GNSS-R TECHNOLOGY:
STATE OF THE ART AND USER REQUIREMENTS
JOSÉ DARROZES

European Global Navigation Satellite Systems Agency
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GNSS-R Technology
State-of-the-Art and User Requirements

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EXECUTIVE SUMMARY

In the MISTRALE project activities are taken to build the foundation of GNSS-R technology applications for soil moisture monitoring. As such, the State-of-the-Art analyses as well as the User Requirements collection are two activities in the project. This report contains the outcome of these two tasks.

The State-of-the-art will begin with an introduction on GNSS constellations and their quick development over the past decades. Since its premises in the 90s, the interest in reflectometry has grown with the arrival of new GNSS (GPS and GLONASS are now followed by Galileo, Beidou, etc.). GNSS-R, the common abbreviation for GNSS reflectometry, is based on the comparison of direct GNSS signal and the corresponding reflected ones.

In positioning application, the signal used corresponds to the direct path between the satellite and the receiver. Reflected signals are called “multi-path” and are avoided as much as possible. On the opposite, in GNSS-R applications, we take advantage of those reflected signals, not for positioning, but for characterizing the reflection surface properties (continental or oceanic surface). Since the power of reflected signal is lower than the direct one, conventional GNSS receiver needs to be adapted.

The MISTRALE project aims at developing this new type of dedicated instrument, not for altimetric purpose but for soil moisture measurements. The chosen technology for this receptor is so called interferometric GNSS-R (iGNSS-R). For specific moisture measurement, we used the interferometric complex field (ICF) method, which corresponds to the power ratio between the reflected and the direct signals. The complexity of this receptor is amplified by the fact that it must have a light weight, and it must also require low power consumption to be embedded on a Remotly Piloted Aircraft System (RPAS). The proposed solution must allow to quickly map the moisture of agricultural plots as well as flooded areas (moisture ≈ 100%) for a much lower cost than other receiver solutions embedded on an aircraft or a satellite. Another interesting aspect is the flexibility of the MISTRALE system, since the RPAS can fly at very low elevation (few meters) until few thousand meters. Moreover, the accuracy of the real time navigation system embedded on the RPAS will allow flights in complex environment like in mountainous areas or in adverse weather conditions and poor visibility.

Clearly, the MISTRALE product quality is nothing if there is no market that corresponds to this “high technological” product. To this end, we have explored the potential user needs to define the correct product for corresponding markets. The categories of potential users defined had been i) water use, ii) agriculture; and iii) research. The interviews of each users group gave us a insights in their needs. In this way, we have defined the priorities of the users and the technical capabilities that they want for the MISTRALE system: sampling frequency, covered areas, moisture uncertainties, processing chains, costs, and warning systems.

The water use group needs have been summarized in five key points:

  i) this group is interested in both “moisture measurement” and “flooding mapping” options;
  ii) they would like to characterise water properties (moisture and/or flooded surfaces) and in some case as hydropower electricity production they want information on the vegetation (plant moisture) during drought for example;
  iii) they would like to map “hidden water” in forest zone;
  iv) altimetric measurement is one of the minimum expectations of this group;
  v) for us the cost is not the most significant concerns, an automatic processing line is a priority.

For the farmers group, four key points were identified:
i) this group is primarily interested in moisture mapping;
ii) an information on soil moisture and water content of plant is essential;
iii) the cost is also essential: cheaper is better for this group;
iv) the possibility to have an automatic warning or a decision support system to define the areas where they have to sprinkle the plants during the heats period.

For the researchers, things are a bit different:

i) they want to get the raw data even though, for some members, the processed data could be an additional information;
ii) have a complete observation namely soil moisture, plant water content, flooded areas and altimetric measurement;
iii) they are interested on mapping but also in in situ measurement;
iv) the cost does not seems to be the main priority of this group;
v) the sampling frequency should vary between 1 s to few months;
vi) last point if the RPAS license (for flights) should be include in the MISTRALE solution.

FOREWORD

Observational evidence shows that many natural systems are being affected by regional climate changes, particularly temperature increases. Many studies present evidence of this phenomenon, with particular attention to issues facing water resources managers. Water resources are directly impacted by climate change, and the management of these resources affects many other parameters like ecosystem vulnerability, or human health. Water management is also expected to play an increasingly central role in adaptation. Climate change has the potential to affect many sectors in which water resource managers play an active role, including water availability, water quality, flood risk reduction, ecosystems, coastal areas, navigation, hydropower, and other energy sectors (e.g. cooling down of nuclear power station).

The goal of the project Mistrale is to develop a new sensor based on the GNSS Reflectometry technology to give accurate soil moisture and/or flooded maps to decision makers in water management, like players in water use, in European agriculture, in water policies, and in environmental research. The Mistrale project aims, also, to integrate the new GNSS-R receiver on a new dedicated RPAS. But our project has clear commercial objectives and to achieve this goal we need to know absolutely the users requirements. As the first step the project is focused on main targets correlated to the main players in water management namely water use, agriculture, natural reserve and research.

ABBREVIATIONS AND ACRONYMS

<p>| AB       | Advisory Board       |
| AJ       | L'Avion Jaune        |
| AltBOC   | Alternate Binary Offset Carrier |
| AS       | Administrative Services |
| AV       | AeroVision          |
| ATC      | Air Traffic Control |
| BOC      | Binary Offset Carrier |
| BPS      | Bit Per Second      |</p>
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>CA</td>
<td>Consortium Agreement</td>
</tr>
<tr>
<td>CAP</td>
<td>Common Agricultural Policy</td>
</tr>
<tr>
<td>CBOC</td>
<td>Composite Binary Offset Carrier</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>DEL</td>
<td>Deliverable</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DoT</td>
<td>DESCRIPTION OF TOPIC</td>
</tr>
<tr>
<td>DoW</td>
<td>Description of Work – Annex to the Grant Agreement</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EDAS</td>
<td>EGNOS Data Access Service</td>
</tr>
<tr>
<td>EDF</td>
<td>Électricité de France</td>
</tr>
<tr>
<td>EGNOS</td>
<td>European Geostationary Navigation Overlay Service</td>
</tr>
<tr>
<td>EM</td>
<td>ElectroMagnetic</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>FMS</td>
<td>Farm Management System</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>GBAS</td>
<td>Ground-Based Augmentation Systems</td>
</tr>
<tr>
<td>GCS</td>
<td>Ground Control Station</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary satellite</td>
</tr>
<tr>
<td>GET</td>
<td>Geosciences Environnement Toulouse</td>
</tr>
<tr>
<td>GFZ</td>
<td>German Research Centre for Geosciences</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GLONASS</td>
<td>GLObal NAvigation Satellite System</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite Systems</td>
</tr>
<tr>
<td>GNSS-R</td>
<td>Reflected GNSS</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GSA</td>
<td>European GNSS Agency</td>
</tr>
<tr>
<td>IOV</td>
<td>In orbit validation satellite</td>
</tr>
<tr>
<td>IPT</td>
<td>Interference Pattern Technique</td>
</tr>
<tr>
<td>IRNSS</td>
<td>Indian regional navigation satellite system</td>
</tr>
<tr>
<td>JRC</td>
<td>Joint Research Centre of the EC</td>
</tr>
<tr>
<td>JRC-IES</td>
<td>Institute for Environment and Sustainability, European Commission’s Joint Research Centre</td>
</tr>
<tr>
<td>KGO</td>
<td>Kirchhoff geometrical optics</td>
</tr>
<tr>
<td>LHCP</td>
<td>Left Hand Circular Polarization</td>
</tr>
<tr>
<td>LSIM</td>
<td>Least Square Inversion Method</td>
</tr>
<tr>
<td>MSSB</td>
<td>M3Systems Belgium</td>
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<tr>
<td>MBOC</td>
<td>Multiplexed BOC</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium Earth Orbit</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Agency</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalized Difference Vegetation Index</td>
</tr>
<tr>
<td>PRN</td>
<td>Pseudo Random Noise</td>
</tr>
<tr>
<td>RE</td>
<td>Restricted</td>
</tr>
<tr>
<td>RHCP</td>
<td>Right Hand Circular Polarization</td>
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<tr>
<td>RPAS</td>
<td>Remotly Piloted Aircraft System</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>--------------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>RTK</td>
<td>Real Time Kinematic</td>
</tr>
<tr>
<td>SBAS</td>
<td>Satellite/Space-Based Augmentation Systems</td>
</tr>
<tr>
<td>SMC</td>
<td>Soil Moisture Content</td>
</tr>
<tr>
<td>SME</td>
<td>Small and medium enterprises</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal Noise Ratio</td>
</tr>
<tr>
<td>SPM</td>
<td>Scientific Project Manager</td>
</tr>
<tr>
<td>STR</td>
<td>Starlab</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td>VIR</td>
<td>Visible and Infra-Red</td>
</tr>
<tr>
<td>WAAS</td>
<td>Wide Area Augmentation System</td>
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<tr>
<td>WP</td>
<td>Work Package</td>
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1 INTRODUCTION

1.1 Purpose and scope
The purpose and scope of this document is to report on the activities that aim at defining properly the basis of the project in terms of potential user needs, requirements and expectations, and in terms of technical maturity and performances of the GNSS reflectometry.

This twofold analysis is reflected in the report structure. The first part of the reports contains the state-of-the-art analysis, and the second part of the document covers the user needs and requirements.

1.2 Intended audience / Classification
This document is intended for all project partners and WP participants and is in first instance written as an internal report. As the information is relevant to a wider audience, the report is made public.

1.3 Reference Documentation
There is no specific reference documentation to this document. Used (scientific) references are mentioned in the usual way and taken up in the bibliography.

1.4 Structure of the document
The structure of the document is as follow:

- Chapter 1 is this introduction
- Chapter 2 covers the state-of-the-art of the GNSS reflectometry
- Chapter 3 summarizes the outcomes of the user needs collection work
- Chapter 4 is dedicated to the consolidation of the user needs
- Chapter 5 contains the document conclusions and recommendations
2 STATE-OF-THE-ART

The scope of this section is to document, in a simple and comprehensive way a State-Of-the-art review of the GNSS Reflectometry techniques, know a GNSS-R. Methodological base, technical aspect and applications will be presented.

The section is divided in 3 paragraphs structured as follows:

1. Presentation of GPS and GNSS concept and evolution. We present a brief review of the GNSS constellations and the associated coverage, a short presentation of current and future signals is also presented.
2. Presentation of the GNSS-R concept and 2 two main families of technique:
   i. Interference pattern technique using a classical receiver and a standard antenna;
   ii. Waveform technique using specific receiver and two or more antennas.
3. Highlights on applications linked to moisture measurement, continental water mapping, and looking their user requirements. Some of the analysis techniques have the possibility to be used to any platforms define in the MISTRALE project i.e. rigid masts (ground-based), RPAS (from low elevation/velocity until intermediary elevation/velocity), aircraft (intermediary elevation/velocity to high velocity), we also used the IPT (see below) only for in situ (ground-based) validation of our specific receiver.

2.1 GNSS history

Global Navigational Satellite System (GNSS) constellations were defined to provide a continuous service for a non-limited number of users. The active GNSS satellite generate an all-weather microwave L-band signals designed for navigation, that is, to solve the time, velocity and position coordinates of a device, passive receiver, near the Earth surface, capable of receiving GNSS signals. This system evolves to a more important infrastructure every passing days.

2.1.1 GNSS constellations and coverage

The common ancestor is the Global Positioning System (GPS) that everybody uses routinely in his car or with his mobile phone. It is constituted of 32 satellites at Medium Elevation Orbits (MEO~20000km). But from a scientific point of view it has also demonstrated success, the international GNSS service (IGS) and its network of stations can track with high precision global phenomena such as plate tectonics (Figure 1), the evolution of atmospheric water vapor [97], tsunami [98] or more local events like landslides [99] using real time kinematic (RTK) or differential GPS (DGPS).

But our ancestor has evolved over the last few decades: later satellite model incorporated the first atomic frequency stability, used a satellite ranging called pseudo random noise (PRN), the block II improved reliability, in 2005 the block IIR-M add new signals (L2P (Y) Civilian L2C, and military L2M, L5 in 2010 with the lock IIF see Figure 3). GPS today uses 24 (32 effective) operative satellites and numerous ground stations. And during the 1990–1991 crisis in Iraq, it was the US army, through its involvement in the war that gave a boost to the commercial GPS market. Surely improve of GNSS comes from launching of a new operational Russian constellation known as GLONASS (Figure 2).

GLONASS constellation has similar characteristics with a slightly different signal structure: satellites modulate the central frequency to discriminate GLONASS satellite. These operational systems currently contain 28 MEO satellites.
Figure 1: General plate motions on a global scale. Regional maps show far more complicated motion vectors. Length of arrows indicates rate of movement of that part of the plate. (Map from UNAVCO Plate Motion Calculator).

Figure 2: One day of GPS and GLONASS satellite positionning, laps time between two positions = 15 min (courtesy of N. Roussel).

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Wavelength</th>
<th>Satellites</th>
<th>Modulation</th>
<th>Multiple Access</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>L1, L2, L5</td>
<td>32 MEO</td>
<td>BPSK, BOC</td>
<td>CDMA</td>
</tr>
<tr>
<td>GLONASS</td>
<td>L1, L2, L3, L5</td>
<td>24 MEA</td>
<td>BPSK, BOC</td>
<td>FDMA &amp; CDMA</td>
</tr>
<tr>
<td>GALILEO</td>
<td>E1, E5, E8</td>
<td>4 IOV → 30</td>
<td>BPSK, BOC, MBOC, AltBOC</td>
<td>CDMA</td>
</tr>
<tr>
<td>COMPASS</td>
<td>B1, B2, B3, L5</td>
<td>5 → 27 MEO, GEO; 3–5 IGSO</td>
<td>QPSK, BOC, MBOC</td>
<td>CDMA</td>
</tr>
</tbody>
</table>

Table 1: GNSS constellation characteristics: arrow gives the constellation evolution in term of future launch. Channel modulations encountered in GNSS are BPSK: Binary Phase shift Keying (traditional); BOC: Binary Offset Carrier (sine and cosine variants); MBOC: Multiplexed BOC and AltBOC: Alternate BOC.
Two Global Systems are, currently, being developed. The European Galileo, currently with 2 prototypes and 4 in orbit validation satellites (IOV) orbiting and transmitting navigation signals, Galileo is interoperable with GPS and GLONASS. This interoperability will allow manufacturers to develop multi-frequency receivers (L1/E1 and E5/L5, Figure 3) that work with Galileo and GPS/GLONASS. The Chinese Compass is the new version of the regional navigation system so called Beidou-1 of geostationary satellites (GEO). These systems could be achieved completely with
the deployment of 27 and 25 MEO respectively each by 2020. In addition Beidou-2 will keep 5 geostationary (GEO) and 6 geosynchronous inclined orbit transmitters for regional augmentation. Currently, Beidou-2 has 7 MEO orbiting and transmitting, and 5 geostationary satellites and 6 geosynchronous ones.

