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Detection of Spoofing using Differential GNSS

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Abstract

One of the main problems in modern navigation of both manned and unmanned transport systems is that of transport safety. Differential GNSS technology has been used to improve the accuracy of transport positioning, in which position is calculated relative to a fixed reference station with a known position XYZ. Unfortunately, GNSS is vulnerable to malicious intrusion. GNSS signals and/or correction signals from the reference station can be spoofed by false signals, and special receivers have been used to provide defenses against such attacks. But how can the roving receiver (*i.e.* the user) be sure that the information they receive is authentic? Spoofing is the transmission of a matched-GNSS-signal-structure and/or signals to a reference station in order to cause interference and attempt to commandeer the tracking loops of a victim receiver, thereby allowing manipulation of the receiver's timing or navigation solution. A spoofer can transmit its counterfeit signals from a stand-off distance of several hundred meters, or it can be co-located with its victim. In this article we consider the principles of spoofing detection using Differential GNSS, in which a correction signal from the reference station is used for the detection of spoofing.

Definitions

We introduce some definitions used in this article.

1. **Sat**$_i$, $i = \overline{1, N}$, $N \geq 4$ – the navigation satellites as the spacefaring component of GNSS.
2. **DS** – **Differential Station** – control correction station subsystem in differential GNSS, including a **Reference Station** (RS) with its own coordinates ($\boldsymbol{x_{rs}}$, $\boldsymbol{y_{rs}}$, $\boldsymbol{z_{rs}}$) and the **Radio Beacon** transmitting correction information.
3. **Spoofing** – an attack on a GNSS, in an attempt to deceive the GNSS receiver by transmitting powerful false signals that mimic the signals from the true GNSS, exceeding the power of these true signals.
4. **Spoofer** – complex computer and radio equipment for the implementation of GNSS spoofing.
5. **GNSS Augmentation** – methods to improve GNSS performance, such as accuracy, and other quantities. The accuracy of GNSS positioning on the Earth's surface or in near-Earth space is improved using terrestrial and satellite (usually geostationary) correction systems.
6. **DGNSS** – Differential GNSS.
7. **Rover** – any mobile GNSS receiver that is used to collect data in the field at an unspecified location.
8. **Pseudo-range** – distance to the satellite, resulting in the correlation of the received code and on-board code in the receiver without correction of clock synchronization errors.
9. **RTCM – Radio Technical Commission for Maritime Services** – definition of a differential data link for the real-time differential correction of roving GNSS receivers.
10. **WGS-84 – World Geodetic System 1984** – describes the size and shape of the Earth.
11. **(*x*, *y*, *z*)** – the real coordinates of a vehicle. If the vehicle is a 2D vehicle (ship, vessel, boat, car, etc.), the height coordinate (z) can be omitted and the minimum number of required navigation satellites can be reduced to three ($i = \overline{1, N}$, $N \geq 3$).

12. **(x_v, y_v, z_v)** – the calculated coordinates of the vehicle using the GNSS.
13. $\tilde{x}_v, \tilde{y}_v, \tilde{z}_v$ – the calculated coordinates of the vehicle using the DGNSS.
14. **(x_{rs}, y_{rs}, z_{rs})** – the coordinates of the RS.
15. We also denote for $i = \overline{1, N}$, $N \geq 4$ (if the vehicle is a 2D vehicle (ship, vessel, boat, car, etc.), the height coordinate (z) can be omitted and the minimum number of navigation satellites can be reduced to three ($i = \overline{1, N}$, $N \geq 3$)):
    (x_i, y_i, z_i) – the coordinates of Sat_i;
    T_i^{rs} – the propagation time from Sat_i to the RS in vacuum;
    $\hat{T}_i^{rs}$ – the propagation time from Sat_i to the RS in real atmosphere;
    D_i^{rs} – the real distance from Sat_i to the RS;
    $\hat{D}_i^{rs}$ – the measurement result of the distance from Sat_i to the RS (evaluations of D_i^{rs} or pseudo-range);
    ΔD – the positioning error;
    T_i^v – the propagation time from Sat_i to the vehicle in vacuum;
    $\hat{T}_i^v$ – the propagation time from Sat_i to the vehicle in real atmosphere;
    $\hat{D}_i^v$ – the measurement result of the distance from Sat_i to the vehicle (the vehicle pseudo-ranges).

GNSS positioning

The distance from a vehicle (Figure 1) to satellites Sat_i can be written as:

$$D_i^v = \sqrt{(x_i - x_v)^2 + (y_i - y_v)^2 + (z_i - z_v)^2} = cT_i^v \quad i = \overline{1, N},\ N \geq 4 \tag{1}$$

Since the measurement of distance from the vehicle to the satellites is carried out by measuring the propagation time $\hat{T}_i^V = T_i^V + \Delta T_i^V$ of GNSS signals

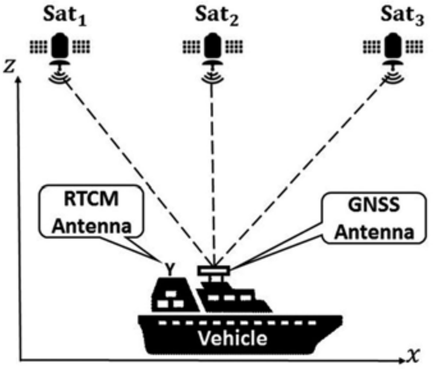

Figure 1. GNSS: Sat_i – Satellites; $i = \overline{1, N}$, $N \geq 4$; the visible part of GNSS satellite constellation

from Sat_i to the vehicle, then (1) can be represented as (excluding time synchronization errors):

$$\sqrt{(x_i - x_v)^2 + (y_i - y_v)^2 + (z_i - z_v)^2} = c\hat{T}_i^v \quad i = \overline{1, N},\ N \geq 4 \tag{2}$$

