AMATEUR RADIO ASTRONOMY EQUIPMENT

How to use RAL10KIT and RAL10AP to build a Microwave Radio Telescope

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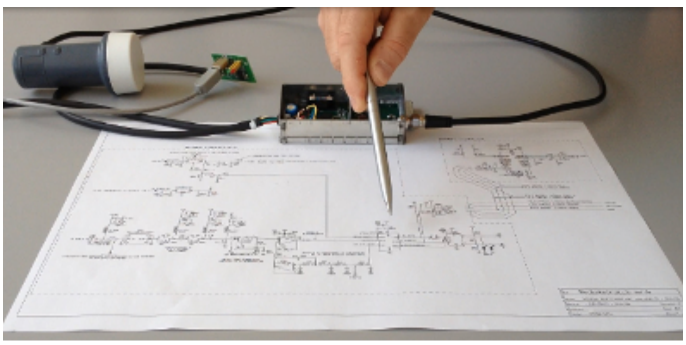

Build your first Microwave Radio Telescope with RadioAstroLab products.

Chapter 1

The basics of Radio Astronomy

1.1 Introduction

We can observe the sky in many ways: the view is always wonderful, fascinating and exciting. You will be astonished contemplating the stars on a clear winter night, away from city lights, the wonder increases observing the details of the moon with binoculars or the planets with a telescope.

These tools, which amplify our visual possibilities, are familiar: who has never had the pleasure of getting close to a telescope's ocular during an educational evening held by the local group of astronomers? However, not everyone knows that there are other ways to look at the sky, no less fascinating than the visual.

We live in a sea of electromagnetic waves generated by technology (mobile phones, wireless devices, and television repeaters ....) and from the natural world, with radiation also coming from extra-terrestrial space. Planets, stars and even the farthest galaxies emit electromagnetic waves: from gamma rays to X-rays, ultra-violet and visible radiation, up to infrared and radio emissions. The human being perceives the emissions in the band of visible because Mother Nature has equipped us with the sense of sight, essential for living, but to ”see” other ”windows” of the electromagnetic spectrum different tools are needed, each specialized to measure radiation in a certain frequency band.

This document has a very ambitious goal: we would like to add a small piece of knowledge to make radio astronomy accessible to everyone.

You will be able to build a small radio telescope to study celestial objects in a different way, mastering the basics of this fascinating observational technique, even in broad daylight and with a cloudy sky. Undoubtedly it is not trivial to capture the radio emission of a distant galaxy: the signals are very weak, choked by artificial interference from background noise. To be successful you need a minimum of study, passion and tenacity. But isn't it true for any activity?

RadioAstroLab s.r.l. was the first Italian company to launch on the market, in 2000, the *RAL10* receiver along with the information needed to build and use an amateur radio telescope. This instrument, economic and designed to take advantage of commercial modules for the reception of satellite TV, started many fans to radio astronomy. Students, amateur astronomers, radio amateurs, schools and universities, have built their small radio telescopes to start exploring the ”radio-sky”. We have received appreciation and new requests, gave answers and supported enthusiasts organizing events and conferences in many cities. We are happy and proud if our work and our passion can contribute to the development of amateur radio astronomy.

We keep going on in this direction with renewed vigor, maintaining the primary objective of the divulgation, of the economy and ease of use: now we have a complete range of products that meets the demands of the passionate and allows everyone to learn about radio astronomy through the construction, installation and operation of a small telescope.

FIGURE 1.1: The *RAL10KIT* radiometric module.

FIGURE 1.2: *RAL10AP* receiver.

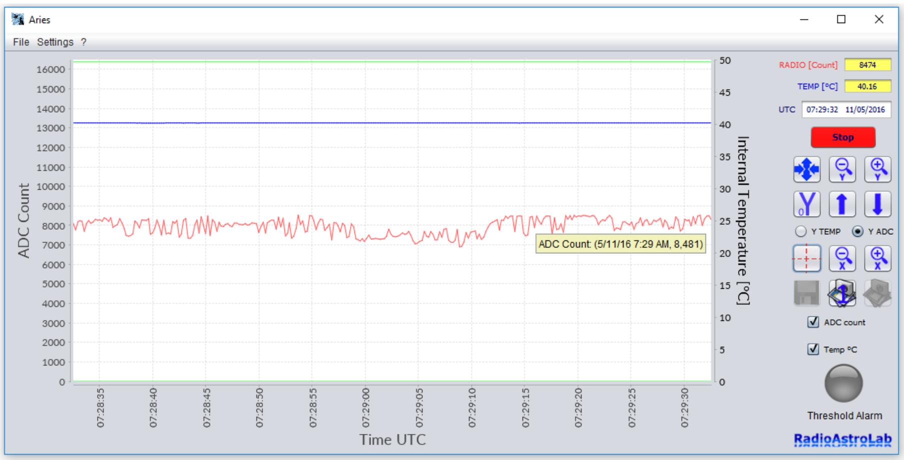

FIGURE 1.3: *Aries*, the control and acquisition software provided for free with every receiver of the *RAL10* series.

The experimental approach way is always the best: to record the radio waves coming from celestial objects with a ”homemade” tool is a very exciting experience. Of course, we cannot expect the performances of great research telescopes, incomparably larger and more complex. However, the construction and installation of a radio telescope built with your own hands offers a lot of satisfaction and has great educational value.

This is a feasible and educationally very interesting way: there are many examples available on the web that describe the construction of simple, inexpensive radio telescopes using components and modules from the satellite TV market. These are interesting solutions and of immediate realization that, in any case, require some practice and experience with the assembly of electronic circuits and, especially, with their tuning.

If, on the other hand, we want to start with a guarantee of success, it will be preferable to move towards ”ad hoc” applications planned for amateur radio astronomy, without leaving out the ease of use.

For these reasons, we propose to the experimenters the *RAL10KIT* pre-assembled kit (figure 1.1) and the *RAL10AP* receiver (figure 1.2). These tools, combined with commercial components of easy availability, become a complete radio astronomy receiver that includes the interface for communication with a personal computer (PC) and the control software *Aries* (figure 1.3). Realize and learn to use a tool like this is didactically very interesting, since it allows a simple, straightforward approach to radio astronomy and to the basic instrumental techniques.

RAL10KIT is designed for people who like to build up the receiver and has a minimum of practice in electronic assembly: you must assemble the base module into a suitable container, completing the work with a power supply, even homemade.

RAL10AP is a receiver whose characteristics are comparable to those of the *RAL10KIT*, and it is ready to use, supplied in a sleek and compact enclosure in anodized aluminum complete with external power supply.

In this document we propose the construction of an interesting amateur microwave radio telescope (11.2 GHz) based on these devices. The experimenter completes the instrument by adding a few (and economic) commercial modules from the satellite TV market: an antenna with external unit (low noise amplifier-frequency converter *LNB Low Noise Block*) including the feed, the coaxial cable and the personal computer for the acquisition. There is great freedom in the choice of these devices, since with *RAL10KIT* or *RAL10AP* you can use any product designed for satellite reception in the band 10-12 GHz. These components are widely available at low cost due to the commercial deployment of this service.

Using a parabolic reflector antenna with LNB including the illuminator and connecting the system to the *RAL10KIT* module or the *RAL10AP* receiver you can realize a radiometer operating at 11.2 GHz suitable for the study of thermal radiations from the Sun, the Moon, and the most intense radio sources, with sensitivity mainly a function of the antenna size. It is a complete instrument, which also provides the USB interface circuit for communication with the PC equipped with our software *Aries*. The experimenter only has to connect the components according to the instructions: the telescope is ready to begin the observations.

The construction and optimization of this tool could be dealt with satisfaction by students, amateurs and fans of radio astronomy, with results all the more attractive the higher the size of the antenna used and the higher the ”fantasy” and care taken to expand and improve the basic performance.

Given the small wavelength, it is relatively easy to build tools with good handling features and acceptable resolving power. Although in this frequency range do not ”shine” particularly intense radio sources (excluding the Sun and the Moon), the sensitivity of the system is enhanced by the large bandwidths usable and by a reduced influence of

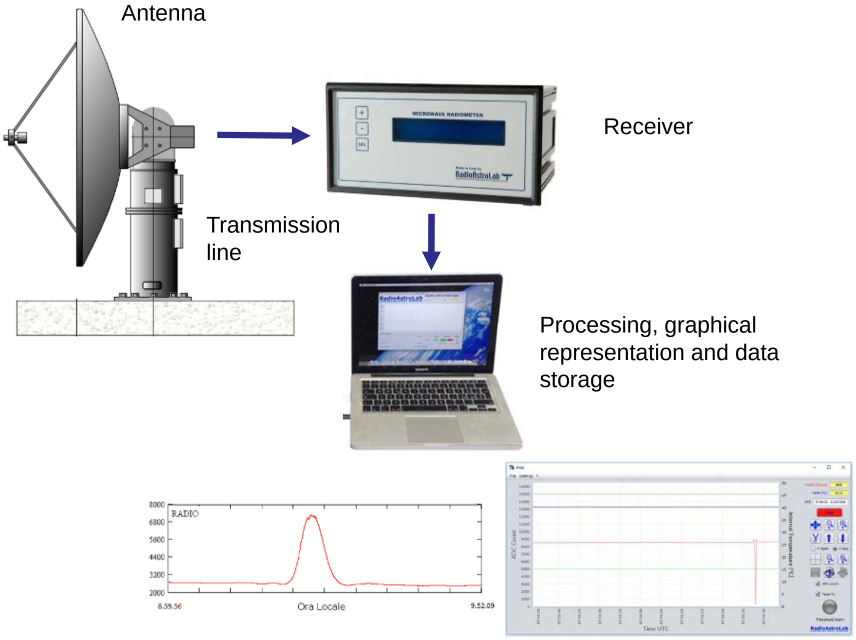

FIGURE 1.4: Basic structure of a Microwave Radio Telescope.

man-made disturbances: the telescope can be conveniently installed on the roof or the backyard, in the urban area. Television geostationary satellites that can create interference are in a fixed and known position in the sky and is not too hard to avoid them without limiting the observational field.

1.2 Radio Astronomy and Radio Telescopes

Radio astronomy studies the sky by analyzing the natural radio waves emitted by celestial objects: any object radiates measurable electromagnetic waves that, picked up by the antenna and displayed, can show the incoherent characteristics of a broad spectrum electrical noise.

In general, the term *radio source* stands for any natural emitter of radio waves: in common usage the term has become synonymous with the cosmic sources of radio waves.

The *radio telescopes*, instruments that record the faint radio stream coming from extraterrestrial space, include an antenna system, transmission lines and a receiver: the electronics amplifies the signal received by the antenna to make it measurable. There follow the devices for the processing and recording of information, in addition to the tools for the control of the instrument and for the orientation of the antenna (figure 1.4).

In honor of K. Jansky, the initiator of radio astronomy, was defined the unit of measurement of the flux density of radio sources: $1\,Jy = 10^{-26}\,W/(m^2 \cdot Hz)$. From this expression you can see how a radio telescope measures a radiant power coming from space, specifically the power (W) which affects the antenna reception area (m^2), included in the receiver bandwidth (Hz).

An alternative way, very convenient to express the power associated to the radiation "collected" by the antenna, is the so-called *brightness temperature*: in fact a radio telescope measures the temperature of the equivalent noise of the scenario "seen" by the antenna. The terms "noise" and "equivalent" will be made clear in the following paragraphs. As you will see, it is possible to demonstrate that the *brightness temperature* of a radio source is directly proportional to its radiated power.

If we orient the antenna of the instrument in a given region of the sky, in particular to a radio source that stands out from the background noise, we will measure an increase in signal intensity (namely, a power) proportional to the *brightness temperature* of that object, which will coincide with its physical temperature only if this is a black body, ie a (ideal) material which perfectly absorbs all radiation incident on it, without reflecting it. In nature there are no blacks bodies, but there are objects that approximate very well their behavior, at least within a specified frequency band.

We can imagine the telescope like a sky thermometer: the temperature measured, the *brightness temperature*, will be proportional to the physical temperature of the region "seen" by the antenna through a coefficient called *emissivity* of that region. The *emissivity* of a material is a measure of its ability to radiate energy and is a function of the chemical-physical properties of the radio source and the frequency characteristics. A black body *emissivity* is equal to 1, thus having a brightness temperature coincident with its physical temperature, while a material body (gray body) has an *emissivity* between 0 and 1, so a brightness temperature inferior to its physical temperature.

As we will see, the technology of a radio telescope is not substantially different from that of a home radio-receiving apparatus (such as, for example, a television, a car radio or a mobile phone): obviously, some features are specialized and performance are optimized to measure the very weak signals from space. In radio astronomy it is fundamental (and hard...) to highlight the weak noise from radio sources (useful signal) with respect to the noise generated by the electronics and the environment (unwanted signal), that is usually very intense: these "hiss" on the background, electrically similar to those we hear when on an FM radio no station is tuned, have the same nature and are, in principle, indistinguishable.

1.3 The Earth Atmosphere

The official classification of the frequency bands of the radio spectrum is shown in the figure 1.5.

Our atmosphere restricts the frequencies usable for radio astronomical observations carried out from the Earth's surface, since it behaves as a true barrier against the electromagnetic radiation coming from space. In fact, the direct measurement of the cosmic radiation is limited to two "windows" of the electromagnetic spectrum, one comprised between about 0.3 and 0.8 micrometers (visible band, with amplitude of about one octave) and one between about 1 centimeter and 1 meter wavelength (radio band, with amplitude greater than 10 octaves). The "radio" window is itself bounded below by the shielding effects of the ionosphere (electrically charged particles that act as a reflector for radio waves), and above by the molecular absorption phenomena due to water vapor and oxygen (figures 1.10, 1.11 and A.1).

For these reasons, as can be seen from the graphs in figure 1.7, the range of useful radio frequencies for radio astronomical observations from the ground is between about 20 MHz and 20 GHz.

1.4 Amateur Radio Astronomy

Admiring the technology and the structural impressiveness of professional radio telescopes, not to mention the "astronomic" costs, it is legitimate to ask ourselves whether it

ITU designation

Band	Frequencies	Wavelengths
ELF	3 – 30 Hz	100 000 km – 10 000 km
SLF	30 – 300 Hz	10 000 km – 1000 km
ULF	300 – 3000 Hz	1000 km – 100 km
VLF	3 – 30 kHz	100 km – 10 km
LF	30 – 300 kHz	10 km – 1 km
MF	300 – 3000 kHz	1000 m – 100 m
HF	3 – 30 MHz	100 m – 10 m
VHF	30 – 300 MHz	10 m – 1 m
UHF	300 – 3000 MHz	1000 mm – 100 mm
SHF	3 – 30 GHz	100 mm – 10 mm
EHF	30 – 300 GHz	10 mm – 1 mm
THF	300 – 3000 GHz	1 mm – 0.1 mm

FIGURE 1.5: Classification in the frequency bands of the radio spectrum.

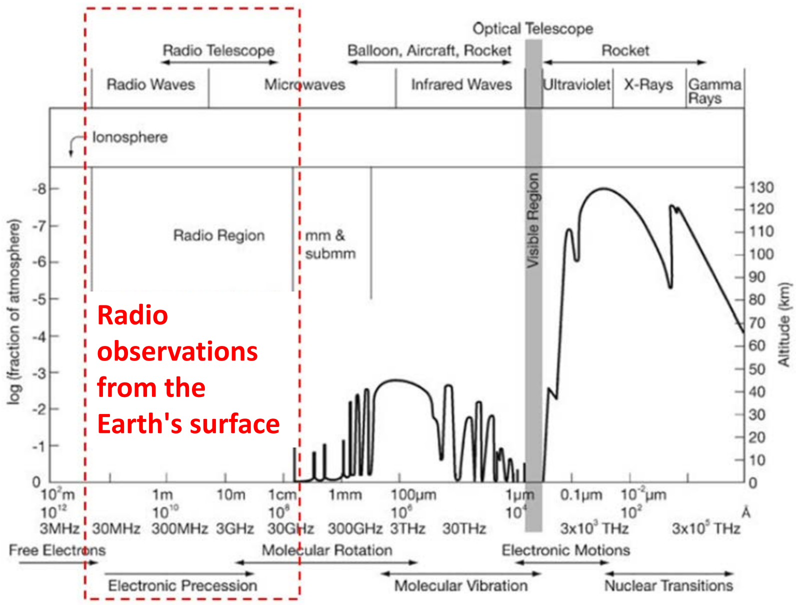

FIGURE 1.6: Representation of the electromagnetic spectrum: the radio "window" has been highlighted.

