MISTRALE: Soil moisture mapping service based on a RPAS-embedded GNSS-Reflectometry sensor

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Abstract

The objective of the MISTRALE project (**M**onitoring so**I**l moi**S**ture and wa**T**e**R**-flooded **A**reas for agricu**L**ture and **E**nvironment) is to provide RPAS-based soil moisture maps. To do so, MISTRALE project relies on an innovative use of the GNSS signals, named reflectometry (GNSS-R). This approach consists in comparing the direct signal, i.e. the signal received directly from satellites, with those reflected by the ground. In the context of the MISTRALE project, both GPS and GALILEO signals will be used, which will improve the system performances.
In July 2015, two experimental flights were conducted in the South of France with the aim to validate the technical feasibility of the project concept. The analysis of the data collected has shown very promising results: high reflectivity values were observed for rivers, basins or irrigation canals, whereas the low reflectivity values were associated with dryer areas or with a higher presence of vegetation.
This extended abstract presents the results of this early analysis. The paper will be complemented by comparison between the MISTRALE data with other soil moisture measurements (in situ probes and near infrared measurements that have also been used to collect data during the July experimental flights).

Introduction and context

Around 70 percent of worldwide freshwater is used by agriculture. To be able to feed an additional 2 billion people by 2030, water demand is expected to increase tremendously in the next decades. Farmers are challenged to produce "more crop per drop". In order to optimize water resource management, it is crucial to improve soil moisture situation awareness, which implies both a better temporal and spatial resolution.

To this end, the objective of the MISTRALE project (**M**onitoring so**I**l moi**S**ture and wa**T**e**R**-flooded **A**reas for agricu**L**ture and **E**nvironment) is to provide RPAS-based soil moisture maps that could complement satellite-based and field measurements. In addition to helping farmers make more efficient decisions about where and when to irrigate, MISTRALE moisture maps are an invaluable tool for risk management and damage evaluation, as they provide highly relevant information for wetland and flood-prone area monitoring.

MISTRALE approach

In order to measure soil water content, MISTRALE project relies on an innovative use of the GNSS signals, named reflectometry (GNSS-R). This approach consists in comparing the direct signal, i.e. the signal received directly from satellites, with those reflected by the ground. At GNSS signals frequency (near 1.5 GHz), the characteristics of the reflection mainly depends on the Fresnel reflection coefficient, which is related to soil moisture content. Therefore, the computation the ratio between the ground-reflected GNSS signals and the direct one provides measurements of the soil's reflectivity, hence, of the humidity content.

When it comes to soil moisture, using GNSS-R technique has several advantages compared to the other usual techniques such as visible/NIR imagery. Since GNSS signals lies in L-band (between 1 and 2 GHz), the GNSS-R is operational under cloud cover and during the night. In addition, it is less influenced by variation on the thermal background. Yet, it is worth noting that GNSS-R measurements are affected by soil roughness and by vegetation. Roughness impact can be mitigated using polarimetric measurements and computing the apparent reflectivity for both left-hand and right-hand circular polarizations reflected signals.

In the context of the MISTRALE project, the GNSS-R receiver will use both GPS and GALILEO signals, which will improve the system performances. Thanks to a higher number of available satellites and to the GALILEO signals characteristics, the sensor's measurements accuracy will be enhanced. This dual constellation sensor will be embedded on a fixed-wing RPAS which is able to fly continuously for 10 hours and has a range of 1000 km. The large flight envelope of the RPAS (low speed and low altitude) will enable high spatial resolution of the soil moisture maps can be achieved.

Early flight campaign

Description of the test area and equipment

In order to validate the feasibility of the MISTRALE concept, two experimental flights were conducted in the South of France in July 2015. The first experiment was performed over the Camargue area and the second one over the Pech Rouge area (see Figure **1**).

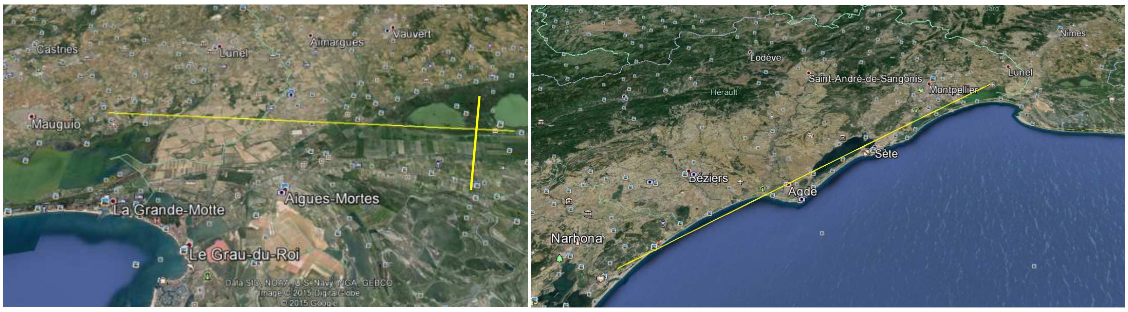

Figure 1- Extend of the test area in Camargue area (left), and Pech Rouge (right).

