Final project

“Soil moisture retrieval using an airborne L-Band Radiometer”

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1 Introduction

1.1 Background

The improvement of weather forecast and climate motorization, to prevent for example natural disasters, requires global scale knowledge of the soil moisture (SM) and of the surface salinity (SSS), non-existent at present due to the difficulty to carry out in-situ measure. These parameters influence the heat exchange among land, sea and air. On the one hand, thanks to the SM, the amount of water on Earth and the exchange of energy between the Earth’s surface and the atmosphere can be known. On the over hand, knowing the distribution of the SSS will inform about sea currents and differences between evaporation and precipitation. The knowledge of these parameters will contribute to improve the weather forecasts, hydrological studies, vegetation motorization and risk of fires in the forests.

As part of the program “The living planet programme: Earth Explorer Opportunity Missions”, the European Space Agency (ESA) has chosen the mission Soil Moisture and Ocean Salinity (SMOS), designed to observe soil moisture over land and salinity over the oceans. It will be launched in 2009 and will put in orbit the first microwave imaging radiometer using aperture synthesis. Over the sea, sea surface salinity will be remotely measured by means of L-band (1400-1427 MHz) microwave radiometry. As the brightness temperature also depends on the sea surface temperature and on the sea state, post processing corrections will be needed to get the surface salinity. Over land, soil moisture will be retrieved from the changes in the L-band brightness temperature, although post processing correction for surface roughness and vegetation will be also required.

1.2 Motivation of the project

In the perspective of the SMOS calibration/validation activities in the REMEDHUS site (Salamanca, Spain), planed six months after its launch, an airborne light-weight L-band radiometer (ARIEL) [1.1] has been designed and implemented by the Universitat Politècnica de Catalunya (UPC) to obtain brightness temperature data-sets. Its goal is to perform test campaigns from a point of view higher and “closer” from the SMOS.
Chapter 1. Introduction

In order to minimize the cost, the platform, designed especially for the requirements of the project, is remotely controlled and is allowed to fly on any aerodrome area. Consequently test campaigns to test the equipment aboard and the algorithm of data processing can be performed whenever without any external constraints. Airborne data acquired so far will be processed and other future experiments to deploy the instrument’s capabilities will be planned. The aim will be to produce an application to geo-reference sea salinity and/or soil moisture maps over Google Earth. In order to achieve this goal, the data processing from the different sensors will be performed in an automatic manner and a software will be implemented in order to create automatically soil moisture maps out of the radiometric data. A set of tools will be implemented so as to analyze and interpret the data obtained. Graphical visualisations such as histograms, graphs, display of antenna footprints and trajectory will be provided.

**1.3 Specification of the platform**

The aircraft, which will carry the radiometer ARIEL, has been designed and implemented together with a remote control aircraft capable of lifting 5 kg payload with about 45 min autonomy to scan an area over land and/or sea. It has a good surface in order to provide a stable flight. In addition to the aircraft instrumentation, an hexagonal 7 patch array antenna is mounted under the aircraft (Fig. 1-1) and an on-board nadir-looking video camera is also embedded to help interpret the data acquired by the payload. The inner part of the fuselage allows loading the necessary equipments (Fig. 1-2) as GPS (Global Positioning System) and attitude sensors. Data from these instrumentations are acquired, stored and transmitted to ground for later processing.

![ARIEL radiometer during a flight test in Ripollet, Barcelona](image-url)
3

Chapter 1. Introduction

This work project will be divided in 5 chapters. Firstly, chapter two reviews the basics of radiometry, emission theory and types of radiometer. Chapter three covers the avionic system in place aboard the platform, describing the set of sensors aboard. Chapter four describes the main functions and algorithms implemented in the ARIEL Processor - Soil Moisture Retrieval (AP-SMR). The main steps of data processing will be explained: synchronisation, calibration and soil moisture retrieval. Chapter five describes the graphical interface of AP-SMR, how to use it, and how to get the geo-referenced images over Google Earth. Chapter six presents the soil moisture estimations obtained and comments the radiometric data from two different flights. Finally chapter seven presents some conclusions and future research lines.

1.4 Structure of this work project

Fig. 1-2 : Photo of the interior of the aircraft body
2 Introduction to microwave radiometry

Radiometry is the field of science devoted to the measurement of the thermal electromagnetic energy radiated by the bodies. Since the appearance of man-made satellites, radiometry has played an important role in remote sensing. A radiometer is an instrument that measures the brightness temperature, that is, the power emitted by a body by unit solid angle, and by unit surface, with high resolution and accuracy.

In this chapter microwave radiometry concepts will be introduced and then the simplest two types of radiometer will be described: the total power radiometer (TPR) and the Dicke radiometer (DR).

2.1 Brightness and power collected by an antenna

The power emitted by a body in a solid angle by unit surface is called the brightness, units [W sr\(^{-1}\) m\(^2\)]. If the emitting surface radiates with a pattern \(F_t(\theta,\phi)\), the brightness \(B(\theta,\phi)\) is given by:

\[ B(\theta,\phi) = \frac{F_t(\theta,\phi)}{A_t}, \]  

(2.1)

where \(A_t\) is the total area which is radiating.

The power collected by an antenna surrounded by a distribution of incident power \(B(\theta,\phi)\) can be computed as:

\[ P = F_t \cdot \frac{A_t}{R^2} = B \cdot A_t \cdot \frac{A_t}{R^2}, \]  

(2.2)

with \(A_t\) the effective area of the antenna and \(R\) the distance to the radiating surface.

Taking into account that the solid angle \(\Omega\) subtended by the transmitting antenna is defined by:

\[ \Omega = \frac{A_t}{R^2}, \]  

(2.3)

Then, the power collected by the antenna can be computed as:

\[ P = B \cdot A_t \cdot \Omega. \]  

(2.4)
Replacing the solid angle by a differential solid angle \((d\Omega)\), the corresponding power received by the antenna from an extended source of incidence brightness \(B(\theta, \phi)\) can be expressed (Fig. 2-1) as:

\[
dP = A_s \cdot B(\theta, \phi) \cdot |F_n(\theta, \phi)|^2,
\]

where \(|F_n(\theta, \phi)|^2\) is the normalized antenna radiation pattern.

Moreover, if the brightness is not constant with frequency, a new magnitude must be defined: the spectral brightness density \(B_f(\theta, \phi)\), units \([\text{W sr}^{-1} \text{m}^{-2} \text{Hz}^{-1}]\). The total power collected by the antenna is then obtained by integrating Eq. (2.5) over the system’s bandwidth and over the space:

\[
P = \frac{1}{2} \cdot A_s \cdot \int_{\eta} \int_{\phi} \int_{\theta} B_f(\theta, \phi) \cdot |F_n(\theta, \phi)|^2 \cdot d\Omega \cdot df
\]

where \(B\) is the bandwidth of the receiving system. Since the antenna collects only half of the randomly polarized thermal power emitted, it is multiplied by a factor \(\frac{1}{2}\).
Chapter 2. Introduction to microwave radiometry

2.2 Thermal radiation

2.2.1 Quantum theory of radiation

All bodies at a finite absolute temperature radiate electromagnetic energy. According to Bohr’s equation, the frequency $f$ of an emitted radiation is given by:

$$ f = \frac{\epsilon_1 - \epsilon_2}{h}, $$

(2.7)

where $\epsilon_1$ and $\epsilon_2$ are different energy levels in J, and $h$ is the Planck’s constant ($h = 6.63 \cdot 10^{-34} \text{ J}$).

The emission of radiation is caused by the collision between the particles. The collision probability is a function of the density of the particles and the kinetic energy of their random motion. The increase of the intensity of the energy radiated by a body is proportional to the increase of its absolute temperature.

2.2.2 Planck’s black-body radiation’s law

In general, part of the electromagnetic energy incident on a surface is absorbed, and part is reflected. The spectral brightness (brightness per unit bandwidth) is given by the Planck’s law Eq. (2.8).

$$ B_f = \frac{2 \cdot h \cdot f^3}{c^2} \cdot \frac{1}{e^{hf/kT_o} - 1}, $$

(2.8)

where $f$ is the frequency in Hertz, $k$ is the Boltzmann’s constant ($k = 1.38 \cdot 10^{-23} \text{ J K}^{-1}$), $T_o$ is the absolute physical temperature in Kelvin, and $c$ is the speed of light ($c = 3 \cdot 10^8 \text{ m s}^{-1}$).
Applying the Taylor’s approximation to the exponential function in Eq. (2.8), the exponent $hf/kT_o$ in the denominator of Planck’s law is far smaller than 1 at microwave frequencies, and therefore, the following approximation can be used to simplify Eq. (2.8).

$$e^x - 1 = 1 + x + \frac{x^2}{2} + \ldots - 1 \approx x \text{ for } x \ll 1.$$  \hspace{1cm} (2.9)

Hence, at low microwave frequencies the Rayleigh-Jeans law can be used as a good approximation of the Planck’s law (2.8) and can be written as:

$$B_j = \frac{2 \cdot f^2 \cdot k \cdot T_{phys}}{c^2} = \frac{2 \cdot k \cdot T_{phys}}{\lambda^2}.$$  \hspace{1cm} (2.10)

In this case, if $\lambda$ and $T_o$ appearing Eq. (2.10) satisfy that:

$$\lambda \cdot T_o > 0.77 \text{ m K, } \quad \frac{f}{T_o} < 3.9 \cdot 10^8 \text{ Hz \cdot K}^{-1},$$  \hspace{1cm} (2.11)

The error committed by the Rayleigh-Jeans’ approximation is smaller than $1.2 \cdot 10^{-4}$, if the physical temperature is 300 K and the frequency is 1.4 GHz, which covers a large part of the microwave spectrum. Equation (2.10) will be used from now on. Note that there is a linear relation between the spectral brightness density and the physical temperature.
2.2.3 Power-temperature correspondence

The power received by an antenna with normalized radiation pattern $|F_n(\theta,\phi)|^2$, placed inside of a black-body chamber at a constant physical temperature $T_o$ is (Fig. 2.4)

$$P_{bb} = \frac{1}{2} A_r \cdot \int_{\frac{\lambda}{2}}^{\frac{\lambda}{\lambda^2}} \int_{4\pi} \frac{2 \cdot k \cdot T_o}{\lambda^2} |F_n(\theta,\phi)|^2 d\Omega \cdot df,$$

Eq. (2.12)

where the subscript $bb$ stands for black-body.

The detected power will be limited by the antenna bandwidth $B$. If this bandwidth is small enough to assume that the spectral brightness density does not change over the frequency range, Eq. (2.12) is reduced to:

$$P_{bb} = k \cdot T_o \cdot B \cdot \frac{A_r}{\lambda^2} \int_{\frac{\lambda}{2}}^{\frac{\lambda}{\lambda^2}} |F_n(\theta,\phi)|^2 d\Omega = k \cdot T_o B,$$

Eq. (2.13)

where the antenna solid angle has been expressed as a function of its effective area:

$$\Omega_p = \int_{4\pi} |F_n(\theta,\phi)|^2 d\Omega = \frac{\lambda^2}{A_r}.$$

Eq. (2.14)

Eq. (2.13) shows a linear relationship between the physical temperature of a body and the power collected by an antenna. In 1928, Nyquist found the same expression (Eq. (2.15)) for the available power at the terminals of a resistance at a physical temperature $T_o$. This means that, for an ideal receiver of bandwidth $B$, the antenna delivers to the load the same power as a resistance at a temperature $T_{A_r}$, which is called the antenna temperature:
Chapter 2. Introduction to microwave radiometry

\[ P = k \cdot T_o \cdot B. \]  \hspace{2cm} (2.15)

![Diagram](image)

Fig. 2.4: The power delivered by: (a) an antenna placed inside of a black-body enclosure of temperature \( T \) is equal to the power delivered by (b) a resistor maintained at the same physical \( T \) (assuming each one is connected to a matched receiver of bandwidth \( B \)).

2.2.4 Gray-body radiation

2.2.4.1 Brightness temperature and emissivity

A black-body is an idealized body and it is a perfect emitter. These bodies absorb all the incident energy, and when the thermodynamic equilibrium is reached at physical temperature \( T_o \), they radiate all the energy omni-directionally. However, real materials (usually called gray-bodies) emit less energy than a black-body since they do not absorb all the energy incident on them. Since the universe is composed of gray-bodies two new concepts are introduced, the brightness temperature \( T_b(\theta, \phi) \) and the emissivity \( e(\theta, \phi) \). Eq. (2.16) shows, the relationship between these two concepts:

\[ e(\theta, \phi) = \frac{B(\theta, \phi)}{B_{bb}} = \frac{T_b(\theta, \phi)}{T_o}, \]  \hspace{2cm} (2.16)

where \( B_{bb} \) is the brightness of the black-body at a temperature \( T_o \).