The navigation processor in the vehicle solves the system of the equations (2), calculates the position of the vehicle (x_v, y_v, z_v) and timing errors on board Δt, which are then used to correct the GNSS navigation clock (this article does not consider the timing errors, Δt). The calculations require the exact time, and most GNSS receivers do not possess a sufficiently precise internal clock. Therefore, to remove the ambiguity with respect to time, we need another equation that allows us to obtain the exact time – this equation requires a fourth satellite. Thus, for high-precision positioning, the receiver must have the capacity to receive signals from four satellites. The positioning error may be defined as:

$$\Delta D = \sqrt{(x - x_v)^2 + (y - y_v)^2 + (z - z_v)^2} \tag{3}$$

on the condition that the real coordinates of the vehicle (x, y, z) are known within geodesic (centimeter) accuracy. Analyzing the problem of positioning accuracy (2), we note that:

$$\left\{ \hat{T}_i^v = T_i^v + \Delta T_i^v \right\},\quad i = \overline{1, N},\quad N \geq 4 \tag{4}$$

that is, the accuracy is largely determined by the size of the propagation time delay from Sat_i to the vehicle ΔT_i^v.

Support for GNSS positioning technology will solve the problem of positioning in the meter range (5–10 m). Currently, differential GNSS is widely used to improve the accuracy of GNSS.

Differential GNSS positioning

In order to increase the accuracy of GNSS to a level that provides ships that are underway in rivers and canals with sufficiently accurate positioning information, differential subsystem DGNSS was developed (DGNSS base station antenna is set to within a few millimeters), consisting of ground differential base stations that receive signals from satellites, counting errors for signals about its (actual) position in the system WGS84 (Specht, 2007; Mihalskij & Katenin, 2009; Januszewski, 2010; GISGeography, 2017) and transmitting errors by a special radio network or by satellite. Correcting Reed-Solomon codes are used for error-correcting coding. DGNSSs are divided into three categories (Figure 2).

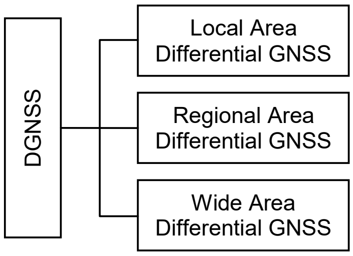

Figure 2. LADGNSS – Local Area Differential; RADGNSS – Regional Area Differential GNSS; WADGNSS – Wide Area Differential GNSS

LADGNSS – differential station transmitting correction information for up to ~200 km of coastline. RADGNSS – formed by combining data from a few LADGNSSs that are located in the same region. A master station transmits correction information for up to ~M·200 km of coastline, where M is the number of LADGNSSs. WADGNSS – formed by combining data from a few RADGNSSs that are located in the same region, state or group of bordering states. The transmitting of correction information to service the entire Earth can be implemented in two ways: through a communication satellite or a group of satellites, for example, using the Network Transport of RTCM *via* satellite link; or through the Internet, for example, using the Network Transport of RTCM *via* Internet protocol (NTRIP).

Local Area Differential GNSS Positioning

Since RS is at a known location (x_{rs}, y_{rs}, z_{rs}), we can compute the real distance from the RS (Figure 2) to satellites Sat$_i$ as:

$$D_i^{rs} = \sqrt{(x_i - x_{rs})^2 + (y_i - y_{rs})^2 + (z_i - z_{rs})^2}$$
$$i = \overline{1,N},\ \ N \ge 4 \tag{5}$$

We calculate the assessment of the distance from RS (Figure 2) to satellites Sat$_i$ (pseudo-range) by determining the signal propagation time from RS to the satellites Sat$_i$ as:

$$\hat{D}_i^{rs} = c\hat{T}_i^{rs},\ \ i = \overline{1,N},\ \ N \ge 4 \tag{6}$$

and now we can compute the correction of a pseudo-range for all vehicles in limited scope:

$$\Delta D_i^{rs} = \left(\hat{D}_i^{rs} - D_i^{rs}\right),\ \ i = \overline{1,N},\ \ N \ge 4 \tag{7}$$

The radio beacon transmits the correction, ΔD_i^{rs}, to all vehicles, adjusting their pseudo-range as:

$$\widetilde{D}_i^{v} = \left(\hat{D}_i^{v} - \Delta D_i^{rs}\right) = \left(c\hat{T}_i^{v} - \Delta D_i^{rs}\right),\ \ i = \overline{1,N},\ \ N \ge 4 \tag{8}$$

In this case the system of the equations (2) assumes the form:

$$\sqrt{(x_i - \widetilde{x}_v)^2 + (y_i - \widetilde{y}_v)^2 + (z_i - \widetilde{z}_v)^2} =$$
$$= \widetilde{D}_i^{v} = \left(c\hat{T}_i^{v} - \Delta D_i^{rs}\right),\ \ i = \overline{1,N},\ \ N \ge 4 \tag{9}$$

The navigation processor in the vehicle solves the system of equations (9) and calculates the position of the vehicle, $\widetilde{x}_v, \widetilde{y}_v, \widetilde{z}_v$. The positioning error may be defined as:

$$\Delta D = \sqrt{(x - \widetilde{x}_v)^2 + (y - \widetilde{y}_v)^2 + (z - \widetilde{z}_v)^2} \tag{10}$$

on the condition that the real coordinates of the vehicle (x, y, z) are known within the geodesic accuracy.