For Europe and part of Africa, the new transmitting signal EGNOS (Figure 4) provides both correction and integrity information about the GPS/GLONASS/GALILEO systems. EGNOS, which is similar to WAAS service for North America, is a satellite based augmentation system (SBAS) developed by the European Space Agency and consists of four geostationary satellites and a network of ground stations with a terrestrial data access called EGNOS Data Access Service (EDAS). The complete service is built for sharpening the accuracy of GPS/GLONASS and GALILEO signals across Europe and part of Africa. The EGNOS Safety-of-life (SoL) Service was certified for civil aviation in 2011.

![Figure 4: EGNOS augmentation system and its associated terrestrial network.](image)

If you look in details we can observe that GPS and GLONASS can provide, by 2020, including future operative GALILEO constellation (Figure 5) as many as 20 or 30 visible satellites simultaneously. Additionally, a simulation of a “future” constellation that uses both the GPS and Galileo constellations have demonstrate the impressive revisit statistics achievable using constellations of GNSS-R remote-sensing satellites with a mean revisit time over entire globe less than two hours.
2.1.2 GNSS signals

The GPS satellites have highly precise oscillators with a fundamental frequency $f$ of 10.23 MHz and transmit continually two microwave L-Band carrier signals (Figure 3 and Figure 6).

- The L1 frequency ($154 \times f = 1575.42$ MHz, $\lambda_1 = 19$ cm) carries the navigation message and the Standard Positioning Service (SPS) code signals.
- The L2 frequency ($120 \times f = 1227.60$ MHz, $\lambda_2 = 24.4$ cm) is used to give Precise positioning Service (PPS) for equipped receivers. Three binary codes (C/A, P(Y), Navigation message, Figure 6), shift the phase of L1 and L2 carrier:
  i. The Coarse Acquisition (C/A) is a repeating 1 MHz pseudo random noise (PRN) code and it modulates in-phase and quadrature the L1 carrier [18] as show in (eq. 1) and on L2, for a long time, only the P code [18] was broadcast as shown in (eq. 2);
  ii. The Precise code P(Y), modulates both L1 and L2 phases. It is a 10 MHz PRN code with a very long period of 266 days; 7 days/sat, and a wavelength of 29.31 m;

$$S_1(t) = \sqrt{2 P_{C/A, L_1}} D(t) C/A(t) \cos(2 \pi f_1 t + \phi_{L_1}) + \sqrt{2 P_{P(Y), L_2}} D(t) P(t) \sin(2 \pi f_1 t + \phi_{L_2}), \quad (eq. 1)$$

where $S_1(t)$ is the transmitted signal of the satellite $j$, $P_{C/A}$ is the transmitted power for the civil signal at L1, and $P_{n_1}$ is the transmitted power for the restricted signal at L1.

$$S_2(t) = \sqrt{2 P_{P(Y), L_2}} P(t) \cos(2 \pi f_2 t + \phi_{L_2}), \quad (eq. 2)$$

where $S_2(t)$ is the transmitted signal of the satellite $j$, $P_{PP}$ is the transmitted power for the restricted signal at L2.
iii. the last code is the navigation message (NAV and it is upgrade version CNAV of 2014) and it is a 50 bit/s with data cycle length of 30s. Data describe the satellite orbits, clock corrections and other parameters, for more details one can see [16].

To improve the accuracy of the positioning mono-frequency receiver needs ionospheric corrections (from SBAS like WAAS or EGNOS) or modelling, but, at the 1st order, bi-frequency ones allow estimation of the ionospheric frequency delay using (eq. 3):

\[
\Delta t_1 = \frac{f_2^2}{f_1^2 - f_2^2} \delta(\Delta t)
\]  

(eq. 3)

where \(\Delta t_1\) is the time delay at L1 due to the ionospheric effect, f1 and f2 are the L1 and L2 frequencies and \(\delta(\Delta t)\) is the measured time difference between f1 and f2.

And the ionospheric-free (eq. 4) linear combination of L1 and L2 is one that eliminates first order ionospheric effects from GPS observables:

\[
\rho_{\text{iono free}} = \frac{\rho_1 f_1^2 - \rho_2 f_2^2}{f_1^2 - f_2^2}
\]  

(eq. 4)

where \(\rho_1\) and \(\rho_2\) the observables as measured at frequency \(f_1\) and \(f_2\). The disadvantage of using a linear combination of observables is that the noise of the combination increases.
2.1.3 New GNSS Signals

The L5 signal starts on April 10, 2009 and includes in-phase (I) and quadrature (Q) components (Figure 3), each with ½ of the total transmitted power. L5 are BPSK(10) modulated yielding a chip rate of 10.23 Mchips and their spreading sequences consist of a combination of two codes. The primary codes (LFSR based) have a length of 10230 chips yielding an I code period of 1 ms and the Q ones have respectively lengths of 10 and 20 chips. The reference bandwidth, defined Space Segment/User Segment L5 Interfaces, is approximately 24*1.023MHz. The I channel is the data channel and the Q one corresponds to a pilot channel, being also modulated by a 100 sps train due to the ½ rate encoding of a 50 bps CNAV navigation data.

The Galileo E5 signal use AltBOC(15,10) modulation/multiplexing and can be separated into two sub-bands, E5a and E5b, which can be processed independently using Single Side-Band (SSB) processing [19] and results in two “equivalent” sub bands with BPSK(10) modulation. E5a and E5b have also I (data) and Q (pilot). The E5a and the GPS L5 band share the same carrier, the E5a and E5b signals maximize compatibility, in terms of modulation and signal structure, with the GPS L5 signals.

Quasi-Zenith Satellite System (QZSS, Japan) is a constellation of four Space Based Augmentation System (SBAS) satellites, including three satellites in Tundra orbits and one in a geosynchronous orbit. It corresponds to EGNOS/WAAS services and gives an additional coverage in the western pacific region.

India’s Regional Navigation Satellite System (IRNSS, India) is a system of seven satellites in lower inclination which are intended to provide a navigation capability for India, but it can also to be used for remote-sensing applications.

2.2 GNSS epic

GNSS reflectometry (GNSS-R) consists in recovering the electromagnetic signals emitted continuously by the GNSS satellites (GPS, GLONASS, BEIDOU and GALILEO) currently in orbit and then reflected on the Earth surface: oceans, continental waters (rivers, lakes), and continental surfaces. The first application of using GNSS signals reflected of the Earth’s surface for scatterometry purposes was proposed by [20]. Years after, one of the pioneer of this new science, Martin Neira, show its applicability to estimate sea level [1]. He used the correlation analysis of the phase delay between the direct and reflected signal of the same satellite to determine the position of the reflection point in time (geometric information) and to estimate parameters such as sea level or level of Inland Water [2-6]. During the calibration phase of the SIR-C radar experiment on-board the U.S. Space Shuttle results gives the first reflection at steep incidence and were serendipitously discovered [21]. With many similitudes to classical method of RADAR remote sensing, the GNSS reflectometry can be applied to remote sensing of various types of natural covers, such as ocean, land, ice, snow, vegetation. The analysis of waveforms gives access, meanwhile, to various parameters such as soil moisture [7,8], surface roughness [9], the wind speed at the sea surface [10], the thickness and structure of the snow cover on the northern plains [11], and the polar ice caps [12,13].

Although originally designed for navigation, GNSS has evolved using signal of opportunity in GNSS-R. GNSS-R can be used for a large variety of applications, and, particularly, for Earth remote sensing [22]. The GNSSR remote sensing techniques can be divided into two main families:
i) The first family used a GNSS Bistatic Multi-Beam Radar and will analyse directly the
GNSS waveform using specific receiver and two or more antenna (see §2.2.1). This
technique is very promising due to is flexibility: it can be used for in situ, aircraft and
satellite applications. For the MISTRAL project, this methodology will be associated to
aircraft/RPAS to develop mapping services for soil moisture and flooded area

ii) the second one (see §2.2.2) use a classical GNSS receiver and only one antenna, so it
is designed as low cost technique, it is also a promising technique but for in situ and low
elevation fly (RPAS, Aircraft). However due to the large amount of GNSS network
existing worldwide it is possible to re-use some of these stations to make
environmental system monitoring (soil moisture, biomass, flooded area etc.). For
MISTRAL project, this methodology will be used to validate aircraft and RPAS
campaigns by appropriated ground measurements.

2.2.1 GNSS Bistatic Multi-Beam Radar – Basic Principle

The observables of the GNSS-R are the waveforms. The observables are defined as measurable
objects (like correlation counts, voltages, power) from which geophysical parameter's (roughness,
motion, electric conductivity, relative permittivity) can be derived. These waveforms can be obtain
by cross-correlating the recorded signal from the down-looking antenna with a replica of the PRN
code of the GNSS satellite for a set of different time lags and different carrier frequency offsets [20].
Only replicas modelled appropriately i.e. with the PRN, the range and frequency corresponding to
the incoming signal will generate waveforms above the noise. The power waveforms are modelled
using the bi-static radar equation [23, 24] (eq. 5), assuming that the electromagnetic propagation
corresponds to “rays” and each contribution to the scattering are locally specular and by considering
Gaussian surface statistics and using the Kirchhoff geometrical optics scattering approach (KGO).

So for fully diffuse scattering of the GNSS signal from a rough surface, the following bistatic radar
equation holds for the ensemble mean of the correlation power as a function of the time delay and
the frequency offset, and it known as a delay-Doppler map (DDM, [27]).

\[
\langle |Y(t,f)|^2 \rangle = \frac{k^2}{4\pi} T^2 \int P_r G_s R_s^2 \int \chi^2(t,f) \sigma_0 dS,
\]  (eq 5)

where: \( T \) is the coherent integration time; \( P_r, G_s \) is the transmitter’s Effective Isotropic Radiated Power;
\( G_r, R_r, R_s \) are distances between the nominal specular point and the transmitter/receiver, respectively; \( \chi^2 \) is the Woodward Ambiguity Function (WAF), which
describes the range and Doppler selectivity of the coherent radar [23]; \( \sigma_0 \) is the normalized bistatic
radar cross section (BRCS) of the rough surface (eq. 6), which gives a portion of the scattered power
carried by the outgoing plane wave in a specific direction, while the unit surface is being illuminated
by the unit wave incoming in another direction [20]. So, if one look that in term of surface coordinates,
it describes the glistening zone of the rough surface \( \sigma_0 \) depends on the signal polarization state,
the complex dielectric constant \( \varepsilon = \varepsilon_r - j \frac{\sigma}{\omega \varepsilon_o} \), and the relative permittivity \( \varepsilon_r \) of the reflecting surface
and the local incidence angle. In the commonly used KGO approximation, the bi-static scattering
coefficient is:

\[
\sigma_0 = \pi k^2 R_{\text{scat}}^2 \int_0^\infty \int_0^\infty \left| \frac{\varepsilon_r}{\varepsilon_0} \right|^2 \text{PDF}(Z_x, Z_y)
\]  (eq 6)

where \( k \) is the wavenumber; \( R_{\text{scat}} \) the scattering coefficients; and \( \text{PDF}(Z_x, Z_y) \) is the 2-D Probability
Density Function of the surface slopes \( Z \), along \( Z_x \), and \( Z_y \). For the direct signal, the incident
polarization is Right-Hand Circular, and for the reflected one it switches to Left-Hand Circular until the Brewster angle (varying with the geophysical parameters of the reflection surface) where the polarization becomes more complex. In the case of the sea surface, the probability density function PDF(Zx, Zy) of the large-scale slopes component (i.e. more than several radio wavelengths) is responsible for the quasi-specular scattering within the glistening zone.

The interesting point came from the WAF which can be approximated by the simple square product of two functions: the correlation function \( \Lambda(\tau) \) and the sinc-shaped function \( S(f) \). The first term corresponds to equi-range annulus zone, and the second one to the equi-Doppler-frequency zone. The width of \( \Lambda(\tau) \) is 2 \( \tau_c \) i.e. 2 x length of PRN chip; and the width of \( S(f) \) corresponds to \( f_{Dop} = 2/T \) i.e. two times the inverse of the coherent integration time. For simplicity ones \([20, 23, 26]\) assume that if the modulation corresponds to a BKPS code (e.g. L1 C/A) the autocorrelation function is then a triangle function and correlates coherently during \( T_c \) seconds (typically \(+1 \text{ ms}\) (eq. 7):

\[
\Lambda_{T_c}(\tau) = \begin{cases} 
1 - \frac{\tau}{T_c}, & |\tau| < \tau_c \\
0, & \text{elsewhere}
\end{cases}
\] (eq. 7)

where \( \tau \) is the time lag, e.g. for the L1 C/A code, \( \tau_c = 0.977 \mu s \), which corresponds to 293 m.

The cross-correlation of the signal against this replica (eq. 8) acts thus as a frequency filter and it is sensitive to residual components of the frequency. This is given by the sinc-exponential function (eq. 9):

\[
\text{rep}(t,f_c) = c(t) e^{i2\pi f_c t}
\] (eq. 8)

where \( f_c \) is the central correlation frequency, and \( \text{rep} \) is the replica of the signal and it is mounted on a carrier or intermediate frequency phasor [26].

\[
S(\delta f) = \frac{1}{\tau_c} \int_0^{\tau_c} e^{-i2\pi f t} dt = \frac{\sin(\pi \delta f \tau_c)}{\pi \delta f \tau_c} e^{-i\pi \delta f \tau_c}
\] (eq. 9)

There are certain limitations associated with the use of bistatic radar equation (eq. 11), it is limited to the case of completely diffuse surface scattering (i.e. negligible coherent specular component). Nevertheless, if the coherent component is noticeable (e.g. calm seas, flat land, or flat sea ice), ones can solve the problem by augmenting bistatic radar equation with a term describing a coherent reflection constructed from a product of a mirrored proxy of the direct signal cross- correlation power [20]: \(|Y_0(\tau, f)^2|Y_0(\tau, f)^2|\)

The absolute value squared of the Fresnel reflection coefficient, and the factor that takes into account the loss of the spatial coherence due to the presence of some relatively weak surface roughness. The equation 11 define an accurate DDM peak centred at the delay and the frequency offset associated with the nominal specular point on the surface:

\[
\langle |Y(\tau, f)|^2 \rangle_{\text{spec}} = |Y_0(\tau, f)|^2 |R_{\text{spec}}|^2 \exp(-8\pi \sigma_k^2 \cos^2 \frac{\theta}{\lambda})
\] (eq. 11)

From the bistatic radar equation (eq. 11), the DDM corresponds as a convolution of the WAF with the BRCS function within the antenna footprint described by its gain pattern. Ones can consider the DDM as an image of the scattering coefficient in the delay-Doppler domain. The WAF is close
to 1 within an area formed by the intersection of the annulus zone and the Doppler zone, and decreases progressively to 0, as an inverse function of the distance to the specular point, outside this area. It means that there are certain contours on the surface for which the scattered signal has the same travelling path length upon arrival to the receiver. Frequently, the bistatic radar equation is used with a BCRS, $\sigma_0$ in the form of the geometric optics limit of the Kirchhoff approximation (KA) but it is not a necessary condition. Any others reasonable EM scattering models can be used in the equation of the bistatic Radar (see § 2.2.2).