The brightness temperature emitted by a black-body coincides with its physical temperature hence its emissivity is 1. Consequently the brightness temperature emitted by real bodies is less than their physical temperature, and then their range of emissivity values are between 0 and 1. In conclusion, the emissivity of a perfect reflecting material is equal to zero and the emissivity of a perfect absorber is one.
2.2.4.2 The apparent temperature

The apparent temperature \( T_{\text{AP}} \) is an equivalent temperature related to the total brightness incident over the antenna, \( B_i(\theta, \phi) \):

\[
B_i(\theta, \phi) = \frac{2 \cdot k}{\lambda^2} \cdot T_{\text{AP}}(\theta, \phi) \cdot B
\]  

(2.17)

In remote sensing applications, the \( T_B \) of the surface is measured by an antenna far away (Fig. 2-5). In this case, the apparent temperature \( T_{\text{AP}} \) is the key parameter that depends on:

- the brightness temperature of the surface under observation \( T_B \),
- the atmospheric upward radiation \( T_{\text{UP}} \),
- the atmospheric downward radiation scattered reflected by the surface \( T_{\text{SC}} \), and
- the atmospheric attenuation \( L_a \),

and can be written as:

\[
T_{\text{AP}} = T_{\text{UP}} + \frac{1}{L_a} \cdot (T_B + T_{\text{SC}}).
\]  

(2.18)

By observing Eq. (2.18), when the atmospheric losses are high, the apparent temperature is almost equal to the atmospheric temperature. It happens at high frequencies or at the absorption windows of some gases. If the brightness temperature of the Earth surface is being measured, it will be necessary to work at frequencies that give low atmospheric attenuation. In the frequency range from 1 GHz to 10 GHz losses for a cloud-free atmosphere are very small and can be neglected. Consequently the apparent brightness temperature \( T_{\text{AP}} \) can be approximated by the brightness temperature \( T_B \).
According to Fig. 2.5, and taking into account the normalized antenna pattern \((F_n(\theta, \phi))\) and normalized by the pattern solid angle \((\Omega_p)\), the antenna temperature is given by:

\[
P = \frac{1}{\Omega_p} k B \int_{4\pi} T_{AP}(\theta, \phi) |F_n(\theta, \phi)|^2 d\Omega = kT_A B, \tag{2.19}
\]

\[
T_A = \frac{1}{\Omega_p} \int_{4\pi} T_{AB}(\theta, \phi) |F_n(\theta, \phi)|^2 d\Omega. \tag{2.20}
\]

### 2.3 Types of microwave radiometer

#### 2.3.1 Introduction

As it has been seen in the previous part 2.2.4.2, if an antenna is pointing to a body, power is obtained on its output (expressed in term of temperature \(T_A\)) related to the brightness temperature \(T_B\) of this body. A radiometer is an instrument that measures the antenna temperature \(T_A\) with high resolution and accuracy. In practice, a radiometer really measures the power delivered by the antenna to the receiver. A radiometer is “simply” a well calibrated and high sensitive microwave receiver.

In the comportment of a radiometer, there are two important factors: sensitivity and accuracy. The first one determines the resolution used to measure the temperature \(T_A\), so the smallest change in \(T_A\) which can be detected by the radiometer output. The second one indicates the accuracy of the measure.
In order to illustrate these two aspects, the following example is analyzed; a radiometer is connected to an antenna which is exposed to a temperature $T_A = 200$ K, and the resolution requirement of the measure is of 1 K. The noise temperature introduced by the radiometer, like any receiver, has to be taken into account; a typical value will be $T_R = 800$ K. Then the aim of the radiometer will be to do a measure which matches with a variation of 1 K over 1000 K. In order to achieve this resolution, a radiometer uses an integration technique.

Therefore, if the radiometer’s gain $G$ and the noise temperature $T_R$ are added in (2.19), the output power resulting is:

$$P = kBG(T_A + T_R).$$  \hspace{1cm} (2.21)

As it is shown, the stability of the power measurement will depend on the stability of the factor in the Eq. 2.21: $B$, $G$ and $T_R$. As $B$ is a parameter of the filter, it is supposed to be constant. Back to the previous example, if the resolution required is 1 K, it is quite reasonable to think to a resolution of 1 K over 1000 K. It means that $G$ and $T_R$ have to be stable in an interval of $0.1 \%$, which corresponds to about 0.004 dB. Therefore, the following problem appears that it will be difficult to get these requirements from an amplifier.

After having seen the two main problems linked to the design of a radiometer, it will be presented the main radiometers and their behaviour in terms of sensitivity and accuracy.

A radiometer block diagram consists basically of an antenna, a super-heterodyne receiver which translates the radio frequency of the signal to an intermediate frequency, a detector and a low-pass filter.

This chapter is focused to the description of the radiometer operation as well as the introduction to different types of radiometers. Although more of radiometer types exist as for example the Noise Injection Radiometer (NIR) or the pseudo-correlation radiometer, the Total Power Radiometer (TPR) will be presented as it is the simplest and one of the most widely used and the Dicke Radiometer (DR) because the radiometer ARIEL is of this type [1.1].

### 2.3.2 Total Power Radiometer

The TPR is the more common radiometer used. It is easy to understand and can illustrate the most important notion of the performance of such instrument. Fig. 2-6 is used to explain it with more details.
In Fig. 2.6 the radiometer gain $G$ is symbolized by an amplifier and its bandwidth $B$ with a low-pass filter. To measure the noisy input signal, a square low detector is used. Its output is directly proportional related to the input signal and so to the temperature $T_A$. An integrator is used to reduce the fluctuations in the detected signal and therefore to increase the stability of the measurement. Moreover, as bigger the integration time, more stable will be the radiometer’s output.

The output voltage of the TPR is the following:

$$V_{out} = kBG(T_A + T_R) = c(T_A + T_R),$$

(2.22)

where the parameters supposed to be constants are grouped in the factor $c$.

On Eq. 1.22, it appears that $V_{OUT}$ is depending on $T_R$ and $G$. As said in the introduction of this chapter, with this dependence, the TPR will not be able to provide enough accuracy for most applications, mostly if the calibration is not performed.

However, regarding the sensitivity of the TPR, it is calculated to be [2.2]:

$$\sigma_T = \frac{(T_A + T_R)}{\sqrt{B\tau}},$$

(2.23)

this will be the maximum sensitivity available for this type of radiometer.

To conclude, with a TPR, the best sensitivity can be performed. However due to the gain fluctuations problems, a calibration process is required frequently.

### 2.3.3 Dicke radiometer

With the aim to correct the stability problem associated to gain fluctuations existing in the TPR, Dicke published in 1946 a radiometer design which holds his name. The Dicke
radiometer (DR), instead of measuring directly the antenna temperature, performs the measurement of the difference between \( T_A \) and a reference temperature \( T_{REF} \) known. With this method, the noise temperature instability \( T_R \) is filtered out and the impact of the gain is largely reduced.

As it is shown in Fig. 2-7, DR is a modified TPR by a switch which changes of position with a given frequency \((f_S)\) with the antenna, the reference temperature \(T_{REF}\) and a demodulator \(\pm 1\) synchronised with the switch. Therefore is obtained two different outputs in distinct time slots. During one \(f_S\) half period, the detector output gives:

\[
V_A = c(T_A + T_R)G,
\]

and during the other \(f_S\) half period:

\[
V_{REF} = c(T_{REF} + T_R)G.
\]

If the frequency \(f_S\) is sufficiently fast to consider the parameter \(T_A, T_R\) and \(G\) constants during an entire period, and also that the period is smaller than the integration time \((f_S > \tau^{-1})\), then radiometer output can be expressed as:

\[
V_{OUT} = V_A - V_{REF} = c(T_A - T_{REF})G.
\]

It can be observed in the Eq. 1.26 that the output of the radiometer now does not depend on the noise temperature \(T_R\), and that the importance of the gain \(G\) is of the same order of magnitude that the difference of temperature \((T_A - T_{REF})\). Therefore if the temperature \(T_{REF}\) is chosen close to the antenna temperature \(T_A\), it supposes that the influence of \(G\) will be small. Then if \((T_A - T_{REF}) \ll (T_A + T_R)\) is fulfilled, the DR increases the accuracy respect to the TPR.

Although the stability of the system is improved, by measuring the antenna temperature just half of the time, the drawback respect to the TPR is a loss of sensitivity. The expression of the sensitivity of the DR can be calculated easily from the TPR equation (Eq. 2.23). Indeed, on each
half period, the radiometer can be assimilated to a TPR pointing to the antenna or to the reference load, using an integration time of $\tau / 2$. Therefore for the first half period, the sensibility obtained is the following:

$$\sigma_{T_A} = \frac{(T_A + T_R)}{\sqrt{B \frac{\tau}{2}}}.$$  \hfill (2.27)

and during the other half period:

$$\sigma_{T_{REF}} = \frac{(T_{REF} + T_R)}{\sqrt{B \frac{\tau}{2}}}.$$  \hfill (2.28)

Then the DR sensibility is obtained by:

$$\sigma_T = \sqrt{(\sigma_{T_A})^2 + (\sigma_{T_{REF}})^2}.$$  \hfill (2.29)

As $T_{REF}$ is assumed to be close from the typical value of $T_A$, from Eq. 2.27 and 2.29 is obtained:

$$\sigma_T = 2 \frac{(T_A + T_R)}{\sqrt{B \tau}}.$$  \hfill (2.30)

this means that, the Dicke radiometer, in spite of being more accurate, its radiometric resolution is a factor of two larger than the TPR.

2.3.4 Conclusion

A Dicke type radiometer has been chosen for its improved stability as compared to a total power one, so it can be calibrated less frequently at the beginning and/or the end of the flight. A Noise Injection Radiometer (NIR) topology was first considered, but the limited improved stability did not compensate the extra weight and power consumption. The radiometric sensitivity that can be achieved with a balanced Dicke radiometer is given by Eq. 2.30. Taking into account that the RF bandwidth is 27 MHz (1400-1427 MHz) and that the maximum flight speed and minimum height determine a minimum integration time of 100 ms for the worst case, a radiometric sensitivity of $\Delta T = 0.71$ K is derived.

2.4 Microwave radiometry applications

There are many microwave radiometry applications. Mainly, they can be included in two
groups: atmospheric applications and Earth surface applications. The main applications and
they suitable frequencies are listed below (Table 1-1).

<table>
<thead>
<tr>
<th>Application</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clouds water content</td>
<td>21, 37, 90</td>
</tr>
<tr>
<td>Ice classification</td>
<td>10, 18, 37</td>
</tr>
<tr>
<td>Sea Oil spills tracking</td>
<td>6.6, 37</td>
</tr>
<tr>
<td>Soil rain</td>
<td>18, 37, 55, 90, 180</td>
</tr>
<tr>
<td>Sea rain</td>
<td>10, 18, 21,37</td>
</tr>
<tr>
<td>Sea ice concentration</td>
<td>18, 37, 90</td>
</tr>
<tr>
<td>Sea surface salinity</td>
<td>1.4, 6.6</td>
</tr>
<tr>
<td>Sea surface temperature</td>
<td>6.6, 10, 18, 21,37</td>
</tr>
<tr>
<td>Sea surface wind speed</td>
<td>10, 18</td>
</tr>
<tr>
<td>Snow coating</td>
<td>6.6, 10,18,37,90</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>1.4, 6.6</td>
</tr>
<tr>
<td>Temperature profiles</td>
<td>21, 37, 55, 90, 180</td>
</tr>
<tr>
<td>Atmospheric Water Vapour</td>
<td>21, 37, 90, 180</td>
</tr>
</tbody>
</table>

As is shown, the frequency at L band (1.4 GHz) is the most suitable for applications related with
the sea surface salinity or the soil moisture.
In this chapter the fundamentals of radiometry theory have been presented. The brightness
temperature and the apparent temperature concepts have been defined, as well as the black and
gray body relationships. Moreover the band frequency used for the airborne radiometer and its
types has also been explained and justified.
3 Avionics system

3.1 Introduction

The aircraft that carries the radiometer has been designed especially for the requirements of the project with an antenna and a remote control to scan an area over land and/or sea. Aboard the aircraft, GPS (position and speed) and attitude sensors are set up in order to georeference the aircraft and so the radiometric data on a map. Until now, several flight tests have been carried out in order to test and then improve the material and some data have already been acquired [3.1].

As already mentioned, the aircraft carries the radiometer and an antenna fixed under its body, which is seen on Fig. 3-1. As the platform is moving, the direction that the antenna beam is pointing, and therefore the radiation that it senses, depends on the attitude of the aircraft with respect to a horizontal reference system (Fig. 3-2). Consequently, in order to properly georeference the data acquired, a study of the attitude of the aircraft is necessary to determine the appropriate sensors, which have to be embedded aboard of the aircraft and know where the antenna is pointing.

For this purpose, a set of inertial sensors have been chosen and incorporated aboard the aircraft in addition to the GPS system, which already provides the position. A set of 3 gyroscopes and a magnetometer have been chosen to determine the attitude of the aircraft. An altimeter, more
Chapter 3. Avionics system

accurate than the GPS, also has been put onboard in order to provide information about the altitude, which it will be seen later, has an important role in data geo-referenced. Finally an accelerometer and a speedometer are as well carried aboard the aircraft to give speed and acceleration information but for future Synthetic Aperture Radar (SAR) applications.