The support for differential GNSS positioning technology will solve the problem of positioning with high-accuracy (10–20 cm).

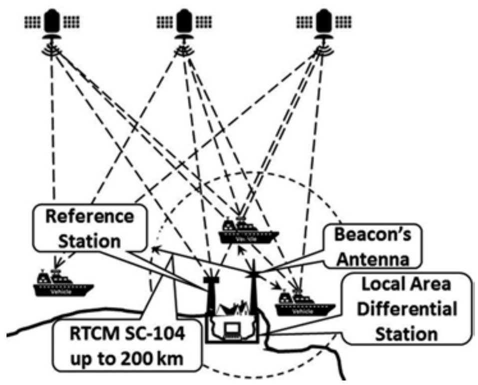

Figure 3. Local Area Differential GNSS

Figure 3 shows a receiver at a known position (the reference station) and a 2nd receiver on board a vehicle at an unknown position (*i.e.* the rover or user) for relative positioning. Because the GNSS position errors for the reference station and for the rover are approximately the same, the difference between the known and unknown locations of the reference station can be used to improve the accuracy of the positioning.

Regional Area Differential GNSS positioning

Let's pretend that Regional Area Differential GNSS is comprised of M reference stations (Figure 4):

$$\mathrm{RS_j},\ j = \overline{1,M} \tag{11}$$

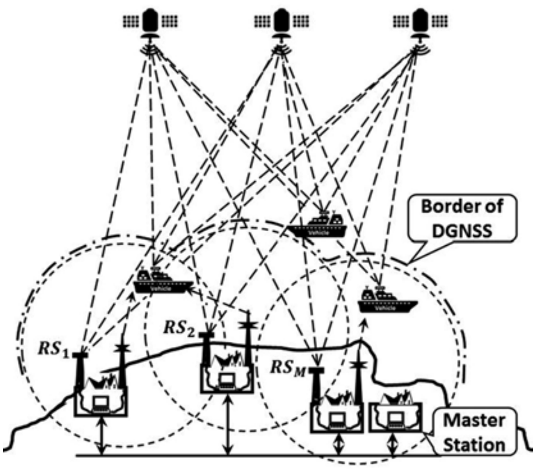

Figure 4. Regional Area Differential GNSS

Since RS_j are at known locations $\{x_j^{rs}, y_j^{rs}, z_j^{rs}\}$ we can compute the real distance from to satellites Sat_i as:

$$D_{i,j}^{rs} = \sqrt{\left(x_i - x_j^{rs}\right)^2 + \left(y_i - y_j^{rs}\right)^2 + \left(z_i - z_j^{rs}\right)^2}$$
$$i = \overline{1,N},\ N \geq 4,\ j = \overline{1,M} \qquad (12)$$

We calculate the assessment of the distance from RS_j to satellites Sat_i (pseudo-ranges) by determining the signal propagation time from RS to the satellites Sat_i as:

$$\hat{D}_{i,j}^{rs} = c\hat{T}_{i,j}^{rs},\ i = \overline{1,N},\ N \geq 4,\ j = \overline{1,M} \qquad (13)$$

and now we can compute the correction of pseudo-ranges for all vehicles in the j-one limited scopes:

$$\Delta D_{i,j}^{rs} = \left(\hat{D}_{i,j}^{rs} - D_{i,j}^{rs}\right), i = \overline{1,N}, N \geq 4, j = \overline{1,M} \qquad (14)$$

Figure 4 shows receivers at known positions (the reference stations) and receivers on board vehicles at unknown positions (*i.e.* the rovers or users) for relative positioning. The radio beacons transmit the local corrections across a radio or wired communication channel to a master station, and the master station after approximation of local data transmits the regional correction *via* radio beacons or perhaps through communication satellites (a selection of communication channel depends on the size and configuration of the region) to all vehicles which are in this region.

The radio beacons transmit the local correction, $\Delta D_{i,j}^{rs}$, to the master station, which solves the problem of interpolating a plurality of samples $\Delta D_{i,j}^{rs}$ into distribution functions of positioning. For each navigation satellite, we know the value of the function (13) at the interpolation nodes, and we can determine the value of $\widehat{\Delta D}_i(x, y)$ at any point (x, y) of a region, in which there are RSs. The solution to this problem is to construct a polynomial interpolation of the receiving nodes in the prescribed values, and to calculate the value of this polynomial at a point of interest to us (x, y) (Table 1).

After approximation of local data, the master station transmits the regional correction $\widehat{\Delta D}_i(x, y, z)$ *via* radio beacons or communication satellites (the selection of communication channel depends on the size and configuration of the region) to all vehicles which are in this region, each vehicle adjusting their pseudo-ranges as:

$$\tilde{D}_i^v = \hat{D}_i^v - \widehat{\Delta D}_i\left(x_v, y_v, z_v\right) = c\hat{T}_i^v - \widehat{\Delta D}_i\left(x_v, y_v, z_v\right)$$
$$i = \overline{1,N},\ N \geq 4 \qquad (15)$$

In this case the system of the equations (14) assumes the form:

$$\sqrt{\left(x_i - \tilde{x}_v\right)^2 + \left(y_i - \tilde{y}_v\right)^2 + \left(z_i - \tilde{z}_v\right)^2} = \tilde{D}_i^v =$$
$$= c\hat{T}_i^v - \widehat{\Delta D}_i\left(x_v, y_v, z_v\right),\ i = \overline{1,N},\ N \geq 4 \qquad (16)$$