2.2.2 EM Scattering model

Among authors ([28], [29], [30], [31]) have look the effect of the Earth’s surface on the bistatic radar equation (eq. 5) through the normalized bistatic BRCS and depends on the directions of incoming and outgoing EM waves, and on the properties of the scattering surface. In most of the models mentioned, when calculating $\sigma_0$ one needs to make an assumption about the probability distribution (e.g. bivariate Gaussian, normal) of the surface elevations or slopes. We look, herein, only the most popular models that sort in the literature (see, e.g., [41]).

The Kirchhoff Approximation (KA) [29, 31, 2], implies that every point on the scattering surface should present a large radius of curvature (compared to the EM wavelength). Moreover, the surface correlation length must be larger than the EM wavelength. The total fields (incident & reflected) at any point on the surface are approximated by those that would be present on an $\infty$ extended tangent plane at the surface integration point. Each contribution to the scattering is considered to be locally specular and it depends on the Fresnel reflection coefficients at the facet plane on each surface point.

The most implemented approaches in GNSS-R studies is the Kirchhoff Geometrical Optics (KGO) [30] and it is a limit of the KA. It needs a large standard deviation of the surface height compared to the EM wavelength (high frequency limit). It estimates the Kirchhoff diffraction integral by the
stationary phase method. The physical meaning of the assumptions behind this limit is to constraint the reflection process to those areas in the surface from where the received phase is nearly constant (mainly well-oriented facets). It also corresponds to those areas in which the surface is locally oriented such that its local normal corresponds to the bisector angle between the incidence direction and the direction pointing from that particular surface point towards the receiver. The KGO approximation gives an incorrect prediction for BRCS for out-of-plane scattering, and for the right-hand circular polarization (RHCP). This is due to the fact that we have to take into account for diffraction effects which are, by definition, neglected.

From the same author [30] another evolution of the KA was presented the so-called Kirchhoff Approximation in physical optics approximation (KPO). It needs small vertical scale roughness and small slope statistic. This approximation does not only works with well-oriented facet like KGO but it take into account all the contribution of the scattered field associated to the entire surface if the vertical roughness is weak.

The Small Perturbation Method (SPM) resolves the partial differential boundary equation by expanding the field in a perturbation series of the slopes of the surface [33], [34]. In that case, the standard deviation of the surface height is smaller than EM wavelength, and the surface correlation length is smaller than EM wavelength. The SPM is a good model for small slopes statistics, it is the most appropriate for Bragg scattering issues, and to assess polarimetric performances.

Most of the Earth reflecting surfaces have a continuous roughness spectra, The Two-Scale Composite Model (2SCM) tries to explore and combines the large, modelled through KGO, and the small roughness scale, modelled through SPM into the scattered field [28][35]. 2SCM is heuristic by nature and it requires an arbitrary spectral splitting parameter which divides the surface elevation spectrum into two parts: small-scale and large scale spectral components of roughness. The main problem of the 2SCM is to define the limit between these two scales. The 2SCM permits to account for scattering mechanisms such as diffraction and Bragg resonance.

The Integral Equation Method (IEM) tries to unify also the gap between KA and SPM and tries to cover all roughness scales [36][37]. The IEM is accurate but computationally expensive and serve as reference to compare with the other models. The integral equations of the EM fields are solved iteratively from the charges and electric currents on the sea surface. In the first iteration, we are in the KA and only the induced currents are used. The second iteration, in the small slope statistics, leads to the SPM.

The Small Slope Approximation (SSA) tries to resolve the same problematic e.g. to unify KA and SPM [38][39]. [40] proved existing differences between KGO and SSA models of normalized BRCS at L1, at off-specular angles of the scattering co-polar component. The SSA provided that the slopes of the roughness are small compared to the angles of incidence and scattering.

2.2.3 GNSS-R Waveform Receiver

This technical section is directly derived from the compilation presented by [24], we have just improve the compilation with the new STARLAB receiver which will be used in the MISTRAL project. This receiver and the associated software were presented in the GNSS+R 2015 meeting in Potsdam.

The classical/conventional GNSS Reflectometer’s architecture (cGNSS-R, [22]) is structured as follows:
\[
Y^c(t, \tau, f_d) = \frac{1}{T_c} \int_0^{T_c} s_n(t') a(t') \exp^{-j2\pi(f_c + f_d)t'} dt'.
\]
(eq. 12)

cGNSS-R correlates coherently during \(T_c\) seconds (typically +1 ms) the reflected/multipath signal \(s_n(t)\) with a locally generated replica of the transmitted signal \(a(t)\) (open C/A codes only) after proper compensation of the Doppler frequency shift \(f_d\) or for a number of Doppler frequencies (eq. 12), and where \(t\) is the start time of the integration.

The reflected signal have a weaker amplitude and a weaker thermal noise than the direct one, but it suffers of an important classical, well known, speckle noise so to diminish this noise a large number of incoherent averages \(N\) is necessary to used the improved SNR of the signal \(Y^c\) (eq. 13).

\[
\langle |Y^c(\tau, f_d)|^2 \rangle \approx \frac{1}{N} \sum_{n=1}^{N} |Y^c(t_n, \tau, f_d)|
\]
(eq. 13)

The main problem with the cGNSSR receiver is that for the same SNR, a larger RMS bandwidth is needed to have a better range resolution, to overcome the bandwidth limitation ones [42] develop the so-called interferometric GNSS-R (iGNSS-R) method.

### 2.2.4 iGNSS-R: INTERFEROMETRIC or PARIS

In this method the reflected signal is cross-correlated with the direct signal itself \(S_d(t)\) after proper Doppler frequency and delay adjustments ([22]):
One can retrieved the same equations that cGNSSR (see eq. 12 & 13) but replacing the replica $a$ by the direct signal $S_d$ (eq. 14 & 15).

$$Y^c(t, \tau, f_d) = \frac{1}{T_c} \int_{t}^{t+T_c} s_R(t') s^*_d(t' - \tau) \exp^{-j2\pi(f_c + f_d)t'} \, dt'$$  \hspace{1cm} (eq. 14)

$$\langle |Y(\tau, f_d)|^2 \rangle \approx \frac{1}{N} \sum_{n=1}^{N} |Y(t_n, \tau, f_d)|.$$  \hspace{1cm} (eq. 15)

The comparison of the two technologies is not so simple (Figure 10) and each one has its advantages and its defaults.

![Figure 9: Schematic Basic Concept of an interferometric GNSS-R instrument (modified from [23])](image)

![Figure 10: Normalized wave forms from measured data acquired over the Baltic Sea at ~3km altitude using two receivers simultaneously. (Left) data from a cGNSS-R receiver working with C/A code (GOLD-RTR), and (right) data from a iGNSS-R receiver for a satellite transmitting C/A+P(Y)+M codes (PIR/A). Coherent integration time of 1ms and incoherent integration time of $T_{in} = 10s$ have been used in these examples. Here, the zero delay is set ad hoc at the peak power, and the delay axis $\tau$ is given in units of length (in meters). From [27].](image)

For cGNSS-R the code replica is generated locally, which provides the following pros and cons:
<table>
<thead>
<tr>
<th>Advantages</th>
<th>Downsides</th>
</tr>
</thead>
<tbody>
<tr>
<td>• it allows one to separate signals from different satellites by their specific code</td>
<td>• An available public C/A code for altimetry is not feasible due to their limited bandwidth which leads to a limited range resolution. But it could be promising in the future, when precise public codes will be widely available (Galileo E5, GPS L5). These precise codes would be needed at two frequencies for ionospheric corrections if not cGNSS-R will have limited performance for altimetric applications.</td>
</tr>
<tr>
<td>• it inherently has an infinite SNR;</td>
<td>• The delay and Doppler frequency dynamics for these codes are larger, and these values must be adjusted more frequently for proper operation [43].</td>
</tr>
<tr>
<td>• small size of antennas can be employed to track the reflected signals</td>
<td></td>
</tr>
</tbody>
</table>

This approach is the one used in all the GNSS-R experiments until 2010, and most of the campaigns between 2010 and 2013. It is also the receiver signal-processing approach to be implemented at the NASA recently approved CYGNSS Mission.

For iGNSS-R, the pros and cons are as follow:

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Downsides</th>
</tr>
</thead>
<tbody>
<tr>
<td>• No need to know the code, since the direct signal itself is used instead. It allows using also other signals of opportunity like satellite radio, satellite television, or any other sources with larger transmitted power, larger bandwidth, and better SNR, leading to potentially improved range resolution.</td>
<td>• The main drawbacks are the very large antenna size (directivity) required for the up-looking antenna, which leads to the use of beam-steering techniques, and/or multi-beam antennas [23].</td>
</tr>
<tr>
<td>• the differential processing produced in the cross-correlation leads to slower delay and Doppler frequency dynamics [43], which are, it seems, easier to track.</td>
<td></td>
</tr>
</tbody>
</table>

ESA consortium have designed and manufactured the only existing iGNSS-R receiver, and three experimental campaigns have been conducted, a ground-based and two air-borne experiments. This technique is the one suggested for the ESA PARIS In Orbit Demonstrator mission (PARIS- IOD) [42], this technique provides altimetric estimates of at least twice precision than the cGNSS- R approach.

To overcome these limitations, newer approaches have been proposed:

• The reconstructed GNSS-R (rGNSS-R) [44]–[46] and this technique is similar to the cGNSS-R technique, but semicodeless techniques are used to reconstruct the P(Y) code which is
then correlated with the reflected signal. The potentiality of P(Y) code has been modelized by [45] to test its effectiveness.

- The partial interferometric GNSS-R (piGNSS-R) [47]. It is similar to the iGNSS-R technique, but the P and M codes of the direct signal are extracted from the direct signal by coherent demodulation, and the interferometric approach is then applied to the reflected signal.

2.2.5 Existing GNSS-R Receiver

Mistrale GNSS-R receiver solution has been compared to the main experimental receivers, including some commercial ones (hardware and software, see table 2). We pointed out many advances in the most up-to-date receivers: for instance, Mistrale GNSS-R receiver has four channels and permits the acquisition of both the direct and the two reflected signals (with RHCP and LHCP polarizations). This feature is particularly interesting for soil moisture applications because we can distinguish moisture from roughness variations of the ground. Thanks to the mitigation between moisture and roughness parameters, the accuracy of soil moisture measurement is improved.

The possibility to have RHCP and LHCP reflected measurements allows to obtain a complete description of the coplanar and crossplanar reflection coefficients (see p. 32). One can also identify the part of the direct signal on the reflected one and reversely, making the correction of this mixed signal possible. This can be done during in-flight manoeuvring, such as a steep turn. Another important point is the synchronization in time of the channels. This is carried out using a very precise clock, allowing the precise comparison of the direct and the two reflected channels (neglected delay due to the synchronization). Mistrale receiver can record many constellations like GPS and GALILEO, and especially the E5 ALTBOC signal (that have a more precise correlation function (see §2.1.3)), but this comes at a cost: the use of E5 signal also needs a larger bandwith (>50 MHz, table 2) than L1 signal.

The accuracy of the Mistrale “Low Cost” receiver has not been neglected, and due to the height of flight of the RPAS, the spatial resolution is also accurate with a submetric resolution (directelly correlated to the flight height and satellite elevation). It is quite a different approach from what is proposed by scientific receivers that are designed for satellite applications and not for RPAS ones. The antenna gain pattern is also very different due to the longer ray path of remote sensing receivers to be embedded on board satellite.
<table>
<thead>
<tr>
<th>Name</th>
<th>hardware/software</th>
<th>RF channels</th>
<th>Bands</th>
<th>Bandwidth (MHz)</th>
<th>sampling rate (MHz)</th>
<th>output rate (Hz)</th>
<th>Architecture</th>
<th>Constellations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(gn)PAU</td>
<td>hardware</td>
<td>(1/2)</td>
<td>L1</td>
<td>2.2 (5.745)</td>
<td>16.384</td>
<td>cGNSS-R(C/A)</td>
<td>GPS</td>
<td></td>
</tr>
<tr>
<td>BJ</td>
<td>software</td>
<td>4</td>
<td>L1+L2</td>
<td>18</td>
<td>20</td>
<td>20MHz</td>
<td>RAW</td>
<td>GPS</td>
</tr>
<tr>
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<td>software</td>
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<td>L1</td>
<td>5.7</td>
<td>-</td>
<td>-</td>
<td>RAW</td>
<td>GPS</td>
</tr>
<tr>
<td>COSMIC IIB 2016</td>
<td>hardware</td>
<td>6</td>
<td>L1 L2 L5 E1 E2 E5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>multiple steered beams</td>
<td>GPS, Galileo, Glonass</td>
</tr>
<tr>
<td>CyGNSS 2016</td>
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<td>4</td>
<td>L1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>unsteered</td>
<td>GPS L1C/A</td>
</tr>
<tr>
<td>DMR</td>
<td>hardware</td>
<td>-</td>
<td>L1+L2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>GPS</td>
</tr>
<tr>
<td>GLORI</td>
<td>hardware</td>
<td>4</td>
<td>L1 L2 L5</td>
<td>160</td>
<td>-</td>
<td>-</td>
<td>iGNSS-R</td>
<td>GPS</td>
</tr>
<tr>
<td>GOLD-RTR</td>
<td>hardware</td>
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<td>L1</td>
<td>8</td>
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<td>GPS</td>
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<td>2(4)</td>
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<td>-</td>
<td>-</td>
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<td>GPS</td>
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<td>-</td>
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<td>-</td>
<td>RAW</td>
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<td>20</td>
<td>20</td>
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<td>L1</td>
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<td>-</td>
<td>-</td>
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<td>GPS</td>
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<td>8(16)</td>
<td>Any 4 with in L-band</td>
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<td>configurable</td>
<td>20/40</td>
<td>0.1-1000</td>
<td>ANY: software configurable GPS, Glonass, FDMA, Galileo, others 1-2GHz</td>
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<td>4</td>
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<td>cGNSS-R(C/A)</td>
<td>GPS</td>
</tr>
</tbody>
</table>

Table 2: List of GNSS-R hardware or software solutions ... current and future (modified from the table of Cardellach E., 2015)

2.2.6 **Interference Pattern Technique (IPT) or Multipath-Reflectometry (GNSS-MR) – Basic Principle**

While major part of the emitted signal from GNSS satellites is received directly in the zenith- looking hemisphere of a geodetic-quality GNSS antenna, a minor part of it comes from below the low elevation angle or horizon, and some time after one or several reflections in the surrounding environment.

