefficient and the user equiva-lent range error ($б_{UERE}$).

Table 2. Position autonomous (code) information about position accuracy of selected receivers for marine (M) and/or navigation (N) users.

Manufacturer model	User	Value [m]
Altus Positioning Systems (APS)	M, N	1.3
Ashtech / Boards & Sensors (MB 800 Board)	M, N	3
Baseband Technologies, Inc. (BTI-2800LP)	M, N	≈ 5
CSR (GSD4e)	N	10
Fetch Radio Frequency System Corporation (FM11)	M, N	3 CEP
GlobalTop Technology (Gmm-u2p)	M, N	without aid 3 (50% CEP)
IFEN GmbH (SX-NSR)	N	≈ 10 (95%)
Jackson Labs Technologies, Inc. (SAASM CSAS)	M, N	< 2 RMS
JAVAD GNSS (TRIUMPH-1)	M, N	< 2
Leica Geosystems AG (Viva GS 10)	M, N	2 – 3
NovAtel (OEM615)	M, N	1.2
NVS Technologies AG (NV08C-CSM)	M, N	RMS:<1.5
ORCA Technologies, LLC (GS-101)	Position	< 9 90%
Rockwell Collins (MPE-S)	M, N	< 4 CEP
Septentrio (AsteRx-m OEM)	M, N	1.3 (1s)
Spectrum Instruments (TM-4MR)	M	2.5
Surrey Satellite Technology (SGR-10)	N	< 10
THALES – Avionics Division (GNSS 1000C)	M, N	< 5 (95%)
Topcon (MR-1)	M	2 – 3
Trimble (BD920 GNSS Receiver)	M, N	1 – 5
u-blox (UBX-M8030-KA/KT)	M, N	2 CEP

Global GPS civil service performance commitment met continuously since December 1993. Root Mean Square (RMS) Signal-in-Space (SiS) User Range Error (URE) was equal 1.6 metres in 2001, 1.1 in 2006 and finally 0.8 in 2013 (Gruber, B. 2012), Martin H. 2013). Signal in Space User Range Error is the difference between a GPS satellite's navigation data (position and clock) and the truth projected on the line of sight to the user.

The HDOP coefficient value depends on the SNS geometry, the user's coordinates, time and the number of satellites fully operational in given moment, in particular. At the beginning of XXI century for GPS system this value was about 1.5, at present (March 2014) is about 1.0 because very robust GPS constellation consists of 31 space vehicles currently in operation (www.navcen.uscg.gov).

5 THE MEASUREMENTS OF GPS POSITION IN MODE 3D

The measurements of GPS position based on stationary receivers were realized in the laboratory of University and on two ships in different ports in Europe.

5.1 *The measurements in the laboratory*

The measurements of GPS positions based on four different stationary receivers were realized in the laboratory of Gdynia Maritime University in Gdynia in Poland in the summer 2012. These receivers were:

- MX 200 Professional Navigator, manufacturer Magnavox, called later MX 200,
- ap Mk10 Professional, manufacturer Leica, called later MK10,
- MX 512 Simrad Navigation System, manufactu-rer Simrad, called later Simrad,
- NR–N124 Marine Navigator, manufacturer MAN Technologies, called later MAN.

The three coordinates of positions (latitude, longitude, height above ellipsoid WGS–84) of all four receivers, the positions of antennas of theses receivers in reality, obtained from geodetic measurements (Real Time Kinematic – RTK) and production year are presented in the table 3. The antennas of these receivers were installed on the masts on the roof of the university building. All positions were measured and presented in WGS–84 datum.

The measurements were made for different input data, the same for all four receivers:

- two different masking elevation angles H_{min}, 5° and 25°, the most frequently used angle in the receivers in open area (e.g. ocean navigation) and typical angle for restricted area (e.g. coastal navigation),respectively,
- two different datums, WGS–84 and Timbolaia 1948, datum officially applied for GPS system and the datum for which the position offset relative to WGS–84 is significant, respectively. For Timbolaia datum (ellipsoid Everest) this offset is S 0°00.2696'; W 0°00.81'.