Table 1. The corrections of pseudo-ranges for all vehicles in the j-one limited scopes and 2D interpolation irregular grid of the pseudo-ranges in the area of the all-region (U is the symbol of interpolation)

		$RS_j, j = \overline{1,M}$				Interpolation for the region $\{x_{\min} \leq x \leq x_{\max}, y_{\min} \leq y \leq y_{\max}, z_{\min} \leq z \leq z_{\max}\}$
		1	2	…	M	
Sat_i $i = \overline{1,N}$ $N \geq 4$	1	$\Delta D_{1,1}^{rs}\left(x_1^{rs}, y_1^{rs}, z_1^{rs}\right)$	$\Delta D_{1,2}^{rs}\left(x_2^{rs}, y_2^{rs}, z_2^{rs}\right)$	…	$\Delta D_{1,M}^{rs}\left(x_M^{rs}, y_M^{rs}, z_M^{rs}\right)$	$\widehat{\Delta D}_1(x, y, z) = \bigcup_{j=1}^{M}\left\{\Delta D_{1,j}^{rs}\left(x_j^{rs}, y_j^{rs}, z_j^{rs}\right)\right\}$
	2	$\Delta D_{2,1}^{rs}\left(x_1^{rs}, y_1^{rs}, z_1^{rs}\right)$	$\Delta D_{2,2}^{rs}\left(x_2^{rs}, y_2^{rs}, z_2^{rs}\right)$	…	$\Delta D_{2,M}^{rs}\left(x_M^{rs}, y_M^{rs}, z_M^{rs}\right)$	$\widehat{\Delta D}_2(x, y, z) = \bigcup_{j=1}^{M}\left\{\Delta D_{2,j}^{rs}\left(x_j^{rs}, y_j^{rs}, z_j^{rs}\right)\right\}$
	…	…	…	…	…	…
	N	$\Delta D_{N,1}^{rs}\left(x_1^{rs}, y_1^{rs}, z_1^{rs}\right)$	$\Delta D_{N,2}^{rs}\left(x_2^{rs}, y_2^{rs}, z_2^{rs}\right)$	…	$\Delta D_{N,M}^{rs}\left(x_M^{rs}, y_M^{rs}, z_M^{rs}\right)$	$\widehat{\Delta D}_N(x, y, z) = \bigcup_{j=1}^{M}\left\{\Delta D_{N,j}^{rs}\left(x_j^{rs}, y_j^{rs}, z_j^{rs}\right)\right\}$

The navigation processor in the vehicle solves the system of equations (15) and calculates the position of the vehicle $\tilde{x}_v, \tilde{y}_v, \tilde{z}_v$.

It is assumed that $\widehat{\Delta D}_i(x, y, z)$ is tabulated (sampling and quantization), *i.e.* interpolation results are presented in the form of a four-dimensional array:

$$\Delta_{i,k,l,n} = \widehat{\Delta D}_i\left(x_{\min} + k \cdot \Delta x,\ y_{\min} + l \cdot \Delta y,\ z_{\min} + n \cdot \Delta z\right)$$
$$i = \overline{1, N},\ \ N \geq 4 \tag{17}$$

where: $k = \overline{0, \frac{x_{\max} - x_{\min}}{\Delta x} - 1}$; $l = \overline{0, \frac{y_{\max} - y_{\min}}{\Delta y} - 1}$; $n = \overline{0, \frac{z_{\max} - z_{\min}}{\Delta z} - 1}$; Δx, Δy, Δz – stepped sampling of function $\widehat{\Delta D}_i(x, y, z)$.

Maritime Wide Area Differential GNSS Positioning

A network of reference stations is the foundation of high precision coordinate-time information regarding the location of vessels in coastal waters (this section deals with the problems of maritime transport, but the results of this section can be extended to all types of vehicles). This type of network is organized in areas where the density of traffic and the existing navigation and hydrographic support of navigation safety demand higher levels of volume and precision to protect the environment, reduce the downtime of vessels, achieve smooth operation of fleets and to provide quality rescue at sea.

The radio beacons transmit the local correction $\Delta D_{i,j}^{rs}$ to the master station, which solves the problem of interpolating a plurality of samples $\Delta D_{i,j}^{rs}$ into distribution functions of positioning. For each navigation satellite, we know the value of the function (14) at the interpolation nodes, and we can determine the value of $\widehat{\Delta D}_i(x, y)$ at any point (x, y) of a region, in which there are RSs. The solution to this problem is to construct a polynomial interpolation of the receiving nodes in the prescribed values, and the calculation of the value of this polynomial at a point of interest to us (x, y) (Table 2).

Figure 5 shows receivers at known positions (the reference stations) and receivers on board vehicles at unknown positions (*i.e.* the rover or user) for relative positioning. The radio beacons transmit the local corrections across a radio or wired communication channel to the master station and then the master station, after approximation of local data, transmits the wide correction across a communication satellite or group of satellites to all vehicles.

And the expression (18) takes the form:

$$\Delta_{i,k,l} = \widehat{\Delta D}_i\left(x_{\min} + k \cdot \Delta x,\ y_{\min} + l \cdot \Delta y\right)$$
$$i = \overline{1, N},\ \ N \geq 3 \tag{18}$$

where: $k = \overline{0, \frac{x_{\max} - x_{\min}}{\Delta x} - 1}$; $l = \overline{0, \frac{y_{\max} - y_{\min}}{\Delta y} - 1}$; Δx, Δy – stepped sampling of function $\widehat{\Delta D}_i(x, y)$.