These reflected signal so-called, in classical GNSS, multipath signals corresponds to an interference with the direct wave and affect the GNSS measurements [48] recorded by the receiver by adding
new frequencies. Geodetic GNSS antennae are thus designed to reduce the contribution of the multipath that degrades the accuracy of the position determination. Classical GNSS antennae use the polarization properties of the GNSS signals to filter out part of the reflected waves. Indeed, the Right-Hand Circular Polarization (RHCP) of the GNSS waves changes upon reflection depending on the reflector type via the reflection coefficient and the grazing angle $\theta$, i.e., the satellite elevation angle.

The reflected signal can be considered as the sum of two circularly polarized signals; one that maintains the co-polarization (original RHCP) and a cross-polarization (opposite LHCP) component. The copolar ($\tau_0$) and crosspolar ($\tau_x$) reflection coefficients (eq. 16), as a function of the horizontal $\tau_H$ and vertical $\tau_V$ reflection coefficients (eq. 17), are respectively given as [49]:

$$\tau_0 = \tau_H + \tau_V$$
$$\tau_x = \frac{\tau_H - \tau_V}{2}$$

(eq. 16)

with

$$\tau_H = \frac{\sin(\theta) - j \epsilon \cos^2(\theta)}{\sin(\theta) + j \epsilon \cos^2(\theta)}$$
$$\tau_V = \frac{\epsilon \sin(\theta) - j \epsilon \cos^2(\theta)}{\epsilon \sin(\theta) + j \epsilon \cos^2(\theta)}$$

(eq. 17)

Where $\epsilon = \epsilon_r - j 60 \sigma$ is the complex dielectric constant with $\epsilon_r$ the relative permittivity and $\sigma$ the conductivity of the reflecting surface medium, $\lambda$ is the wavelength of the signal.

Considering the vector addition of the two linear reflection coefficients (horizontal and vertical), the resultant RHCP polarization of the reflected medium will be elliptical when the coefficients are different, circular when they are equal, and linearly polarized when the vertical component goes to zero. The nature of the final polarization is determined by the relative phase relationship of each linear component upon reflection [50].

Figure 11 shows the magnitude of the horizontal and vertical (a) and copolar and crosspolar (b) reflection coefficients as a function of propagation angle for different materials, at the GPS L1 frequency, 1.575 GHz. For satellite elevation angles below a particular value named Brewster angle [100], the predominant signal component after reflection is the co-polar (RHCP), and hence the result is right and elliptical polarization. Conversely, for elevation angles greater than the Brewster angle, the predominant signal component is the cross-polar (LHCP), and hence the result is left-hand elliptical polarization. GNSS geodetic antennae are designed to reduce LHCP signals to reduce effects of reflections. GNSS antennae radiation pattern focuses the antenna gain for RHCP signals towards zenith and decreases the gain with decreasing elevation angle. These filtering techniques of a GNSS antenna based on the signal polarization affect the total received signal by reducing the reflected signals amplitude with respect to the direct signal amplitude. The energy of the reflected signal is nevertheless not completely dampened.

### 2.2.7 Reflected signal contribution to SNR

The effect of the reflections clearly affects Signal-to-Noise Ratio (SNR) data recorded by a classical geodetic GNSS (cGNSS) receivers on the different frequencies [51]. SNR can be related to
the addition of the direct and reflected GNSS signals in the receiving antenna. Following [8], $SNR$ at any instant is described in the equation 18:

$$SNR^2 = A_r^2 + A_d^2 + 2A_r A_d \cos(\psi)$$

(eq. 18)

where $A_r$ and $A_d$ are the amplitudes of the reflected and direct signal respectively, and $\psi$ the phase difference between the two signals. Since the direct signal is preferred more by the antenna gain pattern than the reflected signal and the reflected signal is attenuated upon reflection, we can assume that $A_r >> A_d$. Total $SNR$ can thus be approximated by:

$$SNR^2 \approx A_r^2 + 2A_r A_d \cos(\psi)$$

(eq. 19)

Figure 11: Amplitude of the horizontal (H) and vertical (V) reflection coefficients (a) and amplitude of the co-polar (RHCP) and cross-polar (LHCP) reflection coefficients (b) for different materials, as a function of the propagation angle. Chosen permittivity $\varepsilon_r$ and conductivity $\sigma$ are the following: Concrete ($\varepsilon_r = 2.10^{-6}$, $\sigma = 3$ S/m), Dry Ground ($\varepsilon_r = 1.10^{-6}$, $\sigma = 4$ S/m), Wet Ground ($\varepsilon_r = 2.10^{-1}$, $\sigma = 30$ S/m), Fresh Water ($\varepsilon_r = 2.10^{-1}$, $\sigma = 80$ S/m), Sea Water ($\varepsilon_r = 4$, $\sigma = 20$ S/m).
The resulting total SNR ($SNR_t$) shows that it overall magnitude is large and mainly driven by the direct signal. The reflected signal noise ratio ($SNR_r$) modifies the SNR by producing a high/medium frequency associated with small amplitude perturbation of the direct signal noise ($SNR_d$), depending on the satellite elevation angle. The reflected signal perturbations will mainly be visible for low satellite elevation angles (Figure 12: green ellipse).

![Figure 12: SNR of GPS satellite PRN12, in blue the total SNR (blue), the green line shows the second order polynomial function of the direct SNR and the red curve is the resulting reflected SNR. The ellipses show the areas where, in green, the high/medium frequencies of the reflected SNR are upper than the noise, and in red, the area where one can not discriminate the reflected signal and the noise. (Modified from [53])]()

In order to analyse the reflected component (Figure 12: red curve), we must first remove the $SNR_r$ contribution from the $SNR$ profile (green line). One [52] proposed to remove the direct signal effect through gain pattern modelling. This method requires the knowledge of the gain patterns of both the receiving and emitting antenna. As the information is difficult to obtain, other one [8] suggested to fit a simple second-order polynomial function from the SNR time series and to subtract it from the $SNR_t$ data to isolate the $SNR$ variations. As this latter method yields to better results than the modelling one [52], many studies [53], [54], [55], [56], [57], [58], [59] among others have adopted the second one and removed a second-order polynomial function to their SNR time series, [60] have presented a complete modelling, from the satellite to the antenna, of the SNR for altimetry but it is, for the time, not useful for in situ applications. Nevertheless this modelling offers promising prospects to solve inverse problem and retrieve the geophysical parameters of the reflected surface.

### 2.2.8 Interferogram metrics

**2.2.8.1 Effective antenna height above the reflecting surface**

According to [61][62], and assuming a planar reflector, the phase difference between the direct and reflected signals can be derived geometrically from the path delay $\delta$ of the reflected signal (eq. 20):

$$\psi = \frac{2\pi}{\lambda} \delta = \frac{4\pi h}{\lambda} \sin(\theta),$$  \hspace{1cm} (eq. 20)
where \( \theta \) is the satellite elevation (in rad), the height (in m) of the antenna phase center versus reflecting surface. From eq. 20 we can derive the frequency oscillations of the SNR w.r.t. time:

\[
f_r = \frac{d \psi}{dt} = \frac{4 \pi h}{\lambda} \sin(\theta) + \frac{4 \pi \dot{h}}{\lambda} \cos(\theta) \dot{\theta},
\]

(eq. 21)

where \( \dot{h} = \frac{dh}{dt} \) is the vertical velocity in m.s\(^{-1}\) and \( \dot{\theta} = \frac{d\theta}{dt} \) the elevation velocity in rad.s\(^{-1}\).

Equation 21 can be simplified by making a variable change \( x = \sin(\theta) \). We thus obtain \( f_r \), the frequency of the multipath oscillations w.r.t the sinus of the satellite elevation:

\[
f_r = \frac{d \psi}{dt} = \frac{4 \pi h \tan(\theta)}{\lambda} + h,
\]

(eq. 22)

For ground application, soil moisture content has an influence on the penetration depth of the GNSS waves into the ground [62], hence slight variations with time of the effective height \( h \) of the antenna above the reflecting surface. Variations of \( h \) with time, retrieved from the measurement of \( f(t) \), are thus an indicator of soil moisture fluctuations [58]. Equation 22 shows that, if \( \dot{h} \) is approximated to zero, the frequency of the multipath oscillation is constant and directly proportional to the antenna height \( h \) above the reflecting surface. Unfortunately, if \( \dot{h} \) is not neglected, the frequency also depends on the satellite elevation \( \theta \), the satellite elevation velocity \( \dot{\theta} \), and the variations of the effective antenna height over time \( \dot{h} \). The two former terms are known but not \( \dot{h} \). That is why many studies neglect the term \( \dot{h} \frac{\tan(\theta)}{\dot{\theta}} \) in Eq. 22 while estimating the time series \( h(t) \).

2.2.8.2 Amplitude and phase of the reflected signal

For a given height \( h \) of the antenna above the reflecting surface, the SNR, is a periodic function with a carrier phase given by can be formalized as:

\[
SNR_r = A_r \cos \left( \frac{4 \pi}{\lambda} \sin(\theta) + \phi_r \right),
\]

(eq. 23)

Where \( A_r \) scales with the intensity of ground reflections, and \( \phi_r \) is the phase. \( A_r \) combines the gain pattern and the reflected intensity, witch, both, depend on the satellite elevation. But field observations, done by different authors [58][8], indicate that both \( A_r \) and \( \phi_r \) vary with soil moisture. The observed effects of shallow soil moisture on \( \phi_r \) are larger than those on \( A_r \) [58], as demonstrated by Larson et al. [58]. \( A_r \), \( \phi_r \) and \( h \) (derived from \( f \)) are thus three metrics which can be inverted to retrieve soil moisture content.

2.2.9 SNRr metrics retrieval

This section presents a simple methodology to retrieve the time variations of the three SNR metrics:

i) effective height \( h \) of the antenna above the reflecting surface

ii) amplitude \( A_r \)
The different time series are supposed to depend on the soil moisture variations and on the satellite elevation. To minimize the elevation dependence, two different ranges, to separate low elevation and high elevation of satellite, were selected: the first group from 2° to 30° [8], and the second one from 30° to 70°. \( SNR_d \) is supposed to be removed from \( SNR_l \) as explained in §2.2.8. The elevation and azimuth, at any instant, are derived from the satellite coordinates obtained from the IGS ephemeris final SP3 products which provide GNSS orbits with a centimetric precision and clock offset data with a temporal resolution of 15 minutes for the past epochs (ftp://igs.ensg.fr/pub/igs/products/).

2.2.10 Retrieval of the effective height \( h \) above the reflecting surface

Frequency of the multipath oscillations is expressed by equation 22. Two cases can be developed depending on the main goals of the analysis: a static one for moisture measurement for example, neglecting … and a dynamic one without neglecting it for water level measurement for example. The static case the most common in the scientific community (e.g., [56], [57]), the second have been recently improved by [64].

2.2.10.1 Static case

The slight variations of soil moisture during the considered portion of the satellite pass (i.e., satellite elevation ranging either between [2°, 30°] or [30°, 70°]) are neglected, and \( h \) (and so \( \hat{h} \)) is thus assumed to be constant during this time period. Larger time-scale soil moisture fluctuations are estimated by comparing the antenna height retrieved from a portion of the satellite passage with its counterpart of the following passes. During the considered time period, the height of the antenna above the reflecting surface is equal to:

\[
\hat{h} = \frac{\lambda f}{4\pi},
\]

(eq. 24)

where the frequency oscillations \( f \) of the \( SNR_l \) is determined using a Lomb Scargle Periodogram LSP [101, 102] and \( \lambda \) is the considered wavelength for GNSS frequency band.

2.2.10.2 Dynamic case

In the dynamic case, \( \hat{h} \) is supposed high enough to be taken into account during the considered portion of satellite pass. \( h \) (and so \( \hat{h} \)) is thus likely to change during this time period. That is why a windowing of this portion is mandatory to correctly estimate the variations of \( f \) over this time period.

Windowing of the \( SNR_l \) time series

The choice of the moving-average window is critical as it should be large enough to get a precise determination of \( f \) on the one hand, but on the other hand it must not be too large so that the frequency of the signal remains quasi-constant over this window. Let \( \Delta \sin(\theta) \) be the size of the moving-average window. To obtain the suited size \( \Delta \sin(\theta) \) corresponding to each central value, an a priori coarse knowledge of the parameters under determination is mandatory. Ones have to consider the following three parameters as known by the user:

- \( h_{\text{min}} \): the minimum height above the reflecting surface the receiver is susceptible to reach during the observation period;
- \( h_{\text{max}} \): the maximum height above the reflecting surface;
- \( h_{\text{max}} \): the maximum vertical velocity of the reflecting surface;

The more precise the knowledge of these three values is, the faster the determination of \( f \) will be. From these values, we estimate expected \( f_{\text{min}} \) and \( f_{\text{max}} \) for each central value, based on eq. 22. In order to get the largest moving window through which the frequency could be considered as constant, and to include enough variations of \( f \) within the chosen window, the following two conditions [64] are considered:

\[
\Delta \frac{F_{\text{max}}}{f} \leq x, \quad \text{(eq. 24)}
\]

\[
\frac{N_0}{f_{\text{max}}} < \Delta (\sin(\theta)), \quad \text{(eq. 25)}
\]

With \( x \) (in \%) the maximal variation of \( f \) accepted within the moving window, \( N_0 \) the minimal number of observed periods within the moving window (needed to get a good estimate of \( \tilde{h} \)), and \( f_{\text{max}} \) is the maximal variation over time of the frequency. \( \Delta f_{\text{max}} \) is computed from equation 22 as follows:

\[
\frac{df}{dt} = \frac{2}{\lambda} \left( h + \frac{h \tan(\theta)}{\cos(\theta)} - \frac{h \theta \tan(\theta) \cos(\theta)}{\theta^2} \right), \quad \text{(eq. 26)}
\]

\[
\frac{df}{d(\sin(\theta))} = \frac{df}{d(\sin(\theta))} - \frac{df}{d(\cos(\theta))}, \quad \text{(eq. 27)}
\]

Considering the maximal value \( \dot{h} = h_{\text{max}} \) and \( \ddot{h} = 0 \) within the moving-average window, we have (eq. 28):

\[
\frac{\Delta f_{\text{max}}}{d(\sin(\theta))} \leq 2 \frac{\dot{h}}{\lambda \theta \cos(\theta)} \left( h_{\text{max}} + \left| \frac{h \tan(\theta) \cos(\theta)}{\theta^2} \right| \right). \quad \text{(eq. 28)}
\]

\( N_0 \) could be estimated using the SNR\( R \) time-series, which means that a minimum of \( N_0 \) periods are required in the moving window to estimate correctly \( f \). With regards to \( x \) (in \%) empirically derived by "trial and error" and verifying the first condition (eq. 24); \( x \) gives the most numerous estimations of \( f \) for each satellite and the best significance result from LSP.

It is worth noticing that \( f_{\text{max}} \) and \( f_{\text{min}} \) will be different for each moving window because the mean elevation (in rad) and elevation rate (rad.s\(^{-1}\)) change for each window. We thus estimate an optimized size \( \Delta(\sin(\theta)) \) of moving-average window guaranteeing to have at least \( N_0 \) periods of a quasi-constant frequency. Thus, this size is not constant over the time-series and is re-estimated for each time increment.

