

Method for detecting a target by GNSS reflectometry and associated system

5 The invention relates to a method for detecting a target by GNSS reflectometry.

 The term “target” is understood to mean an element possessing reflective properties that are different from those of the area in which it is
10 found. These different reflective properties may be due, nonlimitingly, to a different geometry (e.g. ice peak in a flat extent of ice) or a different composition (e.g. metal structure on a body of water).

 The reflective properties may be of specular or diffuse type, or any
15 combination thereof.

 GNSS reflectometry is an original and opportunistic remote sensing technique that consists in analysing the electromagnetic waves continuously emitted by the sixty satellites of GNSS positioning systems
20 (GALILEO, GPS, GLONASS, etc.), which are captured by an antenna after reflection from the surface of the Earth. These signals interact with the reflecting area and therefore contain information on its properties, which may be observed in the signal received after reflection. Although the feasibility and advantageousness of this method have been amply demonstrated, in
25 particular in aeronautical fields, the implementation of this technique poses a certain number of problems in a spatial context.

 The GNSS is therefore used as a radar, and receives the echo after reflection from the surface of the Earth, and deduces, by analysis of the
30 echo, the properties of this surface.

 It is an advantageous alternative to radar, at least for low-cost applications, in particular because it is not necessary to pay for the source (the emitter of the radar, with all that it costs in terms of consumption), and it

is continuously available (no need to wait for the return of the satellite or of the carrier of the radar).

GNSS reflectometry has been used for a number of years, in an
5 airborne context, for example in agriculture and the surveillance of forests.

However, the link budget is not high enough for implementation of
GNSS reflectometry to be simple with conventional low Earth orbit (LEO)
satellites, a low Earth orbit generally being considered to be lower than 2000
10 km.

In the present case, a target may be a ship on the ocean (small
area of specular reflection in the middle of an area of diffuse, on the whole,
reflection), a portion of a pole not covered with ice (small area of diffuse
15 reflection in the middle of an area of specular, on the whole, reflection).

One aim of the invention is to overcome the aforementioned
problems.

20 The invention proposes, according to one of its aspects, an
iterative method for detecting, with at least one receiver satellite in orbit, a
target possessing reflective properties that are different from those of the
area in which said target is found, by GNSS reflectometry, wherein the
reflected GNSS signals are received by phased-array antenna, hereafter
25 named "active antenna" of the receiver satellite comprising a plurality of
antenna elements, the method comprising a step of determining assumed
positions of the target, for which positions it is desired to detect the target,
and, for each assumed position of the target, carrying out the following steps:

- determining a time interval in which said assumed position of the
30 target is visible from the receiver satellite, and dividing this time interval
into time segments, for each of which the following steps are carried
out:
 - determining the direction of arrival of the reflected GNSS signals
issued from said assumed position of the target on the basis of the
35 orbital position of the receiver satellite;

- 5 - determining the orbital positions of the GNSS satellites from their ephemeris data, then the directions of arrival of the direct GNSS signals of the GNSS satellites visible to a GNSS receiver of the satellite, and of the disrupting specular-reflection echo of the GNSS signals from the area in which the target is found;
- 10 - correlating, for each visible GNSS satellite, the assumed position of the target, in the GNSS code corresponding to this GNSS satellite, and forming beams with the active antenna while maximising the gain of the active antenna in the direction of arrival of the signals issued from the assumed position of the target, and while minimising the gain of the active antenna in the directions of arrival of the direct signals of the GNSS satellites visible to the GNSS receiver and of the disrupting specular-reflection echo from said area in which the target is found;
- 15 - determining the expected arrival time and the expected variation as a function of time in the arrival phase of GNSS signals potentially reflected from the target, and averaging, over the visible GNSS satellites, the correlation in the GNSS code for the arrival times and variation as a function of time in the arrival phase, on the basis of the orbital position of said receiver satellite and of its variations and of the orbital positions of the GNSS satellites visible from the assumed position of the target and their variations; and
- 20 - averaging, over the time segments, said averages of the correlation over the GNSS satellites; and
- 25 - determining whether the target is present at the assumed position by comparing said average over the time segments with a reference value.

30 Thus, the method makes it possible to be able to use GNSS signals to locate a target.

In one implementation, the orbital position of the receiver satellite is determined on the basis of a GNSS receiver placed on said satellite.

Thus, the satellite not only has a means for determining its position, but also a capacity to collect the GNSS-satellite ephemeris data required by geometric calculations allowing reception geometries and variations as a function of time in characteristics of the received signals to be
5 evaluated.

In one implementation, the reference value of the step of determining whether the target is present is preset.

10 Thus, it is possible to identify the presence of a particularly reflective (diffuse, respectively) target by observing a high (low, respectively) coherence in the signals received from this direction. This may in particular be useful in an experimental context, or at the start of satellite operation, in order to set the sensitivities of the algorithms on certain known points.

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In one implementation, the reference value of the step of determining whether the target is present is adaptive.

20 Thus, it is possible to adapt the thresholds to the observed environment, for example to define higher detection thresholds in maritime zones containing more ships or boats in order to identify, without confusion, only larger targets, and to return to lower thresholds when detecting smaller targets, when the risk of confusion is lower.

25 In one embodiment, the target is a ship or boat on a body of water.

As a variant, the target is an area not covered by ice at one of the Earth's poles.

30 The invention also proposes, according to another of its aspects, a system for detecting, with a satellite in orbit, a target possessing reflective properties that are different from those of the area in which it is found, by GNSS reflectometry, said system being suitable for implementing the method such as described above.

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The invention will be better understood on studying a few embodiments that are described by way of completely nonlimiting example and illustrated by the drawing in which Figure 1 schematically illustrates one implementation of the method according to one aspect of the invention.

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The iterative method for detecting, with at least one receiver satellite in orbit, a target possessing reflective properties that are different from those of the area in which said target is found, by GNSS reflectometry, wherein the reflected GNSS signals are received by an active antenna of the receiver satellite comprising a plurality of antenna elements, the method
10 comprising a step E1 of determining assumed positions of the target, for which positions it is desired to detect the target, and, for each assumed position of the target, carrying out the following steps:

- determining E2 a time interval in which said assumed position of
15 the target is visible from the receiver satellite, and dividing this time interval into time segments, for each of which the following steps are carried out:

- determining E3 the direction of arrival of the reflected GNSS signals issued from said assumed position of the target on the
20 basis of the orbital position of the receiver satellite;

- determining E4 the orbital positions of the GNSS satellites from their ephemeris data, then the directions of arrival of the direct GNSS signals of the GNSS satellites visible to a GNSS receiver of the satellite, and of the disrupting specular-reflection echo of the
25 GNSS signals from the area in which the target is found;

- correlating E5, for each visible GNSS satellite, the assumed position of the target, in the GNSS code corresponding to this GNSS satellite, and forming beams with the active antenna while maximising the gain of the active antenna of the receiver satellite in the direction of arrival of the signals issued from the assumed
30 position of the target, and while minimising the gain of the active antenna of the receiver satellite in the directions of arrival of the direct signals of the GNSS satellites visible to the GNSS receiver and of the disrupting specular-reflection echo from said area in
35 which the target is found;

- 5 - determining E6, at the receiver satellite, the expected arrival time and the expected variation as a function of time in the arrival phase of GNSS signals potentially reflected from the target, and averaging, over the visible GNSS satellites, the correlation in the GNSS code for the arrival times and variation as a function of time in the arrival phase, on the basis of the orbital position of said receiver satellite and of its variations and of the orbital positions of the GNSS satellites visible from the assumed position of the target and their variations; and
- 10 - averaging E7, over the time segments, said averages of the correlation over the GNSS satellites; and
- determining E8 whether the target is present at the assumed position by comparing said average over the time segments with a reference value.

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The present invention is in particular based on the use of an active multiple-beam antenna in the receiver satellite or receiver satellites, in low or LEO orbits. In the case of a plurality of satellites, it is also necessary to manage the communications between the various satellites. Use of a single receiver satellite will therefore be preferred.

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The use of an active antenna in particular allows coherent recombination of signals in a determined direction, or direction of a potential target, allowing the gain in this direction to be improved in proportion to the number of antennas used for the recombination of the signals, but also signals to be cancelled out in directions that are judged to be interfering, in particular in the direction of the specular reflection of each GNSS satellite, making it possible to concentrate on the reception of non-specular echoes.

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In addition, since these two elements may be implemented dynamically and continuously, and in a way tailored to the relative movements of the GNSS satellites, of the LEO carrier satellite and of the targets (which are assumed to be stationary or slowly moving) on Earth, it is also possible to increase the number of constellations used, the adaptive beam formation also possibly being used to mitigate problems created by the

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disrupting specular-reflection echo of the GNSS signals from the area in which the target is found, a.k.a. the “near-far” effect, and to increase the durations of (coherent and/or incoherent) integration and therefore once again increase target-detection sensitivity.