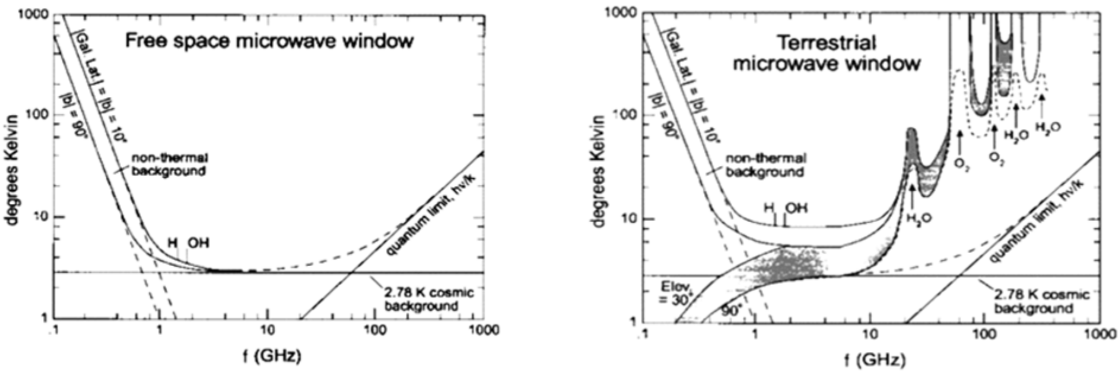

FIGURE 1.7: Effects of Earth's atmosphere, well visible when comparing the graphs that represent the radio "window" of the electromagnetic spectrum seen from the ground and from a radio telescope operating in space.

makes sense to talk about amateur radio astronomy and, if so, what are its real possibilities of experimentation reachable by amateurs.

Many among professionals of the "visible" sky , like amateur astronomers, have fragmentary news on radio astronomy techniques, and those that strike the imagination apply to the large research instruments. The widespread opinion is that radio astronomy is a discipline essentially inaccessible to amateurs, with limited possibilities of amateur experimentation, therefore uninteresting to expand their knowledge of the sky. Of course, things are different, because there is a whole interesting and fascinating world to discover.

To overcome these obstacles it is important to start our journey from the basics, beginning from concrete projects, economic and easy to implement, with "certain" and repeatable performance. It is necessary to understand the limits reachable by amateur activity emphasizing, however, the many interesting opportunities for experimentation. It is essential to start with simple projects of immediate success, so you can gradually gain confidence with the instrumental technique and the practice of radio astronomy observation, not obvious at all. You will need a bit of willpower to invest time and patience in a gradual approach to a discipline that is certainly less immediate and "spectacular" than the observation of the visible sky, since the human being is not sensible to radio waves. In this field, the "visualization" of the cosmic scenario and the "extraction" of the information that results is not immediate: you will need specific instruments (radio telescopes) that can detect radio signals and display them.

Then there is the equipment problem. Do you have to be electronic experts to realize everything in the house? Not necessarily.

Those who have practical knowledge are, of course, advantaged, but on the web you can find excellent examples of construction of small radio telescopes. However, to make the approach to radio astronomy easy for any goodwill person, we will propose the construction of a microwave receiver based on a modular philosophy that favors simplicity, economy and the reuse of the parts for expansions and for future developments.

Anyone can build a radio telescope to explore the fascinating world of amateur radio astronomy.

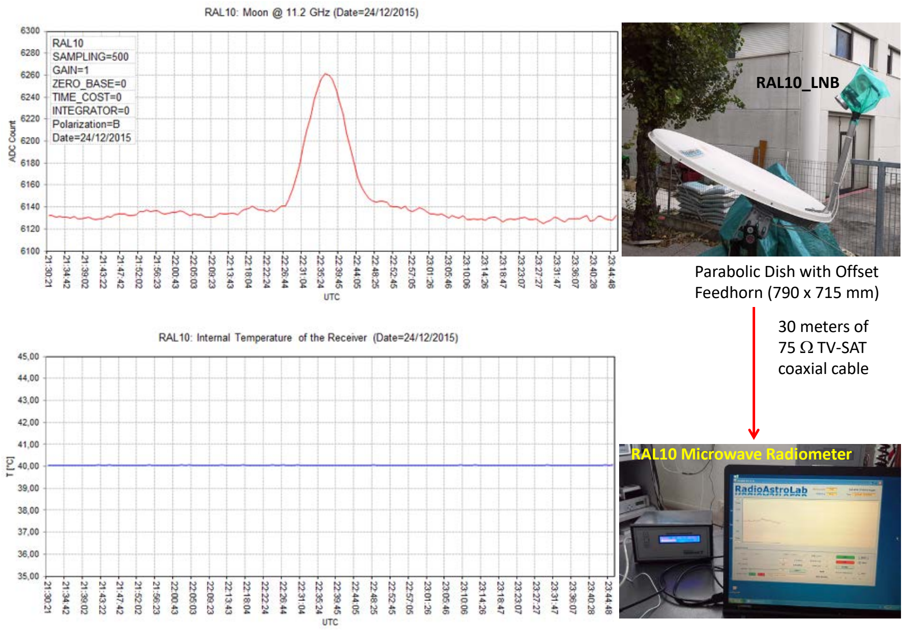

FIGURE 1.8: A lunar transit observation with an amateur telescope based on the *RAL10* receiver.

1.5 How, what and where to look

The radio astronomy observation ”par excellence” (and the easiest one) consists in determining the variation of the intensity of the signal received during the apparent transit of a radio source (such as the Sun or the Moon) in the ”field of view” of the antenna (the so-called *recording at transit*). You orient the telescope at the sky area where the passage of the radio source is foreseen, in its apparent motion, and wait for the formation of the classic ”bell” track in the acquisition software (figure 1.8).

The next step, a bit more complex and laborious, contemplates the recording of signal intensity received from different directions of the sky. Slowly and methodically collecting a series of measures, you can fill in a ”radio-map” of the observed sky region. Obviously ”tracking” observations of the radio sources are possible, such as, for example, when you want to monitor solar activity. This requires motorized and automated equipment for the handling of the orientation system of the antenna.

Why start with a microwave instrument? It will be clear in a moment.

The antenna is the most important component of a radio telescope, being the collector of cosmic radiation: the sensitivity and performances of the instrument will therefore be proportional to the size of the antenna (let’s leave out for a moment the economical, positioning and installation problems). It is also known that, once laid down the requirements in the sensitivity and the resolution power for the radio telescope, the dimensions needed for the antenna increase considerably with the decreasing of the operating frequency. Only this aspect is sufficient to create a mass of doubts and pose a problem to those who intend to start an amateur radio astronomy activity.

We therefore ask ourselves:

- in which frequency band is it better to work?
- what radio sources can be observed with a small telescope?

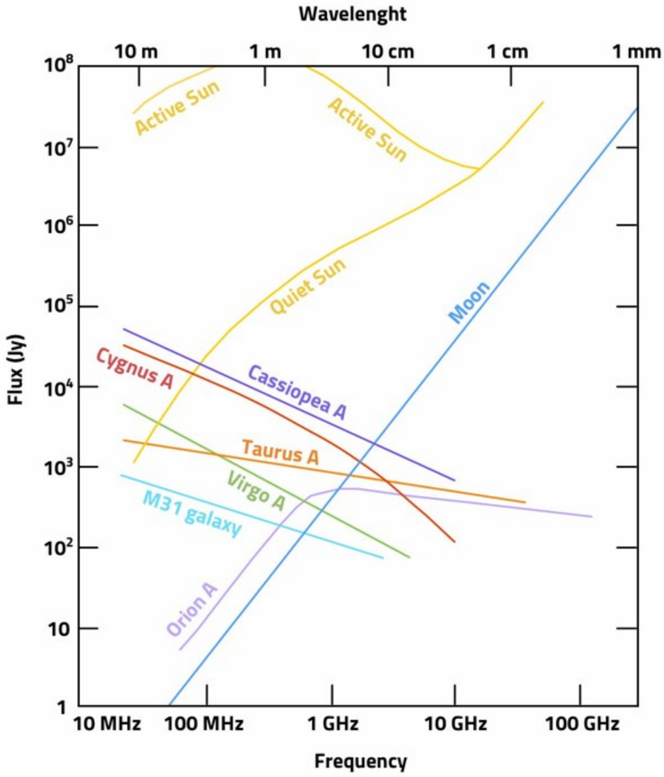

FIGURE 1.9: Spectra of the main radio sources in the radio band.

- are there any special requirements in the choice installation site of the instrument?

The answers are all connected between each other.

The mechanisms that explain the emissions of radio sources are complex, linked to their chemical-physical characteristics. As a first approach will be enough to catalog the most intense radio objects in the sky and discover how does their emission vary at different frequencies (radio source spectra). Taking into account the limitations in sensitivity of amateur instruments due mainly to poor effective area of the antenna, a first reasonable choice seems to favor the frequencies where the radio sources are more intense and numerous. As we see from the chart in figure 1.9, besides the Sun and Moon that behave more or less as blacks bodies in the radio band (at least for what concerns the emission of the quiet Sun), other radio sources radiate with greater intensity for frequencies below 1 GHz, with a mechanism (called *non-thermal*) increasing with a decreasing frequency.

However, we need to consider the radio "crowding" in the area where we will install the telescope, due to the presence of various interferences. The artificial noise, very intense in urban and industrialized areas, is a big problem in radio astronomy observation: the radio spectrum is practically saturated with signals and spurious emissions of various kinds.

The most common natural sources of interference are lightnings, atmospheric electrical discharges, radio emissions produced by charged particles in the upper atmosphere (ionospherical disturbances), emissions from atmospheric gases and precipitations.

Artificial interferences are caused by the distribution and transformation of electric power, by the radar transmissions for the control of the military and civil air traffic, by terrestrial transmitting stations used for radio and television broadcasting services, by the transmitters and transponders on artificial satellites, and by mobile phone network and military stations.

The graph in figure 1.11 highlights the fact that the intensity of the artificial and natural disturbances decreases with an increasing frequency: for this reason the installation of a radio telescope at 10-12 GHz in the ”back yard” or in urban areas is conceivable, while the receiving at the lowest frequencies is very difficult. In the latter case, we must opt for a rural area, electromagnetically more ”quiet”, admitted that you find one.

Indeed, the choices based on the analysis of the spectrum of radio sources are contrary to those deriving from the analysis of the spectrum of disturbances: we have a ”pro” and ”cons” tie. Decisive will be the technological and economic considerations.

An amateur radio telescope ”for all” should be easily achievable, economic and of immediate operation: the heart of the instrument should be a module designed ad hoc for radio astronomy that integrates the essential parts of a basic radio astronomy receiver. Around this core, the researcher completes the telescope using commercial parts and modules, economic and easily available. All this is possible thanks to the spread of satellite TV reception in the 10-12 GHz band, and the availability of antennas, amplifiers, cables and a host of accessories, new and recycled, suitable for building a perfect amateur radio telescope.

We know that the antenna size greatly influences the performances and final cost of a radio telescope. Also the commercial availability of this critical component plays a fundamental role. If we consider that, with the same antenna gain (is a measure of its ability to pick up weak signals in specified directions of space), its dimensions (weight and size) decrease with increasing frequency, we can understand how possible (and simple and economic) it is to build our first radio telescope, using a common parabolic reflector antenna of 1 meter diameter for TV-SAT operating at 10-12 GHz. On the other hand, a parabolic reflector antenna is the most economic structure in the perfomances/dimensions ratio. The only drawback is the limited number of radio sources measurable at these frequencies : the Sun and the Moon, with small diameter antennas. However, being their radiation very intense, their study is an excellent starting point to start familiarizing with the tools and techniques of radio astronomy, waiting for more demanding observations. To record weaker radio sources, like Taurus, Cassiopeia, Cygnus and Virgo, you need larger antennas, keeping the rest of the system unvaried.

1.6 The Antenna

In a radio telescope, the antenna converts the incident electromagnetic energy into a voltage, then amplified and processed by the receiver. The antenna function is analogous to that performed by a lens or a mirror for an optical instrument: a leading role with regard to the performance of the instrument (and its cost).

The topic is very wide and specialized: we will face only some of the essential aspects for the understanding of the measurement process of the sky *brightness temperature* performed by a simple total power radio telescope.

The study of antennas comes from the theory of electromagnetic radiation and the analysis of electromagnetic fields generated by sources in free space. The mechanism of the radiation is no more than the energy of the electromagnetic waves supplied by the sources and transported at a great distance as a result of propagation.

We use the term *directivity* to quantify the ability of an antenna to receive energy from a privileged direction, while the main parameter that characterizes it is the *effective area*, ie the ratio between the power delivered to the load (of the antenna) and the density of the incident power in conditions of adaptation. The *effective area* of the receiving antenna is

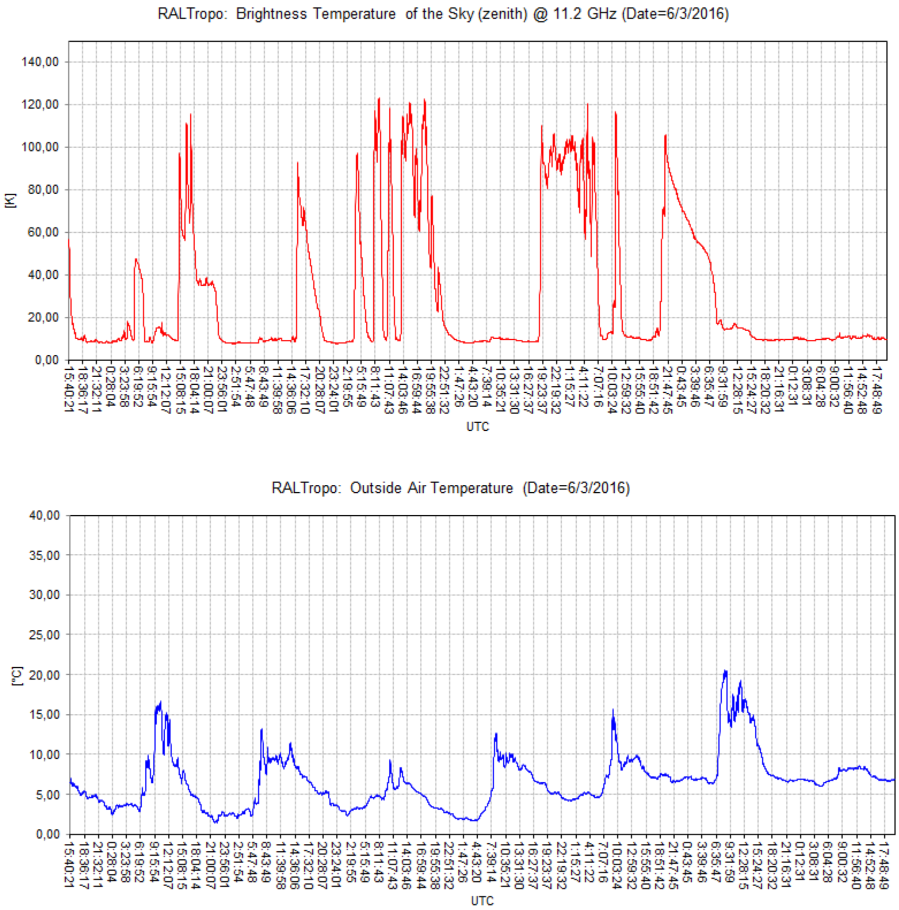

FIGURE 1.10: *Brightness temperature* of the sky at the zenith, measured with a radiometer at 11.2 GHz. We registered wide variations in the typical emission of the atmosphere, due to the presence of rain-bearing clouds formation and of precipitations (corresponding to the signal peaks in the recording). While the clear and dry sky in an area free from radio sources (at 10-12 GHz) is a very "cold" scenario, characterized by a *brightness temperature* inferior to 10 K, in presence of idrometeors it becomes a very "hotter" object, with temperatures up to 200 K if the precipitations are very intense. You can see how, operating at these frequencies, the tropospheric disturbances are important sources of interference for radio astronomy observations, hiding the weak radiation coming from outer space. The effects of tropospheric disturbances become less significant at lower frequencies, as can be seen from the graph of figure 1.11.