![Diagram of aircraft bearing and footprint](image)

Fig. 3.2: Footprint position regarding to the aircraft attitude

3.2 Analysis of the plane attitude

In the simplest use, attitude is the orientation of an aircraft with respect to the horizon. This is a function of three angles: pitch, roll and yaw. The pitch angle specifies the orientation of the aircraft's longitudinal axis, that is, whether the nose is pointing upwards or downwards. The roll angle specifies whether the aircraft is banked left or right, or whether its wings are parallel to the horizon. The yaw angle specifies if the aircraft is derivate to the left or right with respect to the speed vector. These 3 angles constitute rotation around X, Y and Z as it can be seen on the Fig. 3-3 below:
Pitch, roll and yaw will be provided by sensors embedded on board of the aircraft. These sensors will give information about the inclination and the direction of the aircraft with respect to the local Earth axis.

### 3.3 Inertial system

As mentioned earlier, a set of inertial sensors has been embedded aboard of the aircraft. Their aims are to provide information about the behaviour of the platform during a test flight. Their functions have been detailed below.

#### 3.3.1 Gyroscope

A gyroscope is a device for measuring the turn speed on each local axis, based on the principles of angular momentum. Using the information on each axis, the movement pitch, roll and yaw can be determined.

The device chosen is of the type piezoelectric and it is linear. The mechanism of this sensor is based on the detection of torsion applied on the triangular prism (situated in the direction of the rotation axis) when the platform turns. In order to detect this torsion, an ultrasonic signal is transmitted through a piezoelectric transmitter and is then received back using two piezoelectric receivers. According to the spin sense and the force applied, the magnitude signal on each receiver will be different. The turn detected using the gyros can be due to turbulence, wind, cold or hot air current, but are mainly caused by the command of the flight. The drawback of this
sensor is that it provides a relative measurement with respect to the previous one. So the data acquired cannot be interpreted easily and require a complicated algorithm.

3.3.2 Magnetometer

This instrument is used to measure the strength of the magnetic field of the Earth on the 3 local axes of the aircraft. Knowing the magnitude of the field on each axis allows determining the position of the 3 axes of the aircraft respect to the local earth system. The device chosen, HMC2003, is a three axis magnetic sensor which uses three permalloy magneto resistive sensors. These sensors are sensitive to magnetic fields along the length, width and height (X, Y, Z axis). Fields can be detected less than 40 micro Gauss and up to +/- 2 Gauss. Analog outputs are available for each X, Y and Z axis. With the sensitivity and linearity of this hybrid, changes can be detected in the Earth’s magnetic field to provide compass headings or attitude sensing.

The HMC2003’s magnetic sensors can be affected by high momentary magnetic field that may lead to output signal degradation. In order to eliminate this effect, and maximize the signal output, a magnetic switching technique can be applied to the bridge using set/reset pins that eliminates the effect of past magnetic history. Using the data provided by this magnetometer and comparing to the local Earth’s magnetic field at a certain position, the attitude of the aircraft can be found, but is not straight forward.

3.3.3 Altimeter

The GPS system provide the altitude of the platform, however the precision of the measurement is poor. In order to reduce the uncertainty on this value, the use of an altimeter is required. The mechanism of this sensor is based on the relationship between the pressure and the altitude on a standard atmosphere as shown in the Eq. 3.1.

\[
Z_p = Z_0 \left[ 1 - \left( \frac{P}{P_0} \right)^{\frac{1}{\alpha}} \right] \tag{3.1}
\]

This equation brings into play \( p_0 \), the pressure on the sea level, \( \alpha \) a standard thermodynamic constant found on many sources [3.2] and \( Z_0 \), which is function of the temperature on the sea
level \( T_{0\text{std}} \), the gravity constant \( g \), the gas constant \( R \) and the molecular mass of the air \( M \) reminded below where:

- \( P_0 = 1013.25 \text{ hPa} \);
- \( Z_0 = \frac{T_{0\text{std}}}{\mu} \) with \( T_{0\text{std}} = 15 \text{ C or } 288, 15 \text{ K and } \mu = \frac{gM}{\alpha R} \);
- \( \alpha = 5.258797; \ g = 9.80665 \text{ m/s}^2; \ M = 28.95 \text{ g/mol and } R = 8.31432 \text{ J/mol/K} \).

Finally results Eq. 3.2:

\[
h = k \left[ 1 - \left( \frac{P}{P_0} \right)^{\frac{1}{\alpha}} \right]
\]  

(3.2)

with \( k = \frac{T_{0\text{std}} \alpha R}{gM} = 44331 \times 10^{-3} \text{ m} \).

Therefore, it has been demonstrated that using a pressure sensor, the altitude of the platform can be known. The sensor chosen is the MPX4115 and has to be placed inside of the aircraft to prevent interference due to the wind or the speed. The mechanism of this sensor is to convert the pressure on the sensor to voltage using a transducer. The relationship between these magnitudes is expressed in Eq. 3.3 (the units of the pressure is kPa):

\[
P = \left( \frac{V_{\text{out}}}{V_o} + 0.095 \right) \times \frac{1}{0.009}
\]

(3.3)

The output level of this sensor is between 0 V to 5 V and matches to the analog to digital converter (ADC). It just needs to be powered at 5 V and plugged to the ADC. Besides its size is small and it is easy to incorporate in the body aircraft.

However as shown in the Eq. 3.2, theoretical factors are involved in the determination of the altitude: \( k \) and the exponential factor \( \alpha \). The value of \( k \) is known using the model of the standard atmosphere, which is an approximation and can introduce errors. Looking at Eq. 3.2, it appears that the relationship between pressure and altitude is linear for low altitude (< 500 m) with a coefficient of the slope equal to -0.0117 as it demonstrated in Fig. 3-4.
A calibration process can be followed in order to correct the coefficient of the slope: take one measurement of the altimeter and one of the pressure using a simple barometer in two different places with a known altitude, which can be for example at the Tibidabo Mountain in Barcelona, which is at about 400 m and another one on the sea level at 0 m. Two pairs (altitude, voltage) are known, and since the relationship between the pressure and the voltage is linear (Eq. 3.3), the relationship between the altitude and the voltage it is too. Their coefficient of proportionality is then deduced using the pair measured.

### 3.3.4 Digital Compass

As said before, the process of magnetometric data is not immediate and an algorithm has to be conceived in order to compare its response to the Earth’s field. That is why another solution has been underlined: a new sensor which provides the attitude angles pitch, roll and
yaw already processed, a Digital Compass. The advantage of this solution is that the angles will be providing directly and so right away the data will be able to be geo reference.

The Digital Compass (Fig. 3-5) is a fully functional tilt compensated compass and combines sensors in magnetic and tilt measuring. It consists of a magnetized pointer, free to align itself accurately with Earth’s magnetic field.

The Digital Compass provides via USB the set of three angles:

- azimuth angle: angle between magnetic North and the heading direction.
- inclination angle: angles of tilt on both X and Y axis.

Inclination angles can be measured correctly up to 70° on both axes. Moreover, this sensor carries a calibration protocol that has to be executed once at the first use of the device. Once it is done, the compass is ready to be used.

As seen before, the advantage of this device is that it provides the three attitude angles in degrees, however there are some drawbacks.

After a study of the time of response, by programming a timer on the microcontroller code, it has appeared that the compass needs between 1.1 s to 1.2 s to respond to the interrogation by the PIC. These times, provided by the timer, are saved in the data logger to later be used to synchronise the data.

To summarize, using the Digital Compass allow to obtain quickly information about the attitude of the aircraft. However its main drawback is its time response which is quite low compared to the inertial sensors. Indeed the inertial sensors provide 23 data/seconds. If the speed of the flight is 30 m/s, it means that attitude data will be known every 36 meters and in this interval
the attitude can vary, consequently the data will need to be interpolated during the post processing.

### 3.4 Packaging

The inclinometer and the circuit board have to be embedded aboard of the aircraft. In order to prevent interference from the motor, the radiometer and all the circuits already embedded, the compass board is put on the tail of the aircraft far away of any magnetic field. That is why a special packaged has been put in place in order to store the instrument (Fig. 3.6).

![Fig. 3-6: Compass packaged](image)

When positioning the box aboard of the aircraft, the axes of the aircraft have to be collinear to the axes of the compass. However, in our case the axis X of the compass will be collinear to the axis Y of the aircraft, the axis Y of the compass will follow the inverse direction of the X of the aircraft and the both axe Z will have the same direction (Fig. 3.7). Therefore the angles provided by the compass have to be corrected in order to get the pitch, roll and yaw. The azimuth angle of the compass has to be translated following the Eq. 3.4 to obtain the yaw angle. The opposite value of the inclination angle respect to the axis X (IncX) will be pitch angle and the opposite value of the inclination angle respect to the axis Y (IncY) will be roll angle.

\[
\begin{align*}
\text{Yaw} &= 270 - \text{azimuth} \\
\text{Pitch} &= -\text{IncX} \\
\text{Roll} &= -\text{IncY}
\end{align*}
\]
3.5 Complete system

The ADC resolution is 16 bits. This option is necessary to get an altitude resolution lesser than 10 meters. That’s why instead of using the ADC included in the microcontroller, a new one has been added to the system.

The real time transmission is a source of losses in data acquisition. The solution chosen is to keep the data onboard by writing them by data loggers. These data loggers (Fig. 3-8) are recording data on Secure Digital (SD) card, therefore the capacity of them depend on the chosen card. Aboard the system, a SD card of one gigabyte has been chosen.

At the end of the flight, the data recorded on the SD card are uploaded and then are processed.
The inclinometer, as well as the GPS system, and the inertial sensors are synchronised with the PPS. As it is shown on the overview of the entire system on Fig. 3-9, the GPS and the compass are linked to a microcontroller, whereas the inertial sensor signals are first digitalize and then transmitted to the microcontroller. The three microcontrollers are synchronised using the pulse PPS provided by the GPS.

![Diagram of the entire new system](image-url)
4 ARIEL Processor

As said in the introduction, the aim of this project is to obtain brightness temperature maps from which salinity and/or humidity over land and/or sea could be retrieved. Therefore, it is necessary to implement various algorithms which will process raw data acquired from sensors.

The software AP-SMR (ARIEL Processor - Soil Moisture Retrieval) is designed in order to accomplish the entire data processing from the data files to soil moisture maps that could be projected over Google Earth maps.

A graphical user interface (GUI) is proposed to allow an easier and faster way to obtain flight information. It will be described more in details in the next chapter.

In this chapter the main steps of the method used to recover soil moisture will be explained (Fig. 4-1):

- Correction of the errors in data files due to system malfunctioning (data logger, GPS and inertial sensors).
- Synchronisation of data from the different groups of sensors aboard the plane (GPS, Inertial sensors and the compass)
- Calibration automatic of radiometer output data. As the radiometer used is a Dicke radiometer, there is a relationship between its output voltage and the antenna temperature from which we can determine the SM.
- Interpretation of the apparent temperature of the antenna in order to obtain estimated soil moisture.
- Display information in various ways: graphs, histograms, trajectory maps, footprints maps, interpolation maps...

Fig. 4-1 Mains steps of data processing
4.1 Correction of data errors

4.1.1 GPS and Altimeter errors

The data record system aboard the aircraft presented random weaknesses. The solution chosen to sort out this problem is to keep the data onboard by writing them by data loggers. That’s why two types of data sets can be identified: those measured before the addition of the data logger which present a lot of erroneous points (zero values on Fig. 4-2), and those measured after (Fig. 4-3). These errors need to be corrected since GPS and altimeter sensed altitudes will be used later during the synchronisation process. Moreover, an offset correction has to be performed on GPS data as it can be seen on (Fig. 4-2). This offset is due to the projection error on the ellipsoid reference model (WGS-84).

![Fig. 4-2 Measurements done before the introduction of the data logger; the GPS and the altimeter introduce zero values in data files](image1)

A solution to correct data is to carry out an interpolation. To do so, we use the function interp1 of Matlab. The interp1 command interpolates between data points (x, Y). It finds values \( y_i \) at intermediate points \( x_i \), of a one-dimensional function that underlies the data. This function is shown below, along with the relationship between vectors x, Y, x_i, and y_i.
The method used to determine the one-dimensional function that underlies the data has to be chosen. In our case, the three available options are the linear interpolation, the cubic spline data interpolation and the piecewise cubic Hermite interpolation. These methods will be compared and the more appropriate one will be selected.

4.1.1.1 Linear interpolation

This method fits a different linear function between each pair of existing data points, and returns the value of the relevant function at the points specified by \( x_i \). The results are shown in the next figure.
It can be noticed that the results are continuous, but the slope changes suddenly at the vertex points. Moreover the derivative has some plateaus which don’t reflect the underlying physical phenomenon.

4.1.1.2 Cubic spline data interpolation

This method fits a different cubic function between each pair of existing data points, and uses the spline function to perform cubic spline interpolation at the data points. It involves the construction and subsequent use of a piecewise-polynomial approximation.