In practice, the task of 2D interpolation on a non-uniform grid can be solved using standard software procedures, such as MATLAB – a two-dimensional interpolation on the irregular grid:

Syntax: ZI = griddata(x, y, z, XI, YI)
Description: Function ZI = griddata(x, y, z, XI, YI) returns an array of ZI, which is defined on the new grid {XI, YI} as a result of interpolation of the initial function z, defined on a non-uniform grid {x, y} i.e. z = f(x,y).

Two examples of the task solutions of 2D interpolation on a non-uniform grid for 13 RS[i] (a) and

Table 2. The corrections of pseudo-ranges for all vehicles in the *j*-one limited scopes and 2D interpolation irregular grid of the pseudo-ranges in the area of the all-region (U is the symbol of interpolation)

		$RS_j, j = \overline{1, M}$				Interpolation for the region $\{x_{\min} \leq x \leq x_{\max}, y_{\min} \leq y \leq y_{\max}\}$
		1	2	…	M	
$\mathrm{Sat_i}$ $i = \overline{1, N}$ $N \geq 3$	1	$\Delta D_{1,1}^{rs}\left(x_1^{rs}, y_1^{rs}\right)$	$\Delta D_{1,2}^{rs}\left(x_2^{rs}, y_2^{rs}\right)$	…	$\Delta D_{1,M}^{rs}\left(x_M^{rs}, y_M^{rs}\right)$	$\widehat{\Delta D}_1(x, y) = \bigcup_{j=1}^{M}\left\{\Delta D_{1,j}^{rs}\left(x_j^{rs}, y_j^{rs}\right)\right\}$
	2	$\Delta D_{2,1}^{rs}\left(x_1^{rs}, y_1^{rs}\right)$	$\Delta D_{2,2}^{rs}\left(x_2^{rs}, y_2^{rs}\right)$	…	$\Delta D_{2,M}^{rs}\left(x_M^{rs}, y_M^{rs}\right)$	$\widehat{\Delta D}_2(x, y) = \bigcup_{j=1}^{M}\left\{\Delta D_{2,j}^{rs}\left(x_j^{rs}, y_j^{rs}\right)\right\}$
	…	…	…	…	…	…
	N	$\Delta D_{N,1}^{rs}\left(x_1^{rs}, y_1^{rs}\right)$	$\Delta D_{N,2}^{rs}\left(x_2^{rs}, y_2^{rs}\right)$	…	$\Delta D_{N,M}^{rs}\left(x_M^{rs}, y_M^{rs}\right)$	$\widehat{\Delta D}_N(x, y) = \bigcup_{j=1}^{M}\left\{\Delta D_{N,j}^{rs}\left(x_j^{rs}, y_j^{rs}\right)\right\}$

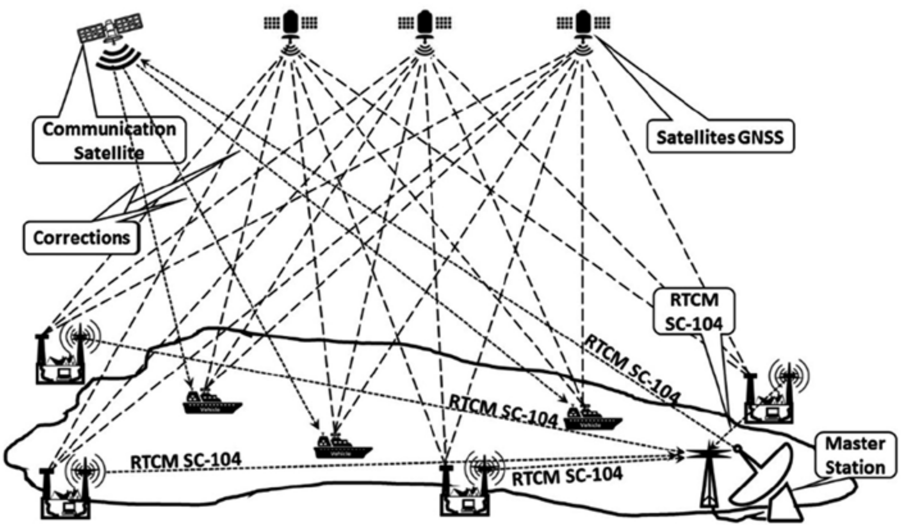

Figure 5. Wide Area Differential GNSS

for 8 RS[ii] (b), located in $\{14 \le \boldsymbol{E} \le 15;\ 54 \le \boldsymbol{N} \le 55\}$ (Figures 6, 7 and 8). Z used the sum of two fields (random and deterministic):

$$Z(E,N) = \left(\frac{\text{REND}(\ )}{10} - 1.2\right) + \\ + \frac{1}{2\pi\sigma_E\sigma_N} e^{\frac{(E-14.5)^2}{2\sigma_E^2} - \frac{(N-54.5)^2}{2\sigma_N^2}} \tag{19}$$

where:

$0 \le \text{REND}() \le 1$ is a random number,

$\sigma_E = \sigma_N = 0.5$.