**Determination of the frequency of the multipath oscillation**

The frequency \( f \) is estimated using LSP (as for the static case), which seems to be a suitable solution. The LSP is achieved for each moving window. Thanks to the knowledge of \( h_{\text{min}}, h_{\text{max}}, \) and \( h_{\text{max}}^{\ast} \), the theoretical value of \( f_{\text{min}} \) and \( f_{\text{max}} \) can be determined. It is thus not anymore necessary to
consider the whole spectra of the signal under study, but it is sufficient to only consider frequencies ranging from $f_{\text{min}}$ to $f_{\text{max}}$ to compute the LSP. Only periodograms peaks significant at 0.01 and presenting a local maximum in the interval between $f_{\text{min}}$ and $f_{\text{max}}$ are considered.

**Height and height change determination**

Once $f$ is accurately estimated for each satellite in sight of the receiver, $h$ can be obtained solving eq. 22, with two unknowns $h$ and $\dot{h}$. The solution presented, in this paper, consists in combining measurements from all the GNSS satellites in sight at a given time to determine conjointly $h(t)$ and $\dot{h}(t)$. Using a classical LSM resolution as detailed hereafter.

Let $f = \frac{d\phi}{dt}$, $U = \frac{4\tan(\phi)}{A\delta}$ and $V = \frac{4\pi}{\lambda}$, equation 22 thus becomes for a satellite $i$ at an instant $t$:

$$f_i(t) = U_i h(t) + V_i \dot{h}(t)$$

(eq. 29)

with $f_i(t)$ being the frequency of the multipath oscillations, with respect to the sine of the satellite $i$. Combining all the visible satellites at each time $t$, we obtain an equation system (eq. 30):

$$
\begin{align*}
  f_{i=1}(t) &= U_{i=1} h(t) + V_{i=1} \dot{h}(t) \\
  f_{i=2}(t) &= U_{i=2} h(t) + V_{i=2} \dot{h}(t) \\
  \vdots & \quad \vdots \\
  f_{i=n}(t) &= U_{i=n} h(t) + V_{i=n} \dot{h}(t)
\end{align*}
$$

(eq. 30)

Or in matrix structure:

$$
F = [U h(t)] + [V \dot{h}(t)] = AX
$$

with $A = [U \ V]$ and $X = \begin{pmatrix} h(t) \\ \dot{h}(t) \end{pmatrix}$

(eq. 31)

Eq. 31 solved with the Least Square Inversion Method (LSIM,[64]) at each time step, thus determining conjointly $h(t)$ and $\dot{h}$ as follows:

$$
X = (A^t A)^{-1} (A^t F)
$$

(eq. 32)

All GNSS satellites from the different constellations (GPS, Galileo, GLONASS and others) are likely combined in this over-determined system.

The main challenge is to find the correct time interval $t$ between each estimation and also the length $t$ of the moving window [48]. $\Delta t$, $\Delta t$ and $\delta t$ must be chosen with attention to have a large enough temporal resolution for $h$ and $\dot{h}$. The number of satellite observations available decreases with $\delta t$ and so the accuracy of the determination of $h$ and $\dot{h}$ using LSIM. Yet, choosing a too large value for $\delta t$ causes an inaccurate determination of the unknown parameters since the receiver height would have changed during this interval. Unlike the static case which provide an estimation of the time series $h(t)$ for each satellite $i$. 

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Mistrale: Grant Agreement no. 641606
For the dynamic case, the LSIM method provides a single time series $h(t)$ combining all satellites. Nevertheless, the temporal resolution of the static consideration is limited by the repeatability of the GNSS constellations (i.e., a maximum of four estimations, one during the descending phase, one during the ascending phase with twice passes per day per satellite for the GPS constellation, whereas the dynamic case provides a far better temporal resolution (depending on the chosen $\delta t$).

Figure 13: Principle of Least Square Inversion Method used to determine $h$ and ... based on LSP estimates of $f$. For reasons of clarity, overlapping was not represented in this figure, even if our case $\delta t > \Delta t$. From [64]
3 GNSS-R APPLICATIONS

The objectives of MISTRAL E project (2015-2018) are focused on three main applications:

- High-precision moisture measurement;
- Inland water mapping
- Sustainable agriculture
- Show the capabilities of vegetation monitoring and Biomass quantification

We present here a compilation of remote sensing applications of the GNSS-R technique, some of their retrieval algorithms and performance. GNSS-R is a new science so most of these applications have been developed in the last decade. Historically, GNSS-R applications start with the ocean altimetry (sea-surface height) and the scatterometric (sea winds and surface roughness) ([6] and [10], respectively). One can find accounts of various GNSS-R Environmental applications in [73], [75], [133], [134]. Only the basic measurement principles are given to a complete review see the tutorial developed by [22]. The section is first organized in four sub-sections, each one devoted to a particular application:

- Ocean altimetry
- Waves and wind
- Cryosphere characterisation
- Soil moisture and/or biosphere characterisation

One important parameter which determines the feasibility of these different applications is the elevation height of the antenna, so different receiving system like, satellite, aircraft, RPAS or mast cannot have the same applications. The Table 3 and Table 4 gives you a good idea of the different receiving system and the possible applications associated to these platforms.

3.1 Flexibility of the GNSS-R receivers

Waveform receiver

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<th>Spaceborne &gt; LEO</th>
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<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Symbol" /></td>
<td><img src="image" alt="Symbol" /></td>
</tr>
</tbody>
</table>

( =not possible,  =may be,  =ok)

Table 3: Application feasibility in function of receiving platform for "waveform" receiver
IPT Receiver

<table>
<thead>
<tr>
<th>Applications</th>
<th>In situ (from 0 to few hundred m)</th>
<th>Aircraft/Rpass 0-1000m or &gt;1000m</th>
<th>Spaceborne &gt; Low Elevation Orbit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean altimetry</td>
<td>![icon]</td>
<td>![icon]</td>
<td>![icon]</td>
</tr>
<tr>
<td>Waves and Winds</td>
<td>![icon]</td>
<td>![icon]</td>
<td>![icon]</td>
</tr>
<tr>
<td>Cryosphere</td>
<td>![icon]</td>
<td>![icon]</td>
<td>![icon]</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>![icon]</td>
<td>![icon]</td>
<td>![icon]</td>
</tr>
<tr>
<td>Biosphere</td>
<td>![icon]</td>
<td>![icon]</td>
<td>![icon]</td>
</tr>
<tr>
<td>Atmosphere Tropo-iono</td>
<td>![icon]</td>
<td>![icon]</td>
<td>![icon]</td>
</tr>
</tbody>
</table>

(  =not possible,  =may be,  =ok)

Table 4: Application feasibility in function of receiving platform for "classical" GNSS receiver for ITP method

3.1.1 Ocean altimetry applications

More than 20 years ago [1] have proposed the new opportunist application -GNSS-R- for altimetry. A large amount of studies have been carrying out like [75]. In altimetry, the main parameter is the vertical height of the reflecting surface, either in absolute terms (e.g., with respect to the center of the Earth) or in relative terms (e.g., with respect to the ellipsoid). Given that the GNSS-R measured surface height will be an averaged value across this area, area which increased with the antenna height [84]. But one GNSS-R receiver can potentially track up to 40 reflections regarding only GPS and GLONASS constellations [78]. Therefore, the spatio-temporal resolution compared to others altimetric remote sensing techniques, is significantly improved. The altimetric retrieval techniques are presented in [14] and [80], whereas [14] suggests to perform altimetry on multiple waveforms at different Doppler frequencies of the full DMM and [80] presents an approach that requires neither surface roughness information nor models. The new signals like Galileo signal (E1, E5, and E6) have also been tested for altimetric applications and compared to GPS L1 and L5 signals [81][82]. The receiver bandwidth as an important parameter for optimizing the altimetric performance, given that this parameter significantly affects the leading edge of the waveform. The PARIS IOD mission test altimetric accuracy for both GPS (L1 and L5) and Galileo (E1 and E5) using the interferometric approach. The altimetric precisions for low incidence angle (0° and 35°) corresponding to 100 km along-track averaging are: between 16.4 and 37.2cm for L1; 29.7 to 56.0 cm for L5; and decrease, for Galileo, between 12.8 to 26.6cm for E1; and between 8.3 and 15.5 cm for E5 [83]. Ground measurements, which image smaller area have broadly a better accuracy (Table 5). And other improvement was proposed by [85] and described results give a good correlation with, not only the tide gauge/model but also with wave model, WAVE WATCH III model (Figure 14).
Table 5: Performance of GLONASS and GPS altimetry using IPT (one receiver) and phase single difference (2 receivers) methods form [84].

Figure 14: Raw (black) SNR-based tide measurements compared with Cordouan tide records (blue) plus SWH values (red) obtained from Wave-Watch III model. Grey area is the 95% Confidence Interval. IPT was improved by LSIM (see §2.2.6, [104])

We have some aircraft mission all around the world for instance Glori experiment to analyse coastal areas (project PRISM, GET, CESBIO).

Currently, there are three GNSS-R altimetric space-borne missions in different stages of development:

- ESA’s PARIS IOD, which concluded Phase-A studies and based on the interferometric concept;
- GEROS-ISS, which will enter into Phase-A studies during 2014: an onboard instrument for International Space Station;
- E-GEM space-borne system: CAT-2 used semi-codeless techniques to measure delays using the precise signal P(Y).

### 3.1.2 Ocean waves and wind

In fact, GNSS reflectometry and/or wind scatterometers measure surface roughness of the ocean and not directly atmospheric wind speed. It is more closely correlated to wind stress, at the sea surface, than wind speed, in the atmosphere. The first result were produced in 1998 by [87]. In [88], the characterisation was performed. [88] used two geostationary satellites visible over USA to demonstrate this feasibility. An experiment [89] using interferometric complex field (ICF) method,
have collected two months of data on Harvest platform, the authors demonstrate retrieval of SWH having a standard deviation of 0.38 m over the range from 1 to 4.5 m. And in situ measurement, at the Cordouan lighthouse, gives similar results using modified IPT method and having a rsme close to 0.7m. The standard deviation is twice than those obtained on Harvest platform but, in Cordouan lighthouse case, the creation of breaking waves due to shallow water could explain the resulting offset because the wave model does not fit well in coastal areas.

3.1.3 Cryosphere applications (snow, ice, sea ice)

![Phase change](image)

**Figure 15**: Snow depth estimation using the variation of the SNRr phase, linear correlation between snow depth GNSS-R and the ultra sonic in situ sensor, modified from [57]

Mid to high-latitude or high elevation continental snow constitute of low density snow or dry snow with little wet content, or sub-surface layers of Antarctica’s dry snow are rather transparent to L-band signals. This property of the L-bands have been employed [67] to retrieve the deep layering of large ice sheet like the Antarctic plateau. Some studies on modelling like [12] show the potential of GNSS-R technique to determine parameters like the accumulation rates of snow. Some other studies used linear polarization antennas to quantify the number and location of the interference notches and solve for the layer thickness of the snow [66]. As for others applications, three main parameters of sea/continental ice (i.e. thickness, surface roughness and ice permittivity) can be retrieved with GNSS-R [11][65]. These parameters can be combined to help characterise different ice types including new ice, young ice, thin first-year ice, etc. The estimated precision is at a few cm level.

Snow is a critical storage component in the hydrologic cycle and an important component of the climate system; however, current in situ observations of snow distribution are sparse. The IPT, [70] can be applied to in situ networks like H2O network [69] in a very impressive way to increase the measurements. Ones, [59][57], demonstrated that the height is a noisy measurement and with outliers. An improved methodology used a fixed reflector height and modelling a sinusoidal adjustment. In so doing, we can estimate the SNR-phase and thus convert phase into snow depth. Same results are also obtained in [66] with a dedicated GNSS-R receiver (GOLD-RTR)
using a linear polarizations. Characterisation of sea ice salinity [66] and ice thickness are a key parameters for classification and characterization of sea ice masses. These data are also important parameters which influence the temperature and circulation pattern of both the ocean/continent and atmosphere and thus can be used for analyses of the Earth’s climate change.

Similar to sea surface wind speed retrieval, model fitting between the theoretical and measured delay waveforms can be used to determine the roughness of an ice surface [73]. In the transition from newly formed sea ice to older and thicker ice, a gradual decrease was observed in bulk salinity and an increase in surface roughness. Roughness may also be inferred by investigating the characteristics of the phase or coherence of the interferometric signal [74]. Permittivity of sea ice is another important parameter which can be estimated by determining the ratio between the co-polar and cross-polar components of the reflected signal [75] or by model fitting of delay waveform.

3.1.4 Soil moisture and biosphere characterisation

One of the most common and critical unknowns in hydrology, agriculture, fluvial geomorphology and ecology is the spatial distribution of soil moisture content. It is often the result of modelling exercises, mainly to translate singular point measurements to a representative area. Single point measurements sensors commonly used for moisture include:

- Frequency domain sensor such as a capacitance sensor
- Neutron moisture gauges, uses the moderator properties of water for neutrons
- Electrical resistance of the soil

Time domain transmission (TDT) and time domain reflectometry (TDR); water has a high dielectric constant; a higher water concentration causes a higher average dielectric constant for the soil. The average dielectric constant can be sensed by measuring the speed of propagation along a buried transmission line.[1][2]

Heat dissipative sensor; Heat dissipation sensors rely on the effective heat R-value (insulation) of soil. Soil with additional water conducts heat more readily than dry soil. [3]

Farmers use information from one of these single point sensors or worse, rely on the nearest hydrological or meteorological station that can be at more than ten kilometres away.

On water logging and flooding side, an important aspect is to monitor the soil moisture content to understand when excess rainfall will cause water logging and/or flooding. Again the spatial extent is difficult to measure as most tools are in situ sensors at a coarse grid. Satellite imaging tools are used, like Remote Sensing but their spatial resolution is coarse too, and the acquisition frequency is fixed and not responsive enough to provide the right image at the right time.

Both cases are demonstrating a larger demand for adequate soil moisture measurements at field scales. The competition for GNSS-R consists of two upcoming technologies: active airborne radar and thermal infrared imagery. The active radar is using similar concept but is as a sensor more complicated, heavier and less practical compared to GNSS-R. Thermal infrared imagery is using the vegetative response to soil moisture content and is hence an indirect measurement. It can however be a relevant alternative when studying crop-water relationships. But for irrigation and flooding monitoring GNSS-R provides better opportunities. Other competition consists of soil moisture estimations from meteorological information. Given the solar energy, the rainfall patterns, the type of soil and type of vegetation cover the soil moisture can be modelled. However, such estimations have little spatial differentiation that is relevant for many applications today. One of the first
experiment, in soil moisture, was presented in 2008 by [8] and demonstrated a good correlation between height and moisture variations.