![Fig. 4-6 Cubic spline data interpolation](image)

The result is more continuous than the previous method. However, the derivative also shows suddenly changes.

4.1.1.3 Cubic interpolation

It uses the pchip function to perform piecewise cubic Hermite interpolation within the vectors x and y. On the figure below, it can be noticed that the derivative is slightly smoother than the spline method.
4.1.1.4 Choice of the interpolation method

The pchip method has been chosen as both the interpolated data and its derivative show the best continuity which is in accordance with our will to get a good approximation of a continuous and natural phenomenon. An example of corrected data is given on Fig. 4-8 and Fig. 4-9.

Fig. 4-7 Cubic interpolation

Fig. 4-8 GPS and Altimeter interpolated and corrected data. Case of data set measured before the addition of the data logger.

Fig. 4-9 GPS and Altimeter interpolated and corrected data. Case of data set measured after the addition of the data logger.
Chapter 4. ARIEL Processor

4.1.2 Data logger errors

The data logger system introduces errors in the inertial sensors set of data. As it can be seen on Fig. 4-11, these errors are present for all the inertial sensors at the same time, and can be detected by the high values they generate. The algorithm implemented detects these picks and replaces them by interpolated values. A cubic interpolation is used since it needs few samples to generate the approximate value (at least four samples). Doing so, the local behaviour of each interpolated value is kept. On Fig. 4-10, the result of the algorithm applied to the radiometer thermometer data is displayed.

![Fig. 4-11 Data logger errors; these errors are visible for each inertial sensor: thermometer, altimeter and radiometer](image)

![Fig. 4-10 Correction algorithm applied to thermometer data](image)
4.2 Synchronisation of the data sets

4.2.1 Introduction

In order to geo-reference radiometric data, it’s necessary to synchronise GPS, radiometric and compass data: GPS gives us the position of the plane, radiometric data is used to estimate soil moisture and compass data is used to determine the shape of the footprints so as to know more precisely which parts of the soil have been covered by the radiometer main beam. The synchronisation is achieved with two steps (Fig. 4-12):

- Synchronisation of GPS and altimeter sensed altitudes. Since radiometric data and altimeter data are already synchronised (they are both in the inertial sensors set), the synchronisation GPS/radiometer is performed too.
- Synchronisation of compass data and GPS data.

![Fig. 4-12 Steps of the synchronisation](image)

4.2.2 Synchronisation of GPS and inertial sensors

This synchronisation is performed using an auto-correlation between GPS and altimeter altitudes. The corrected data are used (Fig. 4-8) to process this correlation. Then the algorithm finds the maximum of the auto-correlation function (Fig. 4-14). The corresponding abscissa is the time shift that should be applied to the altimeter’s altitude. A positive value of the abscissa shifts the altimeter altitude towards the left.

Finally, the two altitudes are aligned in time and the GPS and the inertial sensors are synchronised (Fig. 4-15 and Fig. 4-16). The algorithm also adjusts the offset of the GPS altitude;
the ground’s altitude is taken as reference (0 meter). To determine the value of the vertical offset, the histogram is computed; the ground altitude is the one which has the higher number of samples (Fig. 4-13).

![Fig. 4-13 Histogram of GPS's altitude](image)

Case of data set measured after the addition of the data logger.

![Fig. 4-14 Maximum value of the auto-correlation](image)

Case of data set measured before the addition of the data logger.

![Fig. 4-15 GPS and altimeter's altitudes are aligned and the GPS offset is corrected.](image)

4.2.3 Synchronisation of GPS and compass data

After a study of the time of response, by programming a timer on the microcontroller code, it has appeared that the compass needs between 1.1 s to 1.2 s to respond to the
interrogation by the PIC. These times, provided by the timer, are saved in the data logger to be used to synchronise the data (Fig. 4-17).

Fig. 4-17 Time response of the compass

The synchronisation is performed with two steps illustrated on Fig. 4-18:

- An oversampling is performed via an interpolation over the compass data in order to increase the number of samples. The idea is to get at least the same number of samples as the GPS.
- Then a down sampling is achieved such as the compass kept samples match with GPS samples. Only the nearest (in term of time distance) compass sample from a given GPS sample is kept. We get the same number of samples for GPS and compass data.

Finally the three data sets (compass, GPS and inertial sensors) acquired during the flight are synchronised and ready to be used for the next steps of the processing. A way to visually verify that compass and inertial sensors are synchronised is displaying on the same graph the altimeter altitude and the pitch (Fig. 4-19). Indeed, the pitch angles matches with the altitude changes. It appears that when the altitude increases ((1) in Fig. 4-19), the pitch angle also increases due to the nose of the aircraft which goes up. On the contrary, when the altitude decreases ((2) in Fig. 4-19), the plane nose goes down and the pitch angle decreases.
Fig. 4-18 GPS/Compass synchronisation process

Fig. 4-19 Altitude and pitch angle from the Ripollet flight
4.3 Calibration of the radiometer response

4.3.1 Introduction

Once the synchronisation has been achieved, the radiometric data have to be calibrated. The aim of the calibration step is to convert the radiometer’s raw output voltages, displayed in Fig. 4-20, into antenna temperatures. As the radiometer ARIEL aboard the aircraft is a Dicke radiometer, the relationship between its output voltage and the antenna temperature can be expressed as Eq. 4.1 [2.2]:

\[ v_o = a(T_{ref} - T_A) + b \]  

(4.1)

Where: \( T_{ref} \) is the temperature of the reference load (measured with a thermometer), \( T_A \) is the antenna temperature and \( a \) and \( b \) are gain and offset to be determined during calibration. In a first approximation we consider that these coefficients are constant during the flight, and then we will study their variations (double radiometric calibration).

Therefore, a set of two pairs \((v_o, T_A)\) has to be determined. The first pair is found by using the temperature of the radiometer and its output voltage when the antenna is pointing at the cold load: the sky. It is assumed that the value of \( T_{ref} \) for the cold load is 6 K at the L-band. The other pair is taken when the antenna is pointing at the hot load (a microwave absorber) and \( T_{ref} \) corresponds to the ambient temperature, so 300 K is taken as the reference.

In the case of a simple radiometric calibration, the measures for the calibration are taken either before or after the flight. For a double calibration they are taken before and after the flight. That’s why the algorithm must be informed of what type of calibration has been done so that it knows where it should find the data of interest. For example, on Fig. 4-20, data correspond to a simple calibration at the end of the flight. These choices are implemented in the graphical interface with radio-buttons (see next chapter).

The algorithm must find automatically the pairs \((v_0^{hot}, T_A^{hot})\) and \((v_0^{cold}, T_A^{cold})\). To do so, it must locate the calibration measures on the radiometric data. The cold load can be found easily since it corresponds to the highest value of the output voltage of the radiometer. On the contrary, in order to find the hot load, some requirements have to be fulfilled:

- The measurement of the hot load must be done right before the one of the cold load.
• The time length of the measure must be at least as long as the measure of the cold load.

These constraints are explained more in details in the part 4.3.3 of this work.

The equations system formed by these two calibrations points is then solved and the constants $a$ and $b$ are found (Eq. 4.2 and Eq. 4.3).

$$b = \frac{\left( v_0^{\text{hot}} - v_0^{\text{cold}} \right)}{\left( T_A^{\text{hot}} - T_A^{\text{cold}} - T_{\text{ref}}^{\text{hot}} + T_{\text{ref}}^{\text{cold}} \right)}$$  \hspace{1cm} (4.2)

$$a = v_0^{\text{hot}} - b \left( \frac{T_A^{\text{hot}} - T_{\text{ref}}^{\text{hot}}}{a - T_{\text{ref}}^{\text{hot}}} \right)$$  \hspace{1cm} (4.3)

$T_A^{\text{hot}}$ and $T_A^{\text{cold}}$ are the physical temperatures of the radiometer measured with the thermometer onboard during the measures of the hot and the cold loads.

Finally, a set of calibrated antenna temperatures ($T_a$) can be obtained (Eq 4.4). These measurements are not yet surface brightness temperatures as they are affected by the antenna main beam efficiency (MBE) and they also have the contributions from the atmosphere, Sun reflections, etc.

$$T_a (t) = \frac{b - v(t)}{a - T_{\text{ref}}(t)}$$  \hspace{1cm} (4.4)

For a value $v$ of the output voltage of the radiometer, the corresponding $T_{\text{ref}}$ is the physical temperature of the radiometer measured with the thermometer onboard.

Fig. 4-20 : (a) Altitude and (b) Radiometer raw data of one of the flight
4.3.2 Double radiometric calibration

It can occur that a radiometer does not have a linear behaviour due to temperature changes or other non-linear variations. That is why the coefficients $a$ and $b$ in Eq. 4.1 are not constant during the flight. In order to approximate this evolution, two calibrations could be done: one at the beginning of the flight and one at the end. In this way, two pairs of value $(a_0, a_f)$ and $(b_0, b_f)$ are computed from which $a(t)$ and $b(t)$ are determined, the functions approximating the values of $a$ and $b$ at time $t$.

In a first approximation these functions are considered to be affine; $a(t)$ and $b(t)$ are calculated with the Eq. 4.5 and 4.6.

An example of double calibration is given on Fig. 4.22. The intervals of calibration are indicated in red. On figure Fig. 4-21, we can see the values of $a(t)$ and $b(t)$ for this flight.

\[
a(t) = a_0 + \frac{a_f - a_0}{t_f - t_0} \cdot (t - t_0) \quad (4.5)
\]

\[
b(t) = b_0 + \frac{b_f - b_0}{t_f - t_0} \cdot (t - t_0) \quad (4.6)
\]

Finally, the functions $a(t)$ and $b(t)$ are used in order to compute $T_a(t)$ with the Eq. 4.4.
4.3.3 Recovery of $\nu_0^{hot}$ and $\nu_0^{cold}$ from the radiometric data

At the input of the algorithm the synchronised data from the different sensors are used: GPS, Inertial sensors and the compass (Fig. 4.23).

The first goal is to get rid of the radiometric data acquired during the flight since they are not useful for the calibration. The speed has been chosen to determine if the plane is flying or moving since it is a more accurate criterion than the altitude: for example, if the plane goes on
the runway, the altitude is 0 but the speed is higher. We compute the velocity of the plane as a function of the latitude \(a\) and the longitude \(b\) (Eq. 4.7).

\[
    v(t) = \sqrt{\left(\frac{\partial a}{\partial t}\right)^2 + \left(\frac{\partial b}{\partial t}\right)^2}
\]  

(4.7)

On Fig. 4-24 we can see the evolution of the speed during the flight. As expected, the speed of the plane rises up as his altitude rises (Fig. 4-25 c)).

![Graph of the approximate speed](image)

**Fig. 4-24** Determination of the approximate speed. The threshold chosen for the speed mask is indicated.

A threshold of speed has been chosen to determine if the plane is still or not. The threshold chosen is 10% of the maximum speed. Knowing that the flight speed is approximately 30 m/s, it is reasonable to consider that all moves which speed is less than 3 m/s don’t belong to the flight. All the values higher than the threshold are ignored by the next steps of the calibration process. On Fig. 4-24, the line corresponding to this threshold has been plotted.

The result of the speed mask has been plotted on Fig. 4-25. On the graph a), it can be seen that the cut is coherent with the speed of the plane (ignored radiometric data have been set to zero). On the graph b), it can be concluded that the result is coherent with the altitude. This is easily understandable by having a look at the graph c) which shows the high correlation between the altitude and the speed of the plane.
Fig. 4-25 result of the speed masking compared with the speed of the plane (A) and with the altitude of the plane (B); Comparison between speed and altitude of the plane (C)

In order to perform the next step of the algorithm, the interval of interest has to be specified. It depends on the moment when the calibration’s measure has been done; it is to say before or after the flight. This information is given as an argument of the function implemented on Matlab.

If the measure has been done before the flight, the kept interval begins at the first radiometric data and ends to the beginning of the flight which has been determined previously thanks the flight speed.

If the measure has been done after the flight, the kept interval begins at the end of the flight and ends to the end of radiometric data.
Finally, in the case of a double calibration, the algorithm is firstly executed on the interval before the flight, and secondly on the interval after the flight.

Once the interval of interest is defined the next step is to find the values of $v_0^{hot}$ and $v_0^{cold}$. These values are actually computed as a function of the output voltage of the radiometer over the corresponding time intervals; the time interval corresponding to the measure of the cold load is named $I_{cold}$, and the one corresponding to the hot load is name $I_{hot}$ (Fig. 4-26).

![Fig. 4-26 Illustration of the measuring intervals of the cold and hot loads](image)

These intervals are determined automatically by the algorithm, beginning with the determination of $v_0^{cold}$ and $I_{cold}$ as it follows:

1. The maximum value of the output voltage of the radiometer is determined. By definition, this value belongs to $I_{cold}$ ((1) in Fig. 4-28)

2. The derivative of the radiometric voltage is computed. Indeed, the calibration of the cold load leads to a sudden raise in the value of the radiometer output voltage so the derivative takes a high positive value at the beginning of $I_{cold}$ and a high negative value at the end. However if the radiometric data are noisy, a lot of high values in the derivative function can be detected (Fig. 4-27).
3. In order to find the beginning and the end of $I_{cold}$, the algorithm memorizes the indexes of the derivative values higher than 0.5V/s ((2) in Fig. 4-28).