The days of measurements, the registration duration and the number of positions registered by each receiver in mode 3D for different datums and angles H_{min} are given in the table 4. In each series during about 24 hours selected data:

- three coordinates of position: latitude, longitude and height (above selected ellipsoid),
- Horizontal Dilution of Precision HDOP coefficient,
- the number of satellites ls used in the receiver in position calculation

Table 3. The measurements in the laboratory – the coordinates of the GPS receivers installed in Gdynia Maritime University in Poland (RTK position), datum WGS–84.

Receiver		Coordinates		
Model	Production year	Latitude	Longitude	Height above ellipsoid WGS–84 [m]
MX 200	1991	54° 31′5.04922″ N	018° 33′16.36049″ E	57.48
Mk10	1995	54° 31′5.04918″ N	018° 33′16.39215″ E	57.48
Simrad	2011	54° 31′5.18485″ N	018° 33′16.50982″ E	54.21
MAN	2001	54° 31′5.07664″ N	018° 33′16.38120″ E	54.65

Table 4. The measurements in the laboratory – the days of measurements, the registration duration and the number of positions for different receivers, datums and angles H_{min}.

H_{min} [°]	Datum	Day	Receiver	Start of measurements	Duration	Number of positions
5	WGS 84	12.07.2012	MX 200	10:03:03	24 h 36 min	39 513
			Mk10	10:02:29	24 h 19 min	8 686
			Simrad	10:04:26	24 h 34 min	8 851
			MAN	10:01:40	24 h 37 min	8 868
25	WGS 84	31.07.2012	MX 200	11:50:23	23 h 02 min	36 879
			Mk10	11:52:27	23 h 01 min	8 247
			Simrad	11:51:16	23 h 24 min	8 429
			MAN	11:51:01	23 h 41 min	8 506
5	Timbolaia 1948	01.08.2012	MX 200	11:33:56	24 h 05 min	38 576
			Mk10	11:35:17	24 h 01 min	8 644
			Simrad	11:50:56	23 h 46 min	8 560
			MAN	11:52:51	23 h 43 min	8 545

were registered by PC with sampling interval of 10 second (Mk10, Simrad and MAN) and 2 or 3 second (MX 200). If any data has been incomplete, this measurement was rejected. That's why for the given period of the measurements the number of positions obtained from different receivers is not the same.

In the case of all receivers if we change the masking angle the coordinates of the position determined for the new value of this angle signalized on the screen and registered by PC are the same. Meanwhile if we change the datum from WGS–84 for Timbolaia the coordinates on the screen can differ from coordinated registered. In the case of MX 200, MK10 and MAN receivers the coordinates signalized on the screen are determined in "the new" Timbolaia datum while registered by PC are still in "the old" WGS–84 datum. Only in Simrad receiver all coordinates are in Timbolaia datum in each case.

In MX 200, Mk10 and Simrad receivers the vertical separation between the geoid and reference ellipsoid WGS–84, called geoid undulation, was + 34.3 m (the value for Gdansk Bay). In these three receivers in mode 3D the current value of the geoidal height (the receiver's antenna height above geoide), and no ellipsoidal height, is signalized on the screen, while in MAN receiver the ellipsoidal height is signalized only.

The total number of positions registered by all four receivers was 192314: MX 200 – 114968, Mk10 – 25577, Simrad – 25 840, MAN –25929.

For each series of measurements and for each receiver were calculated:

- three coordinates (latitude, longitude and height above given ellipsoid) of mean position,
- 2D – two dimensional (horizontal) distance from the known position of the receiver (RTK) to the mean receiver position,
- 3D – three dimensional distance from the known position of the receiver (RTK) to the mean receiver position,
- latitude error σ_φ and longitude error σ_λ,
- height error σ_H,
- horizontal position error $\sigma_{\varphi,\lambda}$, (σ_{2D} with confidence level 95%),
- three dimensional position error $\sigma_{\varphi,\lambda,H}$ (σ_{3D} with confidence level 95%),
- mean value of HDOP coefficient.