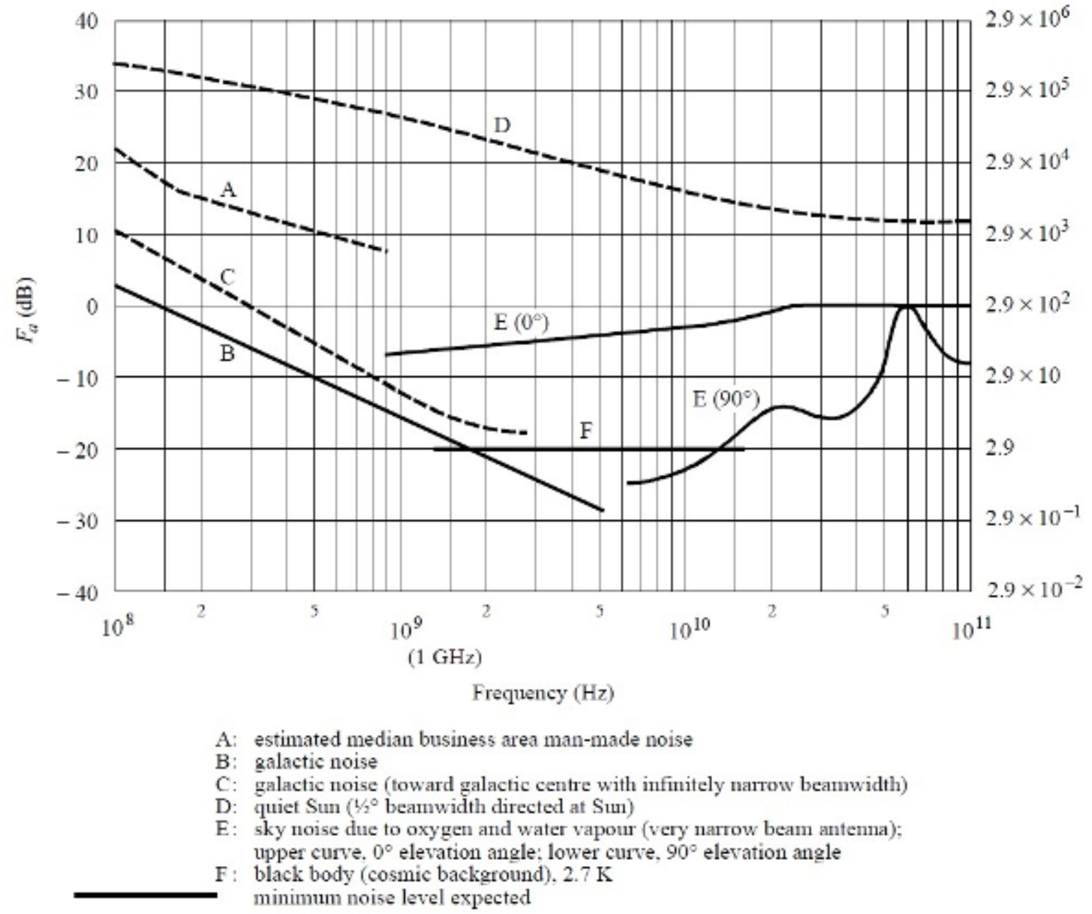

FIGURE 1.11: Natural and man-made noise power as a function of frequency. The estimated levels in the range from 100 MHz to 100 GHz are reported (Recommendation ITU-R P.372-7 "Radio Noise").

therefore the ideal surface, which produces useful power, pulling it out from the incident radiation. This parameter depends only on the antenna characteristics and is a quantity that measures its efficiency as a collector of radio waves. It is important to note that an elementary antenna is sensitive to only a polarized component of the random incident radiation (vertical or horizontal, circular right or left), extracting from this only 50% of the energy.

The great advantage of the directive antenna is the ability to eliminate the signal contributions from unwanted directions improving the reception quality in the direction of interest, with a particularly intense signal when the radio source is in a predetermined direction with respect to the antenna. Another very important feature is the *resolving power*, ie the ability to separate (resolve) two close objects in space, then "see" the fine structural details of an extended radio source. This parameter is proportional to the ratio between the wavelength of the radiation received and the antenna physical size (calculated in wavelength): it will not be possible to distinguish angular details inferior to this value.

These characteristics of the antenna define the performance of the radio telescope.

An antenna widely used in the microwave band is the paraboloid reflector, characterized by a very narrow and symmetrical reception lobe. Its qualities derive precisely from the focussing properties of the parabola: the picked energy, coming from a distant source, is reflected by the surface of the reflector and focused at a point where the external reception unit (LNB) is positioned. The possibility of having a single focal point is very interesting, since if the collecting device (illuminator) is well placed, all the incident electromagnetic energy picked up by the reflector may be used to extract the useful signal.

The gain achieved by an antenna with parabolic reflector can be estimated using the ratio

$$G_a = \eta \cdot \left(\frac{\pi D}{\lambda}\right)^2 \tag{1.1}$$

where D is the diameter of the antenna (in meters). The parameter η is called *efficiency*: usually between 0.45 and 0.55, it takes into account all the factors (errors on the surface, contructive tolerances, focus errors, excessive amplitude of the secondary lobes, etc.) that can reduce the maximum teorical gain achievable.

The Half Power Beam Width $HPBW$ of the antenna can be measured using the following approximate formula:

$$HPBW \approx \frac{(60 \div 70) \cdot \lambda}{D} \qquad [degrees] \tag{1.2}$$

Through these relations it can be seen how the antenna gain is directly proportional to its size, the opposite happens for the width of the receiving beam: a high gain antenna will have a narrower reception beam and will be, therefore, more directive.

The possible structures of an antenna system vary greatly depending on the operating frequency and the type of application. At lower frequencies, the antennas are mainly of wire type (metal dipoles), while at high frequencies (microwave) they are made of radiating elements more easily referable to waveguides (horn and slot antennas) and to optical systems (parabolic reflector antennas). In professional radio astronomy there are composite systems made up of many elements (arrays) and/or focusing elements of optical type (reflectors, lenses): it is always necessary that the dimensions are always greater than the operational wavelength, resulting, at low frequencies, in the construction of structures of impressive complexity and costs.

The temperature of the antenna represents the signal power actually available at the input of the receiver, and so the energy captured from a specific region of the sky that radiates with a given *brightness temperature*. In the measurement process it is important to consider the effect of spatial ”filtering” produced by the shape of the antenna reception diagram: this operation is mathematically described by the convolution of the functions that describe the antenna directive properties and the brightness profile of the observed scenario. The antenna of a radio telescope tends, therefore, to ”level”, to ”dilute” the distribution of real brilliance that will be ”weighted” by the shape of its reception diagram. The extent of the spatial variations of brightness observed will approximate the real one only if the angular dimensions of the radio source are extensive with respect to those of the antenna beam.

Therefore, the problem that arises to the observer is to obtain the true distribution of the *brightness temperature* starting from the measurement of the antenna's temperature: it is necessary to perform an operation of deconvolution between the distribution of the equivalent temperature of the antenna (brightness measured) and the function describing the antenna reception diagram. It is therefore very important to know the shape of the directive diagram of a radio telescope.

All the space that surrounds an antenna helps to increase its equivalent noise temperature, according to its directives characteristics. If the antenna has secondary lobes of too high a level, when directing the main lobe toward a given region of space the antenna's temperature may receive a non-negligible energy contribution from other directions, in particular from the soil (very extended and warm object with a *brightness temperature* of the order of 240-300 K). If the antenna of a radio telescope is oriented toward the sky, it can pick up thermal radiation from the soil only through its secondary lobes: this contribution depends on their width compared to that of the main lobe.

The figure 1.12 shows the track (simulated and real) of the Moon transit (flux of the order of 52600 Jy at 11.2 GHz) ”seen” by a typical amateur radio telescope realised with *RAL10KIT* and a parabolic reflector antenna for TV-SAT of 1.5 meters diametre (beam width under 1.5 degrees).

To highlight the effect of distortion created by the antenna on the spatial brightness profile of a region of the sky, we simulated the response of the instrument approximating the antenna as a circular opening uniformly illuminated. The graphs show, superimposed for clarity of representation, the tracks of the *brightness temperature* profile of the Moon (apparent diameter of about half a degree), and the corresponding antenna temperature measured by the radio telescope during the transit of the radio source (ideal theoretical conditions). There are also shown the radiometric responses of the radio telescope, expressed in arbitrary units of ADC count *count*, of the simulated transit and the ”true” one.

In conclusion, the important issue that must be emphasized concerns the effect produced by the antenna of a radio telescope on the measurement of the scenario observed. When we analyze the recording of the transit of a radio source, for example, we observe a track which does not correspond to the ”true” brightness profile of the scenario, but to one of its distorted version that is the convolution between the form of the reception diagram of the antenna and the real brightness distribution (the latter is ”weighted” by the antenna directives characteristics). The effect is the more pronounced the greater the amplitude of the reception of the antenna beam with respect to the apparent angular size of the radio source. On the contrary, you can measure without distortion the spatial profile of the *brightness temperature* of radio source only if its angular size is very large compared to the width of the antenna beam.

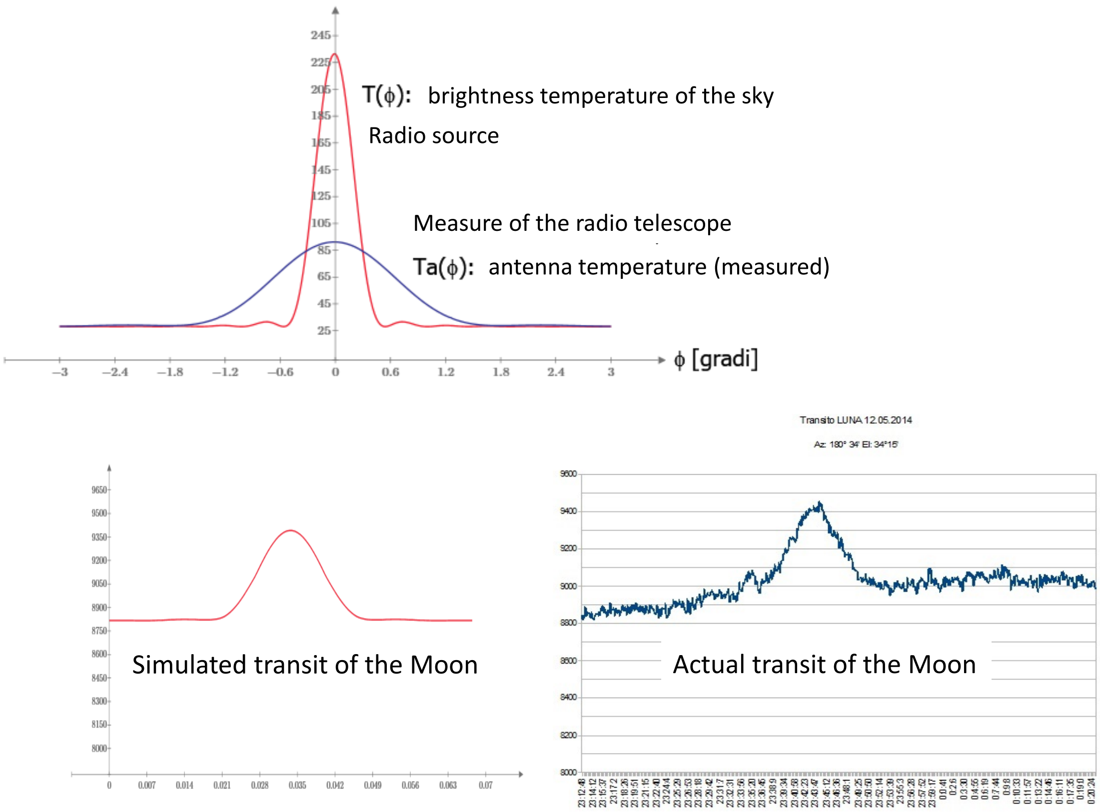

FIGURE 1.12: The profile of the Moon's temperature detected by a radio telescope (antenna's temperature) during a transit is different from the "true" profile of its *brightness temperature* given that the measurement process performed by the antenna is a convolution between the real *brightness temperature* of the scenario observed and the shape of its reception diagram. The antenna of a radio telescope, then, "dilutes" the true distribution of brightness observed: the magnitude of the distortion is due to the spatial filtering characteristics of the antenna and is linked to the relationship between the angular sizes of the reception beam and the apparent ones of the radio source. No distortion occurs if the antenna reception diagram is very narrow compared to the angular extension of the source. The graphs show a comparison between the simulated recording of the lunar transit and the actual observation (performed by Mr. Giancarlo Madiai with *RAL10KIT*).

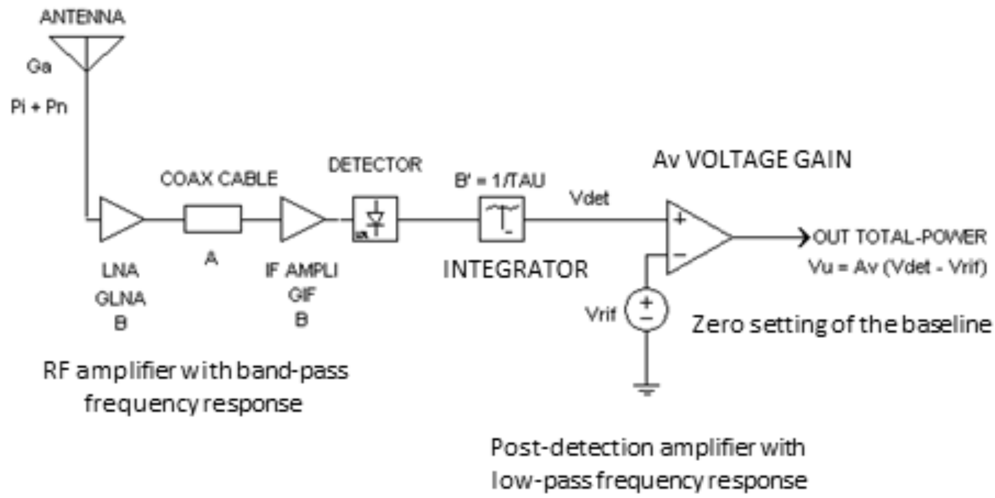

FIGURE 1.13: Block diagram of a *Total Power Receiver*.

It's easy to understand how this problem is particularly relevant for amateur radio telescopes that use individual small antennas, with amplitudes of the reception lobe comparable to the angular dimensions of radio sources like the Sun and the Moon (about half a degree), or much larger compared to all other radio sources that can rightly be considered "punctiform" when "seen" by these small instruments. All this is not valid for the Galaxy that, in the radio band, is characterized by a remarkable angular extension.

1.7 The Total Power Radiometer

A microwave receiver is a very sensitive receiver used to measure the electromagnetic radiation emitted by the scenario observed by the antenna (the average power of the radiation picked up by the antenna) within a specific frequency band, showing how the received signal power varies over time.

Any body with a temperature over the absolute zero emits electromagnetic energy (*Planck's radiation law*) over the whole spectrum, with a maximum at a frequency directly proportional to its temperature. For most of natural bodies the emission peak takes place in the infrared region. Plank's law describes the radiation of a *black body*, an ideal object perfectly efficient in transforming all its thermal energy in electromagnetic radiation.

In the microwave region, Planck's law can be simplified in the *Rayleigh-Jeans approximation* that provides a correspondance between the power of the radiant energy captured by the antenna of a radiometer and the measured temperature of the antenna, quantity that depends on the source, on the characteristics of the measuring instrument and on the surrounding environment. The temperature of the antenna will correspond to the effective *brightness temperature* of the scenario observed (which is a emitting characteristic typical of the source) only in ideal conditions, so when the antenna beam is very narrow with respect to the spatial distribution of brightness observed and when the noise contributions coming from its secondary lobes (soil, interfering sources - paragraph 1.6) are insignificant. For this reason in radio astronomy it is convenient to express power in terms of radiometric equivalent temperature or *brightness temperature* of an object (expressed in Kelvin) to indicate the amount of its thermal radiation.

Essentially, it is always possible to define a black body temperature (called *brightness temperature*) that radiates the same power of the one dissipated by a terminating resistor connected to a receiving antenna. The radiometer then behaves like a termometre that measures the *brightness temperature* of the sky scenario observed.

The simplest microwave receiver (figure 1.13) includes an antenna connected to a low noise amplifier followed by a quadtratic carachteristic detector providing the ”useful” information, which is the power associated to the received signal. To reduce the contribution of the statistical fluctuations of the revealed noise at the output of the detector, and then optimise the sensitiveness of the receiving system, there follows a integrating block (basically a passband filter) which calculates the time average of the measurement basing on a determined time constant.