Two already existing devices were embedded on an ultra light aircraft. The first one is a GNSS-R sensor and the second one is a positioning sensor based on the hybridization of a GNSS receiver and an Inertial Measurement Unit.

Two antennas were also screwed into the plane (see Figure **2**). One on the top, which receives the direct GNSS signal, and one on the bottom, which receives the reflected GNSS signal. The top antenna is Right Hand Circular Polarized (RHCP) whereas that of the bottom is Left Hand Circular Polarized (LHCP) (signal polarization changes when reflected).

Figure 2- Installed antenna in the top (left) and bottom (right) sides of the ultra light aircraft.

Methodology

For the test flights, the following processing steps have been performed. At first, both direct and reflected Radio Frequency (RF) signals have been down-converted to Intermediate Frequency (IF). Then, based on the IF signals, time stamped complex cross-correlations waveforms and Doppler measurements have been extracted (L0 data). In a third step, the direct and reflected complex cross-correlations waveforms have been computed using the L0 data. Finally, the amplitude waveforms are obtained from these complex waveforms and after incoherent averaging (in order to reduce the thermal and speckle noise), the apparent reflectivity can be expressed as:

$$\left|\Gamma'_{pq}\right| = \left|\frac{Y_{r,q}(\Delta\tau, f)}{Y_{d,p}(0, f)}\right|^2, \qquad (1)$$

where $Y_{r,q}(\Delta\tau, f)$ refers to the reflected waveform at RHCP polarization, and $Y_{d,p}(0, f)$ refers to the direct waveform at LHCP polarization. The apparent reflectivity ranges between 0 and 1. The higher the reflectivity, the higher soil moisture content.

Once the apparent reflectivity is computed, each measurement must be geo-referenced. The exact position on the ground where the GNSS signal is reflected is called a “specular point”. The specular position of each reflectivity value is determined using both the position of the satellite and that of the GNSS-R receiver and is expressed in the WGS-84 reference system. The position of the receiver was computed based on the embedded GNSS/IMU hybridized sensor in order to cope with fluctuations on the reflectivity measurements du to the aircraft’s attitude.
It is to be noted that satellites with elevations below 60° were disregarded during the processing since the received signal power was too low.

Results and validation

The georeferenced reflectivity values obtained after post-processing have been shown upon Google Earth layout. The Figure **3** displays specular points for GPS 26 (left) and GPS 29 (right) satellites, respectively for Pech Rouge and Camargue area. Reflectivity values are illustrated with a color scale ranging from red (very low reflectivity, ~0.1) to blue (high reflectivity, ~0.75).

Since the overflown zones are both flood-prone areas, the images cannot be taken for granted: there might be slight differences in soil moisture content between the day when the images where taken and the day MISTRALE flights were performed. Nevertheless, it is very promising to note that the specular points colored in blue properly match the high humidity areas such as the river, basins or irrigation canals locations.

Figure 3- Up, Geo-referenced specular points over Google Earth of the Pech rouge for the PRN-26 (left), and Geo-referenced specular points over Google Earth of the Camargue area for the PRN-29 (right): zoom over an irrigation canal.

Additional results based on in situ humidity probes and near infrared sensors that have also been use to collect data during the July experimental flights will be presented in the full paper.

Conclusion and further improvements

In conclusion, during the early phase of the MISTRALE project, two experimental flights have been conducted with the aim to demonstrate the technical feasibility of measuring soil moisture content using a GNSS reflectometry sensor embedded in a RPAS. The paper will present the complete analysis of these tests (including benchmarking of the reflectometry sensor with in situ and near infrared measurements).
The next phases of the MISTRALE project are the integration of all subsystems in form factor that makes the final product easy to install on a RPAS, and the refinement of the reflectometry algorithm calibration.

The MISTRALE project has received funding from the European GNSS Agency under the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 641606.