Position fix in mode "3D" can be calculated only from these satellites, which elevation angle in observer's receiver at the moment of measurement is higher than masking elevation angle H_{min}. At any moment the user's receiver needs to see at least four satellites.

5.2 *The measurements on the ships*

The measurements were realized on the ship DP3 Edda Fides (the first floating hotel and service vessel to be built exclusively for the offshore oil and gas industry (www.marinetraffic.com) equipped with:

- two identical SAAB R4 GPS/DGPS Navigation System (www.saabgroup.com) receivers, called later SAAB A and B, port Haugesund in Norway, November 2011, a dozen or so one-hour sessions, This receiver L1, C/A consists of 12 channels (2 dedicated to SBAS and DGPS by SBAS or externally RTCM corrections). SAAB R4 is receiver approved for SOLAS and any other precision navigation application. The actual distance between receiver's antennas was 1.5 m;
- two identical Kongsberg DPS 232 (GPS L1/L2 + GLONASS L1/L2 + SBAS) receivers, called later Konsgberg A and B, in the region of the port Castellon in Spain, November and December 2011, a dozen or so one-hour sessions. DPS 232 is an all-in-one DP new generation GNSS-based position reference system, which takes positioning to the next level for secure and robust solutions exerting GPS and GLONASS. SBAS or DGPS horizontal user's position accuracy is less than 1 m (95%)

(www.km.kongberg.com). The actual distance between receiver's antennas was 7.0 m.

In each series of the measurements the geographic coordinates of two receivers were registered at the same time with sampling interval of 60 second, mode 3D, datum WGS–84 for different input data introduced in receiver A or in receiver B or both receivers.

The next measurements of positions based on two GPS receivers installed on the general cargo ship SMT Bontrup (length overall 200.5 m) were realized in three European ports in 2012 year, in each port two one hour sessions. In each case as the real position it was assumed the position coordinates red from the chart which datum was WGS–84. These receivers were Furuno GPS Navigator GP–90, called later Furuno and SAAB R4 GPS/DGPS Navigation System, used as GPS only, called later SAAB. The coordinates of the receivers were registered at the same time with sampling interval of 60 second, mode was 3D, datum WGS–84 and masking angle H_{min} = 5°.

6 THE MEASUREMENTS OF GPS POSITION IN MODE 2D

The measurements of GPS position based on stationary receivers were realized in the laboratory of University in 2005 year (Januszewski J. 2005) and 2014 year. These receivers were:

- MLR FX412, manufacturer MLR Electronic, cal-led later MLR, and
- two receivers MX 200 and MK10 used in the measurements in mode "3D" (p.3).

In each receiver masking elevation angle was 5°, datum WGS–84. In each year the measurements were realized in tens series, the period of each series was one hour. The data, latitude and longitude, for real value of antenna height H_{ant} = 27 m, the same for all three receivers, and five different values H_{ant} = 0 m, 50 m, 100 m, 200 m and 500 m, were registered by personal computer (PC) with different interval of 1 or 2 seconds.

7 THE RESULTS

The distances between the two positions on the ellipsoid WGS–84 were calculated from the relation (Admiralty Manual of Navigation 2008):

$$1' = 1852.22 - 9.32 \cos 2\varphi_m \qquad (4)$$

where φ_m = middle latitude of two positions.

Table 5. The measurements in the laboratory in mode 3D – the coordinates of the mean position, the mean ellipsoidal height and the difference ΔH between mean ellipsoidal height and RTK height for different receivers, angles H_{min} and datums.