<table>
<thead>
<tr>
<th>Elevation angle</th>
<th>A(t)</th>
<th>h(t)</th>
<th>( \varphi(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1° ( \rightarrow ) 30°</td>
<td>-0.34</td>
<td>-0.61</td>
<td>+0.89</td>
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<tr>
<td>30° ( \rightarrow ) 70°</td>
<td>+0.42</td>
<td>+0.02</td>
<td>-0.60</td>
</tr>
</tbody>
</table>

Table 6: Mean linear correlation obtained between IPT parameter sand soil moisture

Another experiment, in Austria, using L-Mingol receiver were made with a dual, linearly polarized measurements shown that incorporating this polarization into the soil moisture estimate can improve the retrieval in areas of bare soil low vegetation [90]. The correlation signs (Table 6), between GNSSR and moisture measurement, change when considering low or high satellite elevation (in rad). This is explained by the adapted Coupled Reflection Coefficient (CRC, eq. 33) proposed by [85] which takes soil dielectric properties and antenna gain pattern into account:

\[
\Gamma = \left(10^{\frac{K_{RHCP}}{20}} \rho_{RHCP} + 10^{\frac{K_{LHCP}}{20}} \rho_{LHCP}\right) e^{-jn}
\]  

(eq. 33)

We took the real Leica AR10 antenna gain pattern into account and computed the CRC in two extremes cases: (I) perfect dry soil and (ii) perfect wet soil. Results are presented in Figure 16.

Magnitude of CRC for dry soil is higher than wet soil for satellite elevation below \( \sim 28^\circ \) and the inverse is observed for elevation above \( \sim 28^\circ \). This inversion around 30° (depending on soil dielectric properties) explains the good correlation at low elevation (Figure 17) and the inversion of the correlation we observed at 30° (Table 6). Many experiments used aircraft campaigns for moisture mapping. The IPT technique is, thus for these applications, not applicable. Using L-band signals, GNSS reflections are mostly sensitive to the upper 1–2 cm soil layer as it is mentioned in [92]. When the soil is covered with dense vegetation, the bistatic scattering
around the specular direction is essentially influenced by the attenuation [93], so that the reflection power decreases with increasing plant biomass.

![Figure 17: Volumetric soil moisture variations at Sutherland a) from GNSS data and b) from TDR sensors. Vertical lines show precipitation events for rain (black dots) and snow (blue). From [57]](image)

Vegetation is also considered by many authors like [96] develop a method forest imaging vegetation water content (VWC, Figure 18) from the multipath variation in the signal received at permanent geodetic receivers. The Normalized Microwave Reflection Index (NMRI) is developed in [96] to remove the first order terrain effects and produce an observable sensitive to VWC.

![Figure 18: Vegetation Water Content derived from GNSS-R measurements](image)

### 3.2 MISTRALE GNSS-R Receiver

For many GNSS-R receivers embedded on aircraft, the main problem is the flight cost. For example, some test flights using “One Talent Front End” card (low cost receiver solution), like in the PRISM project (French funding), have a cost of ten to twenty thousand Euros for each flight (this price does not include the post-processing time and the receiver cost). In this case, you could not have a low cost solution due to the flight
price. However, by using a RPAS instead, you can decrease dramatically the cost. Moreover, it is more flexible. It is also easier to have a good repeatability of the measurement. So from this point of view, the MISTRALE is more competitive than over existing GNSS-R solutions.

RPAS solutions with other sensors, like Visible and Infra-Red (VIR) cameras, also exist. These solutions are not directly in competition with the MISTRALE solution and could be complementary. Indeed, in adverse weather or fog, MISTRALE solution is operational whereas VIR cannot be used.

Another interesting point is that the RPAS can be used in complex environment like mountainous area: due to the MISTRALE navigation solution accuracy, the RPAS does not need to be continuously in the visibility area of the ground-based pilot.

GNSS-R and MISTRALE solutions have a very large spectra of applications, if we look only those that are suitable for the MISTRALE project we can reject all the applications dedicated to ocean altimetry and waves roughness (§ 3.1.1 and 3.1.2).

For the cryosphere like for ocean application all the altimetric part could be rejected. Nevertheless a positive point could be the part dedicated to the permittivity/conductivity changes, meaning the reflected power changes. This aspect may be a potential application of the MISTRALE solution. But it seems difficult to find a market in this area, however two possibilities could be explored: i) iceberg detection for shipping, but it is not sure that the solution could be competitive in terms of cost; ii) another possibility could be the mapping of different types of snow for ski resorts. But it remains to be demonstrated.

For soil moisture and biosphere characterisation, our receiver is in competition with moisture probes; Mistrake solution can make quick and accurate mapping versus punctual measurement for the probes. For integrated farm management it seems more important to have a precise moisture mapping than punctual values. Farmers can have a better estimate of the water needs for the agricultural plots and farmers can used this service only during the plant growth to detect the change of biomass water content or during the drought period in summer. For floods, MISTRALE solution is competing with RPAS associated with VIR sensor. But in this case you cannot identified flooded areas when you have shrub forest (depend on the biomass density), for GNSS-R embedded on RPAS the limit between water and ground can be easily identified because we have a very strong decrease of the reflected power when the RPAS image the ground. However when you have shrub forest, RADAR wave could also penetrate and give the power changes at the ground/water level when VIR waves are blocked by the vegetation cover.
4 USER NEEDS & REQUIREMENTS

The Users Needs and requirements are essential to define developing market targeted by MISTRALE Project. In order to collect, gather and consolidate useful needs and requirements, the questionnaires (see appendix 1) have been sent to various users, from various sectors, including farmers, environmental researchers, users in water management/policies. All of them have been asked about their needs and expectations in terms of soil moisture data and flood warning mapping.

The survey results will contribute to the definition of a new moisture technology based on GNSS-Reflectometry using GNSS constellations (GPS, GLONASS, GALILEO, BEIDOU). After which we aim to create an innovative type of sensor that will be combined to a RPAS platform developed as part of this project. The end user needs and requirements could help us to define the best compromise in term of price, technology, and fly possibility.

This study is also relevant to identify potential participants for the MISTRALE advisory board which will be defined within WP6.1.

As a part of the European project MISTRALE, we proposed for all agricultural stakeholders, environmental researchers, stakeholders in water management to reply to the questionnaire on their needs and expectations in terms of soil moisture data. The main result of the survey will contribute to the definition of a new moisture probe developed as part of this project.

4.1 Users groups description

Details on the user groups that have been contacted are provided hereafter.

4.1.1 Water user

Hydroelectric power comes from flowing water when it is falling by the force of gravity. It can be used to turn turbines and generators that produce electricity. Hydroelectric power is important to European countries. Growing populations and modern technologies require vast amounts of electricity for creating, building, and expanding. Hydropower is an essential contributor in the European power grid because of its ability to respond quickly to rapidly varying loads or system disturbances, which base load plants with steam systems powered by combustion or nuclear processes cannot accommodate. Hydroelectric power plants are the most efficient means of producing electric energy. The efficiency of today's hydroelectric plant is about 90 percent. Hydroelectric plants do not create air pollution, the fuel--falling water--is not consumed, projects have long lives relative to other forms of energy generation, and hydroelectric generators respond quickly to changing system conditions. All of these characteristics continue to make hydroelectric projects attractive sources of electric power. But this technology is completely dependent on water use that is why we included electricity generator group in this study.

4.1.2 Flooding prevention and crisis management

The flooding agency, mainly a public body, but in some cases also a large company which has large floodable, makes decision-support tools designed to anticipate and prevent surface and subsurface risks. They need water level and soil moisture measurement on a regular or continuous manner to feed predictive models, anticipate floods, and plan preventive/mitigating actions. In a crisis situation, mapping of the flooded area is relevant for crisis management and assessment of damage.
4.1.3 Natural preservation areas

Some of the key themes for the natural reserve that have emerged from our discussions with stakeholders and the community, include: health and wellbeing, nature recovery, access to green communities, resilience and safety organisations (e.g. flood risk, wildfires, and climate change), and management of publically owned land. Water resources refer to the supply of groundwater and surface water in a reserve area. Water resources may also reference the current or potential value of the resource to the community and the environment. Natural Reserve is responsible for restoring in some case but mainly protecting this resource (e.g. water quality) but also associated resources—such as native plant communities, but also wildlife diversity.

4.1.4 Agriculture

Farming accounts for ≈70% of fresh water withdrawals in the world today and also contributes to many problems like water pollution (e.g. nutrient excess, pesticides). But the competition for water is increasing and the costs of water pollution can be tremendous. In addition, increased pressure from urbanisation, industrialisation and climate change will provide agriculture with more competition for water resources. And climate change could affect water supply and agriculture through changes in the seasonal timing of rainfall as well as higher incidence and severity of floods and droughts. Sustainable management of water in agriculture is a critical parameter to improve agricultural yield.

In fact, we identify two major groups: farmers who can irrigate and those who generally cannot e.g. winegrowers.

4.1.5 Research

We have first identified the researcher needs and requirements of the GNSS-R community. This active community is constantly renewed and we have chosen to merge the various information’s obtained during 2 main open sessions e.g. i) Soil Moisture and water management and ii) Space borne and land applications during the “GNSS+R 2015” congress in Potsdam (Germany). The interest of these sessions was to present and discuss the advance in term of technology, algorithm, validation of new sensor, and big data acquisitions.

The importance and difficulty of the task were quite plain to the Mistrale members: it was difficult to submit completely the new sensor and new RPAS principles in a nutshell. The questionnaires have evolved with the end users categories even if the same basis for the questionnaires is used.

4.2 User Needs Collection

4.2.1 Introduction

The objective of this section is to clearly identify the user needs and requirements for agriculture, water management or research. This paragraph describes the various possible users for Mistrale sensor and RPAS, after that we have define standard questionnaires and perform the interviews. The methodology used is presented and the user needs are identified and classified and we also translate these needs into requirements.
Water use
We have addressed several fields of interest for the technology of MISTRALE in South France: water management, environmental monitoring and risk management regarding floods, a main issue in the Languedoc-Roussillon region.

In addition, in the Netherlands we addressed water board as opportunity, drinking water companies and sport fields.

We have also analysed nature conservation, and needs of natural reserves associated to water cycle like “le Parc Naturel de Camargue” that records information on climate, water change in the Camargue wetlands.

Agriculture
We have explored several fields of interest for the technology of Mistrale in the Netherlands. In Dutch agriculture, potato farming and orchards are the most important crops because of their extent and their dependency on water availability. For France, we chose wheat/corn, rape, tomato, and maize farmers. For Southern Europe (Italy, Spain, France) we chose the viticulture with its “terroir”, vineyards, winemakers and its various agricultural practices.

Research
In this particular, we used various meeting with GNSS-R sessions like GNSS+R 2015 congress in Potsdam (Germany) or IGARSS 2015 meeting in Milan (Italy) to discuss the needs and requirements of scientists which are clearly different than other users as detailed bellow.

For all fields of interest we contact people and ask them to answer our questions (interview). In the annex you find the questionnaire and all the transcripts of the interviews.

4.3 Methodology
The first step (Diag. 1) begin with a brainstorming and discussion among all consortium partners, we all use our knowledge of the work field and our network to address the users.

The second step makes an inventory of main users and we define three groups of users. This subdivisions correspond to:

- Water users, flooding prevention and crisis management users, natural preservation areas. These users are numbered from UN_WU_1 to UN_WU_4;
- Farmers like potato, orchards, wheat farmers, another main family was the winegrowers. These users are numbered from UN_AG_1 to UN_AG_9;
- Researchers in: GNSS-R technology, climatic change, agriculture, fluvial geomorphology, ecology. These users are numbered UN_RE_1 and UN_RE_2.

The first group is more correlated to wetlands and flooded areas; the farmers are more correlated to moisture measurements and researchers cover both domains. So we have define specific questionnaires adapted to these main groups.

In the aim of standardisation and homogenisation, we choose to define questionnaires with many common binary (yes/no) questions and only few specific open (users can briefly describe its ideas) questions to better understand user’s need and translate it in requirement.
And the next point try to hierarchise needs and requirements but we need first to translate need into requirement. The Kano model (diag. 1) gives this kind of translation. The standard area of the model corresponds to the description "standard" product and associated services. It corresponds to the attributes that must have the product to answer to the basic user needs. Without these attributes, the product is deemed useless. The performance area identifies which will enable to distinguish themselves from the competition by improved product attributes. This allows the client to identify the product and the brand as powerful. The high level of interest area correspond to innovative product attributes and may lead to new needs that the client had perhaps not aware before.

The last point, summarise all the questionnaires, all needs and all requirements to identify possible new market and new commercial actions. And we conclude this analysis and give some recommendation to improve our commercial objective.

![Diagram 1: Kano model to translate needs into requirements](image)

### 4.4 Results of the user needs collection

This part presents and compiles the field work results. For the development of a new service delivering soil moisture maps we need to become aware of possible users and how their interests might influence the success of this project. The interviews occurred from March to July 2015. The main partners of this campaign of interview are l’Avion Jaune, AeroVision and the GET laboratory. AeroVision were focused on Netherlands, l’Avion Jaune in the south of France (Hérault, Gar, Aude) and the GET on Italy, Spain and, south France (Gers, Haute Garonne, Aude, Tarn, Spain). If the same standard questionnaires are used by all the partners some modifications occurred due to local specificities (e.g. Polder in Nederland). We also found different practices especially for agriculture (e. g. no possibility to irrigate the vines during certain periods in France). An adjustment of the questionnaires, during July and August, was carried out before the Kano analysis that permit the translation of needs into requirements. After we could analysed the needs and the corresponding requirements to identify new commercial markets for our project.

#### 4.4.1 Water use

For water and flood risk management, the technical advisor for the “Region Languedoc-Roussillon” expresses several needs. Most of them are continuous monitoring and can be best adressed by *in situ* sensors. Some water resources are not accessible to GNSS-R technology because only the surface water can be detected (e.g. not karstic water). There is an interest in replacing some surface water level measurement by GNSS-R sensors, since the present equipment is often destroyed by strong flood, and therefore useless, since the most interesting measurements are those made during the flood. He sees a large potential in RPAS-based GNSS measurement for post-flood monitoring, and possibly with a weekly service for pre-flood soil moisture monitoring which would greatly help to fuel the flood models with correct moisture data. These needs have also been identified by l’Agence de Basin Adour Garonne, Electricité De France (EDF) and the Bureau de Recherches Géologiques
et Minières (BRGM) in Midi-Pyrénées, and an interesting point for these end-users is the capacities of our sensor to give information for some “hidden waters” under forested areas. They are also interested in soil characterisation (BRGM). EDF is clearly interested in drone survey to see the evolution of riparian forest after dam water releases. EDF is also interested in altimetric measurements.

Irrigation and water use monitoring is a great issue in the Region, and all available measurement methods have been tested or are used, from infrared thermography to in situ soil or plant measurements, radar and TDR sensors. Most of these methods are costly and/or provide only point measurements. There is a great variety of situations, and often one sensor is more suitable than another depending on the measurement conditions. The interesting feature of the MISTRAL measurement for them is their versatility, the possibility to perform measurement on-demand on a surface.