The signal at the integrator's output is an almost continuous component consisting of the average value of the receiver background noise and the small variations (typically of much lower amplitude than that of the stationary component) caused by the emission of radio sources. This device is called *total power receiver* because it measures both the power of the radiation captured by the antenna and the one of the system's background noise. Using a differential circuit of post-detection, if the receiver parameters are stable, you can only measure the power variations due to radiation from the antenna, eliminating the almost continuous component of the internal noise.

In practice, a total power radiometer uses a typical frequency conversion circuit (heterodyne) where the signal picked up by the antenna, amplified and filtered by low noise electronic devices, is applied to a multiplier (mixer) which, supplied by a sinusoidal signal from a local oscillator (OL), performs the translation in frequency (downwards) of the received signal. So it will be technically easier to define the bandwidth of the receiver and amplify the signal before the detection. A schematization of the signals during the computing process in the various stages of a total power receiver is shown in figure 1.14.

It is important to note that the quadratic detection and subsequent integration does not preserve the spectral characteristics of the signal: they provide a single value that represents its average power within the receiver passband. If you use stable and broadband receivers (the amplification factor of the system and the characteristic of the detector should not change during the measurement) you will reach very high sensitivity, also thanks to the possibility of integrating the detected signal with long time constants, assuming that the phenomena that is being studied is sufficiently stationary in time.

It is possible to determine the theoretical sensitivity of a total power receiver, then evaluate the slightest change in the noise equivalent temperature ΔT measurable by the system, using the *radiometer equation*:

$$\Delta T = \frac{T_{sys}}{\sqrt{\tau \cdot B}} \tag{1.3}$$

where $T_{sys} = T_a + T_r = T_a + T_0 \cdot (F_r - 1)$ is the noise temperature of the radio telescope, T_a is the noise temperature of the antenna, $T_r = T_0 \cdot (F_r - 1)$ is the noise temperature of the receiver ($T_0 = 290K$ and F_r is the noise figure of the receiver), τ is the time constant of the integrator (expressed in seconds) and B is receiver bandwidth (in Hz). The temperatures are expressed in K. Any radio source ”seen” by the antenna will produce a slight change in the antenna temperature T_a which represents our ”useful signal”.

To optimize the performance of the radio telescope is desirable to minimize ΔT acting on the system parameters T_a, T_r, B in the receiver's designing phase, on the integration time τ in the setting of the operating parameters during the operation of the system. You can make ΔT smaller making sure that T_{sys} is minimal, or B and τ are as large as possible.

Once the receiver parameters are fixed, like the noise temperature of the system and its passband, the sensitivity can be optimized choosing a proper value for the integration

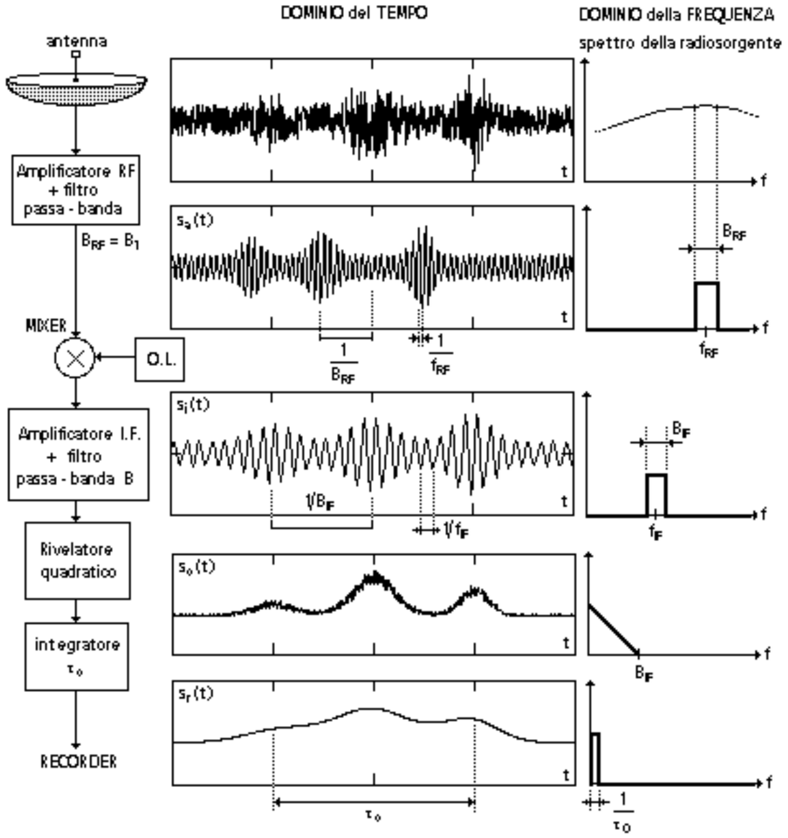

FIGURE 1.14: Changes in the signal picked up by the antenna while it is processed by the various stages of a Total Power Receiver (radiometer). To the left are described the signals as a function of time at a given frequency, to the right is shown the variation of power as a function of frequency (spectrum). The block diagram of the receiver represents a frequency conversion structure: the received signal is shifted in frequency (downwards) through a mixer driven by the local oscillator (OL). At the mixer utput can be found an intermediate frequency signal (IF) subsequently amplified, detected and integrated.

constant of the detected signal. To increase this parameter means to apply a gradual filtering and ”leveling” on the variability of the phenomena observed: changes in the signal duration of less than τ are ”concealed” and you can alter (or lost) the information on the temporal evolution of the quantity studied. For a correct registration of phenomena with own variations of a certain duration it is essential to establish a value for the integration constant sufficiently smaller than such duration. If you observe, for example, a radio source with little apparent diameter that crosses the main lobe of a radio telescope (transit instrument) at a certain time, it is not possible to integrate the detected signal with a too large time constant, without changing the received signal strength and the location of the radio source (apparent time of transit).

A simple way to estimate the maximum usable value for the integration time τ of a signal characterized by temporal variability equal to Δt is given by the approximated relation:

$$\tau \leq 0.35 \cdot \Delta t \tag{1.4}$$

The times are expressend in seconds. This relationship is based on the consideration that, to preserve the characteristics of the integrated signal variability, while eliminating most of the disturbances and of the superimposed noise on a high frequency, it is necessary to integrate this signal with a time constant such that the equivalent noise bandwidth of the integrator (that is a low-pass filter) is approximately equal to the signal occupation in band.

The main problem of radiometric measurements concerns the instability of the receiver parameters with respect to the changes in the ambient temperature. If the total amplification of the instrument is very high, typically exceeding 100 dB, it’s easy to observe fluctuations in the output signal, due to small changes in the receiver parameters, that produce ambiguities and limit the sensitivity and accuracy of the measurements.

This problem can be partially solved with satisfactory results in amateur applications, by thermally stabilizing the receiver and the external electronic unit (LNB) placed on the antenna focal point, where it is more exposed to daily temperature ranges. You can also develop compensation procedures of the thermal drift ”a posteriori” on the data acquired by measuring the internal temperature of the instrument, characterizing the behavior of the receiver compared to the daily temperature changes and implementing a compensation algorithm on radiometric samples acquired tending to minimize variations in the instrumental response due to temperature only.

Chapter 2

A radio telescope for everyone

2.1 Total Power Radio Telescope at 11.2 GHz

In this chapter we will propose the construction of a small but efficient radio telescope operating at 11.2 GHz, equipped with a parabolic reflector antenna of about one meter in diameter, able to measure the brightness temperature of the Sun and the Moon, to highlight the non-thermal component of solar radiation (at these frequencies the most intense phenomena are detectable) and of the interstellar medium in the galaxy, besides the earth's atmosphere radiation.

This tool can be considered the starting point of amateur radio astronomy and a great ″gym″ to become familiar with the radio astronomy techniques. It will be possible, with a simple calibration procedure (Chapter 3), to turn the telescope into a measuring tool that estimates the brightness temperature of the scenario observed. To observe other objects you will only need to use larger antennas.

Such a tool is cheap and easy to install: once the few necessary connections are made (coaxial cable carrying the signal from the antenna to the receiver, USB cable for connection to the acquisition PC and power supply), you are immediately ready for radio observations.

The best experimental approach to radio astronomy always involves starting with compact, ″handy″ instruments that observe the most intense radio sources in the sky, such as the Sun and Moon: in this way it's easy to learn the instrumental and observation technique, you learn how to calibrate the instrument, and you understand the process of radiometric measuring, with the various issues that make the measurement difficult and uncertain. As repeatedly stressed, we are convinced that the best way to gain knowledge and expertise with radio astronomy is, without doubt, the one that involves the construction and implementation of a small telescope.

You have seen that the core on which the operation of the radio telescope is based is a total power radiometer. Our project involves the use of microwave receivers especially developed for this application: the *RAL10KIT* radiometer kit or the *RAL10AP* receiver, combined with the software *Aries* for data acquisition and control.

The radio telescope, then, makes use of the following components:

- Parabolic reflector antenna for TV-SAT with diameter of about 1 mt, including external unit (LNB) and illuminator;
- Coaxial cable of 75 Ω for TV-SAT;
- *RAL10KIT* radiometer kit or the *RAL10AP* receiver;
- *Aries* software for the measurement acquisition and the receiver control;
- Personal Computer (PC) to handle the station.

The antenna, the external unit (LNB) and coaxial cable are standard components used for the reception of satellite TV, available everywhere at low cost. There are no limits in the choice of models: with the *RAL10KIT* module or the *RAL10AP* receiver any device can be used.

As for the antenna, the market for satellite TV offers many choices: the most common ones are the offset type antennas, for the best performance/size ratio they offer with respect to the symmetrical circular ones. To ensure proper operation, it is essential to use kits that include, in one package, the external units (LNB) with feeds and mechanical supports suitable for the specific antenna, which enables the correct "illumination" and the optimum focus for that kind of reflector.

Using imagination and building skills you can realize automatic tracking systems, at least for medium antennas, drawing from the radio amateur equipment market. The reduced dimensions and the lightness of this radio telescope make it possible to use a (equatorial) mount, manual or motorized, like those normally used by amateur astronomers to support and drive the optical instruments. Also in this case there is great room for imagination and inventiveness: it is certainly possible to develop an attaching system for this mount in order to replace the telescopic tube with the antenna of the radio telescope. Those who own and are familiar with the use of these tools, will have no difficulty in exploiting the system to manage the antenna of the radio telescope. The practicality of this solution for the measurement, by tracking, of the solar radio flux is clear. There are many examples of interesting and ingenious creations on the web. Very useful for the correct aiming and for the planning of observing sessions are the sky mapping programs that reproduce, in any location, date and time, the exact location and the movements of celestial objects with remarkable accuracy.

As mentioned, essentially all external units (LNB) existing on the market for satellite TV at 10-12 GHz can be used, with the intermediate frequency output 950-2150 MHz. In modern devices you can manage the polarization change (horizontal or vertical) with a voltage step, typically 12.75-17.25 V: the *RAL10KIT* and *RAL10AP* receivers support this feature through a control via software. A coaxial cable for TV-SAT (75 Ω) of suitable length, terminated with F-type connectors, will link the RF-IF output of the external unit (LNB) with the *RAL10KIT* or *RAL10AP* receiver input.

It is recommended to choose the best quality cables, with low loss. In some cases, when you observe weak radio sources or when the coaxial line is very long, you may need to enter an line IF amplifier (10 to 15 dB of gain) between the external unit and the receiver. These products can be easily found in any electronics supermarket or the best installers of satellite TV systems.

The simplest radio astronomy observation consists in determining the variation of the intensity of the signal received during the "crossing" of a radio source (such as the Sun or the Moon) in the "field of view" of the antenna (the so-called *recording to the transit*). You orient the radio telescope at the sky area where the passage of the radio source is foreseen, in its apparent motion, and wait for the formation of the classic "bell" track in the capture software. The figure 2.1 shows a solar transit recorded with our radio telescope.

If the antenna is controlled by a motorized mount and connected to the PC via one of the various programs normally used by amateur astronomers, it will be interesting to monitor the changes over time of the solar radiation in the band 10-12 GHz, chasing the object during the day.

Other interesting experiences concern the observation of the Moon (which behaves like a black body at 200 K), the observation of the galaxy and of the terrestrial atmosphere radiation.

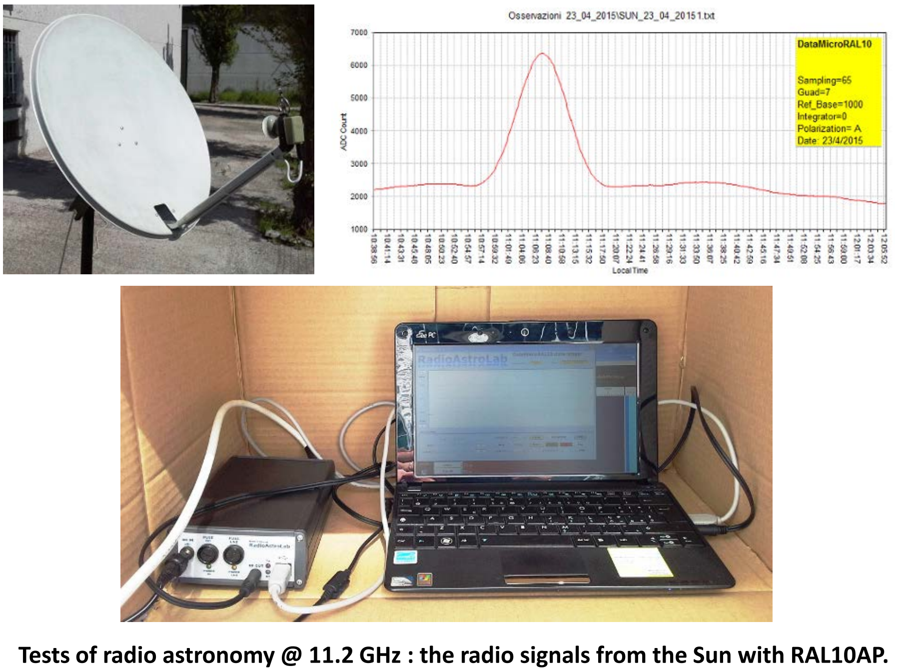

FIGURE 2.1: Test of the reception of the Sun with the *RAL10AP* receiver.

2.2 The *microRAL10* Radiometric Module

It is interesting to describe briefly the characteristics of the *microRAL10* radiometric module which forms the central core of the *RAL10KIT* and *RAL10AP* radiometers. The figure 2.2 shows the structure of the device.

The intermediate frequency signal (IF) from the external unit (LNB) is applied to the *microRAL10* module that, with a bandwidth of 50 MHz centered on the 1415 MHz frequency, filters, amplifies and measures the received signal power (detection block). A post-detection amplifier adjusts the detected signal level at the acquisition dynamics of the analog-to-digital converter (ADC with 14 bit resolution) that "digitizes" the radiometric information.

This final block, run by a processor, generates a programmable offset for the radiometric baseline (it is the signal *ZERO_BASE* in figure 2.2), calculates the average value on an established number of samples and forms the serial data packet that will be sent to the PC. The data acquired by the radiometric measures and the operating parameters of the radiometer are managed by a proprietary communication protocol via the serial port. A non-volatile internal memory allows the recording of the optimal settings of the operating parameters: once the system for a particular application is calibrated, if the recording command of the set parameters is sent (paragraph 2.6), their values are preserved when removing and restoring the supply voltage on the module. The processor performs the processing and control functions minimizing the number of external electronic components and maximizing the flexibility of the system.

The use of a module expressly designed for radio astronomy, which integrates all the functionality required by a radiometer, provides the experimenter with safe and repeatable performance. *microRAL10* implements all the necessary functions for a microwave radiometer suitable for radio astronomy, with particular attention to the sensitivity and stability requirements that such application requires.