Receiver	Datum	H_{min} [°]	Mean position Latitude	Longitude	Mean height [m]	ΔH [m]
MX 200	WGS 84	5	54° 31′5.07213″ N	018° 33′16.39668″ E	54.84	– 2.64
		25	54° 31′5.06263″ N	018° 33′16.40463″ E	57.28	– 0.20
	Timbolaia 1948	5	54° 30′48.88686″ N	018° 32′27.80670″ E	56.62	– 0.86
Mk10	WGS 84	5	54° 31′5.10862″ N	018° 33′16.39753″ E	60.36	+ 2.88
		25	54° 31′5.13099″ N	018° 33′16.40908″ E	62.23	+ 4.75
	Timbolaia 1948	5	54° 30′48.94974″ N	018° 32′27.75545″ E	61.92	+ 4.44
Simrad	WGS 84	5	54° 31′5.21343″ N	018° 33′16.52619″ E	53.75	– 0.46
		25	54° 31′5.21831″ N	018° 33′16.52328″ E	54.31	+ 0.10
	Timbolaia 1948	5	54° 30′49.03898″ N	018° 32′27.92994″ E	54.21	0
MAN	WGS 84	5	54° 31′5.08449″ N	018° 33′16.41743″ E	52.09	– 2.56
		25	54° 31′5.10673″ N	018° 33′16.42334″ E	54.12	– 0.53
	Timbolaia 1948	5	54° 30′48.91694″ N	018° 32′27.82025″ E	53.95	– 0.70

Table 6. The measurements in the laboratory in mode 3D – the distances [m] between RTK positions and between receiver's antennas for all 6 pairs of receivers.

Receiver	MX		Mk10		Simrad		MAN	
	RTK	antenna	RTK	antenna	RTK	antenna	RTK	antenna
MX	–	–	0.57	0.50	4.98	4.79	0.93	0.90
Mk10	0.57	0.50	–	–	4.70	4.92	0.87	0.85
Simrad	4.98	4.79	4.70	4.92	–	–	3.96	4.13
MAN	0.93	0.90	0.87	0.85	3.96	4.13	–	–

Table 7. The measurements in the laboratory in mode 3D – the distance d between RTK position and mean position of the receiver and the bearing α between them from RTK position for different receivers, angles H_{min} and datums.

Datum	H_{min} [°]	MX 200		MK10		Simrad		MAN	
		d [m]	α [°]	d [m]	α [°]	d [m]	α [°]	d [m]	α [°]
WGS 84	5	0.86	42	1.84	3	0.92	16	0.694	69
	25	0.89	62	2.55	83	1.06	77	0.862	61
Timbolaia 1948	5	1004.56	240	1004.89	240	1004.72	240	1003.46	240

7.1 *The measurements in the laboratory in mode 3D*

The coordinates of the mean position, the mean ellipsoidal height and the difference ΔH between the mean height and RTK height for all four receivers, different angles H_{min} and datums are presented in the table 5. For Mk 10 the mean height is greater than RTK height considerably (almost 5 m), for MX 200 and MAN the mean height is less (– 2.78 m) than RTK height for all H_{min} and datums, and for Simrad the difference ΔH is the least, its absolute value doesn't exceed 0.5 m.

The distances between RTK positions and between receiver's antennas for all 6 pairs of receivers are showed in the table 6. After the comparison of RTK distance with the actual antennas distance for each pair we can say that the smallest and the greatest difference ΔD of these distances is in the case of pair Mk10 & MAN receivers (2 cm) and of the pair MK10 & Simrad receivers (22 cm) respectively. The difference ΔD doesn't exceed 13% of the bigger distance that time.

The distance d between RTK position and mean position of the receiver and the bearing α between them from RTK position for different receivers, angles H_{min} and datums are presented in the table 7. For datum WGS–84 and for all receivers because of smaller number of satellites used in position calculation the distance d is for $H_{min} = 25^{O}$ greater than $H_{min} = 5^{O}$ but this increase is little. For datum Timbolaia for all receivers distance d increases considerably, until almost 1005 m. It's because the position offset relative is for this datum significant.