The Parc Naturel Regional de Camargue (Figure 19) mainly relies upon a network of automatic water level measurement stations, and an accurate DTM. They are not happy with the level measurement, since the measurement scales are often shifted, and there is no absolute measurement available, only relative.

For the nature conservation water is very important. Shallow water tables are important for the breeding success of meadow birds and for natural vegetation growth to keep the area wet and the ground water levels as high as possible, they take measurement to keep the rainwater and prevent seepage. To do that they have built (together with the water board) dams to control the water level (see Figure 20). This has to be compromised with the farmers in the surrounding of the nature area because the farmers want to get rid of the water in springtime to go with the tractor on the field to plant the potatoes.
To see the results of new taken measures (dams) the technology of Mistrale can help. But also to plan new actions it maybe can be helpful. In that case they want information on soil moisture? Every month from wintertime till end of July. Actual soil moisture maps are not interesting for all nature conservation managers, for instance not in dry nature areas like dunes or very wet areas like salt marches or water.

In the area of sport field we find fields with and without irrigation. Some big stadiums of the top playing clubs have a fertigation system on 10 to 20 cm below the playing field which in wintertime is also used to warm the field to protect it from frost. The majority of sport fields don't have an irrigation system like that. We distinguish fields on their subsoil: Either on a sandy soil or on a clay soil. On sand sport field managers irrigate their fields with a sprinkler or a gun. Clay soils are less vulnerable to (temporary) droughts and therefore it is less necessary to irrigate. In most cases, the water is either coming from surface water or a well, but in some areas this is not available, especially not in the South West of the Netherlands due to salt-water intrusions. If they irrigate, they use drinking water to do intensive used spots (like the goal area). You need 200 m$^3$ water for 1 time watering a football pitch (a garden hose give 700 l/h and when you may use a tap of the fire brigade you have 5 m$^3$/h) so it is impossible to do a good irrigation.

For golf course we have the same observations: only the areas are smaller as they only irrigate the green. And most times they have ponds/lakes to store water. They have also other type of grass because they have a different use. The grass field doesn't have to be so strong, compared to a football or rugby pitch. And that means you need less water to irrigate.

Most sports fields are owned by the municipality (local government) for football and rugby but the sport club has to do the maintenance. For other sports like golf course many owners are private and have also to do the maintenance. Experts say that most clubs don’t have the expertise to do it right. There is no sport club or golf course that use soil moisture? Sensors (to expensive). They start irrigating based on their own feeling and experience or when they see the grass turns yellow. If the club ask for advice “Traas en Ovaa” gives advice by digging a hole and look to the roots of the grass. If you could measure the soil moisture on 10, 20 and 30 cm deep, it would be a great help to do a better irrigate of the fields. But we don’t save much water. Most clubs don’t have money to irrigate what is necessary. The interest in irrigation is growing because dry spells increase both in duration and frequency. Talking about the spatial scale the best will be 5x5 meter but 10 x 10 meter will do. You have to measure every week from April till September. It is also interesting to measure the field within 12 hours after heavy rain to see if the drainage system is working fine (sport field has drainage pipes every 4 meter only 60 cm deep). Because they don’t have experience with sensors, the
question is what does the measured value actually mean? The best thing to save water is use artificial grass …

The interviewed water board was not very interested in the Mistrale technology. Their managing scale is too large to use RPAS they said. The soil moisture content is also not an important issue for them. Their most important concern is the water level in the polder and they have to manage the water pumps to make sure that everybody keeps dry feet even in times of heavy and sustaining rainfall. Their second concern is to manage the salt water intrusions in both groundwater and surface water. Since a few years, the water board started to manage the fresh water reservoirs. Hereto, they consider the height map and the soil map as the most important information. To manage the salt and fresh water on a better way they participate in the FRESHEM Project (see Figure 21).

Figure 21 The helicopter and cigar to measure the electromagnetic fields to calculate the distribution of fresh and salt ground water in the soil. It works till 50 meters deep in the soil. This maps will be public available from 2017. This maps are of great value to the policy of the water board and agricultural (fresh water supply is very important).

The table herein summarises the needs of the water use group where the positive and negative points for Mistrale project are highlighted. Many interviews highlight as a priority the need to have an automatic processing chain to obtain precise maps or measurements.

<table>
<thead>
<tr>
<th>Water use properties</th>
<th>Positive point for Mistrale project</th>
<th>Neutral for Mistrale project</th>
<th>Negative point for Mistrale</th>
</tr>
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<tbody>
<tr>
<td>time step</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>continuous</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>hours-daily</td>
<td>++</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>weekly-monthly</td>
<td>+</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>RPAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>yes - mapping</td>
<td>++</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>no - in situ</td>
<td>+</td>
<td>+</td>
<td>--</td>
</tr>
<tr>
<td>cost</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1000€</td>
<td>+++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 k€ - 5k€</td>
<td>+</td>
<td>++</td>
<td></td>
</tr>
<tr>
<td>&gt;5k€</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>+++</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>water versus soil</td>
<td>+++</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>altimetry</td>
<td></td>
<td></td>
<td>---</td>
</tr>
<tr>
<td>(important request)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.4.2 Agriculture

When we focus on (potato) farmers, most of them use a gun to irrigate their fields (see fig. 23, 24, 25 and 26). The wind is blowing away a lot of water so it is not equal spread on the field. Some water is also evaporated before it hits the ground. This is an interesting point for the Mistrale technology as farmers want to know how much water really reached the soil on their field.

![Irrigation gun](image)

Figure 22 Irrigation gun

Farmers use different methods to see if, when and how much irrigating is necessary:

1) Calculating the difference between rain and evaporation;
2) Digging a hole in the ground and feel;
3) Look to the plants;
4) Use a sensor;
5) Use an advice or decision support system.

Most farmers use their own knowledge to start irrigating and calculating the amount of water. Some use soil moisture sensors (see fig. 27). The sensors are also important to see how good the water is spread over the field.
The use of arms to irrigate is rare in the Netherlands, however, we spoke to one farmer that will choose an arm (see Figure 25) if he had to decide again today what irrigation equipment to buy.
In the Dutch **orchards** there are in general two ways of irrigating; sprinklers and drip hoses. Farmers who use drip hoses are using their system also to feed the plant and give fertiliser with the water (this is called fertigation). The availability of fertilizer for the plants (potato, tree) is connected to the availability of water to uptake the minerals. In the orchard that is also a big issue but the potato farmers didn’t mention this as an important issue when we spoke to them. When potato farmers spread fertilizer they wait for rain. So when the rain stays away the fertilizer stays on the ground and not in the root zone of the plant. If the rain comes the fertilizer is maybe too late for the need of the plant. In the orchard they look very well to the tree and the young fruit and give minerals with the water when the tree need it to flower, make the fruit and grow the fruit. The use of fertigation gives a reduction in water and fertilizer consumption of 30/40%.

In orchards most farmers are, just like the potato farmers, looking to the soil and the trees to decide when to start irrigating and how much to give, of course they also look at the weather forecast (several times a day). In the orchard they also use sensors. One very modern farmer we spoke has
30 sensors. That is 1 sensor in every block of his orchard. The fertigation systems in the orchard is divided in blocks (trees of one variety planted in the same year) the fertigation systems are designed to give every block its one amount of water at his time (the pumps are too small to give all the blocks water at the same time). The amount of water and fertilizer depends on the size of the tree, the stadia of grow of the fruit and the soil type. But not only the amount differed also the way they give it to the tree: Twice a day a little bit or once a day a little more.

In general all the farmers need better information to decide when to start irrigating and how much water to give. When you use an in situ sensor currently on the market, you have only information of that point of installation. When there is a plant next to the sensor using more or less water than the other plants you give too less or too much water. The goal of better irrigation differs from quality of the potatoes (or the size of the pears)) to costs saving. In dry periods, the farmers need the information every week but if they start with irrigation some farmers like to have a soil moisture map of their field twice a week. The map is also used to control the amount and the spatial distribution of the water. An interesting additional information to farmers is to measure in early spring the performance of the drainage system (detect constipation).
Concerning the spatial scale most people prefer a resolution of 10 x 10 meter. Some people talk about 3 meter because that is the width of their machines to plant potatoes. Almost every potato farmer agreed that 50 x 50 m will also still be helpful. In the orchard there is a point of attention. The trees are growing on rows. Between the rows there is some open space with a grass track. This grass track is for the tractor to drive (Figure 28). The fertigation is done only under the trees. The grass is dry (nice to drive on) the ground under the trees is wet. Some farmers also prune the roots of the trees. So there is quite a sharp edge between the tree zone and the grass track. When we measure the soil moisture content we have to separate the grass from the tree zone. An average value of soil moisture is useless for the farmers.

![Figure 28: grass tracks in the orchard. The drip irrigation is under the trees.](image)

Farmers most times don’t want more data, they want an advice, what to do. “Beregeningssignaal” (=Irrigation-signal) is a new development in the Netherlands. It is an online advisory tool. The farmer fills in his business data (number of plots, plot size, crop etc.). The system then keeps track of the soil moisture using rainfall radar from the weather service. The farmer gets an alert and advice when and how much to irrigate. To keep Irrigation-Signal up-to-date (after registration), the farmer has to fill in his data about irrigation (water gifts) and groundwater levels. The farmer has to enter again a lot of data from other systems like the soil type, field boundaries, crop, sowing dates, etc.

On average the farmers irrigate 2 or 3 times a year. But for example 8 times a year is also happening. Irrigating a potato field costs in the Netherlands between 92 and 117 euro for 25 mm of water per hectare.\(^1\). This is without the cost of the water. In the most areas the water is for free. But the water board can prohibit the use of ground and / or surface water. Than the farmer is not able to irrigate anymore. Some farmers have to pay for their water because they have to use water from a pipeline of the water company. For example in a large part of the south west of the Netherlands the ground water is saline. This water is not suitable to irrigate. We have also focussed our analysis on Viticulture, it is a little bit surprising because in France winegrowers cannot irrigate during drought due to the existing law which limitshs the water use for viticulture. But due to climatic change the environmental policies are on the way to changing. In Languedoc-Roussillon, the Institut National de Recherche Agronomique (INRA) has obtained derogation to experiment controlled vine growing in their plots. In South of Europe many countries controlled the water use for viticulture (biologic label in Italy a controlled irrigation is also needed). The Mistrale Project has a serious role to play to give water management tools for winemakers. But our discussions with INRA (research), Plaimont Producers (winery cooperative), and winegrowers like Filipo Filippi in Italy indicate that the

\(^1\) bron: Praktijkonderzoek Plant en Omgeving - Wageningen UR, 01/07/15
winegrower problem is not the soil moisture due to the abilities of the vine roots to find water at high depth (more than 5m in some calcareous area like Pech Rouge site of Mistrale project). Winegrowers and researchers are more interested in a measurement of the water content of the vine that is a better indicator of the water stress of the vine and in an important key point to start irrigation processes. The experiment leads on the Pech Rouge (Figure 29) site (Aude, France) that have a drip irrigation system using recycling of wastewater, Castelcerino (Soave, Italy) and in Saint Mont (Gers, France) try to answer to this problem and prove the increase of efficiency with our sensor in term of health of a vine.

*In situ* – Vineyard plot of PECH ROUGE

Figure 29: Experimental site of Pech Rouge where a traditional GNSS receiver is used as a GNSS-R sensor was installed for validate early flight measurements with our new sensor. On the left part the antenna installation in end of June and on the right hand the location of the antenna in the Pech Rouge domain (Field measurement defined in WP 5.2).

The table herein summarises the needs of the agriculture group where the positive and negative points for Mistrale project are highlighted. A key point is the possibility to have a warning or a decision support system to define the area where they have to sprinkle the plants during the heats period.

<table>
<thead>
<tr>
<th>Agriculture properties</th>
<th>Positive point for Mistrale project</th>
<th>Neutral for Mistrale project</th>
<th>Negative point for Mistrale</th>
</tr>
</thead>
<tbody>
<tr>
<td>time step</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>continuous</td>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>hours-dayly</td>
<td>+++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>week-month</td>
<td>++</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>
### 4.4.3 Research

The main interesting research domain of application is correlated to the new receivers iGNSSR embedded in new LEO satellites dedicated to GNSSR application like CYGNSSR (PI: C. Ruf, NASA funding, USA) or TechDemoSat (evolution of UK-DMC experiment, UK) or 3Cat-2 (PI: A. Camps, ESA funding, Spain) missions, the German Research Centre for Geosciences (GFZ) have also developed a new one known as GEROS receiver (PI: J. Wickert, ESA funding, Germany) for International Space Station (ISS). The objective are various but mostly dedicated to sea surface changes (altimetry and roughness), ice and storm detections. Even if the MISTRALE receiver could be embedded on other aircrafts than RPAS, it is not possible to embed it on satellite due to the spatial/satellite constrains. In addition to these technical capabilities, satellite applications are not in the scope of MISTRALE project.

Regarding continental applications, a part of the GNSS-R research group is interested on the MISTRALE technical capabilities in term of moisture measurements and in terms of RPAS mapping. Many continental applications of the GNSS-R group used the SNR IPT technique, with an antenna usually located on a mast. With this technique, they obtain accurate altimetric (with centimetric error) and moisture (with ~1% error in volumetric moisture) measurements. But recent experiments embedded on aircraft for flooded area (B. Li et al., submitted) and for moisture mapping [103] that used Interferometric Complex Field like Mistrale instrument to make moisture mapping of agricultural plots.

Mistrale solution embedded on RPAS can give more accurate results (flight height could be few meters) and it is more interesting in terms of time series because the RPAS solution have a cost dramatically smaller than aircraft. Mistrale system is also more flexible, and could be adapted to the measurement campaign depending on the studied events: plant growth or floods. A negative aspect could also been emphasized: no in situ solutions.

All these informations were obtained during the GNSS-R+2015 meeting, we have not brought individual interviews but a global one where each GNSS-R researcher (Dutch, China, USA, Sweden, Switzerland, Italia, Spain, France) respond to the global interview and the figure 34 (see appendix II) is a synthesis of this session.
For meteorological group:
A new sensor for moisture is very interesting because they can assimilated these new data in numerical moisture model like ISBA model of MeteoFrance.
For this group, two points are very attractive like i) the possibility to have a high time resolution (less than a minute and until fifty measurements per second); ii) the possibility to have various scales using two ranges of satellite elevation: low one 2-30° for large scale mapping and a high one 31-80° for small scale.
We can also identify a main negative point: They need calibration functions adapted to various soils so it is necessary for this research group to define their own functions and they need to control the numerical processing chain. This require a greatest amount of stations that must be integrated in the model.
But they need, almost exclusively, *in situ* measurements and not embedded receivers on a RPAS.

For the geomorphologist and the biogeomorphologist group:
Many positive points:
The possibility to look river flooding, vegetation changes and moisture changes using only one sensor is very important and promising technique and it could be really surprising for them. But if, in addition, the material have no risk of being overwhelmed by flooding it is even more interesting. The mapping possibility are also very attractive and if the process is automatic it is even better.
The negative points are: no measurement of the water level. For European country, riparian forest is not very dense but for tropical area? Some experiments led by Portuguese group (Deimos Space, H2020 project) have some promising results but may sound complicated.

The table herein summarize the needs of the research group where the positive and negative points for Mistrale project are highlighted. As a key point, they want to work with the raw data even though, for some members, the processed data could be an additional information. And, if it is possible, the RPAS license (for fly) should be include in the MISTRALE solution.

<table>
<thead>
<tr>
<th>Research properties</th>
<th>Positive point for Mistrale project</th>
<th>Neutral point for Mistrale project</th>
<th>Negative point for Mistrale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>time step</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td>++</td>
<td>+</td>
<td>--- (not possible but needed)</td>
</tr>
<tr>
<td>hours-dayly</td>
<td>++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>week-month</td>
<td>+++</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RPAS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>yes - mapping</td>
<td>+++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>no - in situ</td>
<td></td>
<td></td>
<td>---</td>
</tr>
<tr>
<td><strong>cost</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1000€</td>
<td>+++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 k€ - 10k€</td>
<td>++</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>&gt;10k€</td>
<td>+</td>
<td></td>
<td>--</td>
</tr>
<tr>
<td><strong>type</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>+++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>water versus soil</td>
<td>+++</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Altimetry</td>
<td></td>
<td></td>
<td>--- (Very important)</td>
</tr>
</tbody>
</table>
5 USER NEEDS SUMMARY

This section aims to summarise users’ needs and their associated requirements (defined to ensure full coverage of the needs).

5.1 Needs and requirements

For each user group, needs (referred to as “UN”) are listed and associated functional and technical requirements are defined to ensure full coverage. An unambiguous identifier is given to each need and requirement (referred to as “UR”) in order to harmonise results and ease further referencing.

User needs have been ranked into three categories following their priority level (in the context of MISTRALE):

- Class 1: includes critical requirements in the context of MISTRALE (“must have”);
- Class 2: includes requirements that are not critical to demonstrate the MISTRALE solution (“nice to have”);
- Class 3: covers requirements that are not directly relevant or not technically feasible in the frame of Mistrale project (“out of MISTRALE scope”).

5.1.1 Agriculture

<table>
<thead>
<tr>
<th>ID</th>
<th>Needs Description</th>
<th>Requirements ID</th>
<th>Requirements Description</th>
<th>Priority</th>
</tr>
</thead>
</table>
| UN_AG_1| Frequency:  
  - information every week during dry period  
  - soil moisture maps twice a week during irrigation period | UR_AG_1         | The RPAS shall fly over the farmers’ parcels once (dry period) or twice a week (irrigation period). | 1        |
| UN_AG_2| Resolution:  
  - (1x1m = orchards for separation between grass and tree zone)  
  - (3x3m = width of the machines used)  
  - (5x5 = winegrowers)  
  - 10x10m desired  
  - 50x50m still helpful | UR_AG_2         | The GNSS-R solution shall at least provide a 10x10m resolution on the final product | 1        |
| UN_AG_3| Farmers do not want to interpret results by themselves but want to be advised | UR_AG_3         | Mistrale service shall produce user-friendly results and advice.                         | 1        |
### GNSS-R Technology

**State-of-the-Art and user requirements**

| UN_AG_4 | Farmers want an automated alert | UR_AG_4 | Functional | Mistrale service shall issue un automated alert. | 1 |
| UN_AG_5 | Farmers want to know the amount of water to irrigate | UR_AG_5 | Functional | Mistrale service shall be able to compute an indicator of the amount of water to be irrigated according to users' specification (previously reported in the tool) | 1 |
| UN_AG_6 | Farmers want a prediction to plan future irrigation | UR_AG_6 | Must be interfaced with meteo informations and evaporation / growing culture models. | 2 |
| UN_AG_7 | Farmers do not want to re-enter data and use multiple tools | UR_AG_7 | Must be interfaced with standards from farming management systems | 2 |
| UN_AG_8 [WG] | Winegrowers: measure of the water content in the grapes (twice a day or daily) | UR_AG_8 | Must provide information about water content in the grapes for winegrowers. | 3 |
| UN_AG_9 | Mounting a sensor on tractor instead of RPAS | UR_AG_9 | Development of a standalone sensor and its associated software solution (simplified version of RPAS package) | 3 |

### Water use

<table>
<thead>
<tr>
<th>Needs ID</th>
<th>Description</th>
<th>Requirements ID</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN_WU_1</td>
<td>Frequency: (variable depending on the area and season) - Every month - Every day - And after specific occasions: o After heavy rain o During flood (power companies) o After dam release (water agencies)</td>
<td>UR_WU_1</td>
<td>Technical</td>
</tr>
<tr>
<td>UN_WU_2</td>
<td>Resolution: - 10x10m ok (but 5x5 best)</td>
<td>UR_WU_2</td>
<td>Technical</td>
</tr>
</tbody>
</table>
GNSS-R Technology
State-of-the-Art and user requirements

<table>
<thead>
<tr>
<th>UN_WU_3</th>
<th>Water agencies do not want to interpret results by themselves (for some of them!)</th>
<th>UR_WU_3</th>
<th>The Mistrale tool shall produce user-friendly results and advice.</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN_WU_4</td>
<td>Water agencies want an automated alert system</td>
<td>UR_WU_4</td>
<td>The Mistrale tool shall issue an automated alert.</td>
<td>1</td>
</tr>
</tbody>
</table>

### 5.1.3 Researchers

<table>
<thead>
<tr>
<th>ID</th>
<th>Description</th>
<th>ID</th>
<th>Description</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>UN_RE_1</td>
<td>Frequency:</td>
<td>UR_RE_1</td>
<td>The RPAS shall fly over the target parcels continuously during test period.</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>- continuous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UN_RE_2</td>
<td>Researchers need moisture measurements in an “open” file format.</td>
<td>UR_RE_2</td>
<td>Mistrale shall use international standards (or document the solution used)</td>
<td>2</td>
</tr>
</tbody>
</table>

### 5.1.4 Synthesis

Needs and requirements can be divided into technical and functional groups. While the technical needs will mainly impact technical requirements of the GNSS-R sensor (front-end, GNSS-R receiver, GNSS-R processing…), the functional needs will have a key impact on the MISTRALÉ complete system (such as the RPAS flight capability and endurance).

Both the technical and functional requirements will be used as input for the definition of the MISTRALÉ solution (which will be described in “D1.2 – System Specifications”).

The technical needs are summarized in the following table

<table>
<thead>
<tr>
<th>Key words</th>
<th>Agriculture</th>
<th>Water use</th>
<th>Researcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Every week / twice a week</td>
<td>Month/day/specific</td>
<td>continuous</td>
</tr>
<tr>
<td>Resolution</td>
<td>10x10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>Same as other sensors, 15 minutes (average value)</td>
<td>5 minutes</td>
<td>1 hertz or 20 hertz</td>
</tr>
<tr>
<td>Surface to cover</td>
<td>Plot (10 ha – 100 ha) or a set of plot (more than 100 ha, 300 ha in Nederland)</td>
<td>All the river, the lake, the tank</td>
<td>From the square meter to fifty kilometers</td>
</tr>
<tr>
<td>Delay between acquisition and results</td>
<td>as fast as possible especially for warnings</td>
<td>as fast as possible especially for warnings</td>
<td>Many of them want only acquisition</td>
</tr>
</tbody>
</table>
The functional needs are the following:

<table>
<thead>
<tr>
<th>Key words</th>
<th>Agriculture</th>
<th>Water use</th>
<th>Researcher</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic alert</td>
<td>Yes</td>
<td>Yes (crucial !)</td>
<td>/</td>
</tr>
<tr>
<td>Amount to irrigate</td>
<td>Yes</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

5.2 Requirements ranking

Based on the priority ranking, the following table summarizes the user needs and requirements that will be addressed in the context of Mistral (the class 1 “must have”).

The class 2 “nice to have” will be analysed but not included in the Mistrare prototype.

Class 3 requirements are out of the scope of the project and will therefore not been considered.

<table>
<thead>
<tr>
<th>ID Requirement</th>
<th>Key Words</th>
<th>Priority rank</th>
<th>Included in demo</th>
</tr>
</thead>
<tbody>
<tr>
<td>UR_AG_1</td>
<td>Frequency</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_AG_2</td>
<td>Resolution</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_AG_3</td>
<td>Thresholds and zones</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_AG_4</td>
<td>Automatic alert</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_AG_5</td>
<td>Amount</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_AG_6</td>
<td>Prediction</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td>UR_AG_7</td>
<td>Integration in Farming Management System</td>
<td>2</td>
<td>No</td>
</tr>
<tr>
<td>UR_AG_8</td>
<td>Wine</td>
<td>3</td>
<td>No</td>
</tr>
<tr>
<td>UR_AG_9</td>
<td>Tractor</td>
<td>3</td>
<td>No</td>
</tr>
<tr>
<td>UR_WU_1</td>
<td>Frequency</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_WU_2</td>
<td>Resolution</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_WU_3</td>
<td>Thresholds and zones</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_WU_4</td>
<td>Automatic alert</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_RE_1</td>
<td>Frequency</td>
<td>1</td>
<td>Yes</td>
</tr>
<tr>
<td>UR_RE_2</td>
<td>Format</td>
<td>2</td>
<td>No</td>
</tr>
</tbody>
</table>
6 CONCLUSIONS AND RECOMMENDATIONS

For the user needs a spatial resolution close to the square meter or at least lower than 10m² seems necessary and important. During the driest periods we have to fly on weekly basis for farmers and many of the water use stakeholders; during irrigation period, farmers need flights every 3-5 days.

For nature conservationists, flights should take place on monthly basis (Netherlands). But in wet periods there is no interest, which is unfortunately the case for many users.

For the power companies (EDF) and water agencies (Agence de l’eau Adour-Garonne) we have a possible interesting service after dam release (power companies) or a flood (water agencies) to image the evolution of the flooded area, the evolution of the moisture, and the riparian vegetation after these anthropic or natural flood events. And if it is possible to make altitude measurement it will be better, we explained that our sensor just measure the moisture and/or the geophysical parameter changes due to the reflecting surface.

For water board in Netherlands, no clear need has been defined. But they are interested in soil mapping and it could be a possible use of the Mistrale sensor and RPAS, we have to define if we need to go in this direction or not. In the same idea, characterisation of soil areas with fresh and salt water content could be theoretically possible with our sensor.

For the researchers, to see climatic change for example, a continuous acquisition of the moisture could be interesting and in this case we used the sensor for in situ measurement of the soils. They need a specific solution with an “open” file format. Mistrale project have the opportunity to define a possible international standard like the RINEX file of classical GNSS receivers. Flights are more interesting to see the evolution of flooded areas in terms of water mapping, geomorphological changes, and moisture evolution. For agricultural research (e.g. vineyard), it is also interesting to observe the water content changes within the vegetation.

For hydrogeological agencies like the BRGM or water agencies like the Adour-Garonne basin agency (France) it could be interesting if we have the possibility to decipher moisture but also mineralogical soil. Some laboratories like the LEGOS work with mussel aquaculture groups and they are interested in the characterisation of fresh and salt waters in lagoons.

For work in agriculture like orchard, colza, wheat etc. we have to keep in mind that for a good mapping accuracy we need to identify dry and wet zones of only a few meters wide. The users also ask to the possibility to mount a sensor on their tractor instead of using a RPAS and we explain that is completely possible with an antenna height of 3m (top of the tractor) you can monitoring an area of radius close to 1-10m if we look only high elevation satellite. In this case the Mistrale project has to give the ability to buy the sensor stand-alone with an adapted software solution (in fact a simplified version of those given for RPAS package).

To make a good decision on irrigating you need, for the more technological up to date users (mainly in Netherlands it seems), a lot of information:

- Weather forecast;
- Soil map;
- Organic matter content;
- Precipitation (deepens on the kind of crop and crop size);
- Soil moisture content of the top layer, the root zone;
- Ground water level (capillary rise);
- Detailed height map.
So Mistrale is a link in a long information chain. We have to pay attention on the way we deliver the maps to the farmers. Farmers don’t like to re-enter their data, and nowadays they have to do that a lot.

Farmers, winegrowers, water agencies want an automated alert system (like Dacom sensors and Irrigation-Signal give), but the farmer/winegrower also wants to have insight in what happens so he can plan ahead. For example as provided by the moisture sensor with three colour levels (green ok, orange irrigation is necessary, red irrigation is obligatory) when farmers see a red or orange colour they have a warning to irrigate soon, for winegrower it is more the water content of vine that could have this kind of colours.

Many users want push button applications and do not want to have to interpret the measurements. For this category of applications, we have to consider some intermediate public or private users, such as Chamber of Agriculture, advisors, cooperatives, who will be the operators of the MISTRALE-generated systems and who will provide the end user with the kind of products/information he is able to use: maps, quantitative advice, or event programming of a remote controlled irrigation system are possible levels of service. And many users wanted to see the new receiver or a prototype to have an idea of its performances during a test flight or at least they want a flyer which synthesized the Mistrale project, and its sensor and RPAS.

So we have to think about how to deliver our data. One idea is to redesign the applications of soil moisture for farmers like:

- Soil moisture sensor coupled to a model that calculate evaporation from your parcel. Based on a soil map (for capillary rise). And make that site-specific with Mistrale soil moisture maps. Or

- Integrate Mistrale soil moisture maps to Irrigation Signal model. That system is modelling evaporation and soil moisture. They measure precipitation from weather stations and rain radar. In situ Mistrale sensor can directly give information of sub-surface moisture in an area depending of the antenna height. And in this case it could give real data to the model because farmers actually have no real. Combining Mistrale soil moisture maps with this kind of advice systems and also to the farm management systems of the farmer, is an idea to deliver out maps but in this case we have to discuss with the advice system builder to define the data format need for the advice model.

For winegrowers, we have not identified similar model, one develop some models using remote sensing and in situ meteorological data but model like Vintage project (see http://www.vintage-project.eu/) do not have intermediary scale obtain by new sensors like Mistrale GNSS-R sensor, other interesting point GNSS-R measurements can give soil information’s but also moisture/irrigation, canopy management, disease control using only one sensor. So if it is possible, we could develop a specific model for viticulture or provide information’s for existing models; and it could be an interesting market for South Europe.
6.1 Recommendations

We have to define if some applications like soil characterisation could be included. Theoretically it is possible in terms of device, algorithm etc. but the final version implemented will be different from that proposed for soil moisture and the human cost could increase so we have to define our strategic option.

Another recommendation is due to complexity of the sensor. We have to define technical and theoretical (in some specific case) answers for the non-specialists to make a judgment and it also could help us to answer to end-users which have technical questions.
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