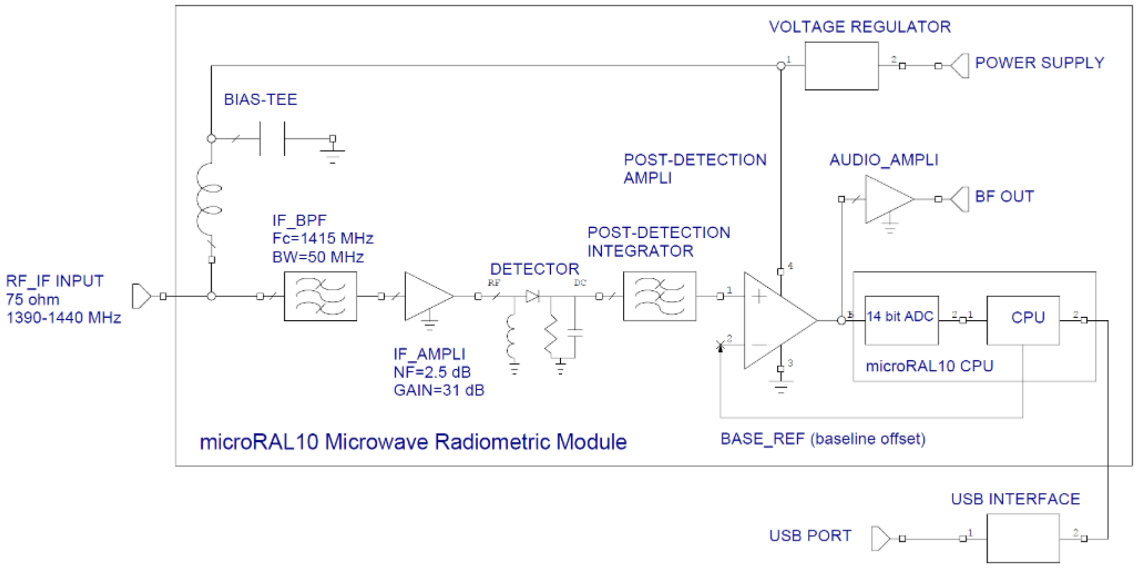

FIGURE 2.2: Block diagram of the *microRAL10* radiometric module, the central core of the *RAL10KIT* and *RAL10AP* receivers.

MicroRAL10 represents the central block of the *RAL10KIT* and *RAL10AP* receivers which have, therefore, identical performances. In fact, assuming that we use a good external unit (LNB), with a noise figure of about 0.3 dB and an average gain of 55 dB, you can achieve a noise equivalent temperature of the order of 21 K and a gain in power of the radio frequency chain of about 75 dB. These performances are suitable to build an amateur radio telescope to observe the most intense radio sources in the frequency 11.2 GHz. The sensitivity of the system will depend, however, on the size of the antenna, while the external thermal changes will affect the stability and repeatibility of the measurements.

The imagination and the skills of the experimenter are crucial to optimize the performance of an amateur radio telescope: the choice and adequate installation of radio frequency critical parts (antenna, feed and LNB), the implementation of countermeasures that minimize the negative effects of thermal excursions, provide important advantages in the final performance.

The following features specialize *microRAL10* for amateur radio astronomy applications:

- Radiometer including the pass-band filter, the IF amplifier, the quadratic detector with temperature compensation, the post-detection amplifier with programmable gain, programmable offset of the base line and constant of integration, the analog-to-digital converter (ADC) for the acquisition of the radio signal with 14-bit resolution, a processor to handle the device for serial communication. A regulator powers the external unit (LNB) via the coaxial cable by switching on two different voltage levels (about 12.75 V and 17.25 V) enabling the selection of polarization in reception (horizontal or vertical).

- Central frequency and input bandwidth compatible with the frequency protected in radio astronomy of 1420 MHz and the standard intermediate frequency values (IF) for satellite TV. To define and limit the bandwidth of the receiver is important to ensure repeatability in performance and to minimize the effects of external interference (the frequencies close to 1420 MHz should be free enough from emissions,

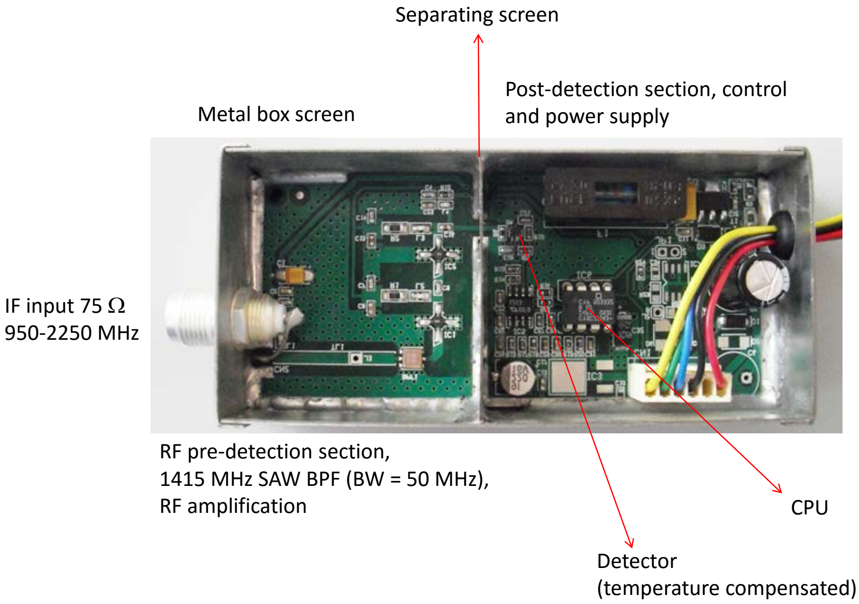

FIGURE 2.3: Internal particulars of the *microRAL10* radiometric module, the "heart" of the radio telescope.

because reserved for radio astronomy research). The receiving frequency of the radio telescope will be close to 11.2 GHz when using standard external units (LNB) with local oscillator at 9.75 GHz.

- Reduced power consumption, modularity, compactness, economy.

The electronics are assembled within a metal case comprising a F-type coaxial connector for the signal from the external unit (LNB) and a cable gland from which come the cables for serial communication and those for the connection to the power supply (figure 2.3).

The figure 2.4 shows the answer of the radiometer when a post-detection gain *GAIN=7* is set and when a sinusoidal signal with a frequency of 1415 MHz is sent to the input of the module. The graph shows the variation of the values at the radiometric output (expressed in arbitrary units *count* for the counting of the ADC) at the changing of the signal power applied at the input (expressed in dBm). Tolerances in the nominal values of the components, above all for what concerns the gain in operating devices and the detection sensitivity in the diods, can create differences in the characteristic input-output among different devices. It will be thus necessary to calibrate the measurement range of the instrument if you wish to achieve an absolute evaluation of the power associated to the received radiation.

Let's summarize the technical characteristics of the *microRAL10* radiometric module:

- Input frequency RF-IF: 1415 MHz;
- Bandwidth: 50 MHz;
- Typical gain of the section RF-IF: 20 dB;
- Input impedence (Type-F connector): 75 Ω;

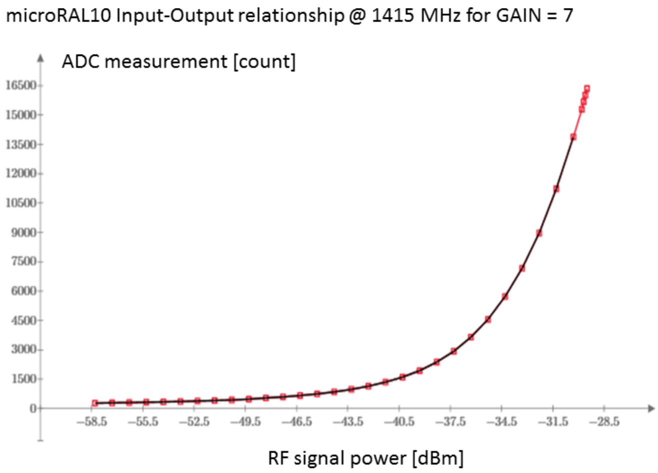

FIGURE 2.4: Input-output relationship of the *microRAL10* module with a post-detection gain *GAIN=7* (voltage gain 168). In the abscissa is described the level of the applied signal RF-IF power (expressed in dBm), in the ordinate the level of the signal acquired by the analog-to-digital converter (expressed in relative units $count$).

- Handling of the polarization change (horizontal or vertical);
- Quadratic detector with temperature compensation (measurement of RF power).
- Offset setting for the radiometric baseline;
- Automatic calibration of the radiometric baseline;
- Programmable gain of the post-detection voltage : from 42 to 1008 in 10 steps.
- Programmable integration constant (from 0.1 seconds to 26 seconds);
- Acquisition of the radiometric signal with ADC nominal resolution 14-bit.
- Processor that controls the receiving system and handles the serial communication.
- Storage of the radiometer parameters (non-volatile internal memory).
- USB interface (B-type connector) for the connection with the PC.
- Compatible with the acquisition and control software *Aries*.
- Supply voltages: 7-12 Vdc / 50 mA.
- Power supply for LNB via coaxial cable, protected by internal fuse.

As mentioned, you can set via software the operating parameters of the radiometer by using appropriate commands encoded in the device communication protocol, automatically handled by the software *Aries*(paragraph 2.6). These parameters are:

- *ZERO_BASE*: is a value proportional to the reference voltage V_{rif}, shown in the block diagram of the total power radiometer in figure 1.13, used to set an offset on the radiometric baseline. It is possible to automatically adjust the value of *ZERO_BASE* activating the calibration procedure that places the reference level of the received signal (corresponding to "zero") in the middle of the measuring range.

INTEGRATOR	Costante di tempo dell'integratore τ $[s]$
0	0.1
1	0.2
2	0.4
3	0.8
4	2
5	3
6	7
7	13
8	26

TABLE 2.1: Time constant of the integrator depending on the value set for the parameter *INTEGRATOR*.

- *GAIN*: it is the amplification factor of the detected signal.
- *INTEGRATOR*: it is the value of the integration constant τ of the radiometric measurement, result of the calculation of a moving average performed on

  $N = 2^{INTEGRATOR}$

  signal samples acquired. By increasing this value you reduce the importance of the statistical fluctuation of the noise on the measurement, improving the sensitivity of the system. The parameter *INTEGRATOR* reduces the detected signal fluctuations with an efficiency proportional to its value. As with any process of integration of the measurement, it must be considered a delay in the recording of the signal related to the sampling time of the information, the conversion time of the analog-digital converter and to the number of samples used to calculate the average (paragraph 1.7). It is possible to estimate the value of the time constant τ (expressed in seconds) referring to the table 2.1.
- *POL*: it defines the polarization used in the external LNB.

These parameters can be stored in the internal non-volatile memory of the device.

2.3 The radio astronomy kit *RAL10KIT*

RAL10KIT is a radio astronomy kit for experimenters with a minimum of practice in the electronic assembly that wish to "home-build" the receiver for the radio telescope. As you can see in figure 2.5, the package includes the *microRAL10* radiometric module, the USB interface to connect with the PC, the assembly instructions and the software *Aries* for the control and acquisition. The modules are pre-assembled and tested: they only have to be enclosed in a suitable case, completed with a power supply, a coaxial cable and a common antenna with an external unit (LNB) operating in the 10-12 GHz satellite TV band (figure 2.7). The first microwave radio telescope is thus created.

The figure 2.8 shows the wiring diagram of the *RAL10KIT* and all the information needed to connect the supply cables: you can use any supply circuit, stabilized and well filtered, or a commercial power supply suited to provide the voltages and the currents indicated. It is advisable to enclose the modules, including the power supply, in a metal casing which acts as a screen for the receiver. As you can see in the diagram, the USB interface module is designed for panel mounting: it will be necessary to prepare the holes and slots for the fastening screws, for the red and green LEDs that indicate the activity of the serial communication and the type B USB connector.

FIGURE 2.5: *RAL10KIT* provided by RadioAstroLab.

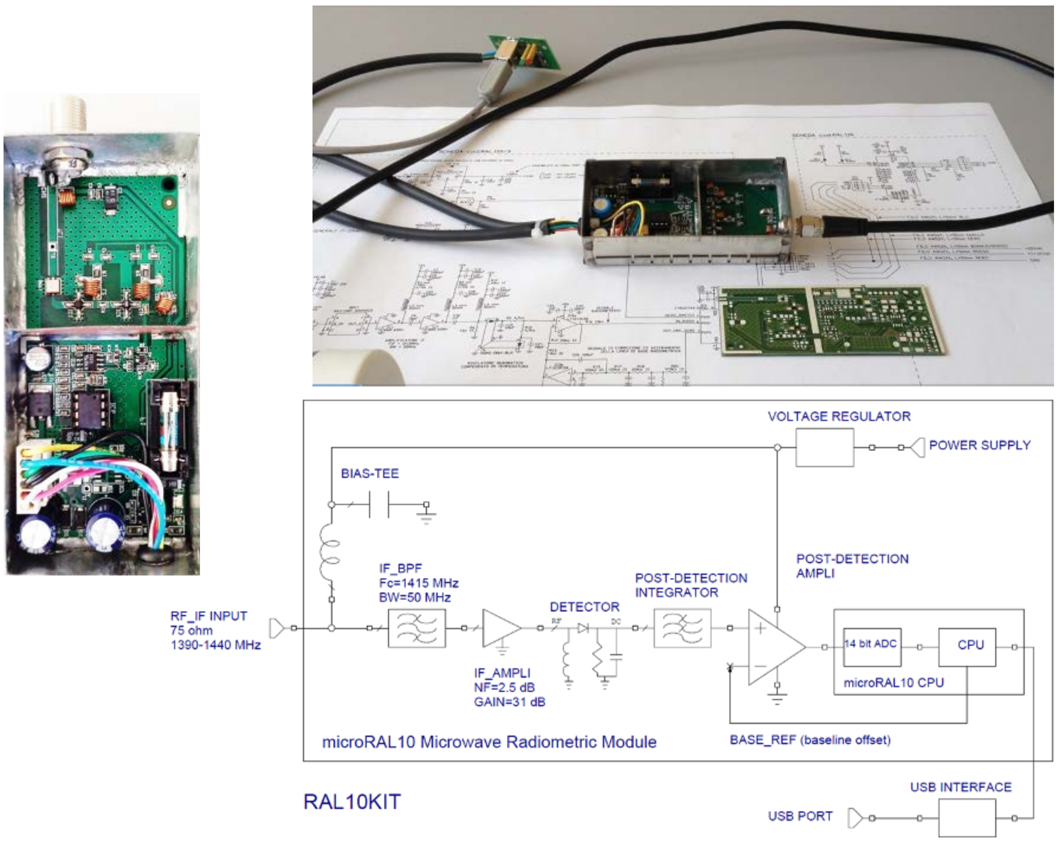

FIGURE 2.6: *RAL10KIT*: you can see the *microRAL10* radiometric module that is the heart of the receiver.

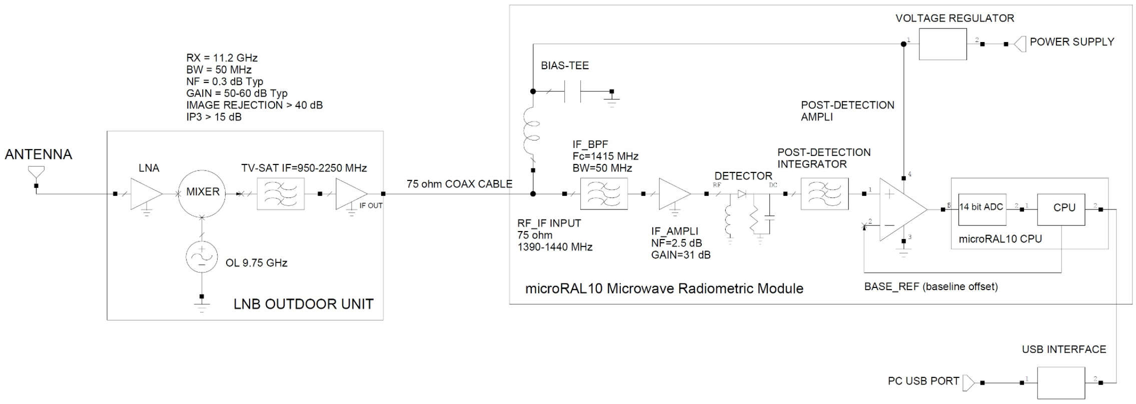

FIGURE 2.7: Structure of a microwave radio telescope (11.2 GHz) built with *RAL10KIT*. The signal received by the satellite dish, amplified and converted in frequency from the external unit (LNB) to the IF standard band TV-SAT 950-2250 MHz, is applied to the group *RAL10KIT* which processes all the information and transmits it to the PC via a USB serial channel. The software *Aries* captures the radiometric measurements, displays the data as a graphic recorder and controls the receiver operating parameters.