4. The beginning of $I_{cold}$ is the index of the high positive derivative value which is the nearest (on the left) from the index of the maximum value of the output voltage computed before ((3) in Fig. 4-28).

5. The end of $I_{cold}$ is the index of the high negative derivative value which is the nearest (on the right) from the index of the maximum value of the output voltage computed before ((3) in Fig. 4-28).
6. Once $I_{\text{cold}}$ is determined, $v_{0}^{\text{cold}}$ can be computed. To do this, the variance of vectors belonging to the interval determined above is computed. These vectors are equally distributed all along the interval and their length is 20% of the length of $I_{\text{cold}}$. Generally
$I_{\text{cold}}$ lasts one minute, so these intervals contain at least 10 samples (1 sample/s). This is sufficient to get an accurate result when the mean value is computed (see below).

7. When the variance of one of these vectors is below than 0.1V (which is approximately the resolution of the radiometer), its mean value is computed. Finally, by averaging the mean values obtained, the value of $v_0^{\text{cold}}$ is obtained. On Fig. 4-29, it can be seen an illustration representing the small vectors used to compute the variance all over the calibration interval, and on Fig. 4-30, the values of the variance that we have been obtained are plotted.

![Fig. 4-29 Illustration of the method applied in order to determine $V_{\text{cold}}$](image)

This method allows avoiding the edge effects that can appear on the extremities of the interval of calibration. These effects can reduce the value of $v_0^{\text{cold}}$ when computing the mean value over $I_{\text{cold}}$. This also allows ignoring erroneous values.

![Fig. 4-30 Evolution of the variance over the moving vectors for the calibration of the cold load](image)
8. \( v_0^{\text{hot}} \) is determined. It is guessed that two requirements are fulfilled:

- The measurement of the hot load must be done right before the one of the cold load
- The time length of the measurement must be at least as long as the measure of the cold load

In this way, \( I_{\text{hot}} \) is defined with the two following parameters:

- \( I_{\text{hot}} \) ends when \( I_{\text{cold}} \) begins
- \( I_{\text{hot}} \) has the same length as \( I_{\text{cold}} \)

9. Then the same method as for the determination of \( v_0^{\text{cold}} \) is applied on \( I_{\text{hot}} \). On Fig. 4-31, an example of the values of the variance obtained is plotted, and on Fig. 4-26, \( v_0^{\text{cold}} \) and \( v_0^{\text{hot}} \) have been plotted over the corresponding intervals \( I_{\text{cold}} \) and \( I_{\text{hot}} \) (green lines).

Fig. 4-31 Evolution of the variance over the moving vectors for the calibration of the hot load

10. The last step is to compute the antenna temperature. The temperatures \( T_A^{\text{hot}} \) and \( T_A^{\text{cold}} \) of the radiometer are needed in order to obtain the coefficients \( a \) and \( b \) (Eq. 4.2 and 4.3). This will be the average temperatures over the same intervals as we used to determine \( v_0^{\text{cold}} \) and \( v_0^{\text{hot}} \). Once the coefficients \( a \) and \( b \) are determined (or \( a(t) \) and \( b(t) \) in the case...
of a double calibration), the calibration formula is applied (Eq. 4.4). The temperature of
the antenna is obtained as it can be seen on Fig. 4-32.

The values seem to be coherent since the temperature of the cold load is around 6 K as expected
and the temperature of the hot load is approximately 300 K.

![Antenna temperature](image)

**Fig. 4-32 determination of antenna temperature**

It can be noticed on Fig. 4-32 that the antenna temperature obtained when the plane is on the
ground differs in the parts (1), (2) and (3). This variation is due to the non-linear behaviour of
the radiometer. The double radiometric calibration has been implemented in order to solve this
problem. As it can be seen on, part (1) and (2) are approximately at same level.

![Antenna temperature](image)

**Fig. 4-33 Determination of the antenna temperature in the case of a double radiometric calibration**
4.4 Soil Moisture retrieval

In this part, the principles used in order to determined soil moisture from the antenna temperature and the underlying hypothesis are explained

4.4.1 Hypothesis

For this work the following hypothesis are considered:

- Hypothesis 1: in this first approach, the soil is considered to be bare and smooth (surface roughness = 0).
- Hypothesis 2: only the horizontal polarization is taken into account since the positions of the footprints are mainly affected by the roll oscillations as it can be seen on Fig. 4-34.

\[ \text{Fig. 4-34 Footprint position regarding to the aircraft attitude} \]

- Hypothesis 3: it is guessed that the antenna is still looking at the soil in the nadir direction, since only in this case the measurements are relevant in order to determine the soil moisture. That is why it will be considered that the angle of incidence \( \theta_i = 0^\circ \).

4.4.2 Interpolation from a Reference Table

From the previous steps, \( T_A \) the antenna temperature has been determined. In the next lines, it will be called \( T_A^{\text{meas}} \) (\( T_A \) measured).
In order to estimate the corresponding soil moisture, a reference table is used whose generation is explained in the next part. It is a 3D table containing the following coordinates: soil moisture, physical temperature \((T_{ph})\) and an estimated antenna temperature \((T_A^{est})\) corresponding to the two previous parameters; a representation of this table is given on Fig. 4-35.

\[ T_A^{meas} \]

and the physical temperature obtained by the thermometer aboard are used to estimate soil moisture by computing a cubic interpolation over the data in the reference table. It can be noticed that the altitude of the plane and the incidence angle are not taken into account in the reference table. These are a consequence of Hyp.1 and of the low influence of the altitude as explained in the next part.

### 4.4.3 Construction of the Reference Table

In order to construct the table, \(T_A^{est}\) need to be calculated. It is related to \(T_{AP}\) with the following equation:
\[ T_A = \frac{1}{\Omega_p} \int_{-\pi}^{\pi} T_{AP}(\theta,\phi) \left| F_n(\theta,\phi) \right|^2 d\Omega, \]

(2.20)

where \( F_n(\theta,\phi) \) is the normalized antenna voltage pattern and \( \Omega_p \) is the antenna pattern solid angle. Due to the symmetry of the problem, we will only consider the angle \( \theta \).

As explained in part 2.2.4.1 of this work, the \( T_B \) of the surface is measured by an antenna far away (Fig. ). In this case, the apparent temperature \( T_{AP} \) is the key parameter that depends on:

- the brightness temperature of the surface under observation \( (T_B) \),
- the atmospheric upward radiation \( (T_{UP}) \),
- the atmospheric downward radiation scattered reflected by the surface \( (T_{SC}) \), and
- the atmospheric attenuation \( (L_a) \),

and can be written as

\[ T_{AP} = T_{UP} + \frac{1}{L_a} \left( T_B + T_{SC} \right). \]

(2.18)

Due to the low height of the flights, all the contributions from the atmosphere can be neglected. Indeed, if we consider a height of 300m which is the double of the mean flight height, we have

\[ T_{UP} \approx 0.12 \, K \quad \text{and} \quad L_a \approx 0.999 \]

It can be inferred that

\[ T_{AP} = T_B + T_{SC} \]

(4.8)

4.4.3.1 Determination of \( T_B \)

In the case of bare soil,

\[ T_B^p(\theta) = (1 - \Gamma^p(\theta)) \cdot T_{soil} \]

(4.9)

Where \( p \) is the polarization (here it is horizontal due to Hyp.2), \( T_{soil} \) is the physical temperature of the soil. It will be assumed that it is equal to the physical temperature of the air called \( T_{ph} \) measured by the thermometer onboard, \( \theta \) is the angle of observation (Fig. 4-36),
the reflection at the air-ground interface $\Gamma^0(\theta)$ depends on the permittivity $\varepsilon_r$ of the soil:

$$\Gamma^h(\theta) = \frac{\cos\theta - \sqrt{\varepsilon_r - (\sin\theta)^2}}{\cos\theta + \sqrt{\varepsilon_r - (\sin\theta)^2}}$$

(4.10)

with $\varepsilon_r = \varepsilon_r^r + j \varepsilon_r^i$.

The real part ($\varepsilon_r^r$) and the imaginary part ($\varepsilon_r^i$) of the permittivity depends on the volumetric content of soil moisture. This dependence is approximated by the Wang model [4.1]:

$$\varepsilon_r^r = 3.1 + 17.36 \times SM + 63.12 \times SM^2$$

(4.11)

$$\varepsilon_r^i = 0.031 + 4.65 \times SM + 20.42 \times SM^2$$

(4.12)

As it can be seen, $T_{\text{sc}}^h$ only depends on the physical temperature of the soil ($T_{\text{ph}}$), the soil moisture (SM), and the angle of observation $\theta$.

### 4.4.3.2 Determination of $T_{\text{sc}}$

The atmospheric downwelling radiation scattered reflected by the surface ($T_{\text{sc}}$), is related to the reflections from other sources that the radiometer ($T_{\text{DN}}$): Sun, Moon, galactic noise, atmosphere...

$$T_{\text{sc}}^h(\theta) = T_{\text{DN}}^h(\theta) \times \Gamma^h(\theta)$$

(4.13)

where $\Gamma^h(\theta)$ is given by the expression (4.10).

Considering an extreme height of 300 m for the flight and neglecting the galactic noise, $T_{\text{DN}}^h(\theta)$ has been calculated and approximated by the following expression:
\[ T^h_{DN}(\theta) = \frac{4.37}{\cos \theta} [K]. \] (4.14)

Finally \( T^h_{DN}(\theta) \) only depends on \( \theta \) and on the SM.

### 4.4.3.3 Generation of the table

For a given \( T_{ph} \) and SM, the corresponding value of \( T^h_A \) can be computed (Eq. 4.8). Then \( T^h_A \) can be deduced with equation (2.20).

The reference table is generated by computing \( T^h_A \) for different values of \( T_{ph} \) and SM. For the default reference table, the following parameters have been chosen (they can be changed easily with the GUI):

\[
270 \leq T_{ph} \leq 330 [K] \text{ with a step of } 0.1 K, \text{ and} \\
0 \leq SM \leq 0.5 \text{ with a step of } 0.01. 
\]

### 4.5 Display of the antenna footprints

Some options of the implemented GUI allow the user to visualize the footprints of the antenna or even its path by processing the parameters of the flight. In order to reach this aim, some algorithms have been implemented using mathematical and remote sensing theory, which are going to be presented in the following paragraphs. Actually they expose the two mains steps to succeed to plot the shape of the footprint: firstly, how determine the position pointing by the antenna and secondly, the method to specify the shape of the footprint.

#### 4.5.1 Specify position pointing by the antenna

The radiometric data acquired by the antenna depend on where the antenna is pointing. That is why the attitude of the platform where is fixed the antenna is an important issue. The attitude which is defined by 3 angles, pitch, roll and yaw as remembered in Fig. 4-37 are provided by an inclinometer aboard of the aircraft.
These angles define the position of the platform respect to the local Earth system of coordinate. In order to position the centre of the antenna boresight, a change of coordinate is necessary to pass from the aircraft body and Earth coordinate frame as shown in Fig. 4.38. The system (x’, y’, z’) represents the aircraft, (x, y, z) the local Earth system at the altitude of the platform and finally (x”, y”, z”) its projection over land. The position A represents the point which has to be specified. The first step is to find the direction of the antenna boresight named $\mathbf{Z}_b$ in the Fig. 4.38.

As the plane system of coordinate is defined in Fig. 4.39, it appears that the antenna direction is the opposite direction of z’. On the one hand, by using the matrix passage P from the system (x, y, z) to (x’, y’, z’), and on the other hand, by projecting the vector z’ in (x, y, z), the coordinate of this vector is accessed as it is explained below.

The first step is to find the direction of $\mathbf{Z}_b$ in the coordinate frame (x y z). The position of the aircraft, referenced by ($x_{gps}$, $y_{gps}$, $z_{gps}$), corresponds to the position provided by the GPS system aboard of the platform. Although $z_{gps}$, the altitude of the platform, is also provided by the GPS, the measurement taken will be mostly the measurement from the altimeter, more reliable.
With $\mathbf{X}' = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}$ and $\mathbf{Z}_b = \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix}_{xyz}$

and the transformation matrix $P$,

$$P = \begin{bmatrix} \cos \phi \cos \psi & \cos \phi \sin \psi & -\sin \phi \\ -\sin \psi \cos \theta + \cos \psi \sin \phi \sin \theta & \cos \psi \cos \theta + \cos \psi \sin \phi \sin \theta & \sin \theta \cos \phi \\ \sin \psi \sin \theta + \cos \psi \sin \phi \cos \theta & -\cos \psi \sin \theta + \sin \psi \sin \phi \cos \theta & \cos \theta \cos \phi \end{bmatrix}$$

(4.15)
with the following elements: \( \phi = \) roll, \( \theta = \) pitch, \( \psi = \) yaw.