[i] E=[14.00 14.05 14.05 14.25 14.50 14.50 14.50 14.50 14.50 14.75 14.95 14.95 15.00];
N=[54.50 54.05 54.95 54.50 54.00 54.25 54.50 54.80 55.00 54.50 54.05 54.95 54.50];
Z=[0.40 0.17 0.17 0.75 0.39 0.73 0.85 0.65 0.37 0.70 0.15 0.22 0.39];
e=14:0.1:15; n=54:0.1:55; XI,YI] = meshgrid(e,n);
ZI=griddata(E, N, Z, XI, YI); mesh(XI, YI, ZI), hold on, plot3(E, N, Z, ‘ok‘

[ii] E=[14.00 14.05 14.05 14.50 14.50 14.95 14.95 15.00]
N=[54.50 54.05 54.95 54.00 55.00 54.05 54.95 54.50]
Z=[0.40 0.17 0.17 0.39 0.37 0.15 0.22 0.39]
e=14:0.1:15; n=54:0.1:55; XI,YI] = meshgrid(e,n);
ZI=griddata(E, N, Z, XI, YI); mesh(XI, YI, ZI), hold on, plot3(E, N, Z, ‘ok’)

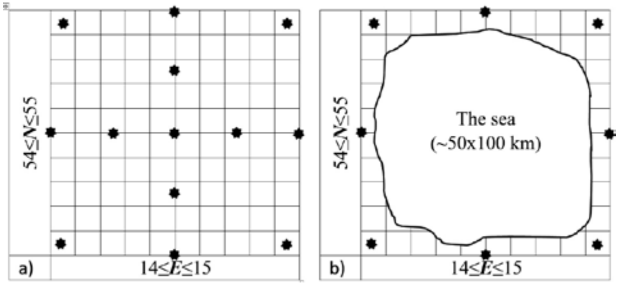

Figure 6. Two non-uniform grids: a) 13 RS on the ground (~60·110 km); b) 8 RS by the sea (~50·100 km)

In this article the application grid data is admissible only for 2D vehicles (ship, vessel, boat, car, *etc.*), *i.e.* for the case where z_j^{rs} = const. For each navigation satellite $i = \overline{1, N}$, $N \ge 3$ ($N \ge 3$ because it considered only a 2D vehicle (ship, vessel, boat, car, *etc.*)), we replace the 3D non-uniform grid $\Delta D_{i,j}^{rs}(x_j^{rs}, y_j^{rs}, z_j^{rs})$ (Table 2) with a 2D non-uniform grid $\Delta D_{i,j}^{rs}(x_j^{rs}, y_j^{rs})$, $j = \overline{1, M}$. Determining the uniform grid {XI, YI} in the region $\{x_{\min} \le x \le x_{\max}, y_{\min} \le y \le y_{\max}\}$ with sampling steps $\{\Delta x, \Delta y\}$ and we use procedure grid data as:

For $i = \overline{1, N}$ *% N ≥ 3 because it considered only 2D vehicle (ship, vessel, boat, car, etc.)*
ZI = griddata(x_*^{rs}, y_{*1}^{rs}, $\Delta D_{i,*}^{sr}$*,XI,YI)*
% Symbol (*) means all elements of the array
$\Delta_{i,*,*}$ = *ZI*
End

GNSS Spoofing

The spoofer can be built on the basis of a laboratory GNSS signal generator designed for debugging GNSS receivers. It is possible for spoofers to build a system based on a particular set of SDR (software-defined radio), if they have the appropriate software. The approximate cost of doing this is 1–10 thousand euro (Dobryakova, Lemieszewski & Ochin, 2012, 2013, 2014; Ochin *et al.*, 2013; Dobryakova & Ochin, 2014). A victim moving in space using the civil GNSS procedure may be subjected to a spoofing attack from other vehicles on the ground or at sea, which will be called “spoofers”. GNSS spoofing is the GNSS signal conversion technology. The spoofer plans to organize an attack,

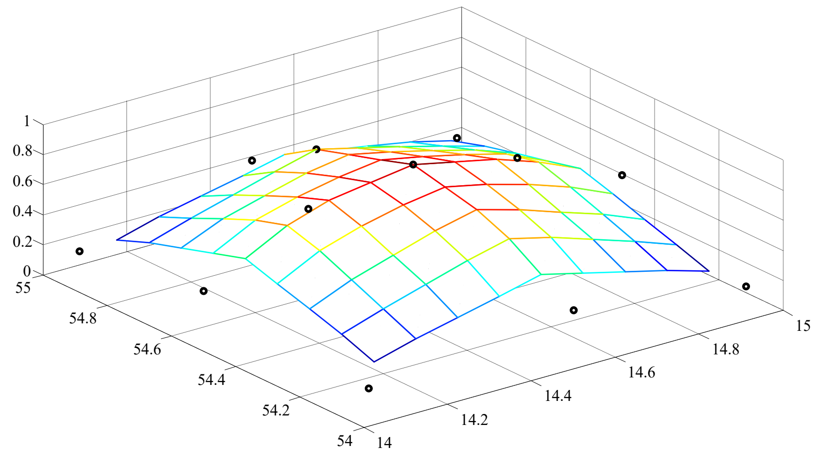

Figure 7. 2D interpolation on a non-uniform grid for 13 RS as Figure 6a

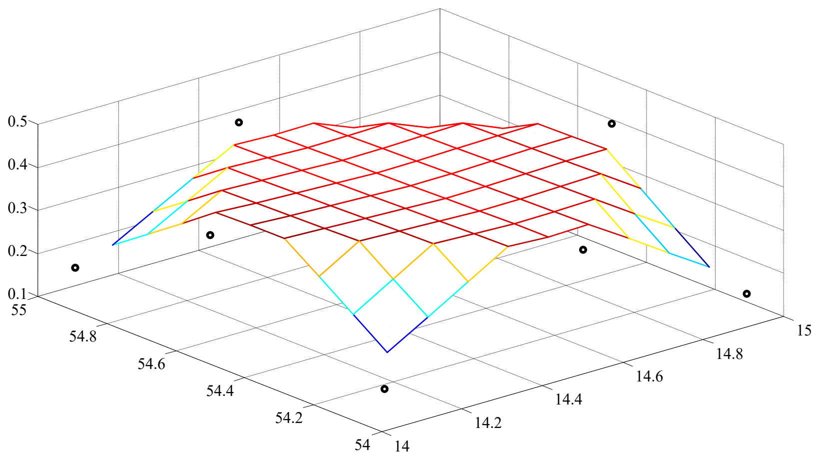

Figure 8. 2D interpolation on a non-uniform grid for 8 RS as Figure 6b

such that the navigator will not know that the signal received by their GNSS receiver is false. As a result of an organized attack, the navigator determines the wrong time and/or location. This means that the spoofer has begun to administer a false GNSS position in time and space.