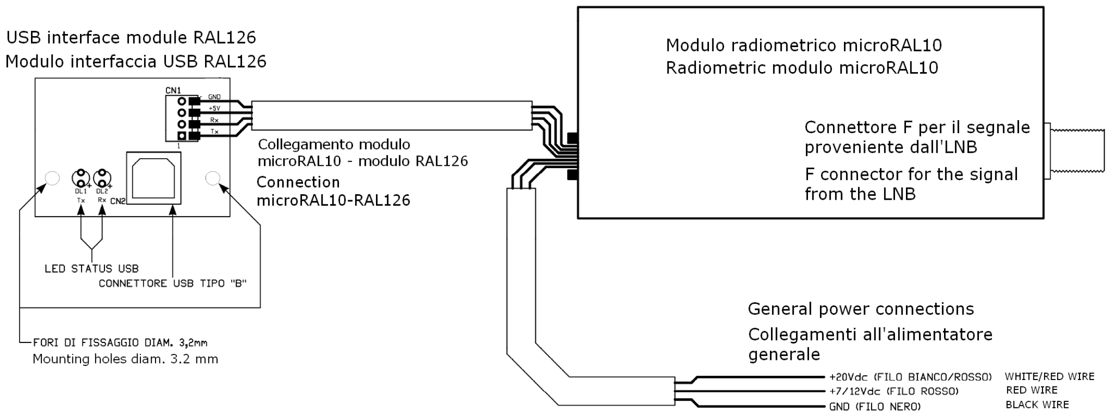

FIGURE 2.8: Wiring scheme of the group *RAL10KIT*: the radiometric module *microRAL10* (provided assembled and tested) is contained inside a metal screened box which provides a coaxial F connector for the connection with the signal from the external unit (LNB) (via a TV-SAT coaxial cable of 75 Ω) and a gum cable gland for the connections of the USB interface and the power supply.

FIGURE 2.9: The *RAL10AP* receiver: you can see (on the top) the socket for the mains power supply to 12 VDC, the fuse holder with interruption indicated via led for the main power supply and the external unit power supply through the coaxial cable (leds turn off when the respective fuse is burnt out), the audio output of post-detection (*BF-OUT*) and the USB port for the connection to your PC (the leds indicate the flow of data). On the rear panel (below) is the F connector for the signal input (*IN RF*) coming from the external unit.

2.4 The *RAL10AP* Receiver

The microwave receiver *RAL10AP* is a complete and simple total power radiometer, a ready to use tool contained in an elegant and compact anodized aluminum case, provided with an external 12 V- 2A power supply. It is possible to power the device with a battery to facilitate ”fieldwork” measures in remote locations where power supply is not available from the network.

On the front panel there are fuses (with interruption signaled via LED) for the main and for the external unit power supply (LNB) through the coaxial cable (figure 2.9).

The entrance of the instrument accepts frequencies in the 1390-1440 MHz band: a filter defines the bandwidth of the receiving system and protects against interference, maintaining the possibility to receive the ”magic” frequency of the hydrogen at 1420 MHz. The receiver amplifies and measures the received signal strength and, via an analog-to-digital converter (ADC) with high resolution (14 bit), converts the detected signal into digital form by positioning the level of ”zero” in the appropriate point of the range. The critical functions of the receiver, as well as the ability to set various operating parameters and communication with the PC via the USB interface module, are handled by the internal processor. To optimize the sensitivity of the system, you can integrate the detected signal with a programmable time constant. The system is handled by the software *Aries* for the data acquisition and the instrument control.

The technical characteristics of *RAL10AP* are identical to those of the *RAL10KIT*, since this instrument too uses the *microRAL10* radiometric module as base unit.

With *RAL10AP* you can build a microwave radio telescope identical to the one described in figure 2.7.

An interesting option, available only on *RAL10AP*, regards the audio output of post-detection: you can apply the detected signal to an external amplifier or the entrance of a

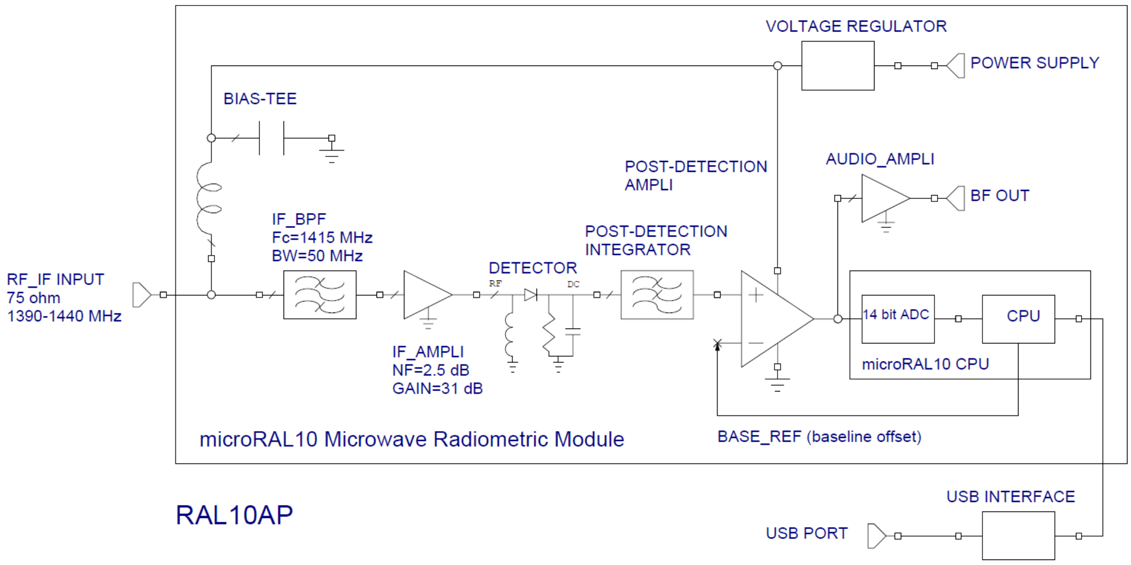

FIGURE 2.10: Internal structure of the *RAL10AP* receiver.

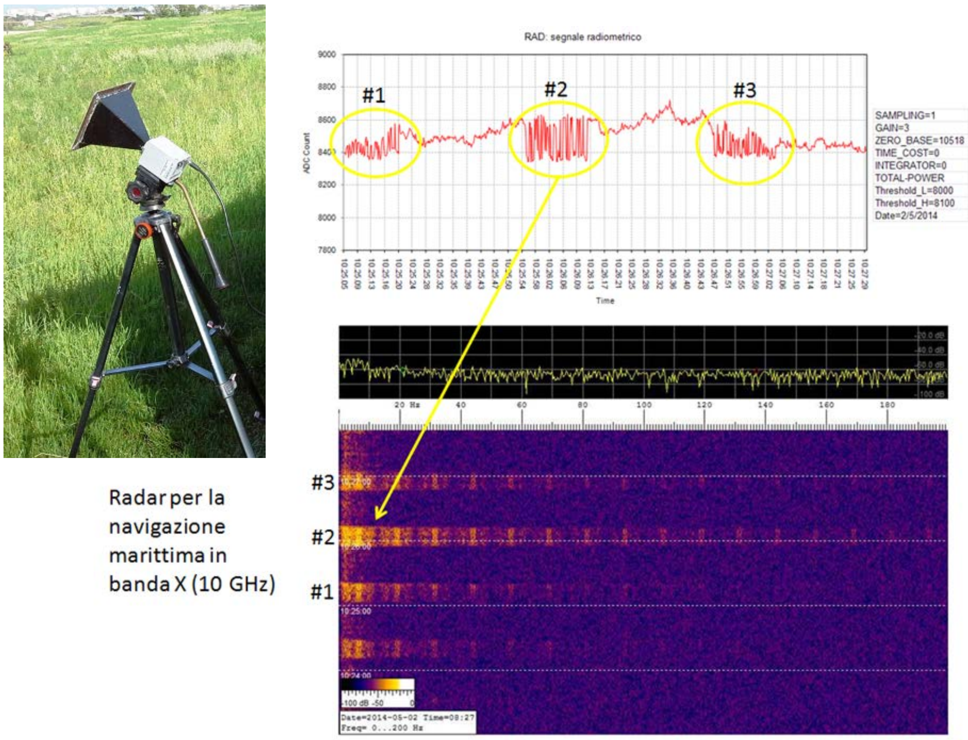

FIGURE 2.11: Test recording carried out with *RAL10AP*. For the experiment we used a pyramidal horn antenna (20 dB gain) with external unit (LNB) positioned on a camera tripod and connected to the receiver *RAL10AP* via coaxial cable. A portable PC records the radiometric signal at 11.2 GHz receiving data from the USB port (upward chart) while the audio signal of post-detection is recorded as a spectrogram through the *Spectrum Lab* software (http://www.qsl.net/dl4yhf/spectral.html). The recordings show the radar signals in X band coming from the ships when the antenna is oriented towards the sea.

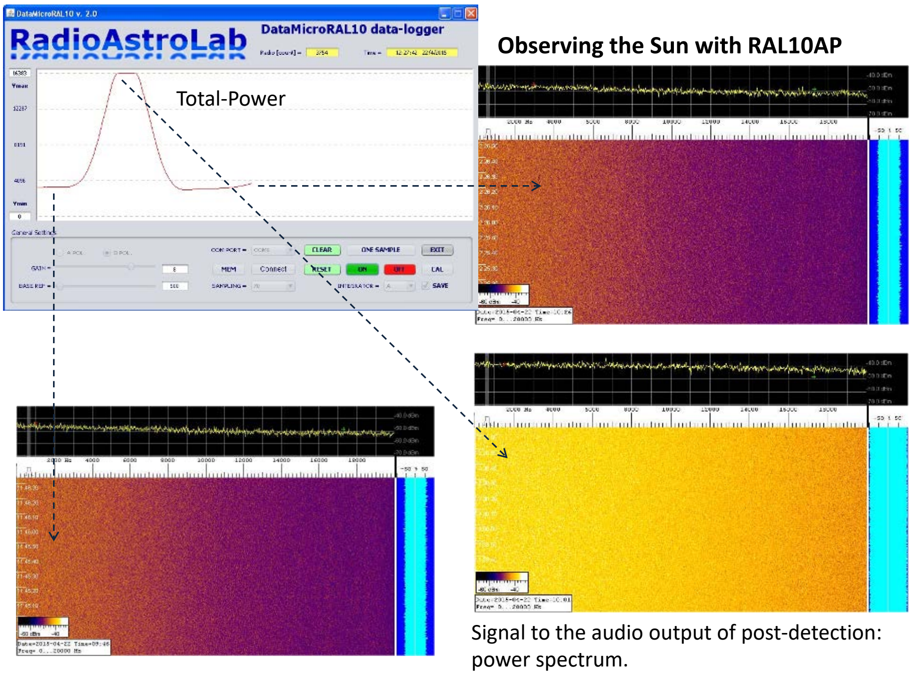

FIGURE 2.12: Observation of the solar transit with *RAL10AP* through frequency analysis (spectrogram) of the audio output of post-detection.

PC audio card to listen to the ”detected noise” for monitoring purposes. This signal, proportional to the received signal power density, can be studied in the frequency domain using one of the many free programs downloadable from the web that display spectrograms in the audio band. As can be seen from the block diagram of figure 2.10, the audio output is drawn after the post-detection amplifier, so its level depends on the level of calibration of the radiometric base line. The figure 2.11 shows an example of use of the post-detection audio output, not exactly radio astronomic, but useful to identify potential interfering signals of artificial origin.

Since the *RAL10AP* receiver provides two outputs, you can monitor simultaneously the radio source from two ”points of view”: the recording of the solar transit shown in figure 2.1 is the result of the radiometric observation captured through via USB port through the software *Aries* that documents the transit of the solar disk within the main lobe of the antenna, while the spectrograms in figure 2.12 show the variation of the distribution in frequency of the revealed signal (the density power of the received signal) during the transit. You can note the uniform increase of the background noise due to the continuous spectrum radiation of the Sun thermal emission during the different steps of the transit. With the PC speakers you can also listen to the corresponding increase in the audio noise.

2.5 Setting of the operating parameters

The signal level at the output of the radio astronomy receiver is proportional to the power associated with the radiation received, so to the *brightness temperature* of the sky region ”seen” by the antenna. Our radio telescope acts as a sensitive thermometer of the cosmos.

If the antenna is oriented toward a clear and dry region of the sky where radio sources are absent, the instrument measures a very low noise equivalent temperature, generally of the order of 6-10 K (the so-called "cold" sky), corresponding to the minimum measurable temperature. By directing the antenna towards the ground the temperature rises considerably, up to values of the order of 300 K. This simple procedure illustrates, roughly and simplified, the technique usable to calibrate the telescope (chapter 3) and represents a great test to verify the efficiency of the instrument.

When a typical amateur radio telescope is oriented toward the Sun, which at 11.2 GHz frequency appears as a disk of about half a degree and radiates like a black body with *brightness temperature* almost equal to the superficial one (about 6000 K), the antenna temperature measured by the instrument is of the order of 300-400 K, a considerably lower value than the "real" one. The radiation of the cosmic background, captured in good proportion by the external crown of the antenna lobe, "dilutes" the powerful solar radiation if the antenna beam is ample as much as to gather a significant contribution of it, and decreases the amplitude of the signal received as if it came from a source with far lower temperature than the actual one. In paragraph 1.6 we illustrated the effects of distortion caused in the shape of the reception diagram of an antenna on the "real" distribution in brightness of the observed scenario.

In this paragraph we will suggest how to set the parameters of the receiver before starting a radio astronomy observation.

The first thing to do is to power up the receiver and wait until the instrument has reached thermal stability. The instability of the system (the main problem of total power radiometers) is mainly caused by changes in ambient temperature and in the radiometer internal temperature: before starting any measurement is advisable to wait at least an hour after the switching on of the instrument to allow the reaching of the operating temperature in the system of electronic circuits. This condition is checked by observing a long-term stability of the radiometric signal when the antenna points a "cold" region of the sky (absence of radio sources): the fluctuations displayed by the graphic track on the software *Aries* are minimal.

The *GAIN* amplification factor should be set on intermediate values ($GAIN = 7$). Each installation will be characterized by different performance, being unpredictable the characteristics of the components that will be chosen by the users. You may adjust the value of this parameter starting with minimum test values (to avoid saturation of the receiving system), and subsequently optimizing with repeated scans of the same region of the sky. To observe the Sun is advisable to choose $GAIN = 7$ (or lower values if the signal tends to saturate), to observe the Moon is better to start with $GAIN = 10$. However, these settings are very influenced by the antenna dimensions and the characteristics of the external unit (LNB) and should always be checked carefully.

Once found the appropriate values for the amplification factor, you can adjust the integration constant *INTEGRATOR* to stabilize the measurement. It would probably be better to begin with minimum values (0.1 seconds), adequate in most cases. As we have seen, it is possible (and desirable) to improve the measurement sensitivity, at the cost of slower system response and lags behind the signal changes, by adopting a longer time constant: we recommend to increase the value of this parameter during the observation of radio sources with relatively stationary emissions. When recording rapidly varying phenomena or of transitory nature (as, for example, the microwave solar eruptions) it will be appropriate to select the minimum value. It's always possible to further increase the integration of the received signal by adjusting the value *SAMPLING* in the software *Aries* (paragraph 2.5).

The *ZERO_BASE* parameter defines the reference level (offset) of the radiometric baseline: its proper setting depends on the global amplification of the receiver. As a general rule, you should define *ZERO_BASE* so that the minimum signal level corresponds to the "cold sky" (ideal reference) when the antenna "sees" a region without radio sources:

an increase over to the reference will indicate the presence of a radio source. The location of the baseline on the measuring range is a function of the *GAIN* amplification factor and of the value set for *ZERO_BASE*: if the signal tends to move outside of the measuring range (start-scale or end-scale) because of the internal drifts, it will be necessary to manually change the value *ZERO_BASE* or activate the automatic calibration for the radiometric baseline so as to position the track correctly.

If you use suitable external units (LNB), you can change the polarization in reception to observe radio sources where an emission with a polarized component is predominating. In most of the observations accessible to the amateur the radio sources emit with random polarization: in these cases it may be useful to change the polarization to minimize any interference of artificial origin.