The minimal ls_{min} and maximal ls_{max} number of satellites used in the position calculation for different angles H_{min}, datums and receivers are showed in the table 8. For all receivers the numbers ls_{min} and ls_{max} depend on the number of receiver's channels lc. In the case MX 200 and Mk10 receivers as lc = 6 the number ls_{max} is for $H_{min} = 5^{O}$ and independently of datum equal 6 only, it means that the number ls_{max} is less than the number of satellites visible by the antenna considerably. For the same receivers if $H_{min} = 25^{O}$ the number ls_{max} is the same (6) but ls_{min} decreases up to 3, it means that the position was determined in mode 2D. For Simrad and MAN receivers the number ls_{max} is for $H_{min} = 5^{O}$ equal the number lc, 10 and 12 respectively. For these receivers the number ls_{min}, 8 and 7, respectively, is greater than the number ls_{max} (6) for MX 200 and Mk 10 receivers.

Table 8. The measurements in the laboratory – minimal ls_{min} and maximal ls_{max} number of satellites used in the position calculation for different angles H_{min} and datums and for different receivers.

Receiver	WGS 84				Timbolaia 1948	
	$H_{min} = 5^{O}$		$H_{min} = 25^{O}$		$H_{min} = 5^{O}$	
	ls_{min}	ls_{max}	ls_{min}	ls_{max}	ls_{min}	ls_{max}
MX 200	5	6	3	6	5	6
Mk10	4	6	3	6	4	6
Simrad	8	10	4	8	6	10
MAN	7	12	4	8	8	12

The errors σ_{φ}, σ_{λ}, σ_{2D}, σ_{H}, σ_{3D} and HDOP coefficient value for different receivers, angles H_{min} and datums are showed in the table 9. We can say that:

- for each receiver and independently of datum the errors σ_{φ}, σ_{λ}, σ_{H} are for $H_{min} = 25^{O}$ greater than for $H_{min} = 5^{O}$,
- for all 3 series of measurements the errors σ_{φ}, σ_{λ}, σ_{H} are for Simrad and MAN receivers smaller than for MX 200 and MK10 receivers considerably, twice or even more,
- for all 3 series of measurements the error σ_{H} is for all receivers greater than σ_{φ} as well as σ_{λ}. This difference is particularly evident if $H_{min} = 25^{O}$, at least twice. It's because the number of satellites used in position calculation is that time less considerably,
- the error σ_{2D} (95%) is for all receivers less than 10 m, also for angle $H_{min} = 25^{O}$,
- if $H_{min} = 5^{O}$, independently of datum, the error σ_{3D} (95%) is the smallest for Simrad receiver, if $H_{min} = 25^{O}$ this error is the smallest for MAN receiver. It's because of the greater number of satellites used in position calculation, MAN – 12, Simrad – 10 only,
- if $H_{min} = 5^{O}$, independently of datum, HDOP coefficient value is for Simrad and MAN receivers less than for MX 200 and MK 10 receivers, if $H_{min} = 25^{O}$ this coefficient is almost the same for all receivers. It's because for this angle the number of satellites which can be used for calculate HDOP is for all receivers almost the same (6 or 8) while for $H_{min} = 5^{O}$ this number is for MAN (12) and Simrad (10) greater than for two others (6) considerably.

7.2 *The measurements on the ships in mode 3D*

The latitude error σ_{φ}, longitude error σ_{λ}, horizontal position error σ_{2D} (95%) and the distance D_{AB} between mean positions of two SAAB receivers for different input data (6 one-hour sessions) and two Kongsberg receivers for different daytimes and the measurements conditions (4 one-hour sessions) are showed in the table 10 and table 11 respectively. We can conclude that:

- in the case of two identical receivers, error σ_{2D} is not the same, but the difference is few per cent only,
- the error σ_{2D} of position determined 23 h 56 min later than the first position with the same satellite constellation is not the same because the measurements conditions (signal in space in particular) change with time,
- for different daytimes and the measurements conditions the position's accuracy is almost the same, about 1 m or less,
- if masking angle of the receiver increases few times, all errors increases considerably also,
- the distance between mean positions of two identical SAAB receivers and two identical Kongsberg receivers (D_{AB}) is not greater than 4.7 m and 2.3 m, respectively.