Then operating mathematically

\[
\tilde{X}' = \begin{bmatrix} P \end{bmatrix} \begin{bmatrix} \tilde{Z}_b \end{bmatrix}
\]

(4.16)

and finally the projection relationship (Eq. 4.17) is achieved

\[
\tilde{Z}_b = \begin{bmatrix} P^{-1} \end{bmatrix} \begin{bmatrix} \tilde{X}' \end{bmatrix}
\]

(4.17)

The second part of the calculation specify the coordinate of the point A by executing a change of coordinates from \((x, y, z)\) to \((x'', y'', z'')\). As the equation of a curve in the system \((x, y, z)\) containing the vector \(\tilde{Z}_b\) is of the type (Eq. 4.18). Then if the same reasoning is made for the system \((x'', y'', z'')\), the curve equation resulting is (Eq. 4.19), hence the system of equations is:

(Eq. 4.20).

\[
\begin{align*}
(x - 0) & = \frac{y - 0}{y_b} = \frac{z - 0}{z_b}, \\
\end{align*}
\]

(4.18)

and

\[
\begin{align*}
\frac{x'' - x_{gps}}{x_b} & = \frac{y'' - y_{gps}}{y_b} = \frac{z'' - z_{gps}}{z_b}.
\end{align*}
\]

(4.19)

As \(z''_{A} = 0\), from (Eq. 4.18) and (Eq. 4.19), the following solution is found:

\[
\begin{align*}
\begin{cases}
{x''_A} & = -\frac{z_{gps}}{z_b} \times x_b + x_{gps} \\
y''_A & = -\frac{z_{gps}}{z_b} \times y_b + y_{gps}
\end{cases}
\]

(4.20)

Finally the coordinates of A, position of the centre of the antenna footprint, are found. Knowing this information, it is necessary now to determine the shape of the footprint.

### 4.5.2 Specify the shape of the antenna footprint

#### 4.5.2.1 Antenna characteristic

In order to specify the shape of the footprint, the characteristics of the antenna like its pattern and its beam, have to be studied.

The antenna, developed in [4.2], is a hexagonal 7 patch array with a 22 degrees beam and a Main Beam Efficiency over 90% (Fig. 4-40), that is thermally controlled.
Remote sensing theory shows that the projection of the typical footprint of this type of antenna is an ellipse. So that its parameters have to be calculated using the elements known as the altitude and attitude. Fig. 4.41 underlines the shape of the footprint and the incidence angle. This angle then has to be projected over ground in order to know how position the ellipse.

Fig. 4-40 (a) Antenna pattern measurement mounted on the plane at the anechoic chamber of the Dept. of Signal Theory and Communications, Universitat Politècnica de Catalunya.
(b) Measured full radiation pattern.
(c) Copolar radiation pattern at E-plane.

Fig. 4-41 (a) Beam of the antenna
(b) Footprint as a function of incidence angle with the Eq. 4.21, 4.22 and 4.23

\[ \Delta h = \frac{R^2 \Delta \theta}{h}; \]  \hspace{1cm} (4.21)

\[ \Delta z = R \Delta \theta \quad \text{and} \quad (4.22) \]

\[ R = \sqrt{(x''_A - x_{gps})^2 + (y''_A - y_{gps})^2 + z_{gps}^2}. \]  \hspace{1cm} (4.23)

4.5.2.2 Ellipse theory

An ellipse is defined with a semi major axis \( a \) and semi minor axis \( b \), centred at the point \((h,k)\). Having its major axis parallel to the x-axis, it may be specified by the equation:

\[ \frac{(x - h)^2}{a^2} + \frac{(y - k)^2}{b^2} = 1. \]  \hspace{1cm} (4.24)

This ellipse can be expressed parametrically as:

\[ x = h + a \cos t, \]  \hspace{1cm} (4.25)

\[ y = k + b \sin t, \]  \hspace{1cm} (4.26)

where \( t \) is restricted to the interval \(-\pi \leq t \leq \pi\).

In the particular case, where the axes of the ellipse are not parallel to the x and y axes, the parametric form of an ellipse rotated counter clockwise by an angle \( \phi \) is more adequate:

\[ x = h + a \cos t \cos \phi - b \sin t \sin \phi \]  \hspace{1cm} (4.27)

\[ y = k + b \sin t \cos \phi + a \cos t \sin \phi \]  \hspace{1cm} (4.28)

Thanks to these formulas, it will be easy to draw an ellipse with the semi mayor axis \( a \), the semi minor axis \( b \), and the position of the centre of the ellipse are already known. Indeed these parametric formulas calculate a set of points; the ellipse can be then approximated by connecting the points with lines. One beneficial consequence of using the parametric formula is that the density of points is greatest where there is the most curvature. Thus, the change in slope between each successive point is small, reducing the apparent "jaggedness" of the approximation.

According to what it has been said before, most of the parameters are known except the angle \( \phi \): the projection of the incidence angle. In order to specify it, the scalar theorem has to be applied (Fig. 4-42).
Fig. 4-42 : Scalar theorem to determine the incidence angle

If:

\[
\vec{u} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix},
\]

(4.29)

and

\[
\vec{v} = \begin{bmatrix} h - x_{GRS} \\ k - y_{GRS} \\ 0 \end{bmatrix}.
\]

(4.30)

Then:

\[
\cos \phi = \frac{\vec{u} \cdot \vec{v}}{\|\vec{u}\| \|\vec{v}\|}.
\]

(4.31)

Finally, all the shape parameters of the footprint are determined and it can be plot with AP-SMR.
5 Description of the AP-SMR (ARIEL Processor - Soil Moisture Retrieval)

In this chapter, a description of the software implemented is given. By exploring more in details its different parts, the options and the performance of AP-SMR are exposed. More details about the underlying functions and their interaction are given in Appendix A.

5.1 Overview

The GUI is composed of four main parts as shown on Fig. 5-1:

- Data part: data files can be selected and the type of calibration chosen.
- Basic display part: basic graphs and histograms can be displayed easily.
- Advanced display part: trajectories, footprints and interpolated maps can be generated.
- Reference table part: the reference table used for the SM retrieval can be modified.

Fig. 5-1 Overview of the GUI
5.2 Data part

The aim of this part is to perform the different steps of the processing: correction of data sets, synchronization, calibration and retrieval of soil moisture. Three files are required: the first one is related to the posture of the aircraft, the second one is related to its position obtained with the GPS, and the third one concerns the inertial sensors, the thermometer and the radiometer. This last file is processed in *.mat extension to reduce the data extraction time but originally comes from a *.txt file.

![Fig. 5.2 Representation of the data part](image)

The data part is represented on Fig. 5.2. In order to make the comprehension easier, the different sections of the data part have been surrounded by slashed lines. In section 1, the data files can be selected. The software can handle raw data files which come directly from the datalogger of the aircraft (files *.txt). A button has been added (section 2) in order to convert the inertial sensors’ data file to the appropriate format (*.mat). This button opens the window shown on Fig. 5.3 where the file *.txt can be selected and then converted.

![Fig. 5.3 Conversion of the inertial sensors’ data](image)
In order to give robustness to the whole system, the software has been designed in order to handle the worst case. It can occur that the recording of the compass file is missing or is erroneous due to many possible reasons. If it is the case, it is possible to launch the processing without it, knowing that the result won’t be as accurate as desired (loss of footprints shapes). In the case, the user has to check the checkbox in section 3. The software then creates a dummy file where all the posture angles are set to 0 and the rest of the processing can be performed.

In section 4, the type of calibration can be chosen easily as explained in chapter 4.

Before running the processing it is important to verify that the reference table, from which is generated the SM approximation, is selected in the reference table part is the appropriate one.

Once the files have been selected and the type of calibration chosen, the processing can be launched by clicking on the button \textit{Process Data}. During the processing a waiting bar appears in order to inform the user of the progression (Fig. 5-4).

When the automatic calibration step is done, a question window appears; if the user answers “Yes”, then the calibrations intervals for the hot and the cold loads can be chosen manually (Fig. 5-4). In his case, the selection is done very intuitively using the mouse cursor on the graph where the automatic calibration has been suggested by the algorithm.

Fig. 5-4 Waiting bar and question window

Fig. 5-5 Manual selection of the calibration intervals
Once the manual choice has been done, a new graph is displayed where appears the manually selected calibration intervals (Fig. 5-6).

![Fig. 5-6 Display of the manually selected intervals](image)

Once the processing is finished, a confirmation window is displayed if everything has been done successfully. It can be noticed that if an error occurs, then a message is displayed indicating in which step of the processing is concerned (Fig. 5-7).

![Fig. 5-7 Confirmation window and error message](image)

The user can decide if he wants to display verification graphs or not by checking the checkbox in the section 5 (Fig. 5-2). These graphs are used to appreciate the accuracy of the algorithm (Fig. 5-8):
Graph 1: Pitch and altimeter’s altitude are displayed in order to verify the synchronisation between the inertial sensors’ set of data and compass data. Indeed, as explained in part 4.2.3, the pitch angle matches the altitude changes.

Graph 2: It’s an overview of the different steps of the synchronisation of the inertial sensors’ set of data and GPS data as explained in part 4.2.2. The original data, the corrected data, the values of the autocorrelation function and the final result are displayed.

Graph 3: It’s used to appreciate the speed mask applied in the calibration algorithm over the radiometric data as explained in part 4.3.3. Moreover, the speed is displayed versus the altitude in order to estimate the coherence of the speed calculation.

Graph 4: It displays the antenna temperature obtained in order to appreciate the accuracy of the antenna temperature calculation (explained in part 4.3).

Fig. 5-8 Verification graphs
5.3 Basic displays part

The basic display part represented on Fig. 5-9, allow the user to display the data coming from the flight and the results coming from the processing. The representation can be done either with one or more graphs or with one or more histograms. The following data can be selected in section 1 (Fig. 5-9): yaw angle, pitch angle, roll angle, GPS altitude, altimeter altitude, radiometer raw data, antenna temperature and soil moisture.

The user can choose the type of representation in the section 2 (Fig. 5-9). If option “plots” is selected, the data chosen are displayed in the same graph (Fig. 5-10, part 1). If option “subplots” is selected, data chosen are displayed in different subplots in the same window (Fig. 5-10, part 2). Finally if option “histogram” is selected, the histograms of data are displayed in different subplots in the same window (Fig. 5-10, part 3).

It can be noticed that in the case of the radiometer output voltage and the soil moisture, if the option “plots” is selected, and more than one source of data is displayed, their values are multiplied by 100 for the voltage and by 1000 for the soil moisture in order to make the reading easier.
5.4 **Advanced displays part**

The advanced displays part (Fig. 5-11) allows the user to perform high level data analysis such as the representation of the footprints with the corresponding antenna temperature or soil moisture, the trajectory of the plane during the flight, and to perform an interpolation over the radiometric data in order to obtained maps which can be used with Google Earth.

![Fig. 5-11 Representation of the advanced displays part](image)

5.4.1 **Display of the footprints**

The footprints are calculated and displayed as explained in part 4.5. They can be displayed alone or the user can choose to add their corresponding antenna temperature or soil moisture (section 2 of Fig. 5-11). In this case, the user can select which interval of values he wants to represent with the colours of the *colorbar* of Matlab (section 1 of Fig. 5-11). The values out of this interval are represented in white (Fig. 5-12).

If the user chooses to display the soil moisture, the values that the algorithm was not able to compute are displayed in black (Fig. 5-12). This occurs when the antenna temperature is out of the range of the reference table. This is typically the case during the calibration of the cold load when the antenna temperature is very low.

Moreover, the user can split the flight in time intervals (by default 200 s), depending on the chosen value in the section 3 of Fig. 5-11. The footprints are displayed in different windows.
Each time the user generates a graph (or more if the flight is split), at least two files are generated in the current directory:

- One or more images in format PNG corresponding to the graphs generated (figure.png or figure_part_X.png)
- One or more KML files used to superimpose the generated images over Google Earth maps (Flight_simulation.kml or Flight_simulation_part_X.kml)

In order to view the footprints in Google Earth, the user must convert the PNG images to GIF images specifying that the background colour is the transparent colour [5.1]. Then the user just has to double-click on the corresponding KML file and the image is displayed on Google Earth (Fig. 5-13).

**Fig. 5-12** Example of footprints representation; here the flight is split every 150 seconds and the footprints are displayed with the soil moisture. The selected range is [0; 0.2]

**Fig. 5-13** Example of footprints representation in Google Earth; here the flight is split every 150 seconds and the footprints are displayed with the soil moisture. The selected range is [0; 0.2] and the colour scale is the same as Fig. 5-12.
5.4.2 Trajectory

In section 4 of Fig. 5-11, the user can display the trajectory of the plane during the flight either in a 3D view, or only the projection on the ground (Fig. 5-14).

Fig. 5-14 Displays of the trajectory: in 3D view or the projection on the ground. The latitude and the longitude are given in meters (UTM) and the altitude in meters.