When purchasing commercial products for satellite TV reception the position of the illuminator (integrated with the external unit LNB) is generally fixed along the antenna focal line. If it was mechanically possible and you want to improve the performance of the radio telescope, you should orient the antenna in the direction of a sample radio source (like the Sun) and toggle back and forth the illuminator position along the axis of the parabola in order to register a maximum intensity signal. Repeated measures and lot of patience help to reduce errors.

The confirmation for a correct setting of the receiver parameters requires some test observations. This procedure, normally adopted also by professional radio observers, allows you to ”tune” the telescope so that the dynamics of its response and the scale factor are adequate to record the observed phenomenon without errors. If properly performed, this initial setting (necessary especially when longer periods of observation are foreseen) adjust the gain and offset of the scale for a correct measurement, avoiding risks of signal saturations or resets with consequent loss of information. After the initial setup, it will be preferable to store the radiometer settings by using the appropriate command.

It is always worth recalling how the main factor limiting the stability and accuracy of the radiometric response are the temperature changes experienced by the radiometer, especially from the external unit (LNB): these temperature changes cause small variation in the front-end gain and the internal parameters of the radiometer, enough to cause significant fluctuations in the reference level, given the high amplification system. You get the best performance from the radio telescope when the receiver is thermally stabilized. This is a key condition for the quality of the measurements.

The simplest radio astronomy observation involves the orientation of the antenna to the south and its positioning at an elevation as to intercept a specific radio source during its transit to the meridian, that is, the apparent passage of the source for the local meridian (the one containing the poles and the installation point of the radio telescope).

By setting in the acquisition software *Aries* a sufficiently slow period of sampling (for example, a screen every 24 hours), you can verify if, during the day, the antenna intercepts the radio sources desired, and if the values chosen for the parameters are suited for the observation. You might have to increase the amplification factor to amplify the trace, or change the level of the base line to avoid that, at some point on the graph, the signal is out of range. After the setup procedure you can start long automatic and unattended recording sessions.

2.6 The control and acquisition software *Aries*

Aries (figure 2.13) is a software for Personal Computer (PC), advanced and simple to use, developed to manage the automatic acquisition and control of total power microwave receivers of the *RAL10* series.

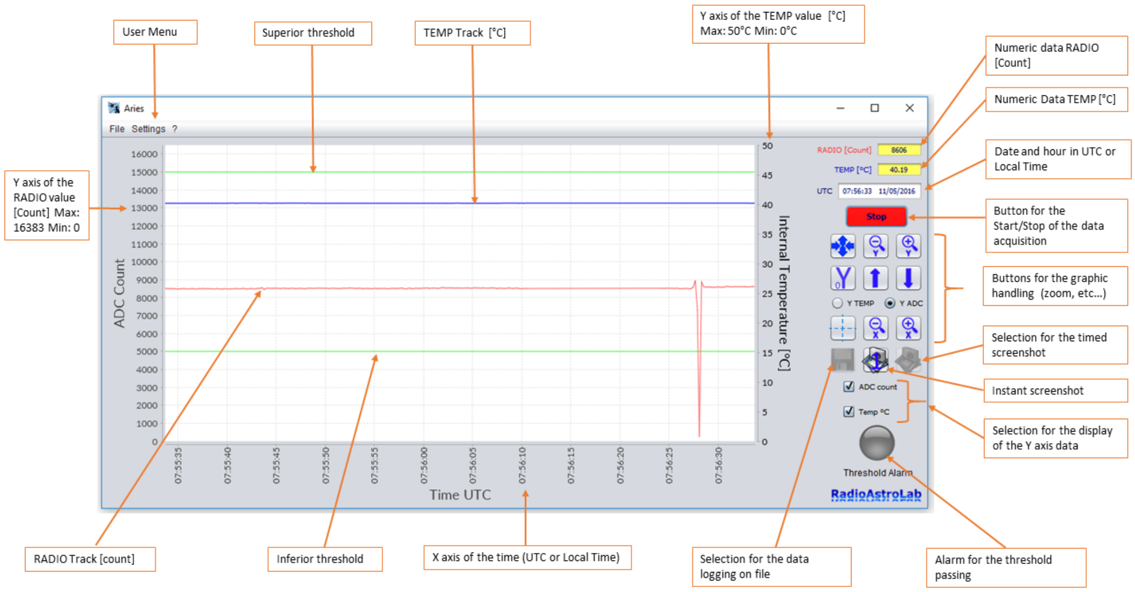

FIGURE 2.13: Main window of the software *Aries* (the settings concern the receiver mod. *RAL10*)
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Designed to optimize the "robustness" and the communication flexibility typical of these products, the program checks the operating parameters of the specific model used (*RAL10KIT* or *RAL10AP*): in the style of a graphic recorder, *Aries* displays the evolution of the measurements in time and stores the acquired information in different ways and formats. The variation of the acquired data is displayed in function of the time as a mobile red track, represented in a rectangular diagram where the abscissa is the time variable (expressed in Local Time or UTC time) and the ordinate is the intensity of the signal expressed in relative units ADC_count.

Given that, at present, it is not possible to handle a signal calibration procedure received in absolute units of *brightness temperature* (this option will be implemented in a later version of the program), the radiometric signal strength is displayed on a scale of counting units of the internal analog-to-digital converter (ADC). This scale ranges from 0 to 16383, since the measurement resolution of the instrument is equal to 14 bits.

With *Aries* you can check quickly and easily all the parameters of a single receiver, or handle different and simultaneous measurement sessions with multiple devices (even of the same type) connected to a single PC: the communication protocol implemented in the instruments and the interface of *Aries* provide very reliable communication management, perfect even in applications involving continuous measurements for a long time and in unattended locations. Designed as a data acquisition system for amateur radio astronomy stations, *Aries* includes everything you need to handle and display the measurements of observations, with various setting opportunities for the graphic scales and the operating parameters. The ability to automatically record the data and to set appropriate alarm thresholds when events occur in the measured signal, ensure ease and versatility in the management of the radio astronomy station.

In figure 2.13 you can see the main console for the visualization and control of the software: it is a graphical window that displays the trend over time of the radiometric signal acquired and, possibly, other auxiliary signals managed by the particular receiver

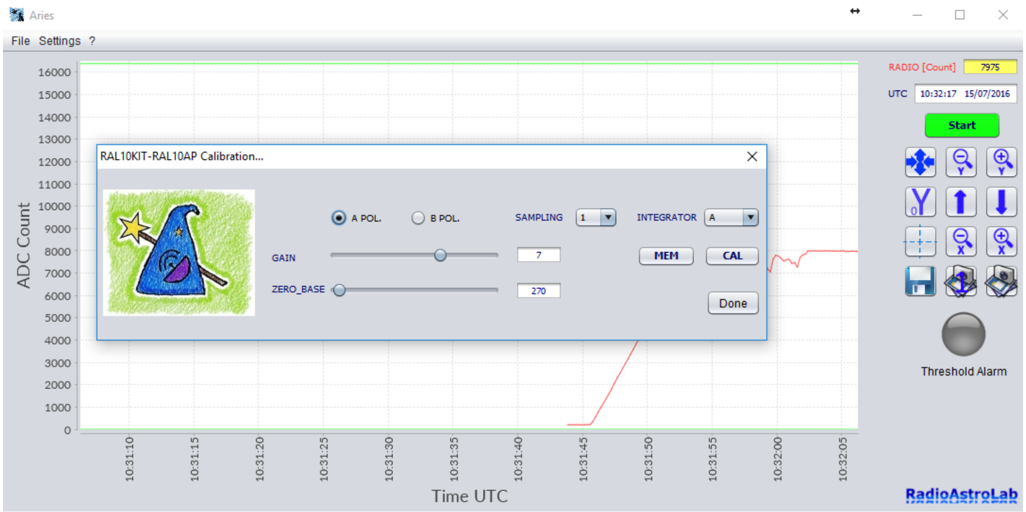

FIGURE 2.14: The prompt box to set the parameters of the receiver.

used. There are the most frequently used control buttons in the data acquisition management, in the graphical representation of measurements and the automatic data logging. The program works on Microsoft Windows x86 and x64 platforms (minimum requirements Windows XP SP3) and, soon, the corresponding versions for Mac OS and Linux environments will also be released.

The window shown in figure 2.14 contains the commands required to set the parameters of the instrument: you can see the buttons for selecting the polarization in reception, the sliders and boxes for the setting of post-detection gain, for the offset of the radiometric baseline and for the setting of the constant of integration of the measurement. It is possible to select after how many samples received the measure must be updated by choosing the sampling period *SAMPLING*, function which includes the calculation of the average value of acquired samples, so a further integration of the signal in addition to the one established by the *INTEGRATOR* parameter: the program will update the graphic tracks after acquiring the number of samples set, then will calculate the average over that number.

The *CAL* key activates the automatic calibration of the baseline ("zero" reference) for the radiometric measurement. It is possible to save the operating parameters in the internal non-volatile memory of the receiver via the *MEM* command: in this way, every time you power the radiometer, the optimum operating conditions are restored, chosen after appropriate calibration depending on the receiving system characteristics and the observed scenario (paragraph 2.5).

Using the zoom buttons of the Y-axis you can increase or decrease the axis of ordinates resolution while moving the arrow buttons up and down to position the trace on the chart so that it is fully visible in all its dynamic range (this is, essentially, the command that enables the translation of the entire track along the Y-axis). Similarly, you can zoom on the time axis (abscissa) using the corresponding buttons, also changing the scroll speed of the track. The maximum speed settable is sixty seconds per screen: the track will take a minute to cover the entire graphic window. In the program settings menu you can choose the format of representation of time (in UTC or Local Time).

In addition to the simple graphical display, *Aries* records the measurements in various formats. You can choose to save the data in text or image format using the buttons dedicated to the data recording.

To check the progress of the received signal during a measuring session, *Aries* offers the ability to set two control thresholds (upper and lower) that, if exceeded by the radiometric track, will trigger a visual alarm by turning a control light red and activating an audible alarm if desired. The thresholds are presented as two horizontal green lines on the graphic window.

More details about the features and functions of *Aries* can be found on the web pages of RadioAstroLab s.r.l. and in the user manual, downloadable from

`http://www.radioastrolab.it/pdf/ARIES_Manuale_IT_11.pdf`.

Chapter 3

Calibration of the radio telescope

Any instrument analyzes a quantity according to a scale of specified measurement units. This is true also for a radio telescope: in fact, a very important and delicate part of its functioning concerns the calibration.

It is necessary to establish a calibration procedure to achieve, at the output of the radio telescope, data consistent with an absolute scale of *brightness temperature* (or flow units). The manufacturing tolerances, environmental conditions and parametric variations of operating devices cause changes in the characteristics of the receiver, moreover each instrument is unique in its response and is difficult to compare measurements from different telescopes or those of the same system carried out at different times.

By repeatedly observing a radio source you may experience changes in the intensity of its emission. It is important to understand whether these fluctuations are due to real changes in the intensity of the flux emitted by the source or to unwanted variations in the response of the instrument: it is therefore necessary to use a universal measuring system. The calibration procedure of a radio telescope is used to establish a relationship between the *brightness temperature* of the observed scenario (expressed in K) and a given quantity outgoing from the instrument (expressed, for example, in arbitrary units $count$ of the ADC counting).

In this paragraph we will give you some tips to calibrate the measurement scale of an amateur radio telescope, in a simple and practical way, observing easily "available" reference sources. As a practical example, we will describe the calibration of a small radio telescope that uses the *RAL10AP* receiver and an offset dish antenna for satellite reception in 10-12 GHz band: the instrument is similar to the one in figure 2.1.

The technique is simple, although approximate, adapted to the needs of an amateur telescope and converts the measured radiometric values in an absolute temperature scale. This procedure can be used to calibrate any radiometer operating in this frequency band.

If the input-output characteristic of the radiometer is linear between the power level of the radio signal and the corresponding value obtained from the analog-to-digital converter (ADC), you can calibrate the instrument by measuring two different power levels of the radiation received: first you observe a "hot" target (object at ambient temperature), then a "cold" target (as, for example, the sky at the zenith) calibrating the antenna temperature directly in K.

Basically:

- *Measurement of the "cold" target*: you orient the antenna toward the sky at the zenith, on a clear and dry day. If the radiative contribution of the Sun, the Moon and other radio sources are absent, the brightness temperature T_{sky} of the sky at the zenith can be estimated, at 11.2 GHz frequency, using the procedure described in Appendix A. Leaving out the noise contribution due to radiation collected by the antenna secondary lobes, you can use the value $T_{sky} = 7\,K$.

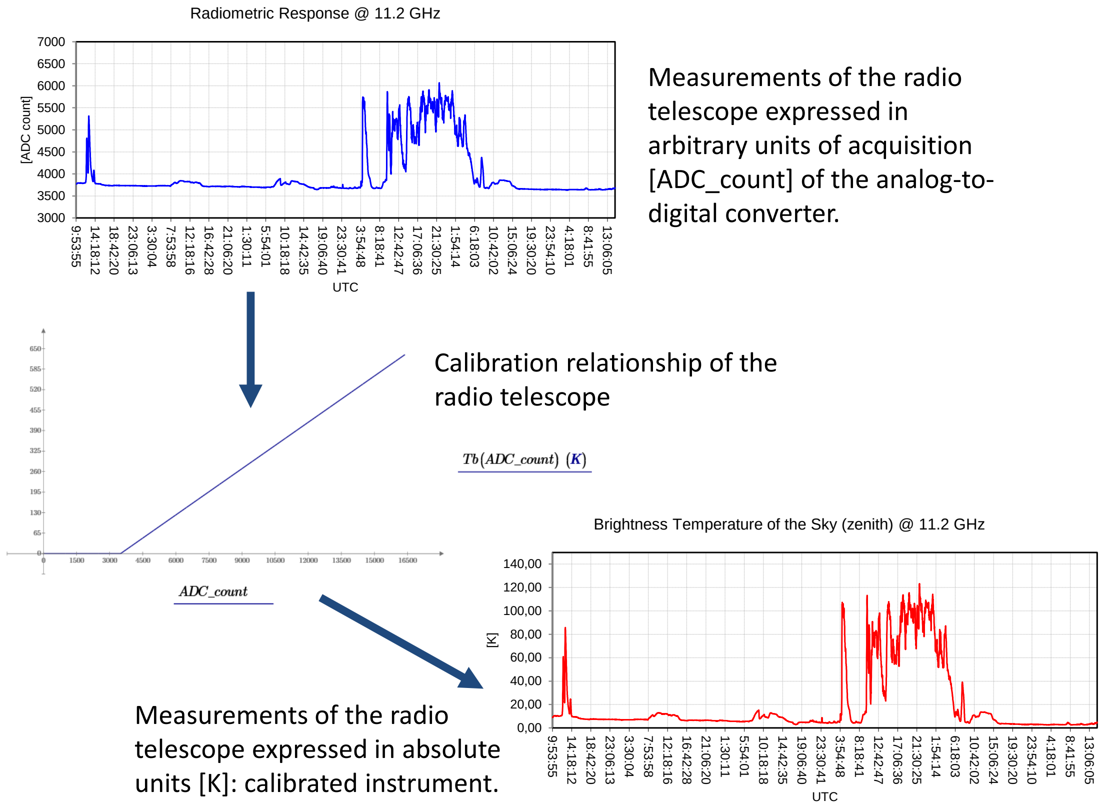

FIGURE 3.1: A radio telescope measures the intensity of the radiation coming from the scenario observed in *count* arbitrary units, which represent the numeric value, at the output of analog-to-digital converter (ADC), of the analog quantity "digitized" (revealed radio signal). A calculation transforms the response of the instrument in absolute temperature units K using the calibration ratio.

- *Measurement of the "hot" target*: the antenna is oriented towards the ground so that it fill his entire field of view and is sufficiently distant to consider fulfilled the far field condition. If the physical soil temperature (measured with a thermometer) is T_{soil} and its microwave *emissivity* is = 0.95 (an average value, reasonably estimated), its *brightness temperature* is:

$$T_{b\_soil} = \eta \cdot T_{soil} \qquad [K] \tag{3.1}$$

  Since the *emissivity* is high, we left out the radiation of the sky reflected towards the radiometer.