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The orbital position of the receiver satellite may be determined using the GNSS receiver. A variation in position may be calculated via a time derivative of the position.

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The reference value may be preset or adaptive.

The target may be a ship or boat on a body of water or an area that is not covered with ice at one of the Earth’s poles.

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The principle of the invention is the application of a series of interrelated loops, the inputs of which are the outputs of GNSS correlations and reception:

Each position on Earth, defined by a mesh dependent on the GNSS signal of highest resolution (of largest bandwidth):

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- If it is not visible: nothing
- If it becomes visible: start the integration
- If its visibility ends: decision on the presence of a target
- If it is still visible:

- For each GNSS satellite:

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- Determining the optimal beamforming allowing pointing toward the reflection, from this source, of the signal emitted by the GNSS satellite, and the removal of sea clutter and of visible satellites liable to create a near-far effect, in an amount of $N-2$ satellites removed with a number of antennas N

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- Determining the reception time and frequency expected for such a signal reflected from the target given the position of the target and the positions and speeds of the LEO and GNSS satellites.

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- Coherently correlating the GNSS replica for this expected reflected signal after beamforming
- Carrying out an accumulation over all the GNSS satellites

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A system according to the invention for detecting, with a receiver satellite in orbit, a target possessing reflective properties that are different from those of the area in which it is found, by GNSS reflectometry, is suitable for implementing the method such as described above.

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CLAIMS

- 5 1. Iterative method for detecting, with at least one receiver satellite in orbit, a target possessing reflective properties that are different from those of the area in which said target is found, by GNSS reflectometry, wherein the reflected GNSS signals are received by an active antenna of the receiver satellite comprising a plurality of antenna elements, the
- 10 method comprising a step (E1) of determining assumed positions of the target, for which positions it is desired to detect the target, and, for each assumed position of the target, carrying out the following steps:
- 15 - determining (E2) a time interval in which said assumed position of the target is visible from the receiver satellite, and dividing this time interval into time segments, for each of which the following steps are carried out:
- 20 - determining (E3) the direction of arrival of the reflected GNSS signals issued from said assumed position of the target on the basis of the orbital position of the receiver satellite;
- 25 - determining (E4) the orbital positions of the GNSS satellites from their ephemeris data, then the directions of arrival of the direct GNSS signals of the GNSS satellites visible to a GNSS receiver of the satellite, and of the disrupting specular-reflection echo of the GNSS signals from the area in which the target is found;
- 30 - correlating (E5), for each visible GNSS satellite, the assumed position of the target, in the GNSS code corresponding to this GNSS satellite, and forming beams with the active antenna of the receiver satellite while maximising the gain of the active antenna in the direction of arrival of the signals issued from the assumed position of the target, and while minimising the gain of the active antenna in the directions of arrival of the direct signals of the GNSS satellites visible to the GNSS receiver and of the disrupting specular-reflection echo from said area in which the target is found;

- determining (E6) the expected arrival time and the expected variation as a function of time in the arrival phase of GNSS signals potentially reflected from the target, and averaging, over the visible GNSS satellites, the correlation in the GNSS code for the arrival times and variation as a function of time in the arrival phase, on the basis of the orbital position of said receiver satellite and of its variations and of the orbital positions of the GNSS satellites visible from the assumed position of the target and their variations; and
 - averaging (E7), over the time segments, said averages of the correlation over the GNSS satellites; and
 - determining (E8) whether the target is present at the assumed position by comparing said average over the time segments with a reference value.
2. Method according to Claim 1, wherein the orbital position of the receiver satellite is determined on the basis of a GNSS receiver placed on said satellite.
 3. Method according to one of the preceding claims, wherein the reference value of the step (E8) of determining whether the target is present is preset.
 4. Method according to one of Claims 1 to 2, wherein the reference value of the step (E8) of determining whether the target is present is adaptive.
 5. Method according to one of the preceding claims, wherein the target is a ship or boat on a body of water.
 6. Method according to one of Claims 1 to 5, wherein the target is an area not covered with ice at one of the Earth's poles.
 7. System for detecting, with a satellite in orbit, a target possessing reflective properties that are different from those of the area in which it is found, by GNSS reflectometry, said system being suitable for implementing the method according to one of the preceding claims.