Table 9. The measurements in the laboratory – the errors σ_{φ}, σ_{λ}, σ_{2D}, σ_{H}, σ_{3D} and HDOP coefficient value for different receivers, angles H_{min} and datums.

H_{min} [°]	Datum	Receiver	σ_{φ} [m]	σ_{λ} [m]	σ_{2D} [m]	σ_{2D} (95%)[m]	σ_{H} [m]	σ_{3D} (95%) [m]	HDOP
5	WGS 84	MX 200	1.74	1.07	2.04	4.08	3.43	7.98	1.74
		Mk10	2.51	1.88	3.14	6.28	3.51	9.42	1.27
		Simrad	0.60	0.45	0.75	1.50	0.81	2.43	0.92
		MAN	0.71	0.44	0.83	1.66	2.00	4.33	0.89
25	WGS 84	MX 200	4.03	1.20	4.20	8.40	9.23	20.29	2.04
		Mk10	3.43	2.36	4.16	8.32	8.09	18.20	2.01
		Simrad	1.71	0.74	1.86	3.72	3.52	7.96	2.00
		MAN	1.66	0.70	1.80	3.60	3.22	7.38	2.06
5	Timbolaia 948	MX 200	1.87	1.34	2.30	4.60	3.81	8.90	1.73
		Mk10	3.25	2.71	4.23	8.46	5.52	13.91	1.31
		Simrad	0.59	0.52	0.79	1.58	1.21	2.89	0.92
		MAN	0.72	0.68	0.99	1.98	2.03	4.52	0.89

Table 10. The measurements on the ship DP3 Edda Fides – latitude error σ_{φ}, longitude error σ_{λ}, horizontal position error σ_{2D} (95%), distance D_{AB} between mean positions of two SAAB R4 GPS/DGPS receivers for different input data.

No	Input data		Receiver A			Receiver B			D_{AB} [m]
	Receiver A	Receiver B	σ_{φ} [m]	σ_{λ} [m]	σ_{2D} [m](95%)	σ_{φ} [m]	σ_{λ} [m]	σ_{2D} [m](95%)	
1	GPS/SBAS,	GPS/SBAS, $H_{min} = 5^{o}$	0.17	0.19	0.51	0.22	0.14	0.52	0.75
2	$H_{min} = 5^{o}$	23 h 56 min later than the measurements number 1, the same satellite constellation	0.17	0.19	0.51	0.17	0.14	0.44	0.60
3	GPS/SBAS, $H_{min} = 5^{o}$	GPS/SBAS, $H_{min} = 20^{o}$	0.18	0.15	0.47	1.72	0.62	3.66	1.02
4	GPS/SBAS, $H_{min} = 5^{o}$, different GPS satellite constellation for A and B		0.52	0.48	1.42	1.48	0.60	3.19	4.64
5	GPS/SBAS, $H_{min} = 5^{o}$	GPS/DGPS, $H_{min} = 5^{o}$	0.15	0.32	0.71	0.27	0.16	0.63	1.20
6	GPS/SBAS, $H_{min} = 5^{o}$	GPS only, $H_{min} = 5^{o}$	0.21	0.27	0.68	1.45	1.38	4.00	1.88

Table 11. The measurements on the ship DP3 Edda Fides – latitude error σ_{φ}, longitude error σ_{λ}, horizontal position error σ_{2D} (95%), distance D_{AB} between mean positions of two Kongsberg DPS 232 receivers for different daytimes and the measurements conditions.