If the instrument's responses when measuring the target with different *brightness temperatures* T_{b_soil} and T_{sky} are, respectively:

$count_{soil}$ when the radiometer measures the "hot" target T_{b_soil}

$count_{sky}$ when the radiometer measures the "cold" target T_{sky}

you can express the equivalent antenna temperature T_a in function of the corresponding $count$ answer as:

$$T_a(count) = T_{b\_soil} + (T_{b\_soil} - T_{sky}) \cdot \frac{count - count_{soil}}{count_{soil} - count_{sky}} \qquad [K] \tag{3.2}$$

which is the equation of a straight line in the plane $\{count, T_a\}$.

In general, the temperature T_a measured by the radiometer will depend on the antenna directivity (shape of its reception diagram) and it will be different from the *brightness temperature* of the scenario observed, given that the antenna operates a mathematical convolution between the shape of its reception diagram, and the brightness profile of the source. As seen in paragraph 1.6, to get the true *brightness temperature* of the observed region is necessary to know the spatial trend of the antenna's reception diagram (the gain in function of the azimuth angle and elevation angle) and perform a deconvolution between this and the measured temperature.

The newly found calibration line converts the radiometric measurements expressed in arbitrary units of acquisition of the ADC in an absolute temperature scale, and then determines the instrument calibration characteristic.

This simple procedure is adequate for our needs, although approximate, and provides a reliable idea of the dynamics of the measurement scale in K of the instrument. Its accuracy depends on many factors, instrumental and environmental: the estimates on the sky *brightness temperature* T_{sky} and on the *emissivity* η of the soil (the "hot" target), the constancy of the radiometer parameters (stability, especially in temperature) and the linearity of its characteristic applied power / detected voltage have a great influence.

The figure 3.2 shows the recordings of the radio telescope response of figure 2.1 when the antenna is oriented toward the ground (we chose a large piece of uniform ground, freshly plowed, for which we estimated an *emissivity* of about 0.95) and when antenna "sees" the clear sky at the zenith. After measuring the physical temperature of the soil, we used the radiometer responses to the two target "hot" and "cold" to calculate, using the formula (3.2), the instrument's calibration line shown in 3.3.

The *brightness temperature* of the sky at the zenith was estimated as equal to $T_{sky} = 6.8\,K$.

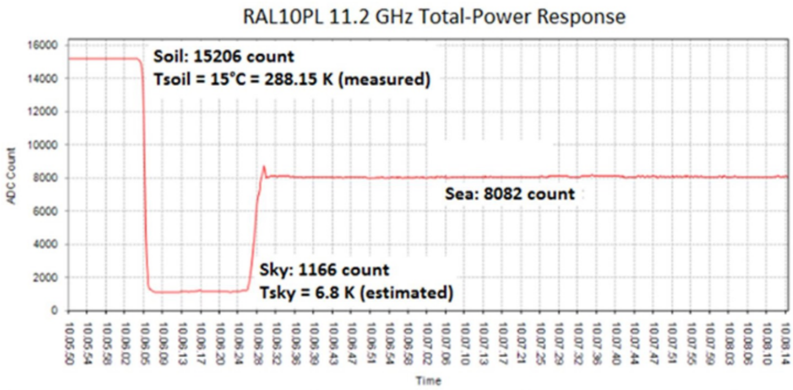

FIGURE 3.2: Measurements of the soil and of the sky at the zenith for the calibration of a radio telescope that uses the *RAL10AP* receiver.

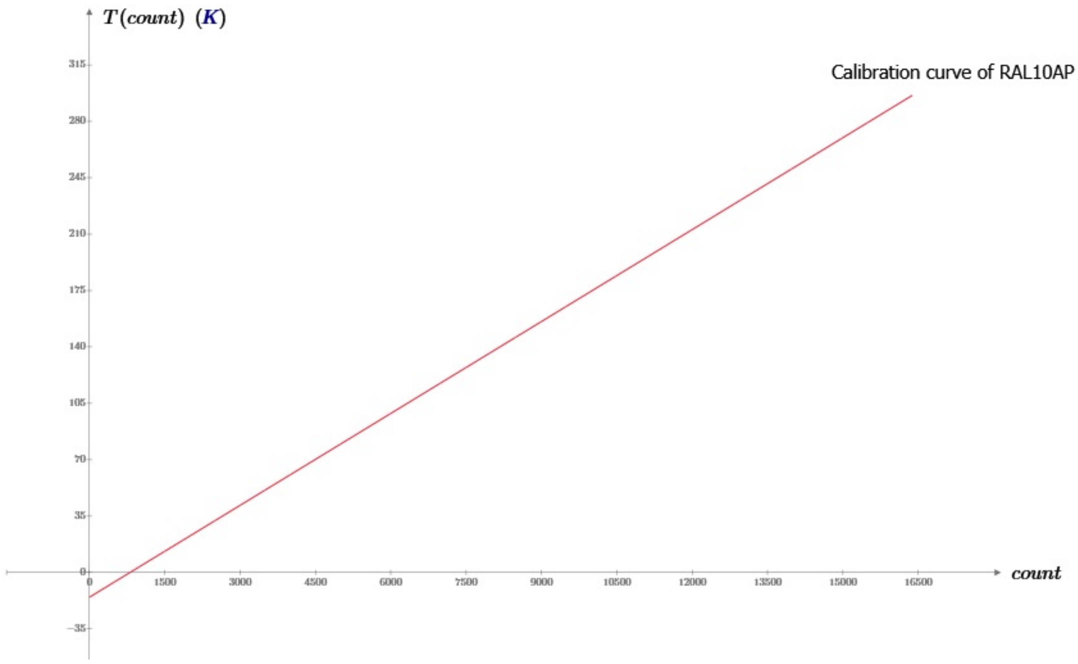

FIGURE 3.3: Calibration line for the telescope that uses the *RAL10AP* receiver.

Appendix A

Estimate of the brightness temperature of the sky at 10-12 GHz.

The following estimate of the *brightness temperature* of the sky at the zenith, in the microwave frequency band 10-12 GHz, considers negligible the noise contribution of the antenna due to natural atmospheric disturbances (hydrometeors, lightning, thunder electrical discharges) and the one due to interfering noise of artificial origin.

It is supposed, therefore, that the only radiation source of the atmosphere is the noise due to the absorption of atmospheric gases and of the constituent molecules, expressed as atmosphere radiant temperature $T_{atm}(f, \theta)$, which depends on the frequency f and on the antenna's elevation angle θ with respect to the horizon.

For its assessment we used the graph in figure A.1, extracted from the document: "Recommendation ITU-R P.372-12 (07/2015) Radio Noise", which calculates the *brightness temperature* of the atmosphere using the equation of radiative transfer in the approximation of Rayleigh-Jeans, excluding the noise contributions due to the microwave cosmic background ($T_{cmb} = 2.725\,K$), to the emission of the galaxy and of other cosmic sources like the Sun and the Moon, to the ground (T_{gnd}) picked up by the antenna side lobes.

Extrapolating data from the graph, at the 11.2 GHz frequency, we get a table of values, by interpolating which we can calculate the noise contribution of the atmosphere $T_{atm}(\theta)$ due to absorption phenomena (atmosphere model US Standard Atmosphere, 1976), depending only on the angle of elevation of the antenna with respect to the horizon (figure A.2).

The *brightness temperature* of the sky at the zenith ($\theta = 90°$) will be:

$$T_{sky}(90°) = T_{cmb} + T_{atm}(90°) = 7.025\ [K] \tag{A.1}$$

This value can be used in radiometer calibration procedure as the "cold" target temperature. If you want to consider also the radiation coming from the ground, captured through the antenna side lobes, you can add a contribution of the order of 3-5 K, depending on the antenna characteristics and the maximum level of its side lobes. This approximation is generally acceptable for amateur radio telescopes focused on the sky at the zenith, sufficiently distant from obstacles or buildings.

Angle of elevation of the antenna θ $[°]$	*brightness temperature* of the atmosphere T_{atm} $[K]$
0	170
5	41
10	22
20	11.5
30	8.2
60	5
90	4.3

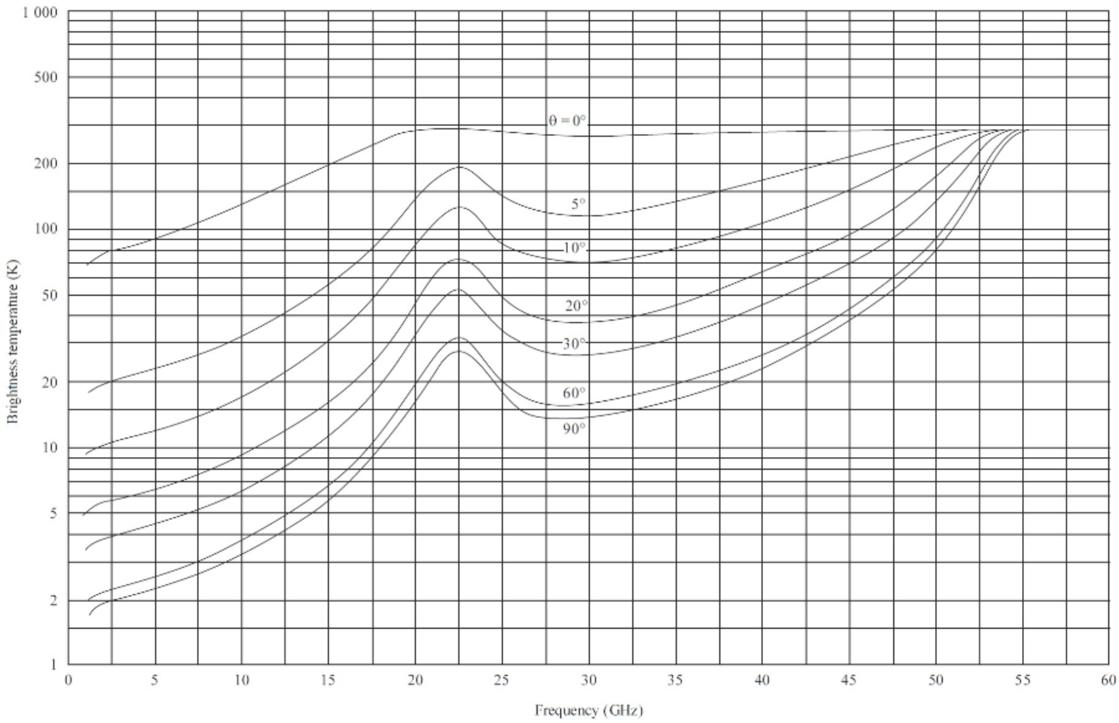

FIGURE A.1: Simulated *brightness temperature* of the atmosphere (Recommendation ITU-R P.372-12 (07/2015) Radio Noise).

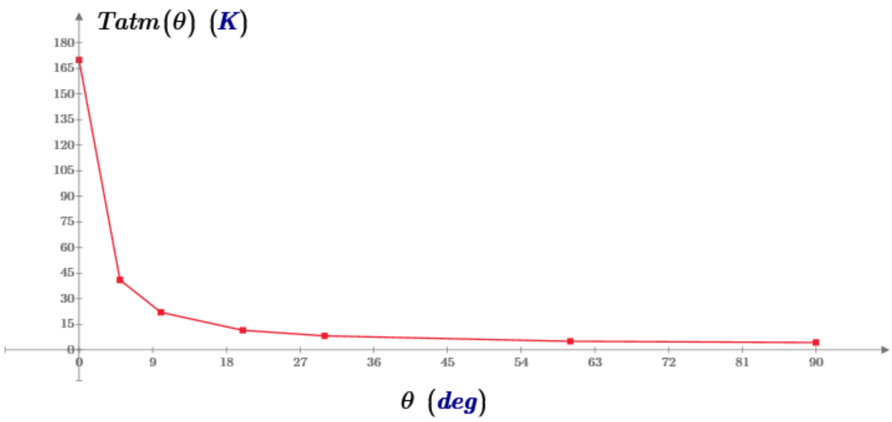

FIGURE A.2: *Brightness temperature* of the atmosphere at 11.2 GHz, in function of the angle of elevation of the antenna, obtained by interpolating the values shown in the table above.

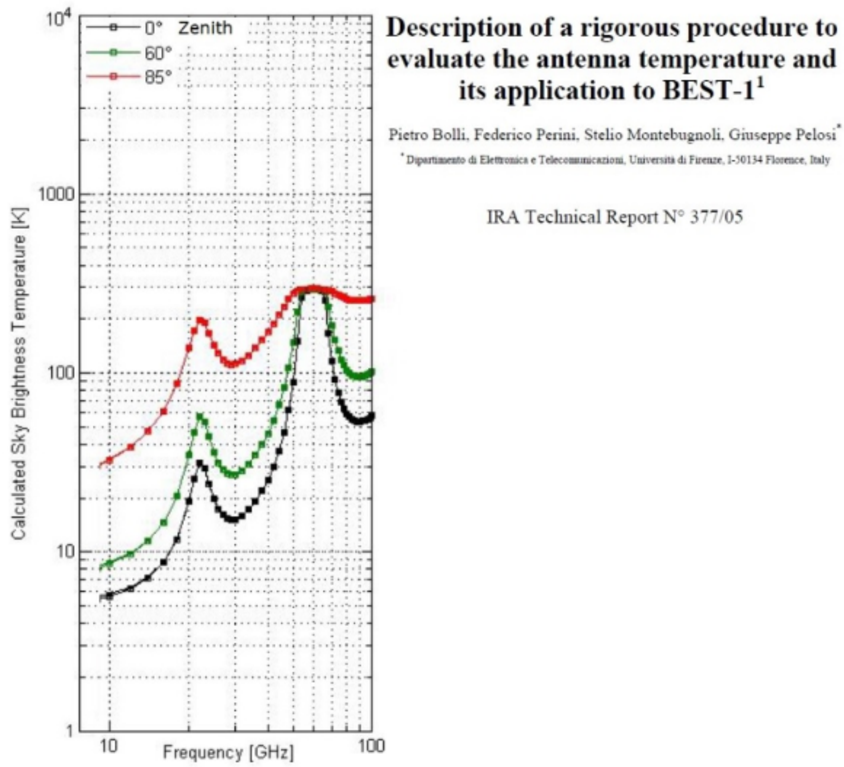

FIGURE A.3: *Brightness temperature* of the atmosphere (IRA Technical Report N. 377/05).

For comparison, it is useful to try an alternative estimate of the *brightness temperature* of the sky at the zenith using other data. We used the graph in figure A.3, which calculates the *brightness temperature* of the atmosphere using the equation of radiative transfer (in the approximation of Rayleigh-Jeans), including the noise contributions due to the cosmic background and to the galaxy. Extrapolating the data for the 11.2 GHz frequency we can see how, when the antenna of the radiometer is oriented towards the sky at the zenith, we can measure a *brightness temperature* of the order of $T_{sky}(90°) = 7\,K$, in agreement with the previous rating.

Bibliography

Abrami, A. (1984). "Corso di radioastronomia". In: *Hoepli, Milano*.

"Basic of Radio Astronomy" (1998). In: *Documento JPL D-13835*.

Christiansen, Hogbom. "Radiotelescopes". In: *Camb. Univ. Press.*

Dicke, R. H. (1946). "The Measurement of Thermal Radiation at Microwaves Frequencies". In: *The Review of Scientific Instruments* 17.7, pp. 268–275.

Falcinelli, F. (2003). "Radioastronomia Amatoriale". In: *Il Rostro, Segrate, MI*.

— (2008). "Tecniche Radioastronomiche". In: *Sandit, Albino, BG*.

— (2013). "Unità Radiometrica Esterna RAL20_LNB". In: *Rapporto Interno RadioAstroLab 18102013*.

— (2015). "RAL10 1.2 GHz Total-Power Microwave Radiometer". In: *Rapporto Interno RadioAstroLab 13012015*.

Kraus, J. D. (1988). "Radio Astronomy". In: *Cygnus-Quasar Books, Powell, Ohio*.

Liou, K. N. (1980). "An introduction to atmospheric radiation". In: *Academic Press, New York, NY*.

N. Skou, D. Le Vine (2006). "Microwave Radiometer Systems – Design and Analysis (2nd ed.)" In: *Artech House*.

Papoulis, A. (1984). "Signal Analysis". In: *McGraw-Hill International Editions, New York*.

R. E. Collin, F. J. Zucker. "Antenna Theory". In: *Mc Graw-Hill Book Co.*

"Recommendation ITU-R P.372-12 (07/2015) Radio Noise" (2015). In: *Recommendation ITU-R*.

Rohlfs, K. "Tools of Radio Astronomy". In: *Springer Verlag*.

Sinigaglia, G. "Elementi di tecnica radioastronomica". In: *C. e C., Faenza*.