The distortion of the signal includes a signal capture and playback at the same frequency with a slight shift in time and with greater intensity, in order to deceive the electronic equipment of a victim and, therefore, the operator, if there is one on board the vehicle.

The only GNSS systems which cannot be deceived are military GNSS systems, which utilize cryptographic technology. However, for civil GNSS use, such protection does not exist. Therefore, research into spoofing activities and anti-spoofing technology must be conducted. The main idea of spoofing is illustrated in Figure 9. The spoofer is generally located in the immediate vicinity of the victim and moves in space using a civilian or military GNSS mode (L1 or L1/L2).

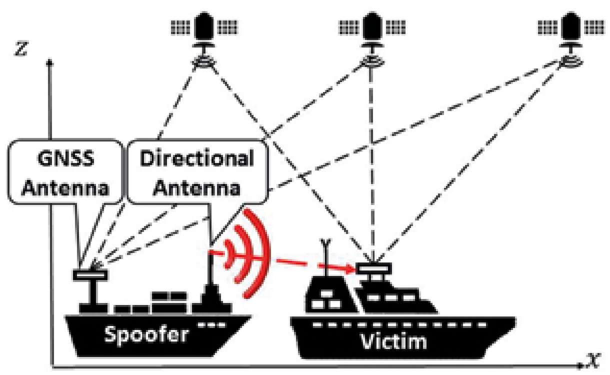

Figure 9. GNSS Spoofing: a vehicle, such as a vessel, boat *etc.*, called a victim

The spoofer performs short-term disruption of the GNSS signal L1 using a GNSS jammer. As a result of jamming the GNSS receiver, it "loses satellites" and starts looking for GNSS signals. At this time, the spoofer then begins to imitate GNSS signals, which are set up to indicate the spoofer's desired false coordinates of the GNSS receiver. Generally, the GNSS signal strength of the false spoofing signal exceeds the strength of the real GNSS signal, and so the victim GNSS receiver cannot determine that its movement in space is being controlled by a spoofer.

Spoofing of Local Area Differential GNSS Positioning

The radio beacon with which the spoofer transmits the false correction ΔD_i^f to the victim (Figure 10), "adjusts" their pseudo-range as:

$$\widetilde{D}_i^v = \left(\hat{D}_i^v - \Delta D_i^f\right) = \left(c\hat{T}_i^v - \Delta D_i^f\right)$$
$$i = \overline{1,N},\ \ N \geq 4 \tag{20}$$

In this case the system of the equations (2) assumes the form:

$$\left\{\sqrt{\left(x_i - \widetilde{x}_f\right)^2 + \left(y_i - \widetilde{y}_f\right)^2 + \left(z_i - \widetilde{z}_f\right)^2} = \left(c\hat{T}_i^v - \Delta D_i^f\right)\right\}$$
$$\to \left(\widetilde{x}_f, \widetilde{y}_f, \widetilde{z}_f\right),\ \ i = \overline{1,N},\ \ N \geq 4 \tag{21}$$

The navigation processor in the vehicle solves the system of equations (9) and calculates the false position of the victim $\left(\widetilde{x}_f, \widetilde{y}_f, \widetilde{z}_f\right)$.

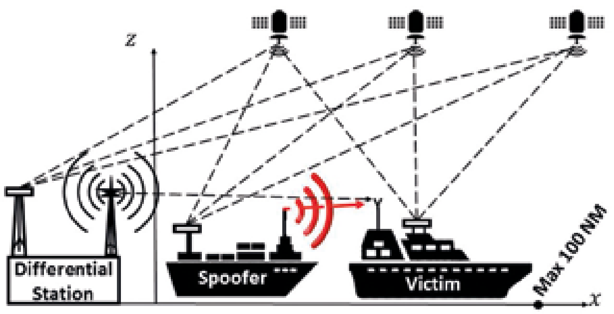

Figure 10. DGNSS spoofing

Spoofing Detection of Local Area Differential GNSS Positioning

The navigation processor of the victim solves the system of the equations (22):

$$\sqrt{\left(x_i - x_v\right)^2 + \left(y_i - y_v\right)^2 + \left(z_i - z_v\right)^2} = c\hat{T}_i^v$$
$$i = \overline{1,N},\ \ N \geq 4 \tag{22}$$

and calculates the coordinates of the victim (x_v, y_v, z_v) using the GNSS signals without any corrections. It then computes the distance between the two victim positions:

$$\Delta\widetilde{D} = \sqrt{\left(x_v - \widetilde{x}_f\right)^2 + \left(y_v - \widetilde{y}_f\right)^2 + \left(z_v - \widetilde{z}_f\right)^2} \tag{23}$$

If the vehicle is not being exposed to this type of spoofing attack, the difference between the calculated coordinates cannot exceed a certain maximum positioning error ΔD_{max} in normal mode GNSS (DGNSS mode is not available), *i.e.*:

$$\Delta\widetilde{D} \leq \Delta D_{\max} \tag{24}$$

and the decision rule of the algorithm for determining if spoofing is occurring can be written as:

$$\begin{gathered}\text{if } (\ \Delta\widetilde{D} \leq \Delta D_{\max}\ ) \text{ then OK} \\ \text{else goto SPOOFING}\end{gathered} \tag{25}$$

Spoofing Detection of Maritime Wide Area Differential GNSS

The section "Spoofing Detection using Regional Area Differential GNSS" is omitted because it is implemented similarly to that described above. We consider 2D spoofing detection for maritime applications.