No	Measurements conditions		Receiver A			Receiver B			D_{AB} [m]
	Receiver A	Receiver B	σ_{φ} [m]	σ_{λ} [m]	σ_{2D} [m](95%)	σ_{φ} [m]	σ_{λ} [m]	σ_{2D} [m](95%)	
1	GPS/GLONASS, sunset		0.25	0.17	0.60	0.33	0.21	0.78	0.16
2	GPS/GLONASS, sunrise		0.37	0.31	0.97	0.24	0.48	1.07	0.56
3	GPS/GLONASS, trans-shipment		0.30	0.19	0.71	0.24	0.30	0.77	2.21
4	change of GPS and GLONASS satellites used in both receivers in position calculation		2.16	2.97	7.34	0.37	3.23	6.55	1.69

Table 12. The measurements on the ship SMT Bontrup – latitude error σ_{φ}, longitude error σ_{λ}, horizontal position error σ_{2D} (95%), distance D between mean position and real position, maximal distance between GPS position and real position for different receivers in different days and ports.

Port	Day	Receiver	σ_{φ} [m]	σ_{λ} [m]	σ_{2D} [m](95%)	D [m]	D_{max} [m]
Amsterdam (Netherlands)	22.02.2012	Furuno	1.25	2.12	4.90	8.17	13.05
		Saab	1.48	2.36	5.58	7.50	13.00
	23.02.2012	Furuno	1.37	1.79	4.50	6.78	11.34
		Saab	1.60	1.96	4.92	8.85	16.67
Antwerp (Belgium)	21.01.2012	Furuno	1.98	1.84	5.40	5.60	10.98
		Saab	1.63	1.46	4.36	7.88	11.58
	02.03.2012	Furuno	1.63	2.44	5.86	4.18	9.23
		Saab	1.28	1.87	4.54	4.98	9.83
Bremanger (Norway)	01.01.2012	Furuno	1.80	2.54	6.22	7.19	15.17
		Saab	1.35	1.60	4.16	7.30	13.14
	18.02.2012	Furuno	1.89	2.30	5.96	5.53	13.53
		Saab	1.35	2.26	5.26	7.66	13.68

Table 13. GPS System, position "2D"; mean differences between maximum and minimum values of latitude and longitude, respectively $\Delta\varphi$ and $\Delta\lambda$ [m], horizontal position error M with 95% confidence level [m] for different receiver's antenna heights H_{ant} and for different years of measurements in Gdynia.

H_{ant} [m]	Year	MX 200			MLR			Mk 10		
		$\Delta\varphi$	$\Delta\lambda$	M	$\Delta\varphi$	$\Delta\lambda$	M	$\Delta\varphi$	$\Delta\lambda$	M
0	2005	19.5	16.8	9.6	18.5	10.6	20.0	33.5	20.8	11.8
	2014	11.1	6.2	6.1	10.4	6.3	6.1	42.4	18.7	11.3
27	2005	14.4	10.5	3.8	18.5	10.5	19.6	9.9	11.1	4.8
	2014	6.3	3.9	2.9	8.5	5.8	3.6	9.6	7.3	3.9
50	2005	36.5	22.8	12.4	18.6	10.7	18.6	34.5	18.6	11.8
	2014	13.9	2.8	9.0	12.6	7.5	7.9	60.7	58.3	22.6
100	2005	103.0	58.4	32.6	92.6	53.1	34.8	94.3	58.0	31.4
	2014	32.6	20.0	25.0	45.6	16.0	32.0	66.2	40.0	32.5
200	2005	229.5	135.4	73.6	203.7	127.4	75.2	192.2	106.9	84.2
	2014	91.1	57.9	72.4	64.6	61.3	65.8	129.9	134.3	64.2
500	2005	615.0	403.0	349.2	481.5	339.9	239.2	554.8	288.6	242.8
	2014	155.9	171.0	130.2	237.4	85.5	175.0	484.6	261.3	263.6

In the case of the measurement based on Furuno and Saab receivers on the ship SMT Bontrup we can say that the errors σ_φ, σ_λ and σ_{2D} are almost the same for these receivers, error σ_{2D} is about 4.1 ÷ 6.2 m (table 10). For both Furuno and Saab the distance between mean position and real position is from interval 4.1÷8.9 m while maximal distance between GPS position and real position from interval 9.2÷16.7 m. These values are typical for GPS accuracy in real conditions.