5.4.3 Interpolation

In section 5 of Fig. 5-11, the user can perform an interpolation of the antenna temperature or the soil moisture computed by the algorithm. The interpolation takes advantage from the redundancy in the flight footprints in order to provide global soil moisture information about the sensed area. The linear interpolation has been chosen because it generates less edge effect around a missing pixel than the cubic interpolation. Indeed, with the cubic interpolation a missing pixel creates a region of missing pixels around itself (Fig. 5-15).

Fig. 5-15 Illustration of the two types of interpolation. For the cubic calibration, the edge effects can be seen. Example of soil moisture interpolation. The range of the soil moisture values is [0; 0.2]
A missing pixel corresponds to a value of soil moisture that the algorithm was not able to compute. This occurs when the antenna temperature is out of the range of the reference table. This is typically the case when the antenna temperature is very low (during the calibration of the cold load or when the antenna is looking at the sea) or when the antenna temperature is very high (when the antenna is looking at road for example).

When there is more than one measurement for a single pixel (several values of the soil moisture at the same position), an average of the values is done.

Once again, the user selects the interval of values he wants to represent with the colours of the `colorbar` of Matlab (section 1 of Fig. 5-11). The values out from this interval are represented in white (Fig. 5-16). If the user chooses to displays the soil moisture, the missing pixels are displayed in black (Fig. 5-12).

Moreover, the user can choose the size of the pixel (in meters) in order to have a more accurate interpolation (section 5 of Fig. 5-11).

![Fig. 5-16 Example of soil moisture interpolation with different pixel sizes: on the left the size is 2 m, and on the right 10 m. The units are given in pixel. The range of the soil moisture values is [0; 0.2].](image)

By checking the option, the user can produce an image more suitable to the superimposition over the Google Earth maps; the axis and the grid are hidden and the values out of the selected interval are displayed in black like the missing pixels (Fig. 5-17). This option makes the selection of the transparent colour (background colour) easier when using the created image in Google Earth.
Fig. 5.17 Example of image generated with Google Earth option. The parameters are the same as above.

Again, when the user generates an interpolation two files are generated in the current directory:
- An image in format PNG corresponding to the graph generated (figure_interpolation.png)
- One KML file used to superimpose the generated image over Google Earth maps (Flight_simulation_interpolation.kml)

In order to view the soil moisture map in Google Earth, the user must convert the PNG image to GIF images specifying that the background colour is the transparent colour. Then the user just has to double-click on the corresponding KML file and the image is displayed on Google Earth (Fig. 5.18).

Fig. 5.18 Example of soil moisture interpolation displayed in Google Earth. The range of the soil moisture values is [0; 0.2]
5.5 Reference table part

In order to estimate the soil moisture corresponding to a given antenna temperature, the implemented algorithm uses a reference table whose generation is explained in the part 4.4.2 of this work. In the section 1 Fig. 5-19 of the reference table part, the user can generate his own table with his customized parameters. The minimum value, the maximum value and the step of the soil moisture and the physical temperature can be easily changed.

Fig. 5-19 Representation of the reference table part

When the user clicks on $\text{Generate}$, he must choose the name of the new table and in which folder he wants to save it. By default, once the table is created, it’s set as the current reference table in section 5 of Fig. 5-19. Moreover at the end of the processing, a graph representing the table is displayed (Fig. 4-35).

Depending on the precision of soil moisture desired or depending on the physical temperature during the flight, the user might change the reference table. This can be done easily at any time by clicking on $\text{Change Reference Table}$.

When the processing is launched in the data files part, the reference table taken into account is indicated in section 5 of Fig. 5-19.
6 Soil moisture retrieval results

In order to test the algorithm implemented, two data sets have been used: the so called second flight test over the Ripollet airfield and the flight test to the Ebro river mouth. The Ebro river mouth test includes flights over the sea shore (fresh and sea water) and land (dry and irrigated rice fields) and allow to test the radiometer response to a large variety of scenarios. In this chapter, the soil moisture results for these two flights are analyzed and commented. The SM has been calculated with the following parameters for the reference table:

- \(270 \leq \text{Tph} \leq 330\) [K] with a step of 0.1K
- \(0 \leq \text{SM} \leq 0.5\) with a step of 0.01

6.1 Flight test in the Ripollet airfield

This test took place in the Ripollet airfield which is an airfield close to Barcelona, easy to access (Fig. 6-1).

![Fig. 6-1 Ripollet airfield](image.png)

This area does not offer a wide choice of scenarios (dry or wet soil) as we can notice on the histograms of antenna temperature and soil moisture given on Fig. 6-2. The antenna temperature is homogenous and varies between 230 and 280 K. The high values correspond to the runway since it was dryer than the adjacent fields. As a consequence, the soil moisture is also homogenous and varies between 0.07 and 0.14 which confirms that the fields are dry.

The interpolations of the soil moisture and the antenna temperature have been performed, choosing the intervals determined with the histograms (Fig. 6-3).
Fig. 6-2 Histograms of the antenna temperature and soil moisture for the Ripollet flight. The homogenous values of the antenna temperature and the soil moisture can be noticed.

The antenna temperature changes during the turns (1 and 2). Indeed, during a turn the antenna is nearly pointing to the sky and as this test has been performed at the end of the afternoon, the Sun is on the West and so in (2) (East direction), the temperature is colder and in (1) (West direction), the temperature sensed is hotter. In the region (3) appear white pixels which means that their values are out of the interval selected ([230; 280]). They correspond to the high values of antenna temperature of the runway.

Fig. 6-3 Soil moisture and antenna temperature interpolation for the Ripollet flight. The selected range is [0.07; 0.14] for the soil moisture and [230; 280] for the antenna temperature. The pixel size is 10 m. The units are given in pixels. On these images, the effects of the turns of the aircraft can be appreciated.
Therefore, the soil moisture is homogenous too (3), except when the plane turns (1) and (2). As expected, the region (2) appears wetter and the region (1) dryer. In order to help the reader to situate the flight with respect to the aerodrome, a view in Google Earth is given on Fig. 6-4.

### 6.2 Flight test to the Ebro river mouth

The test site of this campaign has been the Ebro river mouth, 180 km South from Barcelona, because of the large variety of scenarios that can be found in a reduced area: dry soil (ground), moist or flooded soils (rice fields), dry sand, fresh water (small ponds), and salt water (sea). Indeed the Ebro river mouth is one of the largest wetland areas (320 km²) in the western Mediterranean region and is in intensive agricultural use for rice (Fig. 6-5).
The diversity of the site can be noticed by observing the histogram of the antenna temperature on figure Fig. 6-6. Five areas can be noticed:

- **Area A**: the values are included in the interval $[0; 29]$ [K]. These low temperatures correspond to the noisy measurements during the calibration of the cold load.

- **Area B**: the values are included in the interval $[40; 150]$ [K]. They are supposed to correspond to the presence of salt water under the plane as it can be seen on Fig. 6-7 a) where an interpolation of the antenna temperature has been performed in the interval $[40; 150]$ [K].

- **Area C**: the values are included in the interval $[155; 186]$ [K]. They are supposed to correspond to the presence of fresh water under the aircraft as it can be seen on Fig. 6-7 b) where an interpolation of the antenna temperature has been performed in the interval $[155; 186]$ [K]. It can be noticed that very wet regions are also detected like wet sand on the beach or near the irrigation channels.

- **Area D**: the values are included in the interval $[190; 290]$ [K]. They are supposed to correspond to the presence of soil under the plane as it can be seen on Fig. 6-8 where an interpolation of the antenna temperature has been performed in the interval $[190; 290]$ [K]. Thanks to the results of soil moisture, this region can be classified in two sub-regions: wet soil and dry soil. To do so, it is considered that dry regions have soil moisture less than 0.1. The other regions are wet. Two interpolations of the soil moisture have been performed in the interval $[0; 0.1]$ (Fig. a) to observe dry soil) and in the interval $[0.1; 0.5]$ (Fig. b) to observe wet soil). The result seems to be accurate since the dry areas correspond to the sand far from the shore and to the road, and wet areas correspond to wet rice fields.

It can be noticed that due to the design of the reference table, only the pixel with an antenna temperature in the interval $[142; 303]$ [K] have a representation in soil moisture unit (white and coloured pixels on Fig. ). That’s why the soil moisture map is very similar to the map representing the soil regions on Fig. 6-8.

- **Area D**: the values are included in the interval $[295; 500]$ [K]. They correspond to the presence of roads under the aircraft as it can be seen on Fig. 6-8 where an interpolation of the antenna temperature has been performed in the interval $[295; 500]$ [K]. The extreme high values in this interval are due to radiometric interferences.
Fig. 6-6 Histograms of the antenna temperature and soil moisture for the Ebro river mouth flight. The values of antenna temperature and soil moisture are more scattered due to the diversity of the area.

Fig. 6-7 Classification of regions with the antenna temperature. On the right salt water regions and on the left fresh water regions. On (a) the selected interval is [40; 150] [K] and on (b), [155; 186] [K].
As a conclusion, the soil moisture retrieval seems to be accurate since they are correctly related to the ground truth measurements. Moreover, a classification of wet and dry soil can be done by choosing appropriate parameters in the interpolation. However, it is important to underline that these are approximate soil moisture results since the hypothesis of bare soil is not always respected especially in the case of the flight over the Ebro river mouth.
Chapter 7. Conclusions and future work lines

7 Conclusions and future work lines

7.1 Conclusion

The purpose of this project was to perform the data processing from the different sensors in an automatic manner and implement software to create automatically soil moisture maps out of the radiometric data. In order to reach this objective, the project has been divided in different parts.

The first step was to correct and synchronise the different sources of data aboard the plane. Indeed, due to technical problems, the sampling rate of all the sensors is not the same and the data logger introduces periodical errors. Moreover, so far the data processing from the GPS and attitude sensors from one side and from the radiometric data from another side were performed manually. The proposed solution processes data directly from the source files coming from the dataloggers of the aircraft.

The second step was to implement an automatic calibration of radiometric data. The implemented software is able to perform the calibration in a fully or semi automatic manner. The semi automatic mode allows the user to achieve the calibration easily, quickly and intuitively.

The third step was to develop a set of tools in order to analyze and interpret the data obtained from the previous steps. The processor provides graphical visualisations such as histograms, graphs, display of footprints and trajectory. Besides, in order to take advantage from the redundancy in the flight footprints, an interpolation of radiometric data or soil moisture can be done, providing global information about the area. Most of these features are easily usable in conjunction with Google Earth.

The last step was to give a first approach to soil moisture estimation. In this work, it has been considered that the soil was bare and smooth. Although these restrictive hypothesis, the results turn out to be accurate with respect to the ground truth measurements.
Finally, this work has allowed achieving the main objectives of the final project and represents a powerful tool for further works.

### 7.2 Future work lines

The most important part of future works is the improvement of the soil moisture retrieval’s algorithm. In order to reach this aim, the possible steps should be the following:

- In this work, we have considered that the antenna is still looking at the soil in the nadir direction, since only this case the measurements are relevant in the determination of the soil moisture. However this assertion is not totally true and the small incidence angles should be taken into consideration in the processing.
- Only the horizontal polarisation has been considered in the presented results. An improvement would be to consider the contributions of the vertical and horizontal polarisations as a function of each point depending on the nature of the soil and the dynamic of the flight.
- Soil moisture retrieval models vary in function of the types of soils and depend on the presence of vegetation. Progress should be done by including –whenever possible– the effects associated to the vegetation cover.

Finally, another amelioration line would be the automatic characterization of sensed areas: salt water, fresh water, wet or dry soil, roads ... This could be achieved by a cross-analysis between the histograms and the maps of the antenna temperature and the soil moisture.
Appendix
Appendix A - Flowchart of the AP-SMR
Appendix A. Flowchart of the AP-SMR
Appendix B - Acronyms

ADC - Analog to Digital Converter
AP-SMR - ARIEL Processor - Soil Moisture Retrieval
ARIEL - Airborne Radiometer at L-band
DR - Dicke Radiometer
GPS - Global Positioning System
GUI - Graphical User Interface
PAU - Passive Advanced Unit
PPS - Pulse Per Second
SAR - Synthetic Aperture Radar
SM - Soil Moisture
SMOS - Soil Moisture and Ocean Salinity
SSS - Sea Surface Salinity
TPR - Total Power Radiometer
TSIP - Trimble Standard Interface Protocol
USB - Universal Serial Bus
Appendix C - IGARSS 2008 Article
INITIAL RESULTS OF AN AIRBORNE LIGHT-WEIGHT L-BAND RADIOMETER


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ABSTRACT
This paper presents the description and first results on the performance of a light-weight airborne L-band radiometer. This radiometer will be used in the SMOS CAL/VAL activities in the REMEDHUS site (Salamanca, Spain). First, a brief description of the overall system is presented. The first results obtained during a field experiment over the Ebro river mouth are then presented. These include flights over the sea shore (fresh and sea water) and land (dry and irrigated rice fields). This field experiment has also served to test the aircraft and the data processing algorithms that will be used in future campaigns with PAU-ORA, a reduced airborne demonstrator version of the PAU instrument.