The radio beacons transmit the local corrections across a radio or wired communication channel to a master station and the master station, after approximation of local data, transmits the wide correction *via* telecommunication satellite to all vehicles, adjusting their pseudo-range (Figure 11).

The spoofer's radio beacon transmits the false correction ΔD_i^f to the victim, "adjusting" their pseudo-range as:

$$\widetilde{D}_i^v = \left(\hat{D}_i^v - \Delta D_i^f\right) = \left(c\hat{T}_i^v - \Delta D_i^f\right)$$
$$i = \overline{1,N},\ \ N \geq 3 \tag{26}$$

In this case we can make the system of the equations:

$$\sqrt{\left(x_i - \widetilde{x}_f\right)^2 + \left(y_i - \widetilde{y}_f\right)^2 + z_i^2} = \left(c\hat{T}_i^v - \Delta D_i^f\right)$$
$$i = \overline{1,N},\ \ N \geq 3 \tag{27}$$

The victim's navigation processor solves the system of equations (27) and calculates the false position of the victim $\left(\widetilde{x}_f, \widetilde{y}_f\right)$, solves the system of equations (28) and calculates the coordinates of the victim (x_v, y_v) for $N \geq 3$ using the GNSS signals without any corrections.

$$\left\{\sqrt{\left(x_i - x_v\right)^2 + \left(y_i - y_v\right)^2 + z_i^2} = c\hat{T}_i^v\right\} \to \left(x_v, y_v\right) \tag{28}$$

It then computes the distance between the two vehicle positions:

$$\Delta\widetilde{D} = \sqrt{\left(x_v - \widetilde{x}_f\right)^2 + \left(y_v - \widetilde{y}_f\right)^2} \tag{29}$$

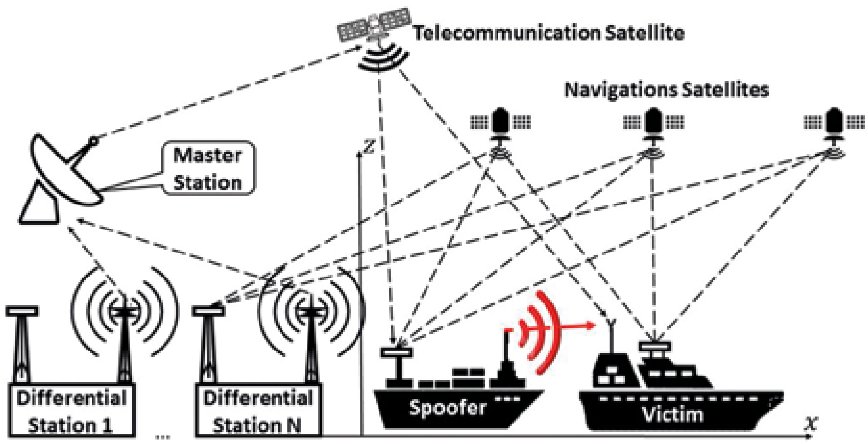

Figure 11. Spoofing Detection of Maritime Wide Area Differential GNSS

If the vehicle is not being exposed to this type of spoofing attack, then the difference between the calculated coordinates cannot exceed a certain maximum positioning error $\Delta D_{\max}$ in normal mode GNSS (DGNSS mode is not available), *i.e.*:

$$\Delta\widetilde{D} \le \Delta D_{\max} \tag{30}$$

and the decision rule of the algorithm for determining if spoofing is occurring can be written as:

$$\begin{gathered}\text{if } (\Delta\widetilde{D} \le \Delta D_{\max}) \text{ then OK} \\ \text{else goto SPOOFING}\end{gathered} \tag{31}$$

Summary and conclusions

The risk of losing GNSS signal is growing every day. The accessories necessary for the manufacture of systems for GNSS "jamming" and/or "spoofing" are now widely available and this type of attack cannot only be taken advantage of by the military, but also by terrorists. The distortion of the signal includes a signal capture and playback at the same frequency with a slight shift in time and with greater intensity, in order to deceive the electronic equipment of a victim and, therefore, the operator if there is one on board the vehicle. The price of one chipset for such equipment is in the range of 1–10 thousand euros, depending on the dimensions and weight parameters. In this article we consider the principles of spoofing detection using Local, Regional and Wide Differential GNSS, in which correction signals of differential stations can be used for the detection of spoofing. This relatively simple and quite effective method has one obvious drawback – it is supposed to use a fixed (stationary) differential GNSS station, the coordinates of which should be known to the geodesic accuracy (centimeters). Our many years of research in the field of spoofing detection (Retscher, 2002; Dobryakova, Lemieszewski & Ochin, 2012, 2013, 2014; Ochin *et al.*, 2013; Dobryakova & Ochin, 2014; GPS World, 2015) gives us confidence that this deficiency is avoidable and in the near future we expect to publish the results of our research, thanks to which the implementation of mobile differential stations, including floating stations, will be possible.

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