7.3 *The measurements in the laboratory in mode 2D*

For each series of measurements and for each receiver were calculated: the coordinates of mean position P_m, latitude error (m_φ), longitude error (m_λ), mean differences between maximum and minimum values of latitude, longitude and altitude, respectively $\Delta\varphi$, $\Delta\lambda$, and horizontal position error M of P_m at the 95% confidence level.

For all these three receivers, for each year and for each H_{ant} the mean values of the differences $\Delta\varphi$, $\Delta\lambda$ and error M are presented in the table 13. We can recapitulate that:

- the lowest values of the differences $\Delta\varphi$, $\Delta\lambda$ and the error M are for real values of H_{ant} for all receivers and for all years
- for real value of H_{ant} the differences $\Delta\varphi$, $\Delta\lambda$ and the error M are for the measurements in 2014 less, in some cases considerably, than in 2005 year for all receivers. For all other values of H_{ant} the both differences and the error M are in 2014 year less, in many cases considerably, than 9 years earlier for the receivers MX 200 and MLR.
- the differences $\Delta\varphi$, $\Delta\lambda$ and the error M increase with the difference between H_{ant} and its real value for all receivers and for all years.
- for each receiver, for all years and for each H_{ant} the differences $\Delta\varphi$ and $\Delta\lambda$ (in degrees) are in almost all cases practically the same, but as $\Delta\lambda$ depends on latitude, its value in meters is usually less.

8 CONCLUSIONS

- the choice of the SNS receiver and the mode of its use depend on the type of the ship and its region of navigation. The accuracy of the position GPS stand-alone (e.g. SAAB GPS only) for the cargo ship during ocean and coastal navigation is sufficient while the same receiver SAAB on specialized ship where high accuracy is needed determines the position using SBAS or DGPS augmentation.
- according to Federal Administration and maritime receivers producers the GPS system makes possible the determination of horizontal user's position (95% confidence level) with the accuracy few metres. The measurements based on different stationary GPS stand-alone receivers realized in the laboratory and on the ships confirm it. With augmentation DGPS or SBAS this accuracy increases to 1 m and less.
- the accuracy of the user's position obtained from the GPS system depends on the number of channels (lc) of user's receiver and the number of the GPS satellites visible at given moment by receiver's antenna above masking angle. That's why the knowledge of technical performances of the receiver and the total number of the GPS satellites fully operational (ls) is very important for the users. There is no direct relation between the number lc, the number ls and the position error M, but we can say the following "when lc and ls greater, M is less" and inversely "when lc and ls is less, M is greater".
- error M of the position fixed in mode "2D" for real value of H_{ant} is less than error M of the same position fixed in mode "3D" for all receivers.
- the accuracy of SNS position indicated by different maritime receivers differ because these units use different methods and algorithms which enable to change the results of pseudorange measurements and information obtained from the navigation messages into the user's coordinates. It concerns the identical models also because in each unit the local oscillator, fundamental element in all radio receivers, is different.
- the accuracy of the position obtained from professional GPS receiver with augmentation DGPS, SBAS or from GPS/GLONASS receiver, error σ_{2D} (95%) less than 1 m, is greater than from GPS stand-alone considerably.
- in the case of maritime GPS receiver the biggest influence on the accuracy of its position has the masking elevation angle and sudden changes in satellite constellation, in integrated GPS/GLONASS receiver, in particular.

- On account of very robust GPS constellation of 30 or 31 satellites fully operational currently produced GPS receivers usually determine and indicate the user's position in mode 3D, i.e. latitude, longitude and antenna height above sea level (geoide).

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