Index Terms—L-band radiometer, SMOS, PAU, brightness temperature, calibration, airborne, geo-reference, geo-rectification.

1. INTRODUCTION
In order to obtain brightness temperature data-sets for the SMOS CAL/VAL activities in the REMEDHUS site (Salamanca, Spain), an airborne light-weight L-band radiometer has been designed and implemented by the UPC.

The unmanned aircraft used has been designed so that other payloads such as PAU-ORA [1] (PAU instrument demonstrator without the IR radiometer) are compatible with it.

A test campaign has been conducted to determine the radiometer performance, as well as to test the algorithms developed to calibrate, geo-reference and geo-rectify the data acquired, which are the same to be used in future PAU-ORA campaigns.

The test site of this campaign has been the Ebro river mouth because of the large variety of scenarios that can be found in a reduced area: fresh and salt water, as well as different types of land.

In section 2 of this paper a brief overview of the overall system is given from the instrument to the data processing. In section 3, the test campaign is described and the first results obtained are presented.

2. SYSTEM OVERVIEW
2.1. The aircraft
To fly the radiometer, a remotely controlled aircraft has been designed and built (Fig. 1). This aircraft has 2.5 meter wingspan with approximately 45 minutes flight autonomy. It has been designed to support different payloads up to 5 kg of weight. The aircraft has also an on-board nadir-looking video camera to help interpret the data acquired by the payload.

In order to properly geo-reference the acquired data, a system composed by a GPS, a 3-axes inclinometer, gyros and accelerometers are used to determine both the position and the attitude of the aircraft. The GPS PPS (Pulse Per Second) signal is used to synchronise the GPS and inclinometer data, as well as the radiometer measurements, which are stored in a flash memory aboard, for later processing.
2.2. The radiometer

Since at nadir both polarizations provide the same information, in order to reduce weight only one radiometer chain has been implemented.

A Dicke type radiometer has been chosen for its improved stability as compared to a total power one, so it can be calibrated less frequently at the beginning and/or the end of the flight. A Noise Injection Radiometer (NIR) topology was first considered, but the limited improved stability did not compensate the extra weight and power consumption. The radiometric sensitivity that can be achieved with a balanced Dicke radiometer is given by:

\[ \Delta T = \frac{2(T_{REF} + T_{REC})}{\sqrt{B \tau}} \]  

(1)

where: \( T_{REF} \) is the reference load temperature, \( T_{REC} \) is the receiver’s noise temperature, \( B \) is the system bandwidth and \( \tau \) is the selected integration time.

Taking into account that the RF bandwidth is 27 MHz (1400-1427 MHz) and that the maximum flight speed and minimum height determine a minimum integration time of 100 ms for the worst case, a radiometric sensitivity of \( \Delta T = 0.71 \text{ K} \) is derived.

The antenna used is a hexagonal 7 patch array with a 22º beam and a Main Beam Efficiency over 90% (Fig. 2), that is also thermally controlled.

Radiometric measurements are digitized with 16 bits and stored in a flash memory aboard the aircraft.

Radiometer calibration is performed by measuring with the antenna pointing to an absorber (hot load) and the sky (cold load) before and/or after the flight (Fig 4) and also, during the flight, pointing to the sky during pitch and/or roll manoeuvres.

2.3. Data processing

Once data has been acquired during a flight it is then downloaded for on-ground processing in three steps.

First, the radiometric data is calibrated using the measurements acquired when pointing the hot and the cold loads to determine the calibration line.

Second, using the GPS and the inclinometer data (height and attitude of the aircraft), each pixel footprint is obtained.

Finally, the measurements for each pixel are geo-referenced over Google Earth using the GPS stored data.

3. SYSTEM PERFORMANCE: FIRST RESULTS

In order to test the complete system described, a test campaign has been conducted during daylight conditions. Sun effects have been observed, but this is not a critical issue since we are not yet looking for quality scientific data.

To verify the system’s performance it is important to have high brightness temperature contrasts and to repeat the pass over the same area to check instrument’s stability. To accomplish this requirement, the Ebro river mouth has been chosen as the test place since there it is possible to measure a large number of different scenarios in one flight: dry
soil (ground), moistened or flooded soils (rice fields),
dry sand, fresh water (small ponds) and salt water
(sea).

Two flights have been performed over this area,
measuring the hot and cold loads after landing. The
raw radiometric data as well as the height for one of
the flights are shown in Fig. 4.

\[ v_o = a(T_{REF} - T_A) + b \]

where: \( T_{REF} \) is the temperature of the reference
load (measured with a thermometer), \( T_A \) is the
antenna temperature and \( a \) and \( b \) are gain and offset
constants to be determined during calibration.

Once the constants \( a \) and \( b \) are computed solving
the equations system formed by the at least two
calibration points (hot and cold loads), a set of
calibrated antenna temperatures \( T_A \) can be readily
obtained. However, these measurements are not yet
brightness temperatures as they are affected by the
antenna main beam efficiency (MBE) and they also
have the contributions from the atmosphere, Sun
reflections, etc.

A comprehensive method to retrieve the \( T_B \) from
\( T_A \) can be found in [3]. In this work, due to the low
height of the flights and to other geometric
considerations, all the contributions from the
atmosphere, but the downwelling radiation scattered
can be neglected. Figure 5 shows the antenna
temperatures during the flight, the calibration and
while the radiometer was on the runway. In this last
case it collected the radiometer’s front-end noise
radiated towards the antenna and reflected by the soil
values above \( T_{HOT} \).

The next step in the data processing is to geo-
reference the retrieved \( T_B \) data-set. After
synchronizing the data with GPS time, each pixel
position and footprint is obtained using the GPS and
inclinometer data. Then each pixel is assigned its
correspondent antenna temperature value to conform
the image (Fig. 6).

Once the image is created, the last step is to geo-
reference it and overlap it in an aerial photography
using Google Earth (Fig. 7).

To determine its validity, a first qualitative
analysis of the image obtained (Fig. 7) has been
performed.

First, it is seen that the colder pixels of the image
are those corresponding to sea water and when the
aircraft’s banking angle make the antenna beam point
North (away from the Sun). Also these pixels are
colder than those corresponding to a fresh water mass
[4].
Second, as expected the $T_A$ values for land are higher than the sea water values. Among all the present soil types the sand appears at a higher $T_A$ (Fig. 6, in red) since it was drier than the runway and adjacent fields (Fig. 6, in orange).

Although these results are coherent with theory, it has been found that sea and fresh water have a higher $T_A$ level than expected (approximately 110 K for fresh water, colder for sea) and even in some cases fresh water appears to be hotter than land. Looking to the aircraft video-camera records, it can be seen that this happens when the plane is over-passing water there are Sun reflections (Fig. 8). To avoid this important effect, future flights for SMOS CAL/VAL activities and other scientific campaigns will be performed before sunrise or after sunset.

5. CONCLUSIONS

This work has presented an airborne light-weight L-band radiometer designed and implemented by the UPC and its first performance results obtained during a test campaign at Ebro river mouth.

The system has been verified to be capable to obtain calibrated antenna temperature data-sets and geo-reference them to conform a $T_A$ image that can be overlapped over an aerial photography on Google Earth. Future scientific flights will be undertaken before sunrise or after sunset to avoid the effect of Sun reflections.

Further work has to be done in order to better represent the obtained $T_A$ image by measuring over a more regular pattern, combining the pixels geographically coincident and interpolating the data gaps.

6. REFERENCES


Appendix D - IGARSS 2008 Poster
1. INTRODUCTION

- In order to obtain brightness temperature data sets for the SMOS CAL/VAL activities in the REMEDHOS site (Salamanca, Spain), an airborne light-weight L-band radiometer has been designed and built by UPC.
- A test campaign has been conducted both to test the radiometer as well as the algorithms to calibrate an geo-reference the acquired data.

2. SYSTEM OVERVIEW

- **Aircraft:**
  - Remotely controlled aircraft designed and built by UPC.
  - 2.3 m wingspan.
  - 45 minutes flight autonomy.
  - Ability to fly different payloads up to 5 kg.
  - GPS, Inertimeters, accelerometers and gyro to determine flight trajectory and plane attitude.
  - Near-looking video-camera.
  - GPS, Inertimeter and instrument data synchronized and stored in a flash memory card.

- **Radiometer:**
  - A Dual single-polarization radiometer topology:
    - Superior stability than total power radiometer.
    - Less complexity and weight than a noise injection radiometer.
    - At radi both polarizations provide the same information.
  - BW: 1400 – 1427 MHz, S/N = 0.73K (worst case).

- **Data processing:**
  - Acquired data is calibrated using the measurements obtained when pointing the hot (absorber) and the cold (sky) loads that determine the calibration line.
  - Calibrated data is synchronized with GPS time.
  - Each pixel footprint is obtained using the flight altitude and aircraft attitude from GPS and accelerometer data.
  - Measurements for each pixel are geo-referenced in an aerial photography on Google Earth.

3. PERFORMANCE FIRST RESULTS

- The test site selected is the Ebro river’s mouth Natural Park for its high brightness temperature contrasts and variety of scenarios.

  - Wet and dry soil
  - Salt and fresh water
  - Rice fields and sand
  - Sea waters and small panels

- A calibrated antenna temperature \( T_a \) has been retrieved and validated qualitatively (figure b):
  - Fresh water appears hotter than salt water.
  - Wet soil (irrigated rice fields) appears colder than dry soil (sand) hottest pixels in the image.
  - Water masses (fresh and salt) appear hotter than expected (about 130 K expected for fresh water).
  - This is due to Sun glint (Fig. 7) that increases the apparent antenna temperature.
  - To avoid Sun glint, future scientific flights will be carried out after sunset or before sunrise to get a more favorable geometry.

4. CONCLUSIONS

- An airborne light-weight L-band radiometer has been designed and implemented.
- The system has been verified to provide calibrated antenna temperature data sets.
- Data processing algorithms have been tested as proved to obtain an antenna temperature image and geo-reference it properly, although further work need be done in order to combine the geographically consistent pixels and to interprete data gaps.
- Future scientific flights will be undertaken after sunset or before sunrise to avoid the effects of the Sun reflection.

5. ACKNOWLEDGEMENTS

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Appendix E - IGARSS 2009 Article (preliminary draft)
ON THE USE OF COMPACT L-BAND DICKE RADIOMETER (ARIEL) AND UAV FOR SOIL MOISTURE AND SALINITY MAP RETRIEVAL: 2008/2009 FIELD EXPERIMENTS

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1. INTRODUCTION

In order to obtain brightness temperature data-sets from an airplane, an airborne light-weight L-band radiometer has been designed and implemented in RS Lab of UPC. The design of the compact L-band Dicke radiometer (ARIEL) and a general overview of the self-designed UAV platform were described in [1]. Avionic and radiometric tests had given some preliminary results (Fig. 1 and Fig. 2) that shown the system performance and capabilities [2]. These results infer that the whole system is suitable for soil moisture and sea surface salinity maps retrieval applications.

Within other activities, ARIEL has been involved in the SMOS CAL/VAL activities that will take in the REMEDHUS site (Salamanca, Spain) [3, 4].

![Figure 1. Hot and cold radiometric calibration procedures](image1)

![Figure 2. Ebre river mouth brightness temperature in Kelvin](image2)

2. SOIL MOISTURE MAPS

The platform flexibility gives a wide range of applications such as agricultural, coastal and scientific ones. In one hand the possibility to perform measurements of soil moisture on a UAV
can be exploited for agricultural applications like crop, bushes and mashes monitoring, it can also be useful for other monitoring and prevention activities, such as firefighting pre-detection. For coastal, the main application is the river mouth monitoring to avoid the sea advance over the river. In the other hand, the system will improve our knowledge about the brightness temperature of the soil. For example, more accurate soil moisture maps can be achieved with the sensor flying at low altitudes. Measuring brightness temperature at different low-altitudes with a UAV will improve the spatial resolution in high order and it will provide a basis for the development of pixel disaggregation techniques [4].

3. EXPERIMENTAL FIELD CAMPAIGNS

In order to retrieve soil moisture and salinity maps experimental field campaigns are been conducted over different scenarios during 2008/2009 activities. Three main different scenarios have been chosen to achieve the three main activities of ARIEL. The sites are: Palau d’Anglesola (Lleida, Spain), for agricultural applications within land and crop monitoring, Ebre river mouth (Deltebre, Spain), for coastal applications, and REMEDHUS site (Salamanca, Spain) for SMOS CAL/VAL activities

4. CONCLUSION

The results of the 2008/2009 activities will be presented. Finally, conclusions will be extracted and discussed.

5. REFERENCES


This project is the continuation of the work of Mathilde Glénat in “Georeferencing in Google Earth radiometric data from UAV”. Advisors: A.Camps and X.Bosch. PFC. UPC, 2008.


- [3.2] Aviation formulary
  http://williams.best.vwh.net/avform.htm

- [3.3] Digital Compass Reference Design Kit :


- [5.1] Google